TRANSPORTATION TECHNOLOGY SUPPORT
FOR DEVELOPING COUNTRIES

COMPENDIUM 6

Investigation and Development of Materials Resources

Investigación y desarrollo de recursos de materiales

Investigation et développement des gisements de matériaux routiers

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Notice

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competence and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

Cover photo: Crushing operation in El Tholar, Bolivia.

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The development of agriculture, the distribution of food, the provision of health services, and the access to information through educational services and other forms of communication in rural regions of developing countries all heavily depend on transport facilities. Although rail and water facilities may play important roles in certain areas, a dominant and universal need is for road systems that provide an assured and yet relatively inexpensive means for the movement of people and goods. The bulk of this need is for low-volume roads that generally carry only 5 to 10 vehicles a day and that seldom carry as many as 400 vehicles a day.

The planning, design, construction, and maintenance of low-volume roads for rural regions of developing countries can be greatly enhanced with respect to economics, quality, and performance by the use of low-volume road technology that is available in many parts of the world. Much of this technology has been produced during the developmental phases of what are now the more developed countries, and some is continually produced in both the less and the more developed countries. Some of the technology has been doc-

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Descripción del Proyecto

El desarrollo de la agricultura, la distribución de víveres, la provisión de servicios de sanidad, y el acceso a información por medio de servicios educacionales y otras formas de comunicación en las regiones rurales de países en desarrollo todos dependen en gran parte de los medios de transporte. Aunque en ciertas áreas los medios de ferrocarril y agua desempeñan una parte importante, una necesidad universal y dominante es para sistemas viales que proveen un medio asegurado pero relativamente poco costoso para el movimiento de gente y mercancías. La gran parte de esta necesidad es para caminos de bajo volúmen que generalmente mueven unicamente unos 5 a 10 vehículos por día y que pocas veces mueven tanto como 400 vehículos por día.

Con respecto a la economía, calidad, y rendimiento, el planeamiento, diseño, construcción y manutención de caminos de bajo volúmen para regiones rurales de países en desarrollo pueden ser mejorados en gran parte por el uso de la tecnología de caminos de bajo volúmen que se encuentra disponible en muchas partes del mundo. Mucha de esta tecnología ha sido producida durante las épocas de desarrollo de lo que ahora son los países mas desarrollados, y alguna se produce continuamente en los países menos y mas

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Description du Projet

Dans les régions rurales des pays en voie de développement, l'exploitation agricole, la distribution des produits alimentaires, l'accès aux services médicaux, l'accès à l'information par l'intermédiaire de moyens éducatifs et d'autres moyens de communication, dépendent en grande partie des moyens de transport. Bien que les transports par voie férrée et par voie navigable jouent un rôle important dans certaines régions, un besoin dominant et universel éxiste d'un réseau routier qui puisse assurer avec certitude et d'une façon relativement bon marché, le déplacement des habitants, et le transport des marchandises. La plus grande partie de ce besoin peut être satisfaite par la construction de routes à faible capacité, capables d'accommoder un trafic de 5 a 10 véhicules par jour, ou plus rarement, jusqu'à 400 véhicules par jour.

L'utilisation des connaissances en technologie, qui éxistent déjà et sont accéssibles dans beaucoup de pays, peut faciliter l'étude des projets de construction, tracé et entretien, de routes à faible capacité dans les régions rurales des pays en voie de développement, surtout en ce qui concerne l'économie, la qualité, et la performance de ces routes. La majeure partie de cette technologie a été produite durant la phase de développement des pays que l'on appelle maintenant déumented in papers, articles, and reports that have been written by experts in the field. But much of the technology is undocumented and exists mainly in the minds of those who have developed and applied the technology through necessity. In either case, existing knowledge about low-volume road technology is widely dispersed geographically, is quite varied in the language and the form of its existence, and is not readily available for application to the needs of developing countries.

In October 1977 the Transportation Research Board (TRB) began this 3-year special project under the sponsorship of the U.S. Agency for International Development (AID) to enhance rural transportation in developing countries by providing improved access to existing information on the planning, design, construction, and maintenance of low-volume roads. With advice and guidance from a project steering committee, TRB defines, produces, and transmits information products through a network of correspondents in developing countries. Broad goals for the ultimate impact of the project work are to promote effective use of existing information in the economic development of transportation infrastructure and thereby to enhance other aspects of rural development throughout the world.

In addition to the packaging and distribution of technical information, personal interactions with users are provided through field visits, conferences in the United States and abroad, and

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desarrollados. Parte de la tecnología se ha documentado en disertaciones, artículos, e informes que han sido escritos por expertos en el campo. Pero mucha de la tecnología no esta documentada y existe principalmente en las mentes de aquellos que han desarrollado y aplicado la tecnología por necesidad. En cualquier caso, los conocimientos en existencia sobre la tecnología de caminos de bajo volúmen están grandemente esparcidos geograficamente, varían bastante con respecto al idioma y su forma, y no se encuentran facilmente disponibles para su aplicación a las necesidades de los países en desarrollo.

En octubre de 1977 el Transportation Research Board (TRB) comenzó con este proyecto especial de tres años de duración bajo el patrocinio de la U.S. Agency for International Development (AID) para mejorar el transporte rural en los países en desarrollo acrecentando la disponibilidad de la información en existencia sobre el planeamiento, diseño, construcción, y manutención de caminos de bajo volúmen. Con el consejo y dirección de un comité de iniciativas para el proyecto, el TRB define, produce, y transmit productos informativos a través de una red de corresponsales en países en desarrollo. Las metas generales para el impacto final del trabajo del proyecto son la promoción del uso efectivo de la información en existencia en el desarrollo económico de la infraestructura de transporte y de esta forma mejorar otros aspectos del desarrollo rural a través del mundo.

Además de la recolección y distribución de la información técnica, se provee acciones recíprocas personales con los usuarios por

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veloppés, et elle continue à être produite à la fois dans ces pays et dans les pays en voie de développement. Certains aspects de cette technologie ont été documentés dans des articles ou rapports écrits par des experts. Mais une grande partie des connaissances n'éxiste que dans l'esprit de ceux qui ont développé et appliqué cette technologie par nécessité. De plus, dans ces deux cas, les écrits et connaissances sur la technologie des routes à faible capacité, sont dispersés géographiquement, sont écrits dans des langues différentes, et ne sont pas assez aisément accessibles pour être appliqués aux besoins des pays en voie de développement.

En octobre 1977, le Transportation Research Board (TRB) initia ce projet, d'une durée de 3 ans, sous le patronage de l'U.S. Agency for International Development (AID), pour améliorer le transport rural dans les pays en voie de développement, en rendant plus accessible la documentation éxistante sur la conception, le tracé, la construction, et l'entretien des routes à faible capacité. Avec le conseil, et sous la conduite d'un Comité de Direction, TRB définit, produit, et transmet cette documentation à l'aide d'un réseau de correspondants dans les pays en voie de développement. Généralement, l'aboutissement final de ce projet sera de favoriser l'utilisation de cette documentation, pour aider au développement économique de l'infrastructure des transports, et de cette façon mettre en valeur d'autres aspects d'exploitation rurale à travers le monde.

En plus de la dissémination de cette documentation technique, des visites, des conférences aux Etats Unis et à l'étranger, et other forms of communication.

Steering Committee

The Steering Committee is composed of experts who have knowledge of the physical and social characteristics of developing countries, knowledge of the needs of developing countries for transportation, knowledge of existing transportation technology, and experience in its use.

Major functions of the Steering Committee are to assist in the definition of users and their needs, the definition of information products that match user needs, and the identification of informational and human resources for development of the information products. Through its membership the committee provides liaison with project-related activities and provides guidance for interactions with users. In general the Steering Committee gives overview advice and direction for all aspects of the project work.

The project staff has responsibility for the preparation and transmittal of information products, the development of a correspondence network throughout the user community, and interactions with users.

Information Products

Three types of information products are prepared: compendiums of documented information on relatively narrow topics, syntheses of knowledge and

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medio de visitas de campaña, conferencias en los Estados Unidos de Norte América y en el extranjero, y otras formas de comunicación.

Comité de Iniciativas

El Comité de Iniciativas se compone de expertos que tienen conocimiento de las características físicas y sociales de los países en desarrollo, conocimiento de las necesidades de transporte de los países en desarrollo, conocimiento de la tecnología de transporte en existencia, y experiencia en su uso.

Las funciones importantes del Comité de Iniciativas son las de asistir en la definición de usuarios y sus necesidades, de productos informativos que se asemejan a las necesidades del usuario, y la identificación de recursos de conocimientos y humanos para el desarrollo de los productos informativos. A través de sus miembros el comité provee vínculos con actividades relacionadas con el proyecto y también una guía para la interacción con los usuarios. En general el Comité de Iniciativas proporciona consejos y dirección general para todos los aspectos del trabajo de proyecto.

El personal de proyecto tiene la responsabilidad para la preparación y transmisión de los productos informativos, el desarrollo de una red de corresponsales a través de la comunidad de usuarios, y la interacción con los usuarios.

Productos Informativos

Se preparan tres tipos de productos informativos: los compendios de la información documentada sobre relativamente limitados

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d'autres formes de communication permettent une interaction constante avec les usagers.

Comité de Direction

Le Comité de Direction est composé d'experts qui ont à la fois des connaissances sur les caractéristiques physiques et sociales des pays en voie de développement, sur leurs besoins au point de vue transports, sur la technologie actuelle des transports, et ont aussi de l'expérience quant à l'utilisation pratique de cette technologie.

Les fonctions majeures de ce comité sont d'abord d'aider à définir les usagers et leurs besoins, puis de définir leurs besoins en matière de documentation, et d'identifier les ressources documentaires et humaines nécessaires pour le développement de cette documentation. Par l'intermédiaire de ses membres, le comité pourvoit à la liaison entre les différentes fonctions relatives au projet, et dirige l'interaction avec les usagers. En général, le Comité de Direction conseille et dirige toutes les phases du projet.

Le personnel attaché à ce projet est responsable de la préparation et de la dissémination des documents, du développement d'un réseau de correspondants pris dans la communauté d'usagers, et de l'interaction avec les usagers.

La Documentation

Trois genres de documents sont preparés: des recueils dont le sujet sera relativement limité, des synthèses de connaissances et de pratique sur des sujets beaucoup plus généraux, et finalement des comptes-rendus practice on somewhat broader subjects, and proceedings of low-volume road conferences that are totally or partially supported by the project. Compendiums are prepared by project staff at the rate of about 6 per year; consultants are employed to prepare syntheses at the rate of 2 per year. At least one conference proceedings will be published during the 3-year period. In summary, this project aims to produce and distribute between 20 and 30 publications that cover much of what is known about low-volume road technology.

Interactions With Users

A number of mechanisms are used to provide interactions between the project and the user community. Project news is published in each issue of *Transportation Research News.* Feedback forms are transmitted with the information products so that recipients have opportunity to say how the products are beneficial and how they may be improved. Through semiannual visits to developing countries, the project staff acquires first-hand suggestions for the project work and can assist directly in specific technical problems. Additional opportunities for interaction with users arise through international and in-country conferences in which there is project participation. Finally, annual colloquiums are held for students from developing countries who are enrolled at U.S. universities.

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temas, la síntesis del conocimiento y práctica sobre temas un poco mas ámplios, y los expedientes de conferencias de caminos de bajo volúmen que están totalmente o parcialmente amparados por el proyecto. El personal de proyecto prepara los compendios a razón de unos 6 por año; se utilizan consultores para preparar las sintesis a razón de 2 por año. Se publicará por lo menos un expediente de conferencia durante el período de tres años. En breve, este proyecto pretende producir y distribuir entre 20 y 30 publicaciones que cubren mucho de lo que se conoce de la tecnología de caminos de bajo volúmen.

Interacción con los Usuarios

Se utilizan varios mecanismos para proveer las interacciones entre el proyecto y la comunidad de usuarios. Se publican las noticias del proyecto en cada edición de la *Transportation Research News.* Se transmiten formularios de retroacción con los productos informativos para que los recipientes tengan oportunidad de decir cómo benefician los productos y cómo pueden ser mejorados. A través de visitas semianuales a los países en desarrollo, el personal del proyecto adquiere directo de fuentes originales sugerencias para el trabajo del proyecto y puede asistir directamente en problemas técnicos específicos. Surgen oportunidades adicionales para la interacción con los usuarios a través de conferencias internacionales y nacionales en donde participa el proyecto. Finalmente, se organizan diálogos con estudiantes de países en desarrollo que están inscriptos en universidades norteamericanas.

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de conférences sur les routes à faible capacité qui seront organisées complètement ou en partie par ce projet. Environ 6 recueils par an sont preparés par le personnel attaché au projet. Deux synthèses par an sont écrites par des experts. Les comptes-rendus d'au moins une conférence seront écrits dans une période de 3 ans. En résumé, l'objet de ce projet est de produire et disséminer entre 20 et 30 documents qui couvriront l'essentiel des connaissances sur la technologie des routes à faible capacité.

Interaction Avec les Usagers

Un certain nombre de mécanismes sont utilisés pour assurer l'interaction entre le personnel du projet et la communauté d'usagers. Un bulletin d'information est publié dans chaque numéro de Transportation Research News. Des formulaires sont joints aux documents, afin que les usagers aient l'opportunité de juger de la valeur de ces documents et de donner leur avis sur les moyens de les améliorer. Au cours de visites semi-annuelles dans les pays en voie de développement, le personnel obtient de première main des suggestions sur le bon fonctionnement du projet et peut aider à résoudre sur place certains problèmes techniques spécifiques. En outre, des conférences tenues soit aux Etats Unis, soit à l'étranger, sont l'occasion d'un échange d'idées entre le personnel et les usagers. Finalement, des colloques annuels sont organisés pour les étudiants des pays en voie de développement qui étudient dans les universités americaines.

Foreword and Acknowledgments

This compendium is the sixth product of the Transportation Research Board's project on Transportation Technology Support for Developing Countries under the sponsorship of the U.S. Agency for International Development. The objective of this book is that it provide useful and practical information for those in developing countries who have direct responsibility for materials resources. Feedback from correspondents in developing countries will be solicited and used to assess the degree to which this objective has been attained and to influence the nature of later products.

Acknowledgment is made to the following publishers for their kind permission to reprint the Selected Text portions of this compendium:

Australian Road Research Board, Melbourne;
Transport and Road Research Laboratory, U.K.;
U.S. Agency for International Development, Washington, D.C.;
U.S. Army, Washington, D.C.

Prefacio y Agradecimientos

Este compendio es el sexto producto del proyecto del Transportation Research Board sobre Apoyo de Tecnología de Transporte para Países en Desarrollo bajo el patrocinio de la U.S. Agency for International Development. El objetivo de este libro es el de proveer información útil y práctica para aquellos en países en desarrollo quienes tienen responsabilidad directa para recursos de materiales. Se pedirá a los corresponsales en los países en desarrollo información sobre los resultados, para utilizarse en el asesoramiento del grado al cuál se ha obtenido ese objetivo ya para influenciar la naturaleza de productos subsequentes.

Se reconoce a los siguientes editores por el permiso dado para re-imprimir las porciones de texto seleccionadas de este compendio:

Australian Road Research Board, Melbourne;
Transport and Road Research Laboratory, U.K.;
U.S. Agency for International Development, Washington, D.C.;
U.S. Army, Washington, D.C.

Avant-propos et Remerciements

Ce recueil représente le sixième volume du projet du Transportation Research Board sur la Technologie des Transports à l'Usage des Pays en Voie de Développement. Ce projet est placé sous le patronage de l'U.S. Agency for International Development. L'objet de ce recueil est de réunir une documentation pratique et utile qui puisse aider les responsables des gisements de matériaux routiers. La réaction des correspondants des pays en voie de développement sera sollicitée et utilisée pour évaluer à quel point le but proposé de ce projet a été atteint et pour influencer la nature des ouvrages à venir.

Nous remercions des éditeurs qui ont gracieusement donné leur permission de reproduire les textes sélectionnés pour ce recueil:

Australian Road Research Board, Melbourne;
Transport and Road Research Laboratory, U.K.;
U.S. Agency for International Development, Washington, D.C.;
U.S. Army, Washington, D.C.

Appreciation is also expressed to libraries and information services that provided references and documents from which final selections were made for the Selected Texts and Bibliography of this compendium. Special acknowledgment is made to the U.S. Department of Transportation Library Services Division and to the Library and Information Service of the U.K. Transport and Road Research Laboratory (TRRL). Photographs provided by TRRL have been reproduced by permission of Her Majesty's Stationery Office.

Finally, the Transportation Research Board acknowledges the valuable advice and direction that have been provided by the project Steering Committee and is especially grateful to W. Ronald Hudson, University of Texas at Austin, W. G. Wilson, International Road Federation, and John P. Zedalis, U.S. Agency for International Development, who provided special assistance on this particular compendium.

También se reconoce a las bibliotecas y servicios de información que proveen las referencias y documentos de los cuales se hacen las selecciones finales para los Textos Seleccionados y la Bibliografía en este compendio. Se hace un especial reconocimiento a la Library Services Division de la U.S. Department of Transportation y el Library and Information Service de la U.K. Transport and Road Research Laboratory (TRRL). Las fotografías proveídas por TRRL fueron reproducidas bajo permisión de Her Majesty's Stationery Office.

Finalmente, el Transportation Research Board agradece el consejo y dirección valiosos provisto por el Comité de Iniciativas, con especial reconocimiento a los señores W. Ronald Hudson, University of Texas at Austin, W. G. Wilson, International Road Federation y John P. Zedalis, U.S. Agency for International Development, que prestaron ayuda especial para este compendio en particular.

Nos remerciements aussi aux bibliothèques et bureaux de documentation qui nous ont fourni les documents et les références utilisés dans les Textes Choisis et Bibliographie de ce recueil. Nous remercions spécialement la U.S. Department of Transportation Library Services Division et les Library and Information Service of the U.K. Transport and Road Research Laboratory (TRRL). Les photos fournies par le TRRL ont été reproduites avec la permission de Her Majesty's Stationery Office.

Finalement, le Transportation Research Board reconnait la grande valeur de la direction et de l'assistance des membres du Comité de Direction et les remercie de leur concours et de la façon dont ils dirigent le projet, spécialement Messieurs W. Ronald Hudson, University of Texas at Austin, W. G. Wilson, International Road Federation, et John P. Zedalis, U.S. Agency for International Development, qui ont bien voulu prêter leur assistance à la préparation de ce récueil.

Overview

Background and Scope

No road can be constructed without using some type of material. Earth tracks may be constructed with in situ material that should be classified to determine its characteristics. Texts included in Compendium 2 provide background data for information contained in Compendium 6. For example, *Subsurface Soils Exploration, Field Identification of Soils and Aggregates for County Roads, Design Manual: Soil Mechanics, Foundations, and Earth Structures,* and *The Identification of Rock Types* discuss how to classify materials. Other texts in Compendium 2, such as *The Engineering Significance of Landforms, Terrain Evaluation for Road Engineers in Developing Countries,* and *Drainage Pattern Significance in Airphoto Identification of Soils and Bedrocks,* will assist the highway location engineer in evaluating soils in corridors under

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Vista General

Antecedentes y alcance

No se puede construir ningún camino sin utilizar algún tipo de material. Vías de tierra pueden construirse con material en situ, que debe clasificarse para determinar sus características. Hay textos incluídos en el Compendio 2 que proveen datos básicos para la información contenida en el Compendio 6. Por ejemplo, *Subsurface Soils Exploration* (Exploración de los subsuelos), *Field Identification of Soils and Aggregates for County Roads* (Identificación en campaña de los suelos y agregados para caminos de condado), *Design Manual: Soil Mechanics, Foundations and Earth Structures* (Manual de diseño: Mecánicas del suelo, fundamentos y estructuras de tierra), y *The Identification of Rock Types* (La identificación de tipos de rocas) hablan de cómo clasificar materiales. Otros textos en el Compendio 2, tales como *The Engineering Significance of Landforms* (El significado ingenieril de formas de terreno), *Terrain Evaluation for Road Engineers in Developing Countries* (Evaluación del terreno para ingenieros viales en paises en desarrollo), y *Drainage Pattern Significance in Airphoto Identification of Soils and Bedrocks* (El significado del patrón de drenaje en la identificación por foto aérea de suelos y lechos de roca), ayudarán al ingeniero de ubicación del camino en evaluar los suelos en las zonas de

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Exposé

Historique et objectif

On ne peut pas construire une route sans utiliser quelque sorte de matériau. Les routes en terres peuvent être construites avec des matériaux trouvés in-situ qui doivent être classifiés afin de déterminer leurs caractéristiques. Certains textes choisis du Recueil No. 2 donnent les données de base qui vont être développées dans le Recueil No. 6. Par exemple, *Subsurface Soils Exploration, Identification of Soils and Aggregates for County Roads, Design Manual: Soil Mechanics, Foundations and Earth Structures,* et *The Identification of Rock Types,* expliquent la classification des matériaux. D'autres textes du Recueil No. 2 comme, *The Engineering Significance of Landforms, Terrain Evaluation for Road Engineers in Developing Countries* et *Drainage Pattern Significance in Airphoto Identification of Soils and Bedrocks,* aideront l'ingénieur routier à évaluer les sols des corridors à étudier pour des routes spécifiques. Ces textes sont importants aussi pour l'ingénieur à la recherche de matériaux pour améliorer une route déjà construite ou pour construire une nouvelle route. Dans le Recueil No. 6, nous examinons la classification et les gisements de matériaux de deux points de vue. Le premier, appelé inventaire de projet, study for specific roads. These texts are important to the engineer seeking materials with which to improve existing roads or to build new ones.

Compendium 6 examines the classification and location of materials resources in two contexts. The first is a project inventory, concerned with the exact location and development of materials to be used on a specific road construction project. The second is a general inventory of materials available throughout a large geographic area for use in the planning and evaluation of future highway locations. The principles of soil classification remain the same in both cases.

Compendium 2 was prepared for the location engineer who has no preliminary soil information available. Compendium 6 provides further information about the methods of inventorying materials on a large scale. Such an inventory not only helps the location engineer with specific problems, but also assists the planning engineer in evaluating corridors before the location engineer becomes involved.

Because the majority of materials used in road construction comes from the earth's crust, the scope of Compendium 6 is limited to an inventory of these resources. The location of timber for bridges or retaining walls and the determination of the availability of manufactured materials, such as culvert pipes, steel beams, cement, and reinforcing bars, are not considered.

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paso estudio para caminos específicos. Estos textos son importantes para el ingeniero que busca el material con el cuál mejorará caminos yá existentes, ó para construir caminos nuevos.

El compendio 6 examina la clasificación y ubicación de recursos de materiales en dos contextos. El primero es un inventario de proyecto, que se concierne con la ubicación exacta y el desarrollo de materiales a utilizarse en un proyecto específico de construcción de camino. El segundo es un inventario general de materiales disponibles a través de un área geográfica amplia para utilizarse en la planificación y evaluación de futuras ubicaciones de camino. Los principios de clasificación de suelos son los mismos en ambos casos.

El Compendio 2 se preparó para el ingeniero de ubicación que no tiene disponible información de suelos preliminar. El Compendio 6 provee más información sobre los métodos de inventariar los materiales en más grande escala. Tal inventario no solo ayuda al ingeniero de ubicación con problemas específicos, pero también ayuda al ingeniero de planificación en la evaluación de zonas de paso antes de que se concierna el ingeniero de ubicación.

Ya que la mayoría de los materiales que se utilizan en la construcción de caminos provienen de capas de la tierra, el alcance del Compendio 6 se limita al inventario de estos recursos. No se consideran la ubicación de madera para puentes ó muros de contención ni se determina si hay disponibles materiales manufacturados tales como tuberías para alcantarillas, vigas de acero, cemento y varillas de refuerzo.

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concerne la localisation et le développement de matériaux routiers pour la construction d'une route spécifique. Le deuxième est l'inventaire général des matériaux routiers d'une région géographique étendue, qui sera utilisé au moment de la planification et de l'évaluation des emplacements des routes à construire. Les principes de la classification des sols sont les mêmes dans les deux cas.

Le Recueil No. 2 est destiné à l'ingénieur qui va déterminer le tracé de la route et n'a aucune information préliminaire sur les sols. Le Recueil No. 6 va plus loin et donne des informations plus détaillées sur l'inventaire des matériaux routiers à grande échelle. Cet inventaire non seulement aidera à résoudre les problèmes spécifiques de l'ingénieur chargé du tracé de la route, mais aidera aussi l'ingénieur planificateur qui le premier, détermine quels corridors seront évalués. Comme la plus grande partie des matériaux de construction est tirée de l'écorce terrestre, ce recueil se limitera à l'inventaire de celle-ci.

Les méthodes de localisation de bois pour la charpente des ponts et des murs de soutènement, et de matériaux manufacturés comme les conduites de drainage les poutres en acier, le ciment et les barres d'armature, ne sont donc pas considérées.

Rationale for This Compendium

Several soil classification systems are used throughout the world. Various texts, therefore, use different terminology to refer to specific soils. An engineer trained in one classification system may have difficulty in understanding literature based on a different system. Compendium 6 presents the basic requirements for any soil classification system. It also compares some of the more commonly used systems.

A more detailed evaluation of soil patterns is presented. Materials inventories in rural and inaccessible areas are often based on aerial photography. Therefore, understanding the significance of clues contained in such imagery is important.

Several types of materials inventories can be

Exposición razonada para este compendio

Se utilizan varios sistemas de clasificación de suelos a través del mundo. Por lo tanto, los varios textos utilizan distintas terminologías para referirse a suelos específicos. El ingeniero entrenado en un sistema de clasificación podría tener dificultades en comprender la literatura basada en otro sistema. El compendio 6 presenta los requisitos básicos para cualquier sistema de clasificación de suelos. También compara algunos de los sistemas más comunmente utilizados.

Se presenta una evaluación más detallada de configuraciones de suelos. Los inventarios de materiales en áreas rurales e inaccesibles muchas veces se basan en fotografías aéreas. Por lo tanto, es importante poder comprender el significado de indicios contenidos en tales imágenes.

Se pueden hacer varios tipos de inventarios de materiales. El más simple y menos costoso es el inventario de materiales que yá se han encontrado y ensayado. El inventario más difícil y costoso incluye (a) la ubicación y proyección de todas las formaciones geológicas en un área, (b) la selección de todas las ubicaciones posibles de material utilizable, (c) la recolección y ensayo de muestras de cada ubicación, y (d) una tabulación de los resultados de los ensayos, ubicaciones de hoyos y estimaciones de cantidades de todos los materiales utilizables.

Se pueden utilizar fotografías aéreas disponibles como base para inventarios de materiales. Si se trata de llevar a cabo un inventario completo y exacto, se deben considerar otros tipos de imágenes. Hoy en día hay muchas nuevas formas de imágenes obtenidas por sensores remotos disponibles para el ingeniero vial. Entre ellas está la fotografía aérea multiespectral visible e infrarroja ("near-infrared") y las imágenes exploradores multiespectrales del satélite LANDSAT. Sin embargo, se requieren téc-

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Objet de ce recueil

Plusieurs méthodes de classification des sols sont utilisées dans le monde. Certains textes donc, utilisent une terminologie différente, pour identifier des sols spécifiques. Un ingénieur qui a étudié une méthode de classification peut avoir des difficultés à comprendre un texte basé sur une autre méthode. Dans ce recueil, nous allons présenter les conditions requises d'un système de classification quelqu'il soit, et faire la comparaison entre les plus communs.

Une évaluation en plus grands détails des types de formations caractéristiques des sols est présentée. Dans les régions rurales ou inaccessibles, les inventaires de matériaux routiers sont souvent basés sur les photos aériennes. De ce fait, l'interprétation correcte de ces photos est très importante.

Il y a plusieurs sortes d'inventaires de matériaux routiers. Le plus simple, et le plus économique, est l'inventaire de matériaux qui ont déjà été découverts et prouvés. Le plus difficile, et le plus dispendieux, est un inventaire qui comprend (a) situer et faire le plan de toutes les formations géologiques d'une région (b) choisir les gisements possibles de matériaux utilisables (c) assembler et analyser les échantillons de chaque gisement et (d) dresser un tableau synoptique des résultats des essais, de la location des gisements et des quantités estimées de tous les matériaux utilisables.

La photointerprétation peut être l'instrument de base d'un inventaire de matériaux. Cepenmade. The simplest and the least expensive is an inventory of materials that have already been found and tested. The most difficult and expensive inventory includes (a) the location and mapping of all geological formations in an area, (b) the selection of all possible sites of usable materials, (c) the collection and testing of samples from each site, and (d) a tabulation of the test results, pit locations, and quantity estimates of all usable materials.

Available aerial photographs can be used as a basis for materials inventories. If a complete and accurate inventory is attempted, other forms of imagery should be considered. Many new forms of remote sensing imagery are available to the highway engineer today. Among them are visible and near-infrared multispectral photography from aircraft and multispectral scanner

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nicas interpretativas especializadas para el uso de estos productos.

Una vez que se decida conducir un inventario de materiales, se debe determinar las mecánicas del inventario. Este compendio describe solo uno de los muchos inventarios de materiales que se pueden utilizar, es decir, un inventario de materiales completo orientado al proyecto. Este ejemplo subraya la importancia de utilizar un interpretador de fotos aéreas competente en el inventario de materiales completo.

Se requiere la investigación subsuperficial de ubicaciones posibles de materiales para determinar el tipo y cantidad del material presente. Esta investigación puede variar de un solo hoyo cavado a mano a una serie de perforaciones. Muchas veces se utilizan métodos sísmicos ó de resistencia específica en las investigaciones exploratorias del subsuelo. Se pueden investigar grandes áreas a bajo costo y rapidamente con equipo portátil. El Compendio 6 examina la teoría y limitaciones de estos métodos.

Se deben desarrollar los depósitos de materiales seleccionados. El socavón de un hoyo debe hacerse metodicamente en secuencia preplaneada para que no se tenga que remanipular el material. Las operaciones de hoyo deben seguir procedimientos establecidos dado el equipo disponible. Se deben determinar los patrones de tránsito para asegurar el uso máximo de todo el equipo disponible. Se deben mantener caminos de acceso para que no se interrumpa la operación de acarreo. El drenaje del hoyo y de los caminos de acceso es tan importante como el drenaje del camino bajo construcción.

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dant si on veut faire un inventaire complet et précis, d'autres genres d'imagerie devaient être aussi considerés. Aujourd'hui, l'ingénieur routier a à sa disposition d'autres moyens comme l'imagerie acquise par télédétection. Un de ceux-ci est la photo aèrienne visible et infrarouge multispectrale et l'imagerie obtenue par les radiomètres multispectraux à balayage du satellite Landsat. Notons cependant que l'emploi de ces moyens demande des techniques d'interprétation spéciales.

Une fois que l'on a décidé de faire un inventaire de matériaux routiers, la façon dont on va le conduire reste à déterminer. Parmi les nombreuses méthodes qui existent, ce recueil en a choisi une et décrit la marche à suivre pour faire un inventaire pratique de matériaux routiers. Cette méthode met l'accent sur le fait qu'il est nécessaire de confier la photointerprétation à un spécialiste confirmé. Un examen du sous-sol des gisements en puissance est nécessaire pour déterminer le type et la quantité des matériaux. Cet examen peut aller du simple prélèvement fait à la main à toute une série de sondages. Fréquemment, les prospections des sous-sols sont faites en utilisant les méthodes de mesure de résistivité ou de sollicitation sismique. De grandes étendues peuvent être examinées de façon à la fois économique et rapide en utilisant un matériel portatif. La théorie et les restrictions de ces méthodes sont étudiées dans ce recueil.

Les gisements de matériaux que l'on a choisi doivent être exploités. La mise en oeuvre d'une carrière doit être faite de façon méthodique et ordonnée afin que l'on ait besoin de manipuler les matériaux qu'une fois. La mise en oeuvre de la carrière doit être faite en suivant des méthodes déterminées par l'équipement disponible. On doit prévoir la circulation afin d'assurer l'utilisation maximale de tout l'équipement. Les pistes de desserte doivent être entretenues afin que le transport des matériaux ne soit pas interrompu. Le drainage des excavations et des pistes de desserte est aussi important que le drainage de la route à construire.

imagery from the LANDSAT satellite. However, special interpretative techniques are required to use these tools.

Once the decision is made to conduct a materials inventory, the mechanics of the inventory must be determined. This compendium describes only one of the many materials inventories that can be used, i.e., a complete project-oriented materials inventory. This example stresses the importance of using a competent air-photo interpreter for complete materials inventories.

Subsurface investigation of possible materials sites is required to determine the type and quantity of the materials present. This investigation can range from a single hand-dug hole to a series of borings. Quite frequently, exploratory subsurface investigations are made using seismic or resistivity methods. Large areas can be investigated inexpensively and quite rapidly with portable equipment. Compendium 6 examines the theory and limitations of these methods.

Material deposits selected for use must be developed. The opening of a pit should be done methodically in a preplanned sequence so that material does not have to be rehandled. Pit operations should follow set procedures given the equipment available. Traffic patterns must be determined to ensure the maximum use of all available equipment. Access roads must be maintained so that the hauling operation will not be interrupted. Drainage of the pit and access

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Presentación de los textos seleccionados

El primer texto, ***A Review of Engineering Soil Classification Systems*** (Repaso de sistemas ingenieriles de clasificación de suelos), apareció por primera vez en el ***Highway Research Record 156*** (Registro de investigaciones viales 156) (Highway Research Board, 1967). Habla sobre la naturaleza y necesidad para la clasificación de suelos y la distinción entre identificación de suelos y clasificación de suelos. Se describen los requerimientos para un sistema satisfactorio ingenieril de clasificación de suelos. Se tabulan las propiedades de suelo que pueden utilizarse para propósitos de clasificación.

Se comparan los sistemas de clasificación de suelos de la AASHO (American Association of State Highway Officials), la clasificacíon unificada de suelos (Unified), y FAA (Federal Aviation Agency). Los sistemas de AASHO y Unified son reconocidos a través del mundo. Las referencias que se han hecho a la clasificación de suelos en compendios anteriores de este proyecto todas han utilizado el sistema de clasificación Unified, una modificación del sistema de clasificación de suelos del Profesor Arthur Casagrande. Algunos de los textos seleccionados en el Compendio 6 se refieren al sistema de AASHO, una modificación del sistema de clasificación del BPR (U.S. Bureau of Public Roads), desarrollado a mediados de los años de 1920 a 1930.

Este texto describe cada sistema utilizando texto y tablas. También presenta diagramas que ayudan en la correcta clasificación de acuerdo a cada una de las tres clasificaciones de suelo. Ya que los criterios adoptados por los sistemas

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Discussion des textes choisis

Le premier texte, ***A Review of Engineering Soil Classification Systems*** (Revue des classifications des sols pour le génie civil), fut publié à l'origine dans le ***Highway Research Record 156*** (Highway Research Board, 1967). La nature et le besoin d'un système de classification sont discutés ainsi que la différence entre la classification et l'identification des sols. Les conditions requises par une classification des sols satisfaisante pour les besoins de l'ingénieur routier sont décrites. Les caractéristiques des sols qui peuvent être utilisées pour effectuer leur classification sont disposées en tables. Une comparaison est faites entre les classifications de l'AASHO (American Association of State Highway Officials), la "classification unifiée" (Unified) et celle de la FAA (Federal Aviation Agency). La classification de l'AASHO et la "classification unifiée" sont connues à travers le monde. Les référence aux classifications des sols des recueils précédents se rapportent à la "classification unifiée" qui est adaptée à celle du professeur Arthur Casagrande. Certains textes choisis du Recueil no. 6 utilisent la classification de l'AASHO, celle-ci étant une modification de la classification BPR (U.S. Bureau of Public Roads) développée dans les années 1920.

Chaque méthode est déscrite et présentée en tableaux. Ce texte contient aussi des tableaux qui permettent de classer correctement les sols roads is as important as the drainage of the roadway under construction.

Discussion of Selected Texts

The first text, ***A Review of Engineering Soil Classification Systems,*** first appeared in ***Highway Research Record 156*** (Highway Research Board, 1967). It discusses the nature and need for soil classification and the distinction between soil identification and soil classification. The requirements for a satisfactory engineering soil classification system are described. The soil properties that may be used for classification purposes are tabulated.

The American Association of State Highway Officials (AASHO), Unified, and Federal Aviation Agency (FAA) soil classification systems are compared. Both the AASHO and Unified sys-

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de clasificación de suelos de la AASHO, Unified, y FAA son algo distintos, hay tablas que correlacionan grupos de suelos comparables entre los tres sistemas. Este texto ayudará al ingeniero a comprender otros textos con los cuales puede no estar familiarizado.

El segundo texto, ***The Engineering Significance of Soil Patterns*** (El significado ingenieril de configuraciones de suelos), fué publicado en el ***Highway Research Board Proceedings, Volume 23*** (Expedientes de la directive de investigación vial, volúmen 23) (1943). Aquí el término configuración de suelo se ha utilizado en sentido comprensivo. Incluye no solo la variación de color de suelos, sino también los muchos otros factores registrados en una fotografía aérea que son influenciados por el suelo. Cuando son correctamente evaluadas, estas configuraciones indican las propiedades ingenieriles del suelo.

El texto se desarrolló de una evaluación ingenieril de pedología, la ciencia de formación de suelos. Ya que la pedología es una fase importante de la interpretación de fotografías, este texto habla sobre una forma simplificada llamada pedología ingenieril. Los ejemplos ilustran la semejanza entre suelos con un orígen común a pesar de su ubicación geográfica. Se incluyen fotografías de varias áreas para mostrar sus configuraciones respectivas.

Las áreas individuales de suelo tienen configuraciones que indican sus propiedades. Con solo utilizar una fotografía aérea, un ingeniero puede estudiar cada uno de los elementos que componen la configuración de suelo. Estos elementos reflejan la naturaleza del perfil de suelo: (a) forma de terreno, (b) características de erosión, (c) color de suelo, (d) drenaje de la super-

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d'après les trois méthodes de classification. Comme les critères adoptés par les classifications AASHO, "unifiée" et FAA sont quelque peu differénts, des tableaux permettent d'effectuer la corrélation pour classer des groupes de sols similaires d'après les trois méthodes. Ce texte permettra à l'ingénieur de se familiariser avec les méthodes qui lui sont étrangères.

Le deuxième texte, ***The Engineering Significance of Soil Patterns*** (L'importance des caractéristiques des sols pour le génie civil), publié dans ***Highway Research Board Proceedings, Volume 23*** (1943). L'expression "caractéristiques des sols" est employée ici dans un sens très large, qui comprend non seulement la couleur des sols, mais aussi les nombreux autres facteurs qui sont influencés par les différents sols et que l'on reconnait dans les photo aériènnes. Ces caractéristiques, quand elles sont interprétées correctement, indiquent les qualités des sols qui intéressent l'ingénieur routier.

Ce texte a été developpé d'après une évaluation pédologique, la pédologie étant la science des formations caractéristique des sols. Puisque la pédologie est une phase importante de la photointerprétation, ce texte discute une forme simplifiée de celle-ci, propre au génie civil. Des exemples illustrent les similarités des sols ayant une origine commune, quelle que soit leur location géographique. Des photos de différentes régions sont incluses pour illustrer les caractéristiques individuelles de ces sols.

Chaque gisement a des caractéristiques qui indiquent les proprietés des sols qu'il contient. En utilisant simplement une photo aériènne, l'ingénieur peut déduire chacun des éléments qui constituent les caractéristiques d'un sol. Ces éléments qui comprennent (a) formations caractéristiques, (b) caractéristiques d'érosion, (c) couleur des sols, (d) caractéristiques de drainage, (e) couverture végétale, (f) pente, (g) utilisation des sols, et (h) de nombreux autres tems are recognized throughout the world. The references made to soil classification in previous compendiums in this project have all used the Unified classification system, a modification of Professor Arthur Casagrande's system. Some of the selected texts in Compendium 6 refer to the AASHO system, a modification of the U.S. Bureau of Public Roads (BPR) classification system developed in the mid-1920s.

This text describes each system by using text and tables. It also presents charts that help in proper classification according to each of the three soil classification systems. Because the criteria adopted by the AASHO, Unified, and FAA systems for classifying soils are somewhat different, tables correlate comparable soils groups among the three systems. This text will help engineers understand other texts with which they may not be familiar.

The second text, ***The Engineering Significance of Soil Patterns,*** was published in ***Highway Research Board Proceedings, Vol. 23*** (1943). The term soil pattern is used here in a comprehensive sense. It includes not only the color pattern of soils but also the numerous other factors that are recorded in an aerial photograph and that are influenced by the soil. When properly evaluated, these patterns indicate the engineering properties of the soil.

The text was developed from an engineering evaluation of pedology, the science of soil formation. Because pedology is an important phase of photointerpretation, this text discusses a simplified form known as engineering pedology. Examples illustrate the similiarity of soils to a common origin regardless of geographic location. Photographs of various areas are included to show their respective patterns.

The individual soil areas have patterns that indicate their properties. Using only an aerial photograph, an engineer may study each of the elements that make up the soil pattern. Among the elements that reflect the nature of the soil profile are (a) land form, (b) erosion characteristics, (c) soil color, (d) surface drainage, (e) vegetative cover, (f) slope, and (g) land use.

The elements of the soil pattern change and their significance varies in differing climatic zones. Climate changes the type of vegetative cover and the significance of soil colors, while the soil pattern emphasizes the significance of land forms and weathered slopes. Therefore, a group of photographs will still show the basic soil patterns, geologic patterns, and the occurrence of granular deposits.

The third text, ***Maps for Construction Materials,*** was published in *Highway Research Board Bulletin 28* (1950). This report states that the

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ficie, (e) cubierta vegetativa, (f) pendiente, (g) uso del terreno, y (h) otros.

Los elementos de la configuración de suelo cambian, y su significado varía, en distintas zonas climáticas. El clima cambia el tipo de cubierta vegetativa y el significado del color de suelo, mientras que la configuración de suelo acentúa el significado de las formas de terreno y pendientes curtidos por la intemperie. Por lo tanto, un grupo de fotografías todavía indicará las configuraciones básicas de suelo, configuraciones geologicas, y la incidencia de depósitos granulares.

El tercer texto, ***Maps for Construction Materials*** (Mapas para materiales de construcción), fué publicado en ***Highway Research Board Bulletin 28*** (Boletín del directivo de investigación vial 28, 1950). Este informe afirma que las rocas y sedimentos de la capa de la tierra son los materiales básicos que el ingeniero necesita para la construcción. Por lo tanto los mapas de materiales son necesarios para la búsqueda de ma-

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éléments, constituent ce qu on appelle le profil du sol.

Ces éléments caractéristiques des sols changent, et leur importance varie suivant les zones climatiques. Le climat change la couverture végétale et la couleur des sols, tandis que les caractéristiques des sols met l'emphase sur la signification des formations de terrain et des pentes alterées par les intempéries. Donc les photographies indiquerons les caractéristiques de base des sols, les facteurs géologiques et les gisements de matériaux granulés.

Le troisième texte, ***Maps for Construction Materials*** (Cartes de matériaux de construction), fut publié dans le ***Highway Research Board Bulletin 28*** en 1950. Ce rapport déclare que les roches et sédiments de l'écorce terrestre forment les matériaux de base de la construction routière.

rocks and sediments of the earth's crust are the basic materials needed by the engineer for construction. Materials maps, therefore, are necessary in the search for construction materials.

Three principal kinds of construction-materials maps are discussed:

1. **Material-Site Maps** inventory materials already found and tested. These maps include only those sites known to the compiler from basic data supplied. They do not show other construction materials that may be present in the same area but have not been needed or tested previously. They provide a poor basis for the search for additional materials.

2. **Material-Distribution Maps** are based on the geologic maps available for a region. Each outcropping formation shown on a geologic map is classified as to the kind of construction material it can produce. This map is a good inventory of all materials available in a region. It also shows the potential production areas for each material.

3. **Surface-Geology Materials Maps** combine many useful features of the other maps. A field

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teriales de construcción.

Se habla sobre tres tipos principales de mapas de material de construcción:

1. **Mapas de Ubicación de Materiales** inventariarían los materiales yá encontrados y ensayados. Estos mapas incluyen unicamente las ubicaciones que el compilador reconoce de los datos básicos que le son suministrados. No muestran otros materiales de construcción que pueden estar presentes en la misma área, pero que no han sido previamente necesarios ó ensayados. No son buena base para la búsqueda de materiales adicionales.

2. **Mapas de Distribución de Materiales** se basan sobre los mapas geológicos disponibles de una región. Cada formación de afloramiento en un mapa geológico se clasifica de acuerdo al tipo de material de construcción que puede producir. Este tipo de mapa es un buén inventario de todos los tipos de materiales disponibles en una región. También indica las áreas potenciales de producción para cada material.

3. **Los Mapas de Materiales de Geología de la Superficie** combinan muchas de las características útiles de los otros dos tipos de mapas. Un equipo de campaña delínea mapas de las formaciones geológicas (rocas consolidadas y sedimentos no consolidados), generalmente sobre fotografías aéreas. El equipo traza las ubicaciones de todos los hoyos y canteras en existencia, ubica materiales adicionales, y recolecta muestras para su ensayo en laboratorios. Este tipo de mapa sirve en forma indefinida como una base totalmente adecuada para la eficiente búsqueda el materiales. También es una valiosa fuente de información para el ingeniero de planificación,

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Les cartes de matériaux sont donc nécessaires pour rechercher les matériaux de construction.

Trois sortes principales de cartes de matériaux de construction sont discutées:

1. Les cartes qui font un inventaire des gisements de matériaux qui ont déjà été découverts et mis à l'épreuve. Ces cartes sont seulement celles des gisements déjà connus d'après des données antérieures. Elle ne montrent pas les matériaux de construction qui peuvent être dans cette région, mais dont on n'a pas eu besoin auparavant, ou qui n'ont pas été mis à l'épreuve. Ces cartes ne constituent pas une bonne base pour chercher des matériaux supplémentaires.

2. Des cartes qui montrent la distribution des matériaux d'après les cartes géologiques qui sont disponibles. Chaque formation de terrain qui montre un affleurement sur une carte géologique est classée selon la sorte de matériaux de construction qui peut en être extraite. Ce genre de carte donne un inventaire satisfaisant des genres de matériaux de construction que l'on peut trouver. Ces cartes indiquent aussi les régions qui peuvent produire chaque genre de matériau pour chaque région.

3. Les cartes géologiques de matériaux de surface, qui combinent les caractéristiques des deux autres cartes. Normalement, une équipe

team maps the geologic formations — both consolidated rocks and unconsolidated sediments — usually on aerial photographs. The team plots the locations of all existing pits and quarries, locates additional materials, and collects samples for laboratory testing. This type of map serves indefinitely as a completely adequate base for the efficient search for materials. It is also a valuable source of information for the planning engineer, the design engineer, and the engineer estimating the cost of construction.

The fourth text, ***Chapter 11, Air Photo Interpretation,*** is excerpted from ***Laterite and Lateritic Soils and Other Problem Soils of the Tropics*** (USAID, 1975). It introduces the concept of imagery by various remote sensors and the application of such imagery to terrain classification. It cites several terrain classifications recently de-

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de ingeniero de diseño, y el ingeniero que calcula el costo de construcción.

El cuarto texto, ***Chapter 11, Air Photo Interpretation*** (Capítulo 11, Interpretación de fotos aéreas), se extrajo de ***Laterite and Lateritic Soils and Other Problem Soils of the Tropics*** (Laterita y suelos lateríticos y otros suelos problemáticos de las areas trópicas) (USAID 1975). Introduce el concepto de imágenes por varios sensores remotos y la aplicación de tales imágenes en la clasificación del terreno. Nombra varias clasificaciones de terreno recientemente desarrolladas, que se basan principalmente sobre procedimientos de evaluación del terreno. El texto delínea la técnica que comunmente se utiliza en el desarrollo de estas clasificaciones.

Se incluye una tabulación resúmen de interpretación de fotos aéreas de suelos tropicales. También se habla sobre la identificación de lateritas y otros suelos tropicales; se dá importancia a aquellas características que le dán al evaluador indicaciones específicas sobre la presencia de varios suelos tropicales. Se identifican los suelos que son fuentes útiles de materiales y aquellos que causan los más grandes problemas.

El quinto texto, ***Techniques for the Interpretation of Remote Sensing Imagery for Highway Engineering Purposes*** (Técnicas para la interpretación de imágenes remotas de impresión para propósitos de ingeniería vial), fué publicado por el Transport and Road Research Laboratory en Inglaterra (TRRL, 1977). Este texto proporciona más información sobre las imágenes obtenidas por sensor remoto. La tecnología que se describe yá ha sido utilizada con éxito en los inventarios regionales de materiales de construcción.

Este texto resume algunos de las nuevas formas disponibles de datos de imágenes y técnicas especializadas de interpretación. El co-

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de cartographes trace les formations géologiques (roches consolidées et sédiments non consolidés) sur des photos aériènnes. L'équipe détermine les gisements de matériaux et les carrières, trouve d'autres matériaux, et collectionne des échantillons pour les laboratoires. Ce genre de carte servira indéfiniment comme outil de base complétement adéquat pour la location de matériaux routiers. Elle servira de la même façon l'ingénieur planificateur, celui qui déterminera le tracé de la route et celui qui calculera le prix de la construction.

Le quatrième texte, ***Chapter 11 — Air Photo Interpretation*** (La photointerprétation) est extrait de ***Laterite and Lateritic Soils and Other Problem Soils of the Tropics*** (USAID, 1975).

Le concept de l'imagerie par différentes sortes de télédétection, et ses applications à la classification des sols est introduit. Plusieurs genres de classification de terrain, développés récemment et basés principalement sur des procédures d'évaluation de ces terrains, sont cités. Le texte extrapole les techniques les plus usitées pour le développement de ces classifications. Une table résume la photointerprétation des sols tropicaux. L'identification des latérites et autres sols tropicaux est aussi discutée. Les caractéristiques qui mettent l'ingénieur sur la piste des sols tropicaux sont accentuées. Les sols qui constituent des sources utiles de matériaux de construction et ceux qui posent des problèmes importants sont identifiés.

Le cinquième texte, ***Techniques for the Interpretation of Remote Sensing Imagery for Highway Engineering Purposes*** (Techniques d'interprétation de l'imagerie acquise par télédétection à l'usage du génie civil), a été publié par le Transport and Road Research Laboratory en Grande Bretagne (TRRL, 1977).

Ce texte élabore en détail l'imagerie acquise par télédétection et résume les nouvelles techniques d'interprétation qui sont maintenant disveloped and based primarily on terrain evaluation procedures. The text outlines the technique commonly used in the development of these classifications.

A summary tabulation of air-photointerpretation of tropical soils is included. The identification of laterites and other tropical soils is also discussed. Those features giving the evaluator specific clues about the presence of various tropical soils are stressed. Soils that are useful sources of materials and soils that cause major problems are identified.

The fifth text, ***Techniques for the Interpretation of Remote Sensing Imagery for Highway Engineering Purposes,*** was published by the Transport and Road Research Laboratory in the United Kingdom (TRRL, 1977). This text provides further information about remote sensing imagery. The technology described has already been used successfully for regional inventories of construction materials.

This text summarizes some of the new forms of image data and specialized interpretative techniques that are now available. The proper

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rrecto uso de estas técnicas requiere una comprensión básica de cómo se obtienen las imágenes.

El informe describe las características de los datos de las imágenes obtenidas por sensor remoto. Presenta los factores y limitaciones que influyen la interpretación de aquellos datos. Dá importancia a los métodos de interpretación como se aplican a las formas comunes de imágenes facilmente disponibles para los ingenieros. Estos incluyen fotografías aéreas multiespectrales visibles e infrarrojas ("near-infrared"), y las imágenes sensoras multiespectrales tomados del satélite LANDSAT.

El sexto texto, ***Terrain Evaluation for Civil Engineering Projects in South Africa*** (Evaluación del terreno para proyectos ingenieriles civiles en Sud Africa), es un artículo publicado en el ***Australian Road Research Board Proceedings*** (Expedientes de la directiva de investigación vial Australiana) (1968). Sigue los desarrollos en la clasificación de terrenos, almacenamiento de datos, y trazado de mapas ingenieriles de suelos en Sud Africa. Se hacen varios comentarios sobre las ventajas y desventajas en el presente curso de ese desarrollo. Además, sugiere que el nivel de estudio del proyecto en lo que concierne al trazado de mapas ingenieriles del suelo provee valiosa información que es aplicable a cualquier forma de almacenamiento de datos.

El informe detalla la preparación y aplicación de mapas ingenieriles de suelos al nivel del proyecto. Subraya la acción recíproca entre el interpretador de fotos aéreas y el ingeniero vial en el desarrollo del inventario de materiales para el

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ponibles. La bonne utilisation de ces techniques demande une certaine compréhension de la façon dont cette imagerie est acquise.

Les caractéristiques de l'imagerie acquise par télédétection sont décrites. Les limites et les facteurs qui influencent l'interprétation de ces données sont présentés. L'emphase est mise sur les méthodes d'interprétation qui peuvent être appliquées facilement par les ingénieurs. Celles-ci comprennent les photographies aériennes infra-rouges, visibles et multispectrales, et l'imagerie du Landsat Satellite obtenue à l'aide de scanners (radiométres multispectraux à balayage).

Le sixième texte, ***Terrain Evaluation for Civil Engineering Projects in South Africa*** (Evaluation des terrains pour les projets du génie civil en Afrique du Sud), est un article publié dans le Australian Road Research Board Proceedings (1968).

Le développement de la classification des terrains, l'enregistrement des données et les cartes des sols en Afrique du Sud sont indiqués. Des commentaires sont faits sur les avantages et les inconvénients des tendances actuelles de ce développement. De plus, il est suggéré que le niveau d'étude du projet, en ce qui concerne le tracé des cartes des sols, fournit des informations précieuses qui peuvent être appliquées à toutes sortes d'enregistrement de données.

Le rapport explique en détail la préparation et l'application des cartes des sols au niveau du projet. Il met l'emphase sur la combinaison des rôles de l'ingénieur routier et du spécialiste de la photointerprétation pour faire l'inventaire des matériaux ou les cartes des sols. Les inventaires de matériaux préparés pour un projet spécifique, forment une base de données qui peut être ensuite élaborée et utilisée pour développer des classifications de terrains sans use of these techniques requires a basic understanding of how the imagery is obtained.

The report describes the characteristics of remote sensing image data. It presents the factors and limitations influencing the interpretation of these data. It stresses methods of interpretation as they apply to forms of common imagery readily available to engineers. These include visible and near-infrared multispectral photography from aircraft and multispectral scanner imagery from the LANDSAT satellite.

The sixth text, ***Terrain Evaluation for Civil Engineering Projects in South Africa,*** is a paper that was included in the ***Australian Road Research Board Proceedings*** (1968). It traces the developments in terrain classification, data storage, and soil engineering mapping in South Africa. Several comments are made about the advantages and drawbacks in the current trends of that development. It further suggests that the project level approach to soil engineering mapping provides valuable information applicable to any form of data storage.

The report details the preparation and application of soil engineering maps at the project level. It stresses the interplay between the air-photointerpreter and the highway engineer in the development of the project-oriented materials inventory or engineering soils map. The paper suggests that materials inventories prepared for a specific project provide data that can be readily used for the development of any overall terrain classification system without sacrificing short-term efficiency.

The previous texts have dealt with the overall location of material sites. Once these sites have been located, the quality and quantity of the material have to be evaluated. Although it is

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proyecto ó el mapa ingenieril de suelos. El artículo sugiere que los inventarios de materiales preparados para un proyecto específico proveen datos que facilmente se pueden utilizar para el desarrollo de cualquier sistema de clasificación general de terreno, sin sacrificar la eficiencia de un procedimiento de corto alcance.

Los textos previos tratan con la ubicación general de zonas de materiales. Una vez ubicados estos lugares, se deben evaluar la calidad y cantidad del material. Está fuera del alcance del Compendio 6 describir en detalle los ensayos de laboratorio necesarios para determinar la calidad del material. Sin embargo, el séptimo texto, *Development of Geophysical Methods of Subsurface Exploration in the Field of Highway Construction* (Desarrollo de métodos geofísicos de exploración sub-superficial en el campo de construcción vial), un informe publicado en *Highway Research Board Bulletin 28* (Boletín de la directiva de investigación vial 28) (1950), describe dos métodos para llevar a cabo una investigación preliminar de las condiciones subterráneas del lugar. Estas investigaciones son necesarias para explorar las condiciones subsuperficiales en general y para estimar las cantidades de los materiales presentes.

Este texto describe el método de refracción sísmica y el método de resistencia específica de la tierra. El equipo que se utiliza para llevar a

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sacrifier l'immédiate efficacité du procédé.

Les textes précédents ont tous eu à voir avec la location générale des gisements de matériaux. Une fois que ces gisements ont été situé, la qualité et la quantité des matériaux doivent être évaluées. L'envergure de ce recueil ne permet pas de détailler les essais en laboratoire qui sont nécessaires pour déterminer la qualité des matériaux. Cependant le septième texte, *Development of Geophysical Methods of Subsurface Exploration in the Field of Highway Construction* (Développement de méthodes géophysiques d'exploration des sous-sols dans le domaine de la construction routière), un rapport publié dans le *Highway Research Board Bulletin 28* (1950) décrit deux méthodes pour faire une investigation préliminaire des conditions du sous-sol d'un gisement. Ces investigabeyond the scope of Compendium 6 to detail the necessary laboratory tests used to determine the quality of the material, the seventh text, ***Development of Geophysical Methods of Subsurface Exploration in the Field of Highway Construction*** — a report published in ***Highway Research Board Bulletin 28*** (1950) — describes the two methods for making a preliminary investigation of underground site conditions. These investigations are necessary to explore the subsurface conditions in general and to estimate the quantities of materials present.

This text describes the refraction seismic method and the earth resistivity method. The equipment used to make these tests has been improved since this text was written; however, the theory remains the same. For example, the seismographic test is now often made with a hammer striking a plate rather than with a small charge of dynamite. This report describes the

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cabo estos ensayos ha sido mejorado desde que se escribió este texto; sin embargo, la teoría es la misma. Es común ahora realizar el ensayo sismográfico con un martillo golpeando una placa, en vez de una pequeña carga de dinamita. Sin embargo, este informe describe la teoría, los usos específicos, y las limitaciones de cada método. Señala que los principios fundamentales de los dos métodos difieren en gran escala. Por lo tanto, donde ambos métodos dan datos comparables, éstos pueden aceptarse con considerable confianza.

El octavo texto, extractos de ***Pits and Quarries*** (Department of the Army Technical Manual TM 5-332, 1967) (Hoyos y canteras; Manual técnico del departamento de armada TM 5-332, 1967), describe un método para desarrollar los depósitos de materiales con una cantidad mínima de equipo.

1. El prefacio contiene definiciones y clasificaciones. Aunque esta sección define tres tipos de canteras, no se ha incluído en este compendio los capítulos detallados del manual para aquellas canteras que requieren voladura y trituración (es decir, roca dura y mediana).

2. El capítulo sobre la selección de ubicación, que se extrajo totalmente, habla sobre el reconocimiento que incluye fuentes de información e investigación geológica. Describe la evaluación de ubicaciones de hoyos y canteras para determinar la calidad y la cantidad del material disponible. También se incluyen en este capítulo los factores que afectan las operaciones, ya que ayudan a determinar la posibilidad

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tions sont nécessaires pour explorer le sous-sol en général, et estimer la quantité de matériaux qui s'y trouve. Ce texte décrit la méthode de réfraction sismique et la méthode de mesure de résistivité du sol. Le matériel utilisé pour faire ces éssais a été amélioré depuis que ce texte a été écrit, mais la théorie reste la même. L'essai sismographique est maintenant fait avec un marteau qui frappe une plaque, plutôt qu'avec une petite charge de dynamite. Ce rapport présente la théorie, les usages spécifiques, et les limites de chaque méthode. On note que les principes fondamentaux des deux méthodes sont si différents, que lorsque les deux méthodes arrivent aux mêmes données, on peut accepter celles-ci avec assurance.

Le huitième et dernier texte, extrait de ***Pits and Quarries*** (Excavations et carrières) (Department of the Army Technical Manual TM5-332, 1967), décrit une méthode pour exploiter les gisements de matériaux avec un minimum de matériel.

1. L'introduction contient des définitions et des classifications. Bien que trois sortes de carrières soient définies, les chapitres qui décrivent en détail les carrières où l'on doit utiliser le sautage et le broyage (i.e., roche dure et mi-dure) ne sont pas inclus dans ce recueil.

2. La sélection des gisements — ce chapitre est inclus en entier. Le stade de reconnaissance, c'est à dire, à la fois l'utilisation des sources d'information et des données géologiques, est discuté. L'évaluation des excavations et des carrières pour déterminer la qualité et la quantité de matériaux disponibles est décrite. Les facteurs qui influencent les opérations sont aussi inclus dans ce chapitre puisqu'ils aident à déterminer la praticabilité de l'utilisation d'un gisement spécifique.

3. Les opérations d'excavation — ce chapitre est aussi inclus en entier. Il décrit (a) la classification des excavations, (b) la préparation des gisements, (c) l'excavation à l'aide de scrapers, ou décapeuses, (d) l'excavation à l'aide de pelles méchaniques et de camions, ou à l'aide de tracteurs avec bennes chargeuses, (e) l'excava-

theory, specific uses, and limitations of each method. It notes that the fundamental principles of the two methods differ widely. Thus, where both methods give comparable data, they may be accepted with considerable assurance.

The eighth text, excerpts from ***Pits and Quarries*** (Department of the Army Technical Manual TM 5-332, 1967), describes a method for developing deposits of materials with a minimal amount of equipment. The four excerpts from this manual included here are

1. The introduction contains definitions and classifications. Although this section defines three types of quarries, the detailed chapters of the manual for quarries requiring blasting and crushing (i.e., hard rock and medium rock) are not included in this compendium.
2. The site selection chapter, excerpted in full, discusses reconnaissance that includes sources of information and geologic investigation. It describes the evaluation of pit and quarry sites to determine the quality and the quantity of the material available. Factors that affect operations are also included because they help to determine the feasibility of using a specific site.
3. The pit operations chapter, excerpted in full, describes (a) pit classification, (b) site preparation, (c) excavating with scrapers, (d) excavating with power shovel and trucks or front-end loader and trucks, (e) excavating with draglines, and (f) the design and operation of loading ramps.
4. The soft rock operations chapter is excerpted in full. Soft rock differs from soil in that it is

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de utilizar una ubicación específica.

3. El capítulo sobre operaciones de hoyo, extraído totalmente, describe (a) la clasificación del hoyo, (b) preparación del hoyo, (c) excavación con escarbadores, (d) excavación con pala a cuchara y camiones ó cargador por el frente y camiones (e) excavación con dragas, y (f) el diseño y operación de rampas de carga.
4. El capítulo sobre operaciones en roca blanda ha sido extraído totalmente. La roca blanda difiere de tierra en que es consolidada y requiere algún método de desprendimiento en el lugar de excavación. Difiere de la roca dura en que no se necesita voladura para excavar. Los materiales incluídos en esta clasificación son: (a) coral blando; (b) toba, que es una forma de ceniza volcánica curtida a la intemperie; (c) caliche; y (d) laterita.

Bibliografia

Le sigue a los textos seleccionados una breve bibliografía que contiene datos y abstractos de referencia para 16 publicaciones. Los primeros

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tions à l'aide de dragues et (f) la théorie et la pratique des rampes de chargement.

Le chapitre sur l'excavation des roches tendres est inclus en entier. Les roches tendres sont différentes des sols en ce qu'elles sont consolidees et ont besoins d'être désagrégées sur place. Ces roches sont différentes des roches dures parce qu'il n'y a pas besoin de les faire sauter pour les excaver. Les matériaux inclus dans cette classification sont (a) les coraux tendres, (b) les tufs, qui sont une sorte de cendre volcanique alterée par les agents atmosphériques, (c) les caliches et (d) les latérites.

Bibliographie

Les textes choisis sont suivis d'une brève bibliographie contenant les références et les résumés de seize publications. Les huit premiers se rapportent aux textes choisis. Les huit autres à des publications qui ont rapport aux textes choisis. Bien qu'il y ait beaucoup d'autres articles, rapports et livres qui pourraient être inclus, l'objectif consolidated and requires some method of loosening at the excavation site. It differs from hard rock in that blasting is not required for excavation. The materials included in this classification are (a) soft coral; (b) tuff, a form of weathered volcanic ash; (c) caliche; and (d) laterite.

Bibliography

A brief bibliography containing reference data and abstracts for 16 publications follows the Selected Texts. The first eight describe the Selected Texts; the other eight describe publications closely related to the Selected Texts. Although many other articles, reports, and books could have been listed, it is not the purpose of this bibliography to contain all possible references for the subject. The bibliography includes only those publications from which a text has been selected or basic publications that would have been selected had there been no page limit for this compendium.

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ocho describen los textos seleccionados. Los otros ocho describen publicaciones que se relacionan intimamente con los textos seleccionados.

Aunque se pudo nombrar muchos otros artículos, informes y libros, no es el propósito de esta bibliografía contener todas las referencias posibles sobre el tema. La bibliografía contiene unicamente aquellas publicaciones de las que se seleccionó un texto ó publicaciones básicas que hubieran sido seleccionadas si no hubiera un límite al número de páginas en este compendio.

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de cette bibliographie n'est pas d'énumérer toutes les références possibles ayant rapport au sujet de ce recueil. Donc, notre bibliographie, telle quelle, se rapporte seulement aux publications dont nous avons choisi des extraits, ou aux textes de base que nous aurions choisi aussi s'il n'y avait pas de limites quant au nombre de pages de ce recueil.

Selected Texts

This section of the compendium contains selected pages from each text that is listed in the Table of Contents. Rectangular frames are used to enclose pages that have been reproduced from the original publication. Some of the original pages have been reduced in size to fit inside the frames. No other changes have been made in the original material except for the insertion of occasional explanatory notes. Thus, any errors that existed in the selected text have been reproduced in the compendium itself.

Page numbers of the original text appear inside the frames. Page numbers for the compendium are outside the frames and appear in the middle left or middle right outside margins of the pages. Page numbers that are given in the Table of Contents and in the Index refer to the compendium page numbers.

Each text begins with one or more pages of introductory material that was contained in the original publication. This material generally includes a title page, or a table of contents, or both. Asterisks that have been added to original tables of contents have the following meanings:

*Some pages (or parts of pages) in this part of

Textos Seleccionados

Esta sección del compendio contiene páginas seleccionadas de cada texto que se catalogaron en la Tabla de Materias. Se utilizan recuadros rectangulares para encerrar las páginas que han sido reproducidas de la publicación original. Algunas de las páginas originales han sido reducidos para entrar en los recuadros. No se han hecho ningunos otros cambios en el material original exceptuando algunas notas aclaradoras que de vez en cuando han sido agregadas. De esta forma, cualquier error que hubiera existido en el texto seleccionado ha sido reproducido en el compendio mismo.

Los números de páginas del texto original aparecen dentro de los recuadros. Los números de páginas para el compendio están fuera de los recuadros y aparecen en los márgenes medio izquierdo o medio derecho de las páginas. Los números de páginas que se dán en los índices del compendio se refieren a los del compendio.

Cada texto comienza con una o mas páginas de material de introducción que contenía la publicación original. Este material generalmente incluye una página título, un índice, o ambas. Los astericos que han sido agregados al índice original significan lo siguiente:

* Algunas páginas (o partes de páginas) en

Textes Choisis

Cette partie du recueil contient les pages sélectionnées de chaque texte qui est énuméré dans la Table des Matières. Les pages du texte original qui sont reproduites sont entourées d'un encadrement rectangulaire. Certaines pages ont dû être réduites pour pouvoir être placées dans l'encadrement. Le texte original n'a pas été changé sauf pour quelques explications qui ont été insérées. Donc, si le texte original contient des erreurs, elles sont reproduites dans le recueil.

La pagination originale apparaît à l'intérieur de l'encadrement. La pagination du recueil est à l'extérieur de l'encadrement, soit à droite, soit à gauche de la marge extérieure des pages et est celle qui est citée dans la table des matières et dans l'index du recueil.

Chaque texte commence par une ou plusieurs pages d'introduction qui étaient incluses dans le texte original. Ces pages sont généralement le titre, ou la table des matières, ou les deux. Des astériques ont été ajoutés à la table des matières d'origine pour les raisons suivantes:

* Certaines pages, ou portions des pages,

the original document appear in the selected text, but other pages (or parts of pages) in this part of the original publication have been omitted.

**All pages in this part of the original document appear in the selected text.

The selected texts therefore include only those parts of the original documents that are preceded by asterisks in the tables of contents of the respective publications.

Broken lines across any page of selected text indicate those places where original text has been omitted. In a number of places, the selected text contains explanatory notes that have been inserted by the project staff. Such notes are set off within dashed-line boxes and begin with the word NOTE.

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esta parte del documento original aparecen en el texto original, pero otras páginas (o partes de páginas) en esta parte de la publicación original han sido omitidas.

** Todas las páginas en esta parte del documento original también aparecen en el texto seleccionado.

Por lo tanto, los textos seleccionados unicamente incluyen aquellas partes de los documentos originales que están precedidas por asteriscos en el índice de las publicaciones respectivas.

Líneas de guiones cruzando cualquier página del texto seleccionado significan que en ese lugar se ha omitido texto original. En varios lugares el texto seleccionado contiene notas aclaradoras que han sido introducidas por el personal del proyecto. Tales notas están insertadas en recuadros de guiones y comienzan con la palabra NOTE.

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dans cet extrait du document original sont incluses dans les Textes Choisis, mais d'autres pages (ou portion de pages) de l'édition originale ont été omises.

** Toutes les pages dans cet extrait du document original sont incluses dans les Textes Choisis.

Les Textes Choisis, donc, incluent seulement ces extraits des documents originaux qui sont précédés d'un astérique dans les tables des matières des publications respectives.

Les lignes brisées sur les pages des textes choisis indiquent les endroits où le texte original a été omis. A certains endroits, les textes choisis contiennent des explications qui ont été insérées par le personnel attaché à ce projet. Ces explications sont entourées d'un encadrement en pointillé et commencent toujours par le mot NOTE.

HIGHWAY RESEARCH RECORD

Number 156

Classification, Safety Factor, Terrain, and Bearing

4 Reports

Subject Classification

61 Exploration-Classification (Soils)
62 Foundation (Soils)
63 Mechanics (Earth Mass)

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Contents

A Review of Engineering Soil Classification Systems

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This paper discusses, with particular reference to transportation engineering, the nature and necessity of soil classification and the distinction between soil identification and soil classification. The soil properties suitable for classification purposes are considered. The requirements for a satisfactory soil classification system are listed as (a) distinct properties as the basis for grouping, (b) logical, simple and concise scheme, (c) meaningful grouping, (d) desirable terminology, (e) appropriate symbols, (f) sufficient flexibility, and (g) ease of application. The AASHO, Unified and FAA systems are compared in light of these requirements. Finally, the equivalent soil groups in each system are correlated on the basis of classification procedures as well as pavement design values.

•EVERY SOIL body consists of an assortment of solid constituents of various compositions and many sizes, a mixture of dilute solutions, and a collection of gases. It is thus a complex system, one which is open rather than closed. The complexity of soil makes it necessary to devise some systematic means so that it can be studied most effectively. Thus, the purpose of soil classification is to group the individual soil units found in nature so that their properties can be easily remembered, and facts about them will be most useful. Another important purpose of a soil classification system is to provide a language by which one engineer's knowledge of the general characteristics of a particular soil can be conveyed to fellow engineers in a brief and concise manner, without the necessity of entering into lengthy descriptions and detailed analyses.

In soil investigations for transportation facilities soil classification plays a very important role. Because of the nature of loading conditions, the properties of surficial soils are of greater interest to transportation engineers. In general, the properties of natural soil deposits vary considerably in the horizontal as well as the vertical direction. Because transportation facilities usually cover very large areas, numerous soil samples must be obtained in order to characterize the soil conditions along the proposed route. It would be impossible to evaluate such a large amount of highly variable samples without some systematic arrangement. Soil classification can fulfill this role admirably. The properties of surficial soils are subject to seasonal variations. In addition, soils are frequently used as material for the construction of transportation facilities. In such case, the in situ properties of the soils are likely to be drastically changed. Thus, classification systems leaning heavily on the composition of the soil are required.

Great care should be exercised not to read into various classifications more information than they are intended to convey. It is also not good practice to rely too heavily on soil classification as a basis for design, since many of the factors which enter into design cannot possibly be incorporated into an engineering soil classification. For example, the susceptibility of a road or runway to frost damage is a question that

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involves not only the properties and characteristics of the soil itself, but climatic and geophysical conditions as well.

A clear understanding of the relation of soil identification to soil classification is necessary to prevent confusion about many factors involved in soil work. To identify is to distinguish, to classify is to group. It is logical that things must be identified before they can be grouped, or classified, and it is also logical that proper classification depends on proper identification. Identification is factual information, whereas classification is interpretative information. Identifications, soil test data and observed or measured soil behavior are factual information because they are the result of observation or experiment. Factual information does not change with time, but forms a growing body of permanent knowledge. On the other hand, classification is essentially an inference of expected behavior deduced from interpretation of factual information. In the very nature of things, interpretative information must be constantly checked against actual experience and actual soil behavior. It must also be brought up to date with increasing knowledge and understanding.

REQUIREMENTS FOR A SATISFACTORY ENGINEERING SOIL CLASSIFICATION SYSTEM

Distinct Properties as Basis for Grouping

Soils are heterogeneous mixtures of various solids, liquids and gases. Because of the uncontrolled natural conditions under which they are formed, there is an infinite variety of natural soils, each with slightly different properties. In order to classify such highly variable objects accurately and precisely, numerous attributes must be used as the basis for grouping. A soil classification system based on a large number of attributes is neither practical nor economical. Thus, a good soil classification should include only a few very distinct attributes for grouping into classes. Each class should include those soils having similar properties and similar general behavior characteristics. Furthermore, the tests required to distinguish the selected attributes should be simple and inexpensive.

Logical, Simple and Concise Scheme

The classification scheme should be based on a logical sequence that can easily be remembered and will not require constant reference to tables, handbooks or other aids. It should also be simple and concise. Moreover, the number of classes or groups should be held to a minimum consistent with the differentiation required by engineering problems. It can thus be easily learned and applied not only by experts but also by novices after a short period of training. Since soil investigation is often performed by personnel relatively inexperienced in soil mechanics, the simplest classification system consistent with adequate utility appears to be most desirable.

Meaningful Grouping

The grouping of soils should furnish an indication of their general broad properties and behavior. It should also permit a crude estimate of permeability, compressibility and shear strength—the three primary properties of a soil—as well as a rough appraisal of soil performance, such as compactability and frost susceptibility. Not all engineers engaged in design and construction can be acquainted in detail with all phases of soils engineering, nor is it necessary that they be. On most jobs a knowledge of the general principles of soil behavior combined with such special information as may be provided by the soil specialists will be sufficient. A usable grouping of soils should be of value in transmitting to the design and construction engineers this information. Moreover, a meaningful grouping should also provide a common language for engineers in various parts of the world in order that experience and knowledge gained in one locality can be applied elsewhere.

Desirable Terminology

Terminology should consist of descriptive, easily understood and commonly used terms which convey an idea of the general properties and behavior of the soils. As a rule, soil mechanics specialists do not develop information for their own use. The soil investigation is generally conducted by drillers and technicians. Then the design information and recommendations are supplied to other engineers. Consequently, the terminology used should express the intended meaning and be familiar to all interested parties, from drillers to designers to contractors.

Appropriate Symbols

Symbols should not replace the descriptive names of soils. However, symbols are useful for graphic abstracts of boring logs and engineering drawings. Where symbols are used as engineering shorthand, they should have a specific meaning and should be descriptive and easy to associate with actual soils. Thus, they can be learned quickly and readily translated into the commonly used descriptive terminology. Coded symbols, which require the use of numbers or letters that are meaningful only to soil specialists, are generally not desirable.

Sufficient Flexibility

The classification, because of its interpretative character, should be made flexible and adaptable, to permit being checked against experience and being brought up to date frequently with increased knowledge and understanding of soil phenomena. It should also be capable of further subdivision without affecting the basic structure and should make allowance for regional use of certain terms which are particularly meaningful in that region.

Ease of Application

A classification system should be applicable from visual examination for both field and laboratory purposes. Usually, time will not permit tests to be performed on all soils encountered in the sampling program. Therefore, it becomes necessary to visually classify a large number of samples. The system should be applicable in the field without special equipment and by relatively unskilled personnel. At the same time, it should be precise enough to classify soils for which detailed laboratory test results are available.

One of the most important applications of a classification system is in the field of identification and description of a large number of soil samples to determine variability of the natural soil deposits, to permit preparation of subsurface profiles, and to form the basis for the choice of representative samples for laboratory testing. These are the basic reasons for a classification system that can be used in the field with rapidity, reliability and ease. Inasmuch as laboratory tests need be applied only to representative samples, the classifications and descriptions made in the field indicate the general properties of the material and its suitability for various engineering purposes. This is important because it provides reliable design data in the shortest time and at least expense.

SOIL PROPERTIES WHICH MAY BE USED FOR CLASSIFICATION PURPOSES

Numerous soil properties may be used for classification purposes. These properties can be divided into two general types, soil grain properties and soil aggregate properties. The soil grain properties are the properties of the individual grains of which the soil is composed, without reference to the manner in which these grains are arranged. The soil aggregate properties depend on the structure and arrangement of the particles in the soil mass. Table 1 gives a partial list of such soil properties.

TABLE 1

SOIL PROPERTIES WHICH MAY BE USED FOR CLASSIFICATION PURPOSES

Soil Grain Properties	Soil Aggregate Properties
Color	Structure
Texture and gradation	Natural water content
Grain shape	Void ratio or porosity
Mineralogical composition	Density or relative density
Base exchange capacity	Permeability and capillarity
Odor and organic matter content	Consistency
Specific gravity of soil solids	Unconfined compressive strength
Plasticity	Sensitivity and thixotropy
Liquid limit	Maximum dry density and optimum water content
Plastic limit	Strength
Plasticity index	Cohesion
Shrinkage limit	Angle of internal friction
Shrinkage ratio	California bearing ratio
Activity ratio	Modulus of subgrade reaction
Chemical composition	Penetration resistance
pH-value	Standard penetration value
Dilatancy	Elasticity and Compressibility
Hardness	Compression or Swelling Index

Generally, the soil grain properties are permanent in nature while the soil aggregate properties vary with changing conditions. It can be argued that the processes of weathering will alter the texture of the surficial soils. However, within the lifetime of an engineering project, such changes are negligible. At the same time, the magnitude of cohesion and angle of internal friction are greatly affected by the test conditions, while the consistency and in-place density of surficial soils are subject to seasonal variations. Moreover, soil grain properties can be determined on any soil sample whether remolded or undisturbed. In order to obtain meaningful information, it is generally preferred that the soil aggregate properties be determined on undisturbed soil samples which are more expensive to acquire. Thus, soil grain properties are more commonly used for identification and classification purposes. It should be realized, however, that the soil aggregate properties have a greater influence on the engineering behavior of a soil.

If the purpose is to classify soils concisely and accurately, many soil properties must be utilized for grouping, which will undoubtedly produce a soil classification system containing a large number of classes and subclasses Such a system is not only difficult to handle but expensive to use. In order to reduce the soil groups to a finite and reasonable number, many important soil characteristics must unavoidably be ignored.

The following general rules can be used in choosing a desirable soil property as a basis for grouping:

1. It should be relatively simple to determine.
2. It should be determined economically.
3. The method used to determine it should be relatively fast so it can be performed on many soil samples in a short time.
4. Most important, it must be significant for the intended use of the soil classification system.

For example, using color to classify soils fulfills the first three requirements. However, it is not possible to conclude that gray soils are better subgrade material than brown soils. Highly organic soils can generally be distinguished by their dark color; at the same time, soil derived from basalt is also dark colored. Thus, color is not a suitable primary basis for grouping. It can only serve as a secondary classification property.

Natural water content of soils can be determined simply, economically and relatively fast. It ranges from less than 1 percent to more than 1000 percent. A particular soil with a water content of 10 percent may be very hard and strong while other soils at the same water content can be soft and compressible. Obviously, natural water content is also not a significant basis for soil classification.

One of the most extensively used soil classification properties is texture. This is well illustrated by the large number of soil textural classification systems that have been proposed over the years—more than 50—and the fact that many of these systems—about 20—are still in use at the present time. The reasons for so many textural classification systems are twofold: first, these systems are devised by people studying soil from different points of view; and second, the grain size distribution is a continuance in nature and the boundaries between the soil separates are arbitrarily defined.

Soil texture can be determined simply and economically. The test procedure, however, is not necessarily fast, particularly the fine-grained portion. It is common knowledge that the grain size distribution has considerable influence on the engineering properties of coarse-grained soils. The difficulty of all textural classification lies in the fact that those physical properties of fine-grained soils which are of interest to the engineer often are not reflected by their textural characteristics. A soil with a given grain size distribution may represent a highly plastic soil in one area while another soil from a different locality having the same texture and gradation may be only slightly plastic. Many discrepancies between grain size characteristics and physical properties of fine-grained soils could be cited. Nevertheless, the grain size curves of fine-grained soil are still extensively used as the exclusive basis for soil classification because of the simplicity of textural classifications and the fact that they can be applied with little experience. In contrast to the misleading impressions which these textural classifications may convey, the pertinent physical properties of such soils can easily be distinguished on the basis of simple laboratory or field identification procedures. 9

COMPARISON OF THE AASHO, UNIFIED AND FAA SOIL CLASSIFICATION SYSTEMS

In the field of transportation engineering, the following three soil classification systems are most commonly used:

1. American Association of State Highway Officials (AASHO) system,
2. Unified system, and
3. Federal Aviation Agency (FAA) system.

Both the AASHO and Unified systems are recognized the world over, the Unified system being generally favored.

In Tables 2 to 4 and Figures 1 through 6, charts which outline the AASHO, Unified and FAA systems are presented to facilitate the ensuing discussion. Figures 2, 4 and 6 are flow charts which are helpful in arriving at the proper classification according to the AASHO, Unified and FAA systems respectively. For a more detailed review of these soil classification systems, the reader is referred to any basic text on soil mechanics or to publications prepared by the different agencies describing the classification system, some of which are listed in the references at the end of this paper (8, 10, 18, 33, 40, 44, 45).

It has been discussed in a previous section that there are seven requirements for a satisfactory engineering soil classification system. The AASHO, Unified and FAA systems will be compared in accordance with the requirements outlined.

TABLE 2

AASHO SOIL CLASSIFICATION SYSTEM (8)

General Classification	*Granular Materials* (*35% or less passing No. 200*)							*Silt-Clay Materials* (*More than 35% passing No. 200*)			
Group Classification	*A*-1		*A*-3	*A*-2				*A*-4	*A*-5	*A*-6	*A*-7
	A-1-*a*	*A*-1-*b*		*A*-2-4	*A*-2-5	*A*-2-6	*A*-2-7				*A*-7-5: *A*-7-6
Sieve analysis: Percent passing:											
No. 10	50 max	—	—	—	—	—	—	—	—	—	—
No. 40	30 max	50 max	51 min	—	—	—	—	—	—	—	—
No. 200	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing No. 40:											
Liquid limit	—		—	40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
Plasticity index	6 max		NP	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min*
Group index	0		0	0		4 max		8 max	12 max	16 max	20 max
Usual types of significant constituent materials	Stone fragments gravel and sand		Fine sand	Silty or clayey gravel and sand				Silty soils		Clayey soils	
General Rating as subgrade	Excellent to good					Fair to poor					

*Plasticity index of *A*-7-5 subgroup is equal to or less than LL minus 30. Plasticity index of *A*-7-6 subgroup is greater than LL minus 30.

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Distinct Properties as Basis for Grouping

The AASHO, Unified and FAA systems are so-called textural-plasticity soil classification systems. In general, all three systems distinguish between two primary soil groups, the coarse-grained or granular group and the fine-grained group. Sands and gravels comprise the first group and silts and clays the latter group. The soils of the coarse-grained group are classified primarily on the basis of grain size. The soils in the fine-grained group, on the other hand, are divided by the degree of plasticity.

Even though the grain size characteristics play an important role in all three soil classification systems, the size limits for various soil fractions recognized by these systems are somewhat different, as shown in Figure 7. In order to classify the soils on the basis of laboratory test results, all three systems require the performance of some relatively simple soil tests—grain size analysis, and liquid limit and plastic limit calculation.

Both the Unified and FAA systems have provided classifications for organic soils (OL, OH and Pt groups of Unified system; E-13 of FAA system); however, no such provisions are made in the AASHO system.

Logical, Simple and Concise Scheme

A logical soil classification scheme should have a concise step-by-step sequence. The classification of a soil can thus be accomplished by answering a few simple "yes or no" questions similar to those utilized in the logical deduction procedures of the modern electronic computer.

The classification schemes of the three systems can best be compared by examining Figures 2, 4 and 6. A quick glance at the figures seems to indicate that the classification scheme of the Unified system (Fig. 4) is the most complicated and the FAA system (Fig. 6) the simplest because the Unified system has the largest number of blocks, the FAA system the smallest number. Closer examination, however, reveals that the opposite is true. The Unified system has the most logical and concise scheme. In other words, it is clearly broken down step-by-step without ambiguity. The large number of blocks tends to overshadow the simplicity of the Unified system. It can be seen that the blocks used to subdivide gravel are identical with those which subdivide sand and the blocks under L are exactly the same as those under H of the fine-grained

TABLE 3

UNIFIED SOIL CLASSIFICATION SYSTEM (44)

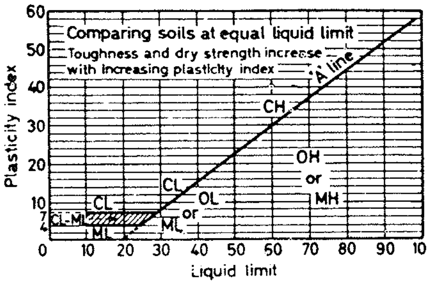
Field identification procedures (Excluding particles larger than 3 in. and basing fractions on estimated weights)						*Group symbols* [1]	*Typical names*	*Information required for describing soils*	*Laboratory classification criteria*			
Coarse grained soils *More than half of material is larger than No. 200 sieve size* [2] (The No. 200 sieve size is about the smallest particle visible to naked eye)	*Gravels* *More than half of coarse fraction is larger than No. 4 sieve size* *(For visual classification, the ¼ in. size may be used as equivalent to the No. 4 sieve size)*	*Clean gravels (little or no fines*	Wide range in grain size and substantial amounts of all intermediate particle sizes			*GW*	Well graded gravels, gravel-sand mixtures, little or no fines	Give typical name; indicate approximate percentages of sand and gravel; maximum size; angularity, surface condition, and hardness of the coarse grains; local or geologic name and other pertinent descriptive information; and symbol in parentheses For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions and drainage characteristics *Example*: *Silty sand*, gravelly; about 20% hard, angular gravel particles ½-in. maximum size; rounded and subangular sand grains coarse to fine, about 15% non-plastic lines with low dry strength; well compacted and moist in place; alluvial sand; (*SM*)	Use grain size curve in identifying the fractions as given under field identification	Determine percentages of gravel and sand from grain size curve Depending on percentage of fines (fraction smaller than No. 200 sieve size) coarse grained soils are classified as follows: Less than 5% *GW, GP, SW, SP* More than 12% *GM, GC, SM, SC* 5% to 12% *Borderline* cases requiring use of dual symbols	$Cu = \frac{D_{60}}{D_{10}}$ Greater than 4 $Cc = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
			Predominantly one size or a range of sizes with some intermediate sizes missing			*GP*	Poorly graded gravels, gravel-sand mixtures, little or no fines				Not meeting all gradation requirements for *GW*	
		Gravels with fines (appreciable amount of fines)	Non-plastic fines (for identification procedures see *ML* below)			*GM*	Silty gravels, poorly graded gravel-sand-silt mixtures				Atterberg limits below 'A' line, or *PI* less than 4	Above 'A' line with *PI* between 4 and 7 are *borderline* cases requiring use of dual symbols
			Plastic fines (for identification procedures, see *CL* below)			*GC*	Clayey gravels, poorly graded gravel-sand-clay mixtures				Atterberg limits above 'A' line, with *PI* greater than 7	
	Sands *More than half of coarse fraction is smaller than No. 4 sieve size*	*Clean sands (little or no fines)*	Wide range in grain sizes and substantial amounts of all intermediate particle sizes			*SW*	Well graded sands, gravelly sands, little or no fines				$Cu = \frac{D_{60}}{D_{10}}$ Greater than 6 $Cc = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
			Predominantly one size or a range of sizes with some intermediate sizes missing			*SP*	Poorly graded sands, gravelly sands, little or no fines				Not meeting all gradation requirements for *SW*	
		Sands with fines (appreciable amount of fines)	Non-plastic fines (for identification procedures, see *ML* below)			*SM*	Silty sands, poorly graded sand-silt mixtures				Atterberg limits below 'A' line or *PI* less than 4	Above 'A' line with *PI* between 4 and 7 are *borderline* cases requiring use of dual symbols
			Plastic fines (for identification procedures, see *CL* below)			*SC*	Clayey sands, poorly graded sand-clay mixtures				Atterberg limits shows 'A' line with *PI* greater than 7	
Fine grained soils *More than half of material is smaller than No. 200 sieve size*	*Identification procedures on fraction smaller than No. 40 sieve size*											
			Dry strength (crushing characteristics)	*Dilatancy (reaction to shaking)*	*Toughness (consistency near plastic limit)*							
	Silts and clays liquid limit less than 50		None to slight	Quick to slow	None	*ML*	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity	Give typical name; indicate degree and character of plasticity, amount and maximum size of coarse grains; colour in wet condition, odour if any, local or geologic name, and other pertinent descriptive information, and symbol in parentheses For undisturbed soils add information on structure, stratification, consistency in undisturbed and remoulded states, moisture and drainage conditions *Example*: *Clayey silt*, brown; slightly plastic; small percentage of fine sand; numerous vertical root holes; firm and dry in place; loess; (*ML*)		 Plasticity chart for laboratory classification of fine grained soils		
			Medium to high	None to very slow	Medium	*CL*	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays					
			Slight to medium	Slow	Slight	*OL*	Organic silts and organic silt-clays of low plasticity					
	Silts and clays liquid limit greater than 50		Slight to medium	Slow to none	Slight to medium	*MH*	Inorganic silts, micaceous or dictomaceous fine sandy or silty soils, elastic silts					
			High to very high	None	High	*CH*	Inorganic clays of high plasticity, fat clays					
			Medium to high	None to very slow	Slight to medium	*OH*	Organic clays of medium to high plasticity					
Highly organic soils			Readily identified by colour, odour, spongy feel and frequently by fibrous texture			*Pt*	Peat and other highly organic soils					

TABLE 4

FAA SOIL CLASSIFICATION SYSTEM (45)

	Soil group	Mechanical analysis				Liquid limit	Plasticity index
		Material retained on No. 10 sieve—percent [1]	Material finer than No. 10 sieve—percent				
			Coarse sand, passing No. 10; retained on No. 60	Fine sand, passing No. 60: retained on No. 270	Combined silt and clay; passing No. 270		
Granular	E-1	0-45	40+	60−	15−	25−	6−
	E-2	0-45	15+	85−	25−	25−	6−
	E-3	0-45	---------	---------	25−	25−	6−
	E-4	0-45	---------	---------	35−	35−	10−
	E-5	0-45	---------	---------	45−	40−	15−
Fine grained	E-6	0-55	---------	---------	45+	40−	10−
	E-7	0-55	---------	---------	45+	50−	10-30
	E-8	0-55	---------	---------	45+	60−	15-40
	E-9	0-55	---------	---------	45+	40+	30−
	E-10	0-55	---------	---------	45+	70−	20-50
	E-11	0-55	---------	---------	45+	80−	30+
	E-12	0-55	---------	---------	45+	80+	---------
	E-13	Muck and peat—field examination					

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[1] If percentage of material retained on the No. 10 sieve exceeds that shown, the classification may be raised, provided such material is sound and fairly well graded.

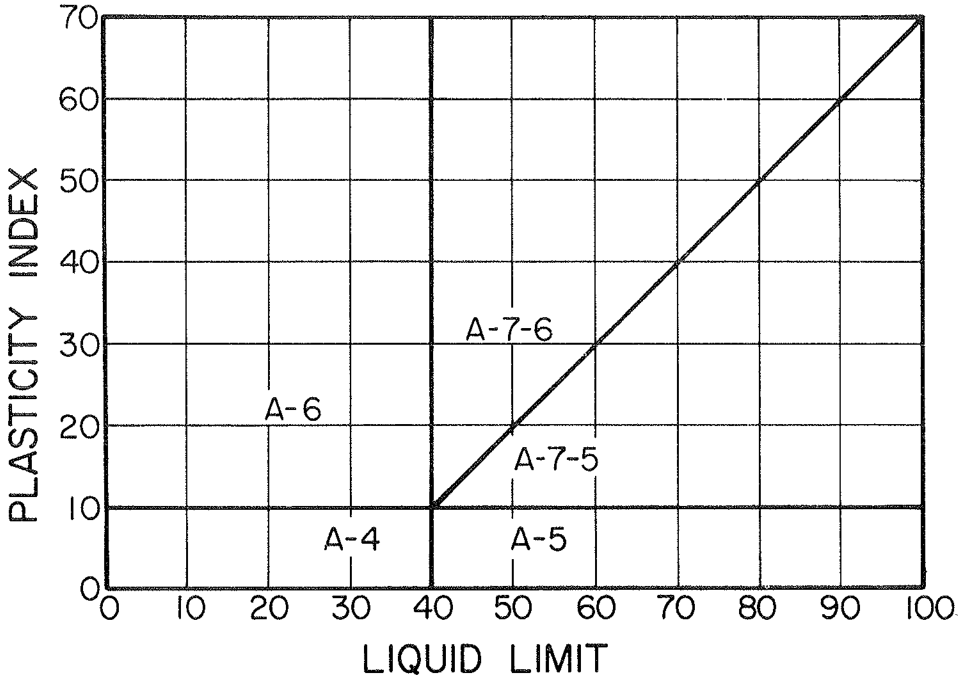


Figure 1. Plasticity chart for AASHO system (8).

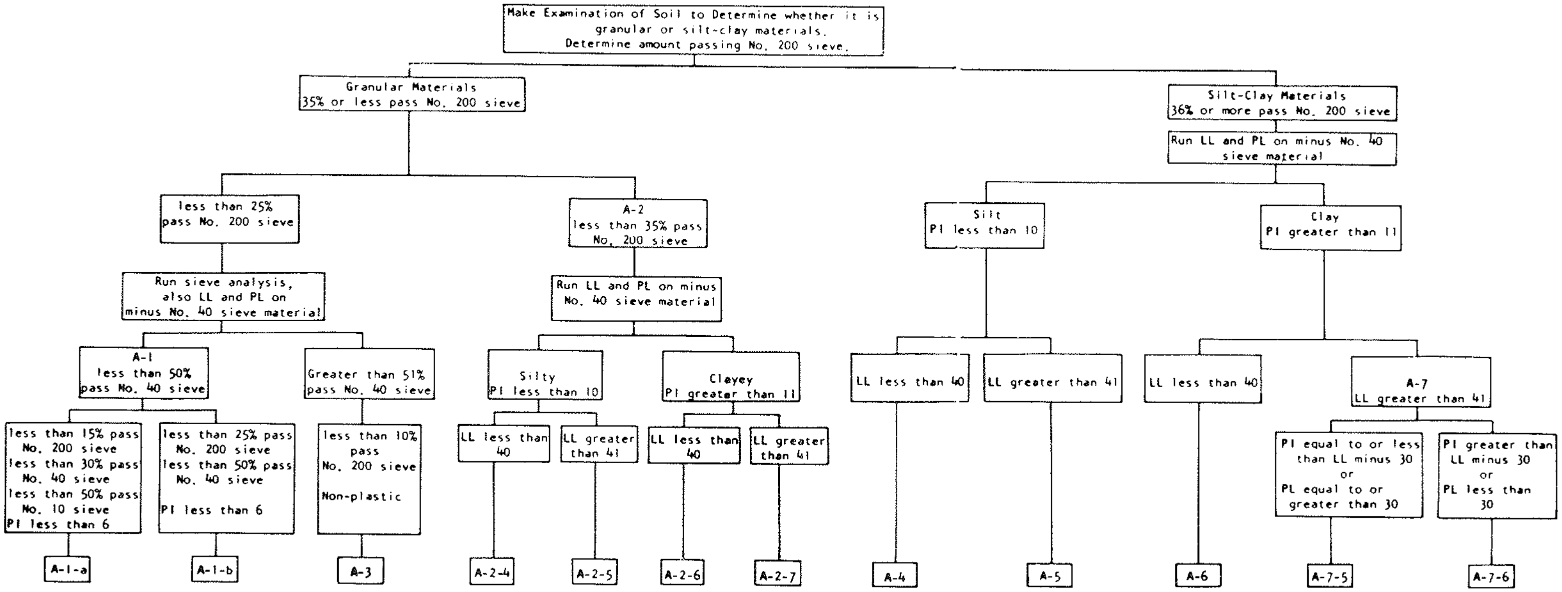


Figure 2. Chart for auxiliary laboratory classification procedure, AASHO system.

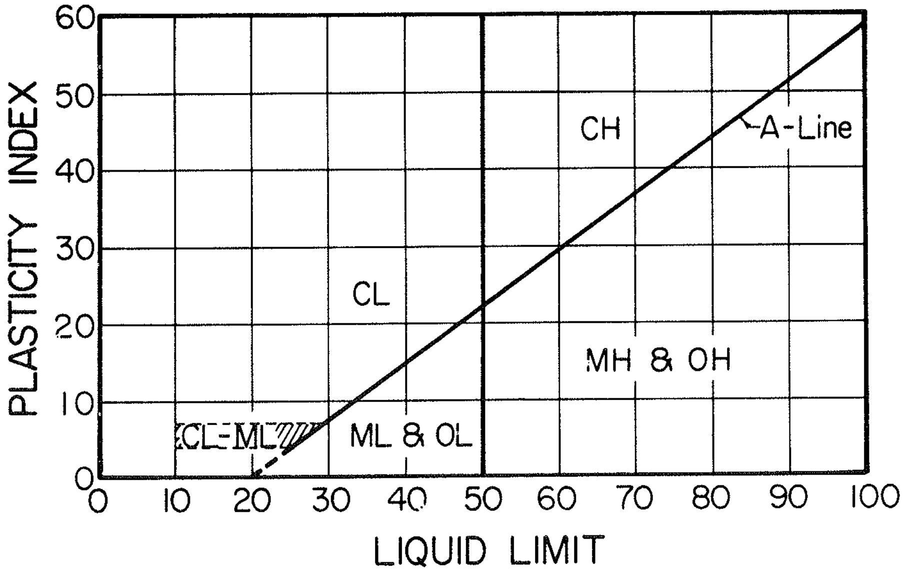


Figure 3. Plasticity chart for Unified system (44).

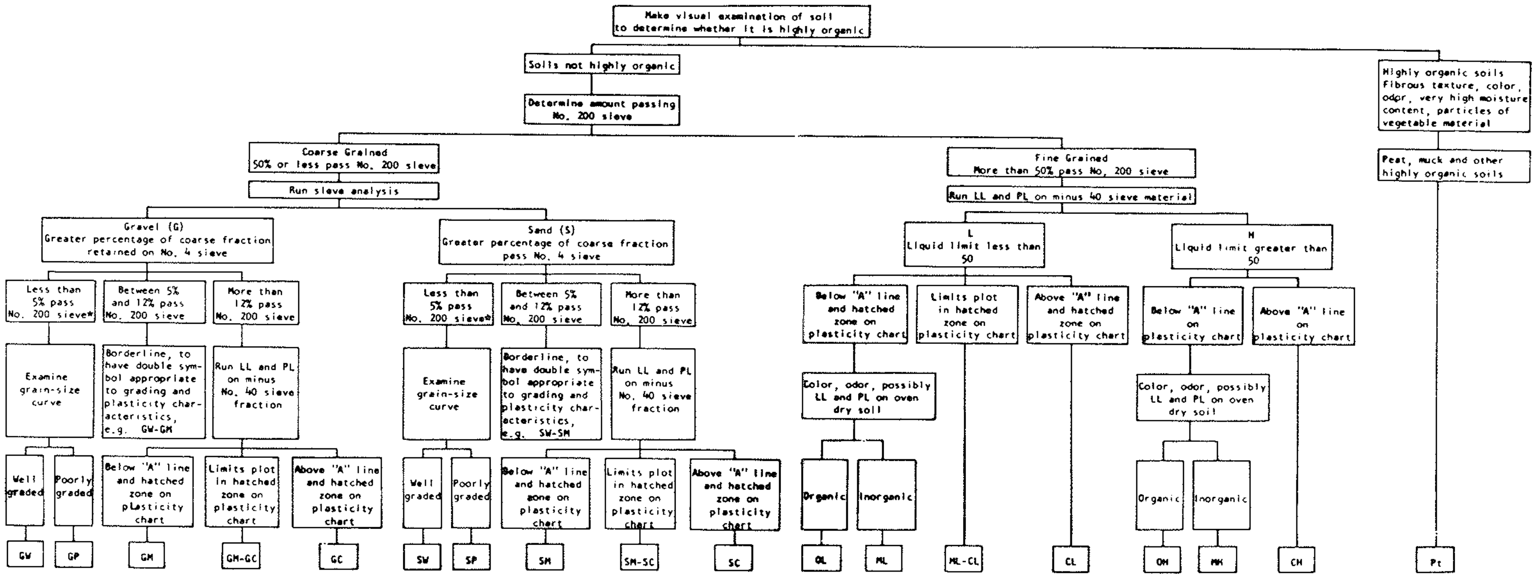
soils with the exception of the block for the ML-CL group. Furthermore, the scheme employed to subdivide gravel and sand with more than 12 percent passing a No. 200 sieve is similar to that for classifying fine-grained soils with low liquid limit, L.

As shown in Figure 2, the silt-clay materials are classified according to a logical step-by-step scheme in the AASHO system. However, the classification of the granular materials is less logical. The separation between the A-1, A-3 category and A-2 category is not concise and distinct. Actually, a granular soil with less than 25 percent passing a No. 200 sieve may not fulfill the other requirements for either the A-1 or A-3 group. It has to be classified eventually in the A-2 category. In addition, the various requirements for the A-1 and A-3 groups cannot be remembered easily, so that a constant reference to tables would be required for classifying these soils. Nevertheless, the A-2 category is subdivided in the same manner as the silt-clay materials.

The FAA system is the least logical and concise as well as the most complicated scheme of the three systems being compared. No clear-cut step-by-step breakdown is provided by the FAA system, particularly the fine-grained soils. Moreover, there is no clear distinction between the granular and fine-grained soils because of the allowance for upgrading and the special requirements for the E-5 group as pointed out in the footnote to Figure 6. It is extremely difficult, if not impossible, to memorize the classification scheme of the FAA system.

The relative advantages of the three systems with regard to the number of soil groups can best be compared from the following table:

Category	AASHO	Unified	FAA
Total number of soil groups	12	15	13
Number of mineral soil groups	12	12	12
Number of coarse-grained soil groups	7	8	5
Number of fine-grained soil groups	5	4	7
Number of organic soil groups	0	3	1



* If fines interfere with free-draining properties use double symbol such as GW-GM, etc.

Figure 4. Chart for auxiliary laboratory classification procedure, Unified system (44).

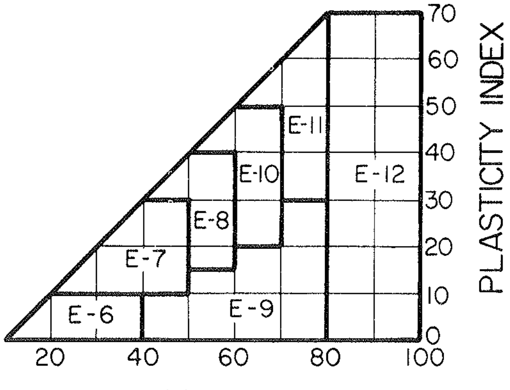


Figure 5. Plasticity chart for FAA system (45).

It is obvious that the AASHO system has not made any provision for classifying organic soils. Otherwise, there is no particular advantage among the three systems on the basis of the number of soil groups.

Meaningful Grouping

As shown in Figure 7, both the AASHO and Unified systems separate the coarse-grained particles from the fine-grained particles on the No. 200 sieve while the FAA system uses the No. 270 sieve. Both the AASHO and FAA systems divide the gravel size and sand size on the No. 10 sieve while the Unified system uses the No. 4 sieve. The difference between the No. 200 sieve (0.074 mm) and the No. 270 sieve (0.050 mm) or between the No. 4 sieve (4.76 mm) and the No. 10 sieve (2.00 mm) is not too large; however, the No. 200 and No. 10 sieve are the more commonly preferred standards.

The criteria used by the three systems to classify fine-grained soils are as follows:

AASHO—more than 35 percent passing a No. 200 sieve.
Unified—more than 50 percent passing a No. 200 sieve.
FAA—more than 45 percent passing a No. 270 sieve on the portion of material finer than a No. 10 sieve.

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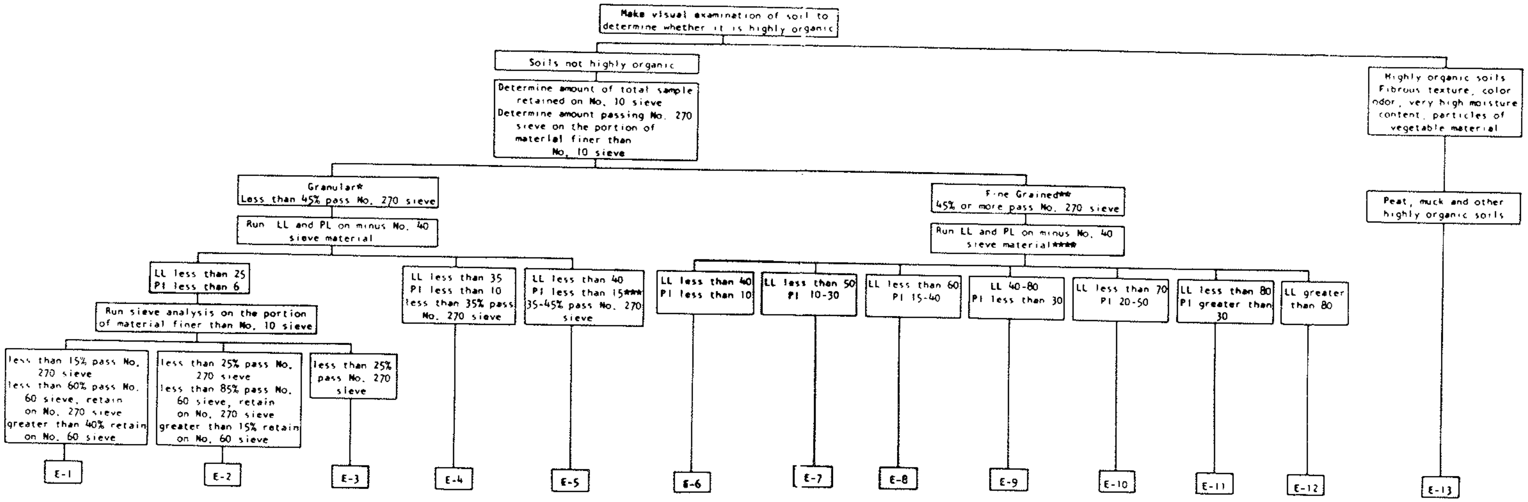
It has been found that the amount of fines required to fill all the voids of a coarse-grained material and thus hold the coarse particles apart from each other is approximately 35 percent. Such a mixture behaves more like a fine-grained soil since the coarse particles are not in contact with each other. For this purpose, the AASHO criterion of classifying fine-grained soil is more appropriate. However, the 50 percent used by the Unified system is a much simpler criterion, particularly for field identification and classification. If the soil possesses only a small amount of material larger than a No. 10 sieve, the FAA criterion of defining fine-grained soils is equivalent to that of the Unified system. Nevertheless, soil classification on the basis of that portion finer than a No. 10 sieve is subject to serious questioning. For example, consider the following test results on a soil sample:

Sieve No.	Particle Size, mm	Percent Finer
4	4.76	100
10	2.00	45
40	0.42	37
200	0.074	29
270	0.050	27
—	0.002	23
	Liquid Limit	62
	Plasticity Index	41

According to the FAA system, this soil will be classified as E-10. Since the grain size distribution indicates that more than 70 percent of the sample is composed of coarse-grained particles, the classification of E-10 seems to be out of line. This same soil will be classified as A-2-7 in the AASHO system and SC in the Unified



* When the percentage of the total sample retained on the No. 10 sieve exceeds 45%, upgrading from 1 to 2 classes may be permitted, provided the coarse fraction is reasonable sound and fairly well graded.

** When the percentage of the total sample retained on the No. 10 sieve exceeds 55%, upgrading from 1 to 2 classes may be permitted, provided the coarse fraction is reasonable sound and fairly well graded.

*** A plasticity index greater than 15 would cause the soil to be classified with fine grained soils even though it may contain less than 45% pass No. 270 sieve.

**** If test results on fine grained soils place the soil in more than one group, the appropriate soil group must be determined from the plasticity chart.

Figure 6. Chart for auxiliary laboratory classification procedure, FAA system.

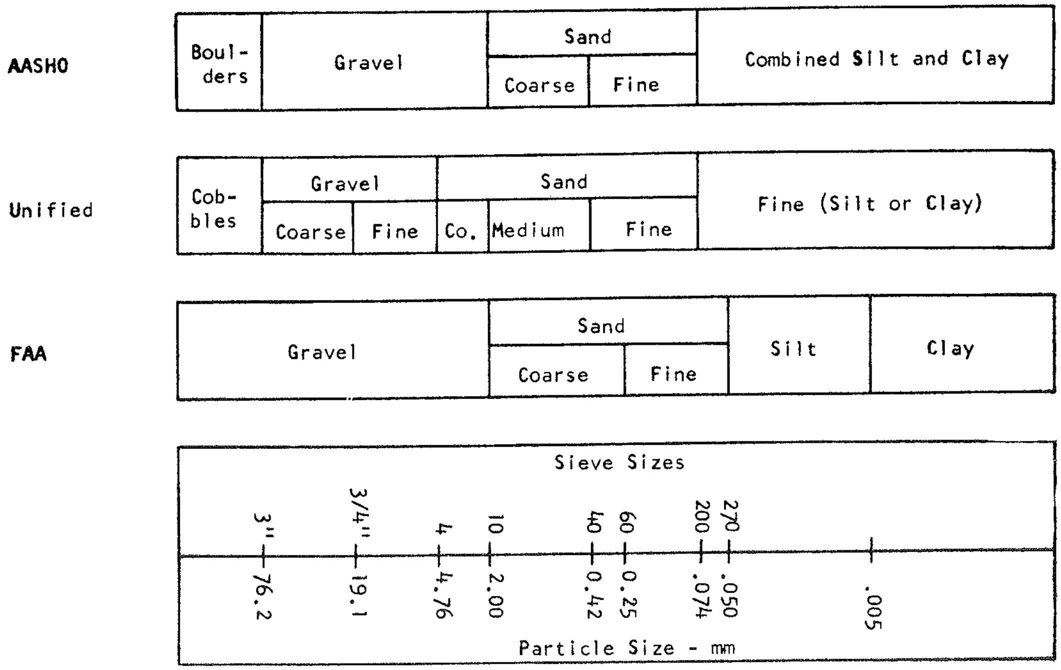


Figure 7. Soil-fraction size limits for AASHO, Unified and FAA systems.

system. It has also been pointed out in the previous section that the separation between the coarse-grained and fine-grained soils of the FAA system is rather ambiguous.

The Unified system distinctly separates the gravelly soils from the sandy soils. No such clear separation is made in the AASHO system, particularly the A-2 category. Consequently, the A-2 category covers a wide range of soil properties, such as CBR values and unit weight. One major deficiency of the FAA system is the lack of definite consideration of the gravel fraction in the soils, since the classification is based on the properties of the portion of the soil sample finer than a No. 10 sieve. The example cited above also illustrates this deficiency, since more than half of the sample falls in the gravel fraction according to the size limits adopted by the FAA system.

It has been proven through both laboratory and field experience that the A-line on the Unified plasticity chart (Fig. 3) serves as the best criterion of separating the clayey materials from the silty materials (16, 36, 37). The AASHO system classifies the silty and clayey soils on the basis of plasticity index only (fine materials having plasticity index less than 10 are classified as silty soils and greater than 11 as clayey soils). This criterion seems to be more artificial, reflecting less realistically the properties of the fine-grained soils. The FAA system, too, does not make any definite provision to distinguish the silty and clayey soils.

The slope of the 45-degree line between A-7-5 and A-7-6 groups on the AASHO plasticity chart (Fig. 1) is steeper than the A-line. It would thus be more difficult to distinguish these two groups of soils without laboratory tests. Although the A-7-5's are described as clayey soils by the AASHO system, they may often behave more like silts.

For ease of memorizing and using, the Unified plasticity chart does not have any particular advantage over the AASHO plasticity chart. However, the FAA plasticity chart (Fig. 5) is extremely difficult, if not impossible, to memorize and use.

Neither the Unified nor the AASHO system clearly marks fine-grained soils with very high limit values, although the break at 50 percent liquid limit is probably closer than the one at 40 percent. The group index value of the AASHO system gives additional useful information but it probably does not go high enough (maximum group index value is 20). Nevertheless, the FAA system does provide definite classification for such soils, the E-12 group.

Desirable Terminology

From Table 3 it can be seen that the Unified system gives each soil group, in addition to the group symbol, a descriptive, easily understood and commonly used terminology which conveys an idea of the general properties and behavior of the soils. For example, the terminology for sandy soils with Atterberg limits above A-line is "clayey sands, poorly graded sand-clay mixtures" and its group symbol is SC. Neither the AASHO nor the FAA system furnishes each soil group with a definite terminology.

Appropriate Symbols

All three engineering soil classification systems have adopted sets of symbols to identify the soil groups. However, the types of symbols are quite different. Both the AASHO and FAA systems use coded symbols which require the use of numbers and letters that are meaningful only to engineers acquainted with the system. There is no particular significance of using the letter "A" in the AASHO system and the letter "E" in the FAA system. The numerals in both systems merely serve as a rating of the soil materials as subgrade for pavements—the desirability as subgrade decreases with increase in numbers. The symbols of these two systems are neither descriptive nor easy to associate with actual soils. Consequently, such symbols are more difficult to learn and understand.

The group symbols of the Unified system are actually the simple initials of the group names, with the exception of the letter M (from the Swedish word "mo" for silt). Each symbol reflects the general character of the soil group. The user may easily learn and remember these symbols. It has been argued that these symbols are initials of English words, and to achieve world-wide significance, the group symbols should be changed in each language. On the other hand, in order to maintain the universal significance of the symbols, they should not be translated. However, considering that the majority of important references in soil mechanics and foundation engineering are, and probably in the future will be, in the English language, the adoption of the English symbols as an international or universal standard would not be too great a hardship. It would mean that, in teaching the classification, the user would have to learn about a dozen English words. Once he has mastered these words, the use of these symbols would be just as understandable to him as if the symbols referred to the words in his own language.

Sufficient Flexibility

The Unified system can be changed or further subdivided without affecting the main framework of the classification scheme. To make allowance for regional use of certain terms and conditions of particular areas of soils engineering, the following modifications are in use or have been suggested:

1. Coarse-grained soils: (a) In order to differentiate between uniformly graded soils and those soils covering a wide range of sizes but of poor gradation, new groups GU and SU, for uniform gravels and sands respectively, can be added to the system. (b) In connection with highway and airfield work, the basic soil groups GM and SM have each been subdivided into two groups designated by the suffixes d and u, which represent desirable and undesirable base materials, respectively. Typical symbols for soils in these groups are GM_d and SM_u, etc.

2. Fine-grained soils: (a) Experience has indicated that the L group covers too large a range. It can be subdivided into two groups by the insertion of an intermediate group identified with the symbol I. Thus, CL would designate a very lean clay, CI would be a clay with intermediate plasticity characteristics, and CH would be a fat clay. The same applies to the ML, MI and MH groups. (b) Kaolinitic clays generally plot below the A-line on the plasticity chart. Thus, such clays will be classified as ML or MH. In localities where kaolinitic clays require attention, it would be desirable

to add such clays as separate groups for which the symbols KL and KH suggest themselves.

Contrarily, changing or further subdividing either the AASHO or FAA system without disrupting the basic framework of the classification scheme is somewhat difficult. In particular, a modification in classifying the fine-grained soils of the FAA system may lead eventually to a complete revision.

The use of dual symbols in the Unified system greatly facilitates the classification of borderline soils (soils possessing characteristics of two groups).

Ease of Application

The basic soil properties involved in the classification according to the Unified system are readily determined either in the laboratory by simple, widely used tests or in the field by standard simple procedures which do not require any special equipment. It is generally not possible to perform laboratory tests on all soil samples because of the large number of samples involved. Reliable field classification will reduce the amount of laboratory testing to a minimum, thus reducing cost and time. Moreover, the field procedure of the Unified system can readily be used by personnel without a background or training in soils engineering.

Even though no standard field procedure is provided by the AASHO system, a person with some training can classify soils in the field according to this system without too much difficulty. However, more laboratory tests are needed to check the field classification.

It is difficult, if not impossible, to classify soils in the field according to the FAA system. Laboratory tests may be necessary on all soil samples in order to classify them.

From the preceding comparisons it would appear that the Unified system is superior to the other two systems and is to be preferred as a general system of engineering soil

TABLE 5

COMPARABLE SOIL GROUPS FOR AASHO SYSTEM

Soil Group in AASHO System	Comparable Soil Groups in Unified System			Comparable Soil Groups in FAA System		
	Most Probable	Possible	Possible but Improbable	Most Probable	Possible	Possible but Improbable
A-1-a	GW, GP	SW, SP	GM, SM	E-1	–	–
A-1-b	SW, SP, GM, SM	GP	–	E-1, E-2	–	–
A-3	SP	–	SW, GP	E-2, E-3	E-1	–
A-2-4	GM, SM	GC, SC	GW, GP, SW, SP	E-4, E-5	E-6, E-2, E-3, E-1	–
A-2-5	GM, SM	–	GW, GP, SW, SP	E-9	–	–
A-2-6	GC, SC	GM, SM	GW, GP, SW, SP	E-5	E-7	E-8
A-2-7	GM, GC, SM, SC	–	GW, GP, SW, SP	E-7, E-8	E-9, E-10, E-11	E-12
A-4	ML, OL	CL, SM, SC	GM, GC	E-6	E-5	–
A-5	OH, MH, ML, OL	–	SM, GM	E-9	–	–
A-6	CL	ML, OL, SC	GC, GM, SM	E-7	E-5	–
A-7-5	OH, MH	ML, OL, CH	GM, SM, GC, SC	E-7, E-8, E-9, E-10, E-11, E-12	–	–
A-7-6	CH, CL	ML, OL, SC	OH, MH, GC, GM, SM	E-7, E-8, E-10, E-11, E-12	–	–

TABLE 6

COMPARABLE SOIL GROUPS FOR UNIFIED CLASSIFICATION

Soil Group in Unified System	Comparable Soil Groups in FAA System			Comparable Soil Groups in AASHO System		
	Most Probable	Possible	Possible but Improbable	Most Probable	Possible	Possible but Improbable
GW	E-1	–	–	A-1-a	–	A-2-4, A-2-5, A-2-6, A-2-7
GP	E-1	–	–	A-1-a	A-1-b	A-3, A-2-4, A-2-5, A-2-6, A-2-7
GM	E-2, E-4, E-5	–	E-1, E-6, E-7, E-8, E-9, E-10, E-11, E-12	A-1-b, A-2-4, A-2-5, A-2-7	A-2-6	A-4, A-5, A-6, A-7-5, A-7-6, A-1-a
GC	E-5	E-4	E-6, E-7, E-8, E-10 E-11, E-12	A-2-6, A-2-7	A-2-4, A-6	A-4, A-7-6, A-7-5
SW	E-1	–	–	A-1-b	A-1-a	A-3, A-2-4, A-2-5, A-2-6, A-2-7
SP	E-1, E-3	E-2	–	A-3, A-1-b	A-1-a	A-2-4, A-2-5, A-2-6, A-2-7
SM	E-2, E-3, E-4, E-5	–	E-1, E-6, E-7, E-8, E-9, E-10, E-11, E-12	A-1-b, A-2-4, A-2-5, A-2-7	A-2-6, A-4, A-5	A-6, A-7-5, A-7-6, A-1-a
SC	E-4, E-5	–	E-6, E-7, E-8, E-10, E-11, E-12	A-2-6, A-2-7	A-2-4, A-6, A-4, A-7-6	A-7-5
ML	E-6, E-7	E-9	E-1, E-2, E-3, E-5	A-4, A-5	A-6, A-7-5,	–
CL	E-7	E-6, E-8	E-4, E-5	A-6, A-7-6	A-4	–
OL	E-6, E-7	E-9	E-1, E-2, E-3, E-5	A-4, A-5	A-6, A-7-5, A-7-6	–
MH	E-8, E-9, E-10, E-11, E-12	–	–	A-7-5, A-5	–	A-7-6
CH	E-8, E-10, E-11, E-12	–	–	A-7-6	A-7-5	–
OH	E-8, E-9, E-10, E-11, E-12	–	–	A-7-5, A-5	–	A-7-6
Pt	E-13	–	–	–	–	–

TABLE 7

COMPARABLE SOIL GROUPS FOR FAA SYSTEM

Soil Group in FAA System	Comparable Soil Groups in AASHO System			Comparable Soil Groups in Unified System		
	Most Probable	Possible	Possible but Improbable	Most Probable	Possible	Possible but Improbable
E-1	A-1-a, A-1-b, A-3, A-2-4	–	–	GW, GP, SW, SP	–	GM, SM ML, OL
E-2	A-1-b, A-3, A-2-4	–	–	GM, SM	SP	ML, OL
E-3	A-3, A-2-4	–	–	SP, SM	–	ML, OL
E-4	A-2-4	–	–	SM, GM	SC, GC	ML, OL, CL
E-5	A-4, A-2-4, A-2-6	A-6	–	SM, SC, GM, GC	–	ML, OL CL
E-6	A-4	A-2-4	–	ML, OL	CL	SM, SC, GM, GC
E-7	A-6, A-7-6, A-7-5	A-2-6, A-2-7	–	CL, ML OL	–	SC, SM, GC, GM
E-8	A-7-6, A-7-5	A-2-7	A-2-6	CH, MH, OH	CL	SC, SM, GC, GM
E-9	A-5, A-7-5	A-2-5, A-2-7	–	OH, MH	ML, OL	SM, GM
E-10	A-7-5, A-7-6	A-2-7	–	CH, OH, MH	–	SC, SM, GC, GM
E-11	A-7-5, A-7-6	–	A-2-7	CH, OH, MH	–	SC, SM, GC, GM
E-12	A-7-5, A-7-6	A-5	A-2-7	OH, MH, CH	–	SM, SC, GM, GC
E-13	–	–	–	Pt	–	–

classification. However, the AASHO and FAA systems were devised for the specific purpose of rating soil materials for subgrades. Particularly, the AASHO system seems to have been successful for this purpose throughout the many years of its use.

CORRELATION OF SOIL GROUPS OF THE AASHO, UNIFIED AND FAA SOIL CLASSIFICATION SYSTEMS

Based on Classification Procedures

Since the criteria adopted by the AASHO, Unified and FAA systems for classifying soils are somewhat different, it is of interest to find the comparable soil groups among the three systems. Such correlations have been worked out and the comparable soil groups for the AASHO, Unified or FAA system are given in Tables 5, 6 and 7, respectively. The tables are self-explanatory. The tables show that it is very difficult to name the exactly identical soil groups between any two of the three systems.

Based on Pavement Design Values

The load-bearing or load-supporting value of subgrade soils is a variable of almost infinite proportions. In addition to the almost innumerable types of soils, there are many variations in load-bearing value of a specific soil. These variations are related to the condition of the soil at time of test and the procedure and equipment used for testing. Some of the factors that influence the load-bearing value as determined by test are the moisture content and density of the soil, the area over which the load is applied and the specific allowable deformation of the soil. The types of load—whether a dead load or a moving load (in the case of dead load, the rate of stress application it is exerting; in the case of moving load, the number of times it is applied)—are also factors that influence the load-bearing capacity.

Methods of evaluating the load-bearing value of soils vary from complex formulas dependent on tests of cohesion, internal friction and shear of the soil, to simple field loading tests. Published data on the range of design values assigned to various soil classifications indicate that most data are given in terms of California Bearing Ratio (CBR) values. A general correlation of soil classifications with California Bearing Ratio values is shown in Figure 8 (33, 44). This figure shows clearly the wide range in bearing values of each soil group as well as the wide overlapping of CBR values in the soil groups of various classification systems.

Considerable data on the range of subgrade modulus (k) for the Unified classifications have also been published (33, 44). These data are summarized in the following tabulation:

Unified Classification	Subgrade Modulus (k), lb per cu in.
GW	300-500
GP	300-500
GM	200-500
GC	200-500
SW	200-400
SP	150-400
SM	100-400
SC	100-300
ML	100-200
CL	50-150
OL	50-100
MH	50-100
CH	50-150
OH	25-100

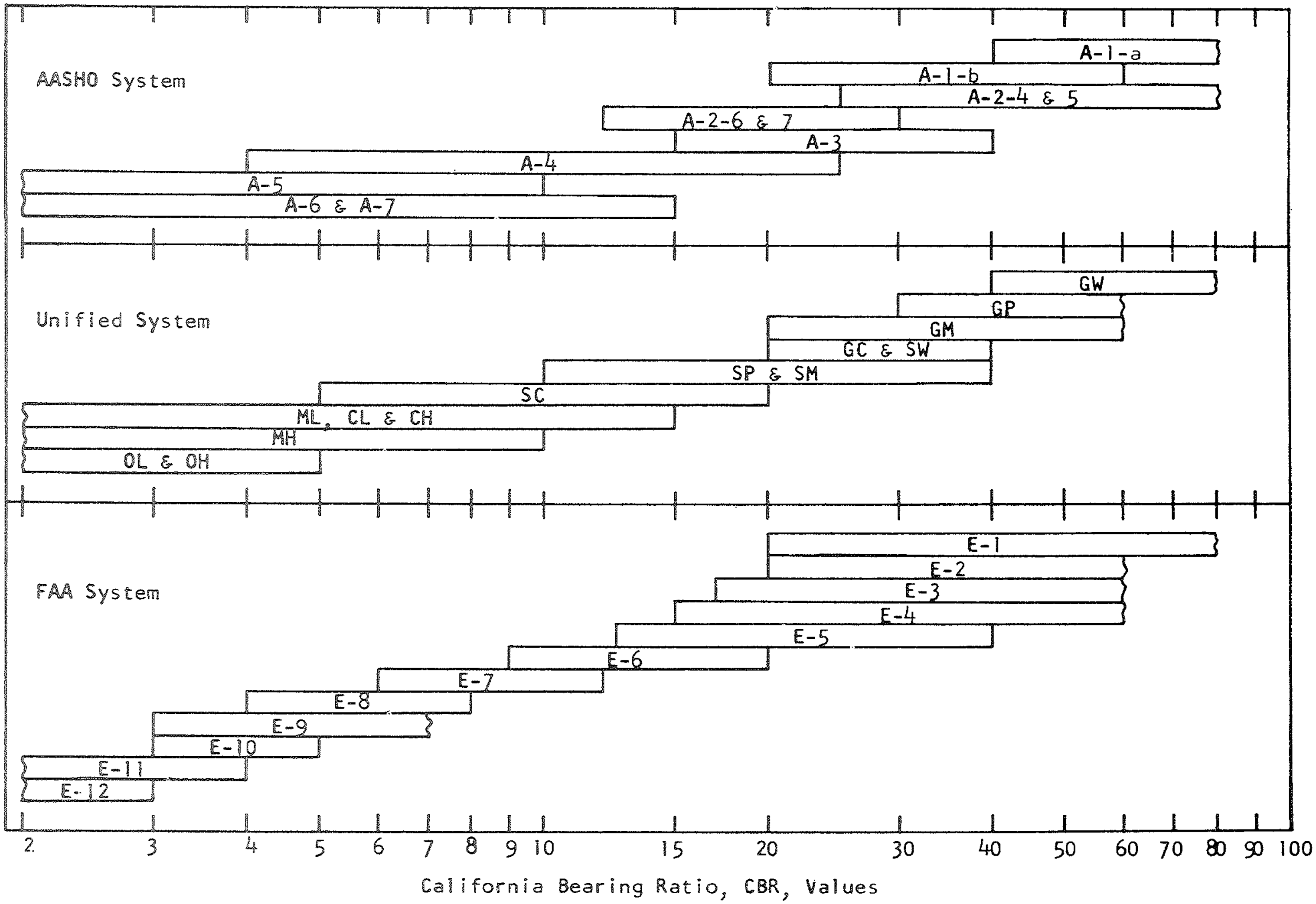


Figure 8. Approximate interrelationships of soil classifications and California Bearing Ratio values (33, 44).

Both the CBR and the subgrade modulus values given are merely relative indications of the load-bearing values of the various soil groups and should only be regarded as a general guide. Wherever these tests are selected for the design of pavement, actual test values should be used instead of the approximate values shown in the foregoing tabulation and in Figure 8.

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[1] The report of the Committee on Economic Highway Planning, L. E. Peabody, Chairman, on "Outline for the Initial Report of the State-Wide Highway Planning Survey", which is not printed in this volume is available for distribution on request.

THE ENGINEERING SIGNIFICANCE OF SOIL PATTERNS

By Donald J. Belcher, *Research Engineer*
Joint Highway Research Project, Purdue University

SYNOPSIS

The term soil pattern is used in the comprehensive sense that includes not only the color pattern of soils but the numerous other factors recorded in an aerial photograph that are influenced by the soil. When properly evaluated they indicate the engineering properties of the soil.

This work stems, in a large measure, from an engineering evaluation of pedology—the science of soil formation—and its application to the problems of highway design, construction, and maintenance. Its subsequent use in airport site selection has permitted an analysis of the soil patterns and their significance in areas existing under a wide range of soil, parent material, and climatic conditions.

Inasmuch as pedology is an important phase of photo-interpretation a simplified form that may be termed engineering pedology is discussed from the standpoint of subgrade problems. Since this soils engineering technique applies to large areas, a number of extensive soil areas are described in detail and test data showing their uniformity are presented. These have been chosen to illustrate the similarity of soils having a common origin regardless of geographic location. Photographs of these areas are included to illustrate their respective patterns.

The individual soil areas have patterns that indicate their properties. Lacking any information other than that shown in the photograph, the observer may study each of the elements that make up the soil pattern. These elements, consisting of erosion characteristics, soil color, surface drainage, and numerous others, reflect the nature of the profile. Gullies assume various shapes and thereby reveal certain properties of the soil such as texture and claypan developments; surface drainage is a function of slope and porosity of the soil; while color patterns often reflect ground water conditions.

The elements of the soil pattern change and their significance varies in differing climatic zones. The effect of climate is to change the type of vegetative cover and the significance of soil color. However, the soil pattern emphasizes the significance of land forms and weathered slopes. Evaluation of the pedologic classification of the great soil (climatic) groups indicates that it is of little value in engineering work. This assessment is necessary since in some western states and in many foreign areas, this is the only type of soil information available. Therefore, reliance must be placed on the interpretation of the soil pattern and its engineering implications. A group of photographs show the basic soil patterns, geologic patterns, and the occurrence of granular deposits.

The geologic pattern is considered in its relation to problems of location and grading. By example and test results the properties of various strata visible in photographs are shown.

The data show that the soil pattern has engineering significance and that it indicates the conditions that affect the location and construction of highways and airports.

THE PATTERN

The soil pattern as seen in aerial photographs[1] is the result of the influence of natural and human forces acting on the original material from which the soil was derived. The elements that make up the soil pattern are visible features that are directly or indirectly influenced by the physical properties of the soil profile. These elements form patterns of their own; among them are the land form, soil color, erosion, surface drainage, vegetative cover, slope, land use, and others such as biological evidence, micro-relief, and farm practices. Although these will be discussed in detail later, it is worthwhile to mention here that apparently insignificant features appear in the photographs in remarkable detail. As an example in photographs of arid and semi-arid

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[1] Aerial photographs have been approved for release by the War Department and the New Zealand Defense Command where concerned

areas it is not unusual to see holes dug by prairie dogs and ants. Since these animals and insects dig their holes in certain types of soil positions, we know something of the soil when there is evidence of their presence in an area.

In some areas all of these visible features are present while in other areas one or more are absent. It is helpful to realize that, independently, the natural elements may vary in their significance and that judgment based on a single element may often be in error. For this reason it is desirable that the aerial photograph contain two, three, or four elements that indicate similar properties of the particular profile. Each element, although not duplicating the exact meaning of the others, adds its portion to the interpretation of the nature of the soil profile. Before examining these elements and their significance some attention must be given to the process of soil formation and profile development.

ENGINEERING PEDOLOGY

Knowledge of the weathering of the parent material and the consequent development of the soil profile into horizons (layers) of differing textures is not widely applied in engineering work. For this neglect we are castigated by the words of Ibn-Al-Awam, the Moor who, in 1250 A.D., wrote in his Kitab-Al-Felahah, "All soils are underlain by a layer that differs radically from that at the surface. Such a subsoil is found everywhere and can be said to form one of the layers of the globe. . . . He who does not possess this knowledge lacks the first principles and deserves to be regarded as ignorant."(1)[2] These radical differences are principally textural and therefore may directly influence the performance of highways and runways.

Figure 1 is an example of profile development. The light topsoil, A, is a silt, the dark, B, horizon appearing as horizontal band is a plastic silty clay, and the semi-granular parent material, C, below contains material of all sizes.

Under some conditions the subgrade may be of plastic clay when located in the B horizon whereas in deeper cuts the pavement will rest on the more stable parent material of the C horizon. In areas of gently rolling relief where profile development is strong each cut presents a similar problem in which the subgrade varies from a compacted fill through the A and B horizon to the parent material, C, in the deepest part of the cut. Drainage problems, performance, and subsequent maintenance vary in the same manner. Proof of this lies in the results of performance surveys, pumping surveys, and inventories of spring "breakups." These highway problems can be traced in part to a disregard of soil conditions. Figure 2 illustrates performance in an average highway cut.

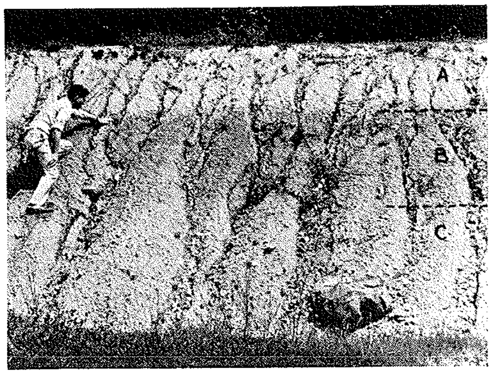

Figure 1. A weathered profile exposed in a highway cut. The light-colored silty topsoil approximates the "A" horizon. The "B" horizon appears as a horizontal dark band below the topsoil and the "C" unaltered parent material marked by granular fragments.

In applying soil science to engineering problems it has been possible, and necessary, to eliminate many of the points on which soils are classified, since they have little direct bearing on present engineering use. The essence of the entire subject can be stated as follows: Regardless of geographic distribution, soils developed from similar parent materials under the same conditions of climate and relief are related and will have similar engineering properties which in comparable positions will present common construction problems and produce like pavement performance.

Whether the parent material is a hard, resistent bedrock; a soft, easily-eroded loess; or a glacial material (till); each in its own manner develops a soil profile. Because of their individual properties, these parent materials

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[2] Numbers in parentheses refer to Bibliography at end of paper.

produce a soil pattern that is related to their texture, slope, ground water conditions, and origin. This can be termed "the principle of the recurring profile" which becomes significant not only in engineering soil surveys but in standardizing highway or airport pavement design and construction methods.

When a soil profile recurs, as it does in comparable positions within a parent-material area, the soil pattern will also occur. This is the link between the soil pattern in the airphotos, the soil profile, and the related soil problems. Thus, by the proper sampling of a given soil area the results may be used to determine soil characteristics in other areas having a similar pattern in the airphoto without respect to distance.

Aerial photographs can be a major factor in making soil investigations a practical economic success for at least two reasons. First; under present procedures the average soils laboratory is handicapped by lack of funds and personnel to keep field and laboratory investigations abreast of design and construction requirements; second, the present methods of pavement design do not, except in a general way, take into account the soil information supplied by surveys.

Aerial photographs combined with geology and pedology (soil science), if used properly, will minimize the first and improve the latter of these two weaknesses. Using the already available standard Agricultural Adjustment Administration photographs as a tool, a soils engineering organization can make a field survey with photos in hand, sample, test and report soil conditions on most projects long before the design department requires the information. The second weakness, that of lack of use of soil data, is equally acute but less easily remedied. The first solution is easily executed since everyone likes to produce more results with less work. The second concerns the field of those not primarily interested in soils but in the final performance of the pavement. If soil tests cannot be shown to effect a reduced cost or an increased pavement life then they will probably be discarded. A soils organization then should pay its own way. If scant use is made of this type of information then something is wrong and soils men are at least partially to blame for not assisting others to use their data.

Aerial photographs can help in this process by providing the necessary factors of interest, understanding of the problem, and a view of the "soil-position." The factor of position is often as important as the physical properties of the soil. The test data plus the relative position of the material tested should equal a given design for one type of road in an area. For example, the results of tests on the extensive silt soils of the Devil's Lake and Lake Agassiz basins in North Dakota and Minnesota are the same as those from the windblown silts that form hills lining the banks of the Mississippi, Missouri, Arkansas, and Platte Rivers. However, the flat, poorly-drained soils of the lakebeds have a high water table—a depressed position—while the silt hills are comparatively dry and well-drained. By any common system of testing, soils from these two areas will appear alike, resulting in one design. Obviously the proper design for one soil-position will result in an over- or under-design for the other situation. Soil tests do not describe the entire situation that effects the subsequent service life of the pavement. The answer lies in relating tests and soil-positions to a standard design proven for each general case.

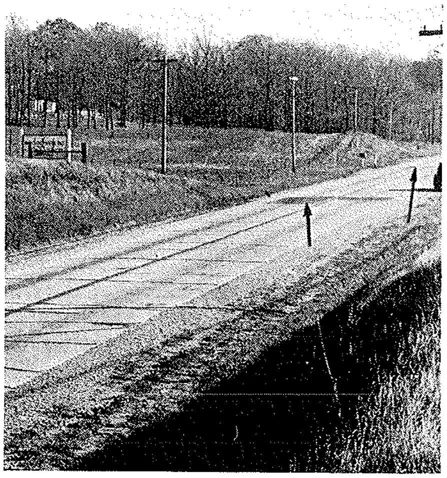

Figure 2. A road cut into glacial drift parent material. Some method of equalizing subgrade conditions between cut and fill would eliminate the wide difference in performance existing in these adjacent positions. Note patches indicating a failure where the subgrade intersects the plastic material in the "B" horizon.

Aerial photographs functioning as a scale model permit examination of the situation without an inspection trip. Since position is determined chiefly by the relief of an area, the number of positions is limited to perhaps two types of cuts, shallow or deep; fills, high or low; level areas; and special or miscellaneous positions. Thus, there are approximately five standard positions. The soil factor then enters into the equation. In working with an average State the soils should be divided into as many groups as will warrant changes in design or construction methods—no more. Currently this permits, as it should, classification of soils—from the most plastic to the granular—into a few groups. Chart I, a tentative step in this direction, has 11 soils with a strong possibility of a future reduction by grouping. The theoretical number of soil-positions (five positions times the number of types of soil) and resulting designs are further reduced inasmuch as the same design may apply to sands and gravels in all positions. Further, there are large areas in which some of these soils do not occur and too there are some soils that occur in one or two positions only.

CHART I — LEGEND AND CLASSIFICATION FOR ENGINEERING SOIL IDENTIFICATION

LEGEND			B.P.R. (1) CLASS	C. AGG. % ON #10	C. SAND % #10—#60	F. SAND % #60—#200	SILT (%) 0.05—0.005M.	CLAY (%) BELOW 0.005M.	LIQUID LIMIT	PLASTICITY INDEX	MAX. DRY WT. LBS. PER CU.FT.	SOIL NO.
SOIL NO.	SYMBOL	DESCRIPTION										
1	▩	TOPSOIL	—	—	—	—	—	—	—	—	—	1
2A	▥	SAND-CLAY	A-2	—	5-30	30-60	5-15	10-35	20-35	5-15	105-115	2A
2B	░	SAND	A-3	0-25	30-70	30-70	0-25	0-10	—	—	100-110	2B
3	▒	GRAVEL & SAND	A-2	35-70	20-40	20-40	0-15	0-10	—	—	115-130	3
4	▒	GRAVEL-SAND, SILT & CLAY	A-1	30-65	15-30	15-30	10-30	5-15	15-35	0-15	120-135	4
5	▓	SILT-CLAY, SAND & GRAVEL	A-2	10-35	15-35	15-30	10-40	5-20	15-40	10-30	115-125	5
6	░	SILT (EXPANSIVE)	A-4	0-5	0-5	0-40	35-90	10-30	20-35	0-10	95-110	6
7	▧	SILT WITH SAND &/OR GRAVEL	A-4	0-5	5-55	0-25	20-65	10-25	20-25	6-12	110-125	7
8	▨	SILT WITH SAND & CLAY	A-4, A-7	0-5	0-20	5-20	30-50	20-50	25-35	10-15	110-120	8
9	▩	SILT-CLAY (EXPANSIVE)	A-5	0-10	0-10	0-10	35-75	15-35	35-50	10-20	95-105	9
10	▦	CLAY WITH SILT & SAND	A-7	0-5	0-35	0-15	15-65	15-40	35-45	15-30	100-110	10
11	▓	CLAY WITH SILT (PLASTIC)	A-6, A-7	0-5	0-15	0-15	30-55	25-60	45-60	20-35	95-105	11
12A	▓	CLAY WITH SILT (COLLOIDAL)	A-6	0-5	0-10	0-5	40-60	30-50	+60	+30	-95	12A
12B	▓	CLAY WITH SILT (ORGANIC)	A-5	0-5	0-5	0-5	50-90	5-35	45-150	10-50	-85	12B
12C	▓	CLAY WITH SILT (EXPANSIVE)	A-5	—	—	—	—	—	50-70	15-25	-95	12C
13	▤	ROCK-SOIL MIXTURE	—	+50	—	—	—	—	—	—	—	13
14	▓	MUCK, PEAT, OR COAL										14
15	▓	SOFT OR WEATHERED SHALE										15
16	█	HARD SHALE										16
17	▤	SANDSTONE										17
18	▦	LIMESTONE										18
19	░	GRANITE										19
20	▧	MICA SCHIST										20
21	▒	BASALT										21
22	▨	CORAL										22
23	□											23

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The resulting table would then combine the soil-position factor in a columnar arrangement with the soil number or class ranging from top to bottom on the left with the various positions forming vertical columns. At the intersection of each "soil" and "position" a box is formed to contain design recommendations wherever the particular situation is encountered. As an example of this system a skeleton table is shown in Table I in which several "soils" require the same design in one position for a given class of road. The table applies to roads carrying the heaviest commercial traffic in a hypothetical region that includes the industrial east and midwest.

It is reasonable that the regions should be established on a climatic basis to include problems produced by weather conditions. On the basis of temperature a boundary has been suggested by the Public Roads Administration (19) defining the practical southern limit of frost action occurrence. This boundary separates the country into two general areas (See Fig. 3): 1, that subject to serious ground freezing, and 2, that relatively safe from ground freezing. In the light of more recent studies other problems directly related to rainfall and pavement performance permit several east-west sub-divisions of the temperature belts into areas based on rainfall. In attempting to establish these boundaries a modification of both the Koppen and the Thornthwaite methods of climatic classification is necessary in order to emphasize the important climatic conditions influencing pavement performance.

In warm climates where frost action is not anticipated the moisture content of the sub-

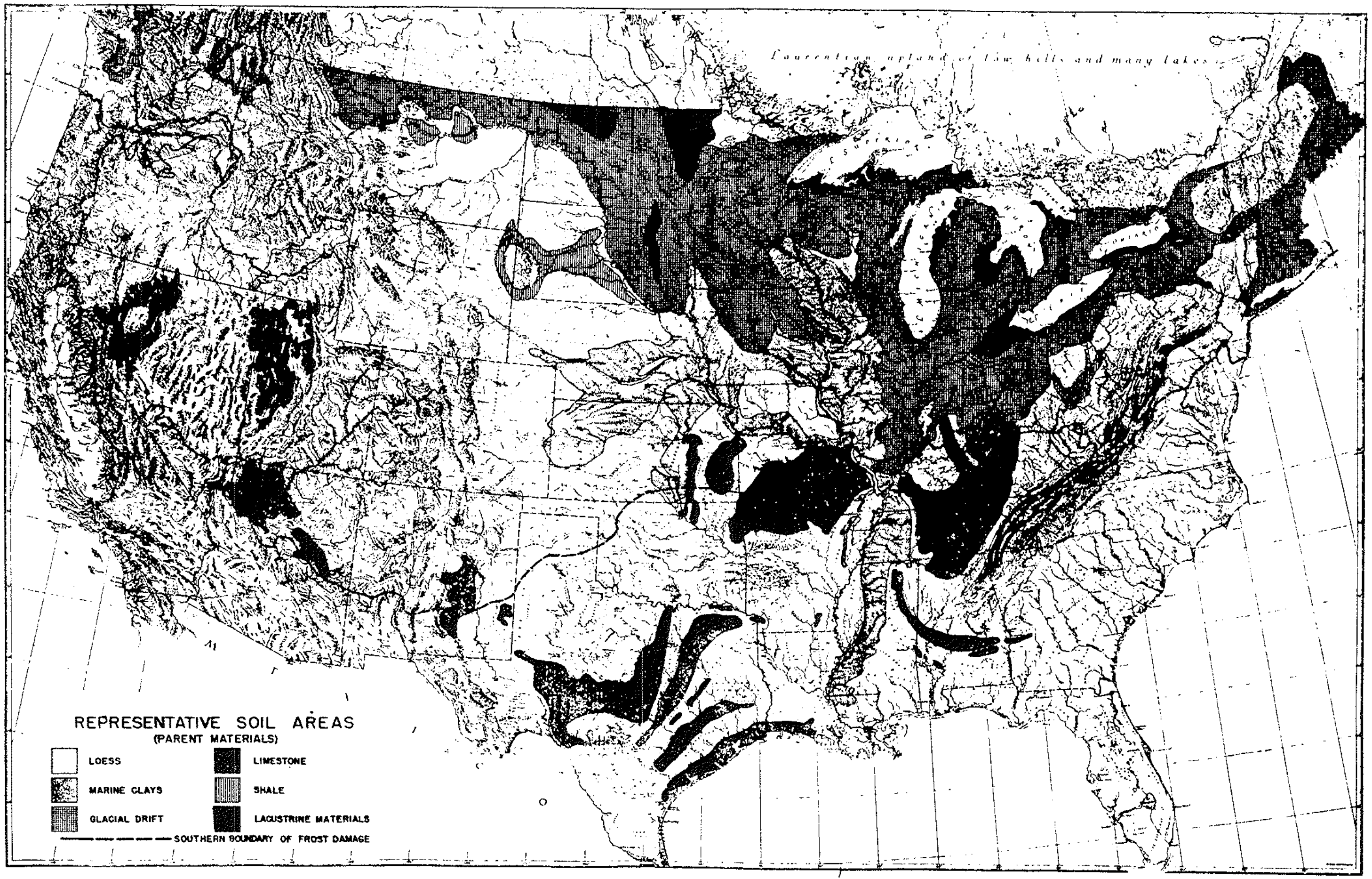

Figure 3. Location map showing the distribution of four soil areas of United States representing different types of parent materials. The balance of the area may be proportioned as follows: Great Plains materials and Coastal plains—water deposited; residual soils from sandstones, shales, granites, volcanics, etc.; and alluvium or recent stream deposits.

grade is governed by the soil and the seasonal rainfall. Tentatively it is indicated that under wide variations in annual rainfall two separate subgrades composed of similar soil would at some period each year reach saturation. The distinction between 20 in. annual rainfall and 50 in. in similar soil areas would exist in the duration of the problem period or the period of highest subgrade moisture content. In desert and semi-arid areas it is becoming increasingly evident that in these areas having a low P/E[3] ratio the subgrade moisture content is cumulative over a relatively long period of time, finally resulting in pavement distress.

TABLE I

TENTATIVE FORM AND CONTENT OF SUBGRADE DESIGN TABLE FOR HIGH TYPE ROADS

REGION W(1)

SOIL NO. (CHART I)	RELATIVE GRADE LINE POSITION			
	CUTS(2)	FILLS	LEVEL	MISCELLANEOUS(3)
2	A	M	A	X (SHALLOW SAND ON IMPERVIOUS TILL)
3	A	M	A_1(4)	—
4	B	M	A	—
5	B	M	A	—
6	C	B	K	K_1 (UNDERLAIN BY CLAYPAN)
7	D	N	—	—
8	D	N	—	—
9	—(5)	O	—	Y
10	E	F	F	Z
11	—	G	G	Z
12	—	R	R	Z

DESIGN OR CONSTRUCTION RECOMMENDATION (BRIEFED)

(A) SUBGRADE PAPER
(C) COMPACTION — SPECIAL MOISTURE CONTROL
(D) 6 INCH, DRAINED, GRANULAR INSULATION COURSE
(E) 8 INCH, DRAINED, GRANULAR INSULATION COURSE

(1) INCLUDES SOILS DERIVED FROM GLACIAL DRIFT, SANDSTONE, LIMESTONE, LOESSIAL AND LACUSTRINE DEPOSITS, AND ALLUVIUM. ANNUAL RAINFALL 25 TO 45 INCHES. SUBJECT TO GROUND FREEZING IN WINTER MONTHS

(2) INTO PARENT MATERIAL.

(3) INCLUDES LOCATIONS WHERE GENERAL SUBGRADE MATERIAL IS UNDERLAIN BY HORIZONS OR STRATA OF CONTRASTING TEXTURE.

(4) SUBSCRIPTS INDICATE DEVIATIONS FROM STANDARD PRACTICE INFLUENCED BY POSITION.

(5) DOES NOT OCCUR IN THIS POSITION

Table I indicates the form that a subgrade design chart may assume. For example Design C applies to silts in rolling terrain and would include the required improvements of the exposed subgrade, such as compaction, to a specified density or some other form of stabilization that had been found to give satisfactory performance with a given pavement design. This design would probably specify the permissable tolerance in moisture content for compacting these materials to the required density. Since this is a critical factor in the compacting of this particular material, that phase would be important to all positions. Furthermore, it is probable that, in this hypothetical Region W, proper compaction in cuts and fills will provide excellent performance with standard pavement design.

The situation with respect to the Nos. 7 and 8 soils (Table I) is sufficiently similar to warrant a single design for all cuts. Under these road conditions in cuts an early failure by pumping is common. A simple design feature incorporated during construction will prevent this failure. Similar failures occur in areas of No. 10 material and if Region W included some of the coastal plains States, Nos. 11 and 12 would also carry a similar design with some possible adjustment to compensate for the increased plasticity (and related properties) of these clays. A corresponding table applying to secondary roads would be necessary.

EXTENT OF SOIL AREAS

If we are to accept the principle of the recurring profile, the burden of proof then lies in the uniformity with which nature has deposited the parent materials of these areas. In the exploration of this question a large number of representative samples were taken. Standard tests were applied on several hundred to furnish a basis of classification (2) and comparisons were made between corresponding horizons in the profiles. Thus, parent material areas were explored and found to be consistent. Where exceptions occur the soil pattern in photographs indicates a change in physical properties as well as the nature of that change. It is important to note that the illustrations that follow are of wide geographic distribution as well as being of a contrasting origin. The intent in selecting these examples has been to show that the uniformity of soil properties and patterns is neither confined to a few selected areas nor to a particular mode of origin. Where parent materials vary they do so in a manner related to their formation. The variation, if significant, can be expected to influence the soil pattern.

Figure 3 is a location map showing the four parent material areas to be described. 1,

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[3] Precipitation—Evaporation.

Marine clays; 2, soils of the loess areas; 3, a residual soil—in this instance derived from limestone; and 4, glacial drift. These represent the major classes of parent materials from the standpoint of origin. The marine clays were deposited under water; the loessial soils, derived from windblown silts; the residual soils, developed in place from rock; and the glacial drift materials were deposited by ice during glacial periods.

The Marine Clays of the Coastal Plains

During one geologic period of the earth's history, large areas of the Gulf and East Coast states were submerged. During this period gravels, sands, silts, and clays washed from the nearby mountains were deposited under water. Subsequently, continental uplift has raised these materials above sea level. The area is now known as the coastal plains and it extends in varying widths from New York to the Rio Grande. Included in the coastal plains (See Fig. 3) is an extensive area of black plastic clay, generally known as the "Black Belt." Figure 4 is an aerial photograph that illustrates the pattern of the upper coastal plains areas' Black Belt. These soils are underlain by a layer of chalk, marl, or limestone in the substratum that sometimes introduces a silt influence that is indicated by the Class No. 9 (Chart I) soil.

Figure 4. The photograph shows the variation in colors in an area that, from the ground, appears black. Chalk underlies the entire area and where light tones appear the influence of the chalk has modified the silty clay to a No. 9 material. The darkest areas represent Nos. 11 or 12 material. Erosion control in the form of "terracing" is evident. Sheet erosion on these gently sloping areas indicates a condition of retarded internal drainage and implies a clay texture in the subsoil. Bar scale on aerial photographs indicates a distance of one mile.

Other areas of the coastal plains vary through the texture range from the famous "sand-clays" in the southeast to the fine sands and sandy silts of local areas in the eastern lower plains, and the sands of the majority of the southern coastal areas, especially of Florida. Some of the other coastal plains clays (light colored, Table II—samples 7-12), developed under similar circumstances, are defined under a variety of catenary[4] names such as Susquehanna, Orangeburg, Oktibbeha, Lake Charles, Lufkin, and others. These soils, being of an impervious nature develop the same indications of clay-like properties in the soil pattern regardless of their pedologic name. Figure 5 is representative of some of these clay areas. In it are the inevitable signs of highly developed surface drainage, "clay shaped" gullies and distinctive color tones. Many highway pavements on these soils show a marked distress directly related to the subgrade conditions.

TABLE II(1)
REPRESENTATIVE SAMPLES OF
COASTAL PLAINS CLAYS

NO.	LOCATION	DEPTH IN INCHES	LIQUID LIMIT	PLASTICITY INDEX	LABORATORY DRY WEIGHT (PROCTOR)	CLASS(2)
1	ALABAMA, SOUTH EASTERN	40 (−)	66.3	27.4	90.8	12 A
2	TEXAS, NORTH CENTRAL	24 (0-40)	69.4	35.2	90.2	11
3	TEXAS, NORTH EASTERN	166	68.4	42.6	—	12 A
4	TEXAS, CENTRAL	60	62.4	31.3	—	11
5	ALABAMA, CENTRAL	60	63.7	34.4	—	12 A
6	ALABAMA, CENTRAL (LIGHT AREAS IN FIG. 4)	60	45.7	19.0	96.0	9
7	ARKANSAS, SOUTH CENTRAL	40	52.6	30.8	—	11
8	ALABAMA, CENTRAL	60	57.4	27.5	89.8	12 A
9	TEXAS, NORTH EASTERN	20	57.9	20.0	82.9	12 C
10	MISSISSIPPI, SOUTH	BORROW PIT	69.5	26.6	—	12 A
11	ALABAMA, EAST CENTRAL	72	59.0	20.4	63.8	12 C
12	TEXAS, SOUTH	24 +	48.2	26.4	107.0	11(3)

(1) The data presented in this and the following tables are necessarily brief because of the stipulations of the Federal contract under which the work is being conducted.

These are random samples representative of large areas and are, therefore statistically significant. However, within each area related variations occur and due weight should be given to the exceptions represented by the single examples.

Locations 1-6 represent Black belt area.

Locations 7-12 represent other Marine clays.

(2) See Chart I.

(3) Gulf Coast Clay.

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[4] A catena is a family of soils derived from the same parent but occurring on different slopes.

Soils of the Loess Areas

Although an unrelated type of soil deposit such as windblown silt offers a restricted parallel, it permits observation of the effect of wide climatic variations on a uniform parent material. The origin of loess is attributed to the wide flood plains of our major rivers, to glacial deposits, and to the great plains areas spreading eastward from the foot slopes of the Rocky Mountains. Violent winds generated by the proximity of the continental ice sheets swept silt size material from these broad open areas. Adjacent uplands were covered with this mantle of silt that today forms one of the outstanding examples of soil uniformity. Where the water-laid coastal plains varied in texture from clay to gravel these wind-laid materials consist of particles principally in the silt size. Clay sizes are absent initially because the cohesive property of clay resists wind erosion; the more coarse materials because of the limited carrying power of the wind, and the absence of sand in the wide alluvial areas. The clay found in some silt profiles is formed by subsequent weathering of the loess.

Figure 5. Soil pattern in a light colored clay area of the coastal plains. Note the well developed surface drainage. "Caswell" sand, occurring as rough light spots (outlined) in some parts of the area, is the only granular material available in many of these localities.

Soils formed from these materials lend themselves readily to airphoto interpretation because of the many distinguishing features that are peculiar to the soils of these deposits (see Fig. 6). In this country (Fig. 3) the loess belt begins in semi-tropical Louisiana and extends northward along the east bank of the Mississippi until near the junction of the Ohio it spreads into Illinois, Iowa, Kansas, Nebraska, Missouri, Indiana, Wisconsin, and

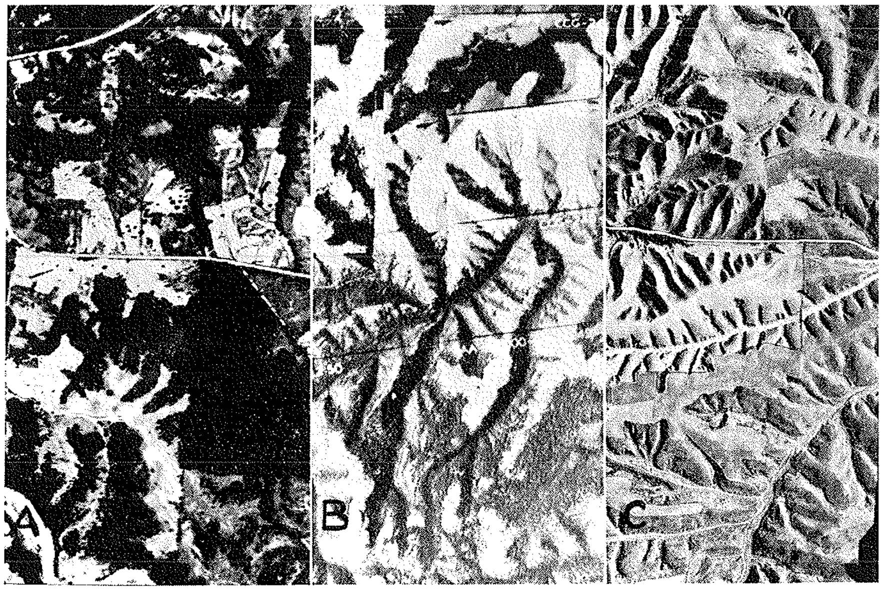

Figure 6. The loess pattern in various climates. A humid Mississippi, B subhumid Washington, and C semi-arid Nebraska. Note the similarity of the erosion pattern. The amount of vegetation is the chief variable in the soil pattern.

Minnesota. Loessial soils are found locally in other disconnected but related areas. In the west a large section of Washington and adjacent areas of Idaho and Oregon are covered with a similar mantle. The remarkable consistency of these materials both in texture and test results can be appreciated only partially by viewing the presented data. The results shown in Table III are divided into two parts, those data obtained on the weathered portion of the profile (A and B horizons) that is influenced by climate and slope and those of the unweathered parent material.

TABLE III

REPRESENTATIVE SAMPLES OF LOESSIAL SOILS FROM VARIOUS DEPOSITS

WEATHERED PORTION OF PROFILE (A & B HORIZONS)

LABORATORY NUMBER	APPROXIMATE LOCATION	LIQUID LIMIT	PLASTICITY INDEX	DRY WEIGHT[1]	CLASS[2]
1158-C	IOWA - EASTERN	38.8	17.0	—	9
1324-C	MISSOURI - EASTERN	33.6	16.3	—	9
1177-C	IOWA - WESTERN	43.2	17.9	—	9
1327-C	MISSOURI - WESTERN	40.5	15.9	—	9
1251-C	WASHINGTON - S.E.	34.5	12.1	—	9
1360-C	KANSAS - WESTERN	31.7	12.5	—	9
1279-C	UTAH - IDAHO LINE	36.1	7.5	—	9
340-1	INDIANA - SOUTHEASTERN	41.2	16.5	101.6	9
957-C	ILLINOIS - WESTERN	53.6	30.2	—	11[3]
903-C	MISSISSIPPI - WESTERN	45.5	16.8	—	9
836-C	TENNESSEE - WESTERN	38.4	11.8	104.2	9
PARENT MATERIAL (LOESS)					
1384-C	KANSAS - WESTERN	(TEXTURAL &	INSPECTION	CLASSIFICATION)	6
1247-C	WASHINGTON - S.E.	30.7	7.5	99.5	6
268-2	INDIANA - SOUTHEASTERN	29.2	7.3	108.0	6
838-C	TENNESSEE - WESTERN	29.0	4.9	104.5	6
901-C	MISSISSIPPI - WESTERN	31.8	3.1	104.5	6
—	CHINA - NORTHERN	—	6.1	—	6[4]
1254-C	WASHINGTON - S.E.	38.9	13.4	—	9
1324-C	MISSOURI - EASTERN	33.6	16.3	—	9

[1] LAB. MAX. AT PROCTOR'S OPTIMUM [2] JOINT HIGHWAY RESEARCH PROJECT CLASSIFICATION [3] DEPRESSION [4] CLASSIFICATION BASED ON PLASTIC LIMIT

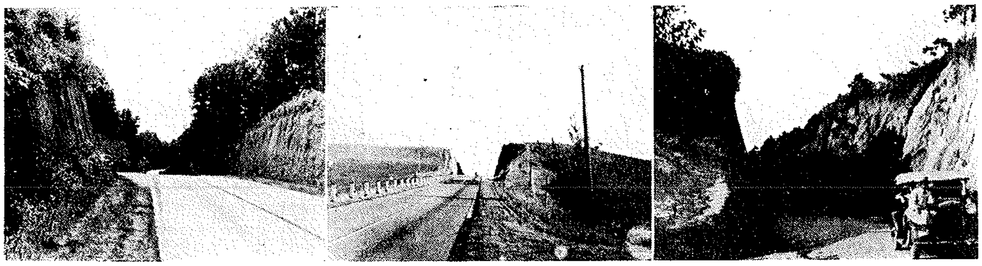

Figure 7. An example of the distribution of a soil material (loess) and the uniformity of engineering treatment required by the physical properties (Table III) of the soil. Nearly-vertical cut slopes are required unless immediate and complete sodding are scheduled. A, Mississippi—note the effect of climate on the tree cover (55–60)[a]; B, Washington (15–20)—lack of tree cover indicates low rainfall. Patch in settled area of fill reflects the difficulty of compacting silt without sufficient moisture; C, Vertical cuts in loess area of China (12–17) (Courtesy of Prof. Mo Chih Li, National Tsing Hua Univ.).

[a] Annual rainfall in inches.

Although only one test has been run on loess from China its properties do not vary materially from those in this country. On the basis of this continuing uniformity it is reasonable to expect the large belts of loess in Europe, South America, and Asia to conform in physical characteristics to those of the United States. In fact, the local silt area of the northwest African coast has textural indications in the form of "sunken paths" similar to the "sunken roads" of Mississippi and to the extremely deep roads reported (3) in the northern China area. One illustration of uniform engineering treatment in similar soil areas is shown in Fig. 7, illustrating vertical cuts in Mississippi, in the Palquse area of Washington, and in north China.

Soils of the Limestone Areas

Residual soils are those developed by the weathering process that destroys the parent bedrock. They are the residue that remains when the soluble materials have been removed by leaching or when the individual grains have become loosened by physical weathering. These two processes largely determine the nature of the soil. In humid climates the leaching by percolating water predominates; in arid climates physical weathering is active and the moisture movement is retarded or reversed.

In this paper limestone has been considered as a consolidated rock high in calcium carbonate and often including appreciable quantities of magnesium (dolomite). Marls and chalk have been excluded because they have not been encountered as soil-producing materials. However, soil information and airphotos of the chalk areas of England indicate

(18) that a silty, friable material is produced. These limestones are divided into two soil-producing types: the hard dolomitic limestones, and the more common, relatively pure limestones. The dolomitic limestone, confined to relatively minor areas, is highly resistant to weathering, retains its features relatively unmodified, and produces very little soil. The majority of limestones produce a rather deep profile and have been found to be remarkably consistent in engineering characteristics in humid and sub-humid climates, regardless of geographic location.

TABLE IV

REPRESENTATIVE SAMPLES OF SOME LIMESTONE RESIDUAL SOILS IN THE UNITED STATES

LABORATORY NUMBER	APPROXIMATE LOCATION	LIQUID LIMIT	PLASTICITY INDEX	DRY WEIGHT	CLASS(1)
838-C	OKLAHOMA, CENTRAL	51.0	30.6	—	11
946-C	MISSOURI, SOUTHWESTERN	38.6	18.88	—	10*
862-C	KENTUCKY, CENTRAL	59.1	20.3	92.8	11
1007-C	OHIO, EASTERN	62.6	42.6	81.2	12A
928-C	OKLAHOMA, NORTH CENTRAL	60.0	40.9	—	12B
1380-C	KANSAS, SOUTHEASTERN	56.8	28.4	—	11
842-C-4	ALABAMA, EASTERN	60.3	27.6	86.0	12A
1026-C	OHIO, SOUTHEASTERN	65.0	36.5	—	12A
1395-C	WEST VIRGINIA, NORTHEASTERN	54.1	31.7	97.7	11
1347 C	ARIZONA, CENTRAL	57.4	33.9	—	11
1060-C	WISCONSIN, WEST CENTRAL	83.8	57.2	84.0	12A
1309-C	UTAH-ARIZONA LINE	68.1	39.3	—	12A
261	INDIANA, SOUTH CENTRAL	63.6	29.5	82.5	12A

* Has a high chart—see Fig. 8 airphoto pattern.
(1) See Chart I.

Table IV illustrates the distribution and representative test data on several limestone soils. Since these soils occur on rolling relief, cuts into the profile are common. Therefore the test data concern the important lower portion of the soil profile exposed as subgrade in cuts.

In some of the limestone deposits there have been appreciable quantities of chert in the soil profile. In some instances there has been a sufficient quantity to make the material in the profile more of a rock-soil mixture. When the chert content reaches this proportion it can be distinguished by a characteristic pattern that is illustrated in Figure 8. In this view surface drainage is undeveloped indicating good internal drainage despite the fact that physical tests give an opposite impression. This is the influence of natural structure in the soil profile that permits drainage even in clay soils.

Figure 8. Illustrations of a soil pattern in a cherty limestone area. Sinkholes (arrows) indicate limestone. The white speckled pattern is related to the chert and indicates a particularly difficult compaction problem. Close observation of cut slopes and detailed ground inspection are necessary to distinguish this condition when on general reconnaissance survey.

There is ample evidence to indicate that the pattern of limestone soils and their similarity of engineering properties can also be projected to the humid tropics. Associated with these limestones there are plastic clays and silty clay soils derived directly from the limestone as well as alluvial soils washed from the hills. In addition plastic soils weathered from limestone occur in North Africa and the adjoining mediterranean coast of Europe (4), Palestine (5), and India (6).

Among sedimentary deposits the clay shales contribute more than their proportional share to highway failures in the form of landslides, fill failures, and unstable subgrades. In general, these materials are of limited extent and occur as minor outcrops in predominantly sandstone or limestone areas; in some notable areas (Fig. 3) however, the shales appear as surface material and dominate the entire region. Where the shale is exposed to erosion it becomes highly dissected forming rounded slopes. Inasmuch as these are marine clays partially consolidated it is logical that their texture when weathered is that of a No. 10, or higher, material. Figures 13, 15, and 20 B, C illustrate the characteristic weathering that distinguishes these materials whether viewed from the ground or from the air.

Soils of the Glacial Drift Areas

The Continental ice sheets provide what is probably the largest continuous parent material area in the United States. Figure 3 indicates the area covered by glacial drift. Similar areas occur in England, Scandanavia, North Germany, and the U. S. S. R. in Europe and Asia. Smaller glacial areas are associated with most of the mountainous regions of the world. The glacial drift that mantles large sections of many of the northern states has been derived from a large variety of rocks and yet the parent material of the till plains consists almost entirely of material that can be classed as Nos. 7 or 8 (Chart I). A small percentage of the area falls into the No. 4 class material and some in the No. 10. Because of the varied origin of the drift in the United States, these parent material classes can also be expected to embrace much of the European and Asiatic till. The major remaining portion of the drift is made up of stratified materials deposited by glacial streams. These take the form of outwash plains, eskers, kames and terraces or valley trains and consist chiefly of sands and gravels. Glacial lakes occupy a small proportion of the area and range in texture from silts to silty clays. Figure 9 shows an area of the glacial Lake Agassiz basin (No. Dakota-Minnesota) in which wave marks, low relief, poor drainage and "clay gullies" indicate the origin and texture of the soil.

Figure 9. Air view of glacial Lake Agassiz basin. The pattern so clearly visible from the air is indistinguishable on the ground. Ponded water, extremely flat terrain and the V-shaped drainage way are directly related to origin, soil conditions, and a definite design procedure to overcome a poor subgrade material in this soil-position.

TABLE V

REPRESENTATIVE SAMPLES OF GLACIAL PARENT MATERIALS (TILL) IN THE UNITED STATES

LABORATORY NO.	LOCATION	LIQUID LIMIT	PLASTICITY INDEX	LABORATORY DRY WEIGHT (PROCTOR)	J.H.R.P.(1) CLASS
1171-C	SOUTH DAKOTA, CENTRAL	30.8	13.4	109.3	7
1370-C	KANSAS, SOUTH CENTRAL	—	—	111.9	7
1392-C	MICHIGAN, WESTERN	—	—	125.2	7
1095-C	MINNESOTA, NORTHERN	20.2	6.5	117.1	7
1102-C	IOWA, NORTH CENTRAL	29.6	10.7	—	8
969-C	INDIANA, NORTHEASTERN	28.4	11.5	112.4	8
965-C	MICHIGAN, WEST CENTRAL	25.5	12.5	115.8	8
1010-C	OHIO, NORTH CENTRAL	29.4	13.1	111.3	8
1032-C	OHIO, CENTRAL	16.6	1.7	—	7
1082-C	WISCONSIN, SOUTH CENTRAL	28.3	14.2	—	8
1081-C	MICHIGAN, UPPER PENINSULA	—	—	130.1	4
1076-C	ILLINOIS, NORTH CENTRAL	35.1	17.1	104.1	10

Table V illustrates the distribution and uniformity of glacial parent materials. Although the texture of these parent materials remain substantially alike, differences in the ground slope or "position" create differences in the weathered horizons of the profile above the parent material (Fig. 1).

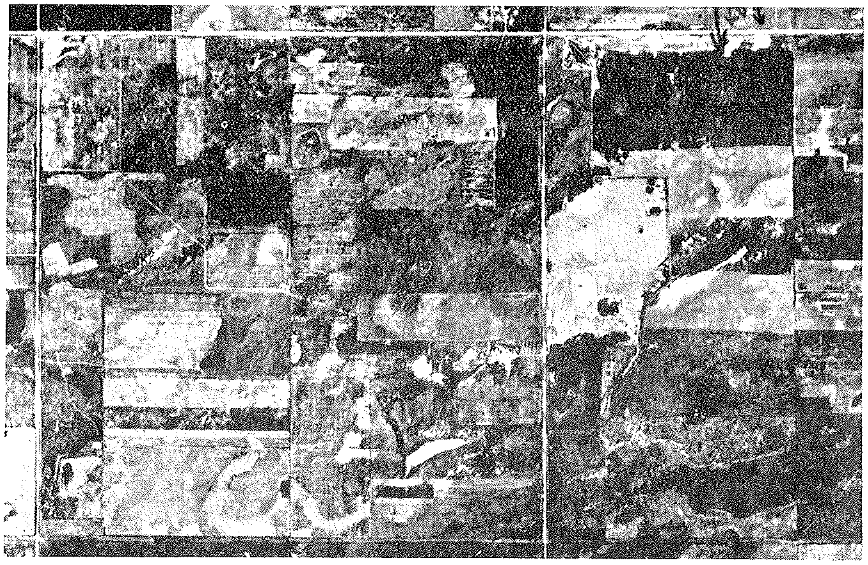

Figure 10. A semi-granular glacial drift area in a dry climate. Lack of vegetative cover and the type of land use indicate a semi-arid condition. Semi-granular texture is indicated by lack of surface drainage. Notice the directional trend of the pattern influenced by the ice movement.

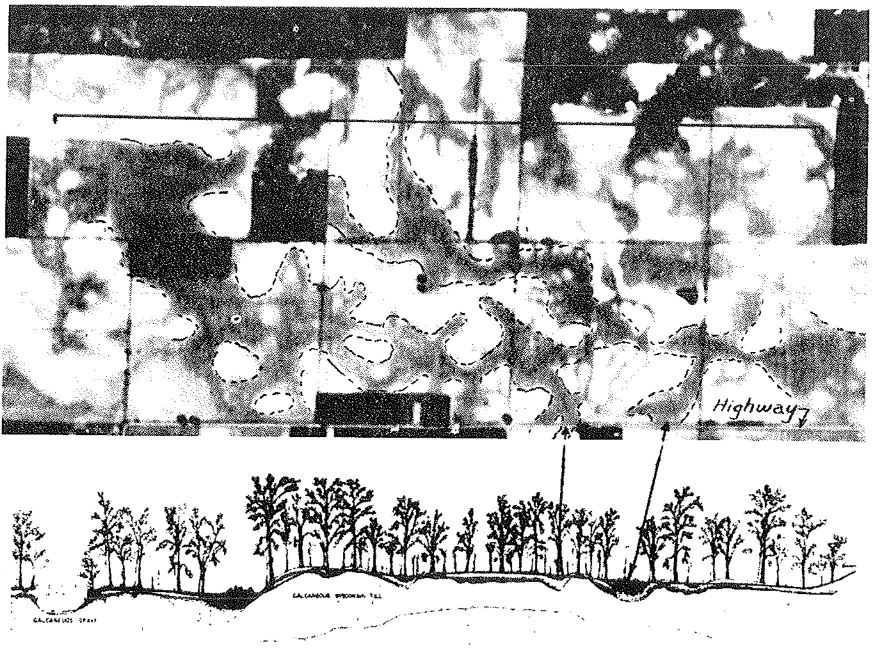

Figure 11. A common glacial till pattern in the younger drift areas of the humid midwestern states—Ohio to Iowa. In this area the color pattern is well developed and the profile recurs in a similar pattern. These are plastic, poorly-drained soils of the till plains. The section sketch shows the relationship between the slope of the ground, profile development, soil color, and vegetation. Gravel terrace on left and rock ledge on right not included in airphoto.

Figures 10, 11, and 12 illustrate a range in glacial drift patterns ranging from semiarid in Figure 10 to humid in the other figures. Although the patterns are not alike, since the textures and profiles vary, each is distinctly a glacial drift pattern.

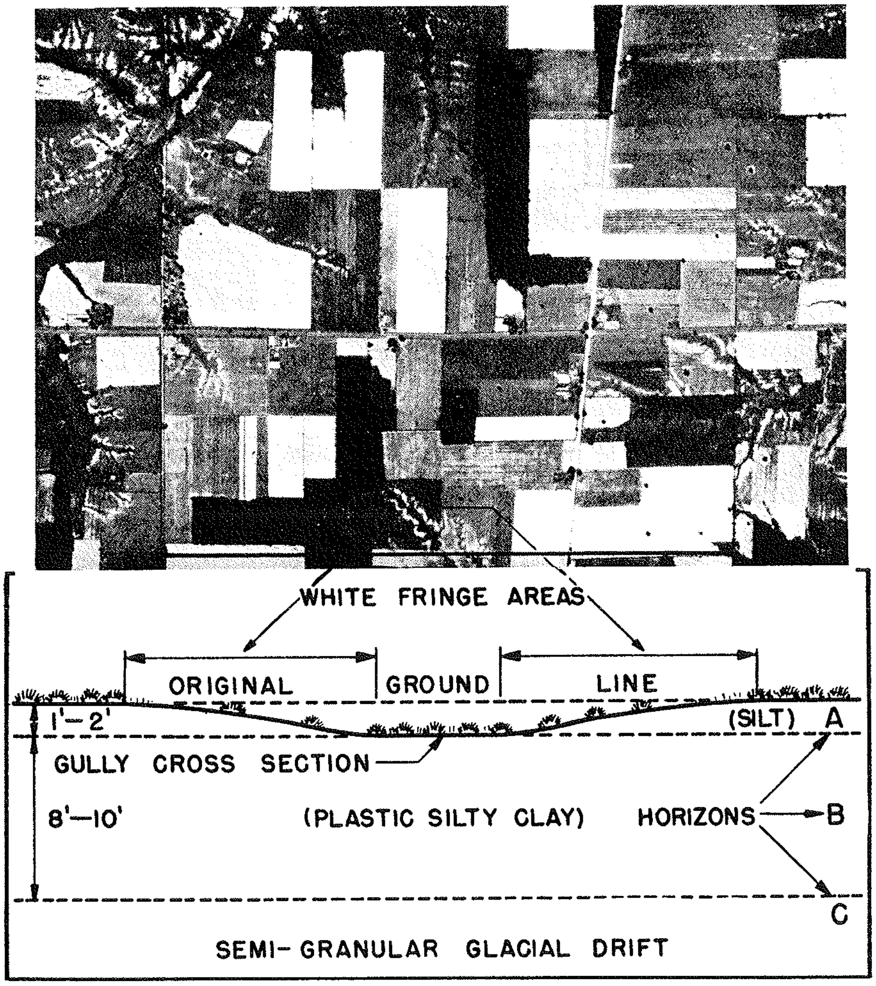

Figure 12. A striking pattern of old drift common to Ohio, Indiana, Illinois and Missouri. These are the clay-pan areas having silty topsoils and deep plastic profiles promoting a surface drainage pattern. Sketch shows relationship between the texture of the horizons in the soil profile and the gully shape (See Figs. 1 and 27). This profile becomes waterlogged for long periods since the "A" is pervious and the "B" relatively impervious. Wet weather construction is seldom practical in these areas.

ELEMENTS IN THE SOIL PATTERN

In making soil surveys of this type without field exploration it is always advisable to check, by photographs, the reliability of data obtained from other sources. In instances where no supplementary soil information is available detailed examination of the elements will permit, in most cases, a rather accurate description of soil conditions. If errors occur they lie within the province of the interpreter and not in whims of nature.

Since it is impossible to deal with each element the more important are presented in as much detail as is feasible.

Landform (Parent Material)

The local structure of the earth is perhaps the most general element of the soil pattern. In single or paired pictures covering an area of several square miles it is not always possible to identify positively the parent material that controls the form of the land. With additional pictures showing a greater portion of local area identification of the land form is usually practical. Figure 13 illustrates two variations in a land form pattern produced by sedimentary rock. Figure 13A is a contour-like pattern produced by dissection of horizontal beds of limestone and shale in a subhumid area; Figure 13B shows the same materials (in beds of greater thickness) tilted and

Figure 13. A. Aerial view of nearly horizontal beds of limestone and shale. Geologic erosion has cut through a series of these strata forming a contour-like pattern. In this relatively dry climate the limestone (white) outcrops to form comparatively steep slopes while the soft shale (dark) assumes low, gentle slopes. Sketch on section A-A′ illustrates formation. B. Down-dipping beds of shale and limestone form the pattern shown. Shallow impervious soils form on the shale while deep soils mantle the limestone. Note the abrupt change in surface drainage.

exposed to erosion in a humid area. Obviously, the greater the area available for inspection the more apparent becomes the landform pattern.

Figure 14. The pattern of weathering in sandstones and stratified rock. This view in arid Iran shows the abrupt slope changes while in moist climates slopes are more modified. Highways and airports are located on the valley floor where soils related to the associated rock are deposited by water. Reprinted from Erich F. Schmidt, Flights Over Ancient Cities of Iran (Areal Survey Expedition, Mary-Helen Warden Foundation) 1941. By permission of the University of Chicago.

By determining the landform the engineer largely determines the type of parent material with which he will deal. Reference to geologic maps will assist in this determination. Geology, like pedology, requires some translation for engineering use and therefore may be disappointing at first. Where bedrock forms the parent material, geologic literature (12) should supplement experience in visualizing the general structure. The photographs will provide most of the necessary details, since it is in these that we have a record of the relative weather resistance, depth of soil mantle, water conditions, and other properties and features that are directly related to construction and location problems. Where transported surface deposits cover the bedrock, geologic maps often prove misleading. As a rule, with the usual exceptions, in areas where bedrock influences the soil, indications of the type of bedrock will be apparent. Likewise, glacial-drift areas also have distinctive patterns as do aeolian deposits of sand or silt. To review these briefly: Sedimentary rocks such as limestone, sandstone, or shale are originally formed under water in nearly level beds. When these are elevated above sea level and remain in a horizontal position, erosion reduces them by dissection that produces a particular type of stream pattern and often leaves flat-topped islands of rock. In arid countries (Fig. 14) these are mesas or buttes, in humid climates they are monadnocks, having the same island-like shape but somewhat modified side slopes caused by the protecting influence of vegetation. These have retained their shape because a cap of resistant rock protects the underlying materials from erosion. Since sedimentary rocks are stratified, and the strata vary in physical properties, a difference is reflected in the weathering resistance of each stratum. Thus, in examining such formations (see Fig. 15) the existence of clay-

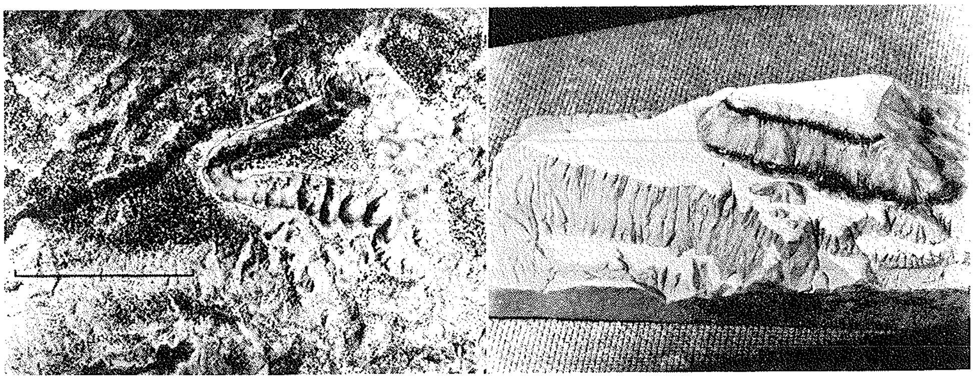

Figure 15. An aerial view and model of a dissected sedimentary rock formation. A thin sandstone caprock protects a deep bed of clay shale that weathers to a "soft" slope typical of clays. In such areas of dipping strata, landslides can be caused or avoided depending upon the right-of-way location.

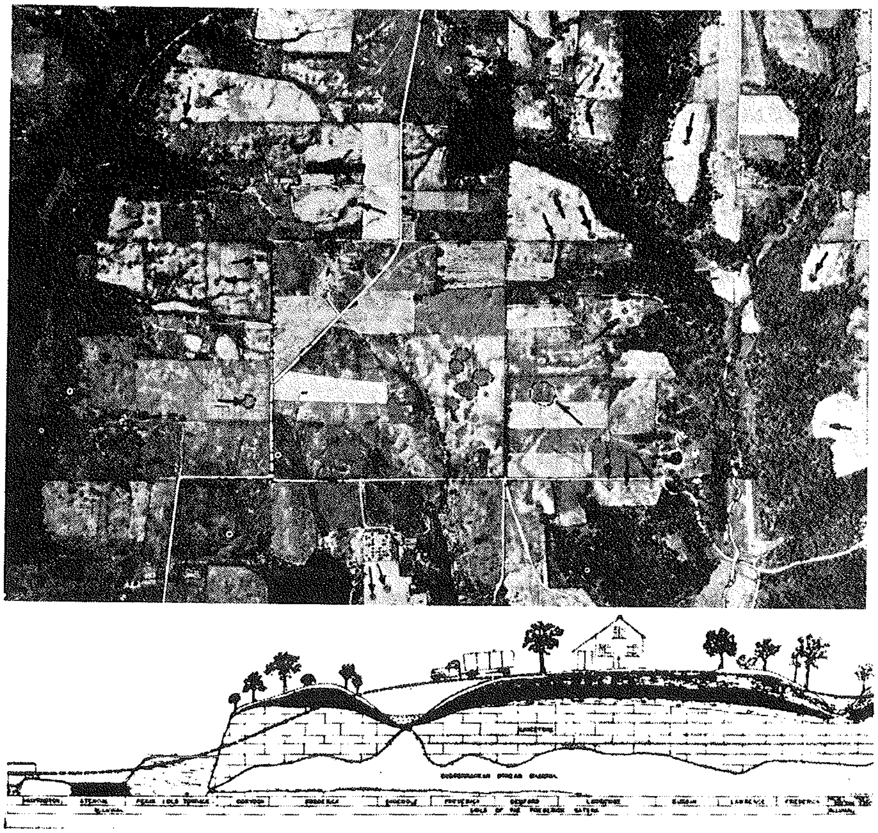

Figure 16. Sinkholes in a limestone area as they appear from the air. On the basis of the uniformity of limestone soils in similar positions subgrade conditions in cuts and compaction requirements for fills can be anticipated from a photograph. Section sketch shows relationship of sinkholes to underground drainage channel and depth of soil mantle to ground slope.

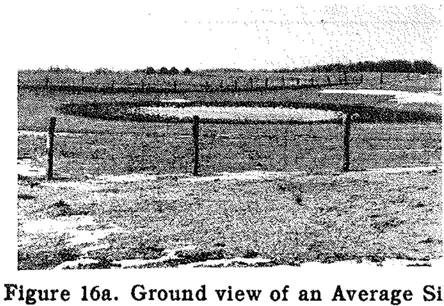

Figure 16a. Ground view of an Average Size Sinkhole in a Limestone Area

shales is indicated by the presence of "soft" slopes occurring below the cap rock. The choice of location in these situations may be optional but slight differences in grade line elevation change the subgrade from sandstone to plastic clay-shale. Consideration of the dip of the strata should influence the location of a road since a location on one side invites landslides because of the necessity of cutting into down-dipping shales.

Where these stratified formations are folded, as in the Appalachian Mountains, they control the stream pattern to such an extent that a rectangular pattern is developed. Branches of streams follow parallel courses in the alternate beds of soft rock or shale. Instead of the ordinary bends expected in a stream the turns are often right-angled.

The intensity of the general pattern is in proportion to the age or progress that weathering has made. As in the case of limestone, sinkholes are usually the first stage of weathering (Fig. 16—Indiana). As weathering progresses the roofs of subterranean caverns collapse and leave ridges of limestone that assume a cucumber shape when viewed from above. These further weather into domelike forms called haystack hills. Figure 17 shows these developments in a tropical climate. Sedimentary rocks and volcanic (basalt) rock develop plateau forms or related patterns when folded. Granites by reason of their method of occurrence as mountain cores and smiliar intrusions readily lend themselves to identification. Again the significance of this particular element is general since it is an indication of the soil mantle as well as the related soils (alluvial) derived by erosion from these areas. Thus the land form is influenced by the parent material. The distinguishing features by which glacial drift, loess, sand, and other parent material areas can be identified are related either to their texture or to some physical features peculiar to their method of deposition. Perhaps the most outstanding feature common to glaciated areas, either continental or mountain, is the disproportion between present and past drainage. Vast rivers of water supplied by melting glaciers cut valleys and built gravel terraces that dwarf the streams that are in balance with our present

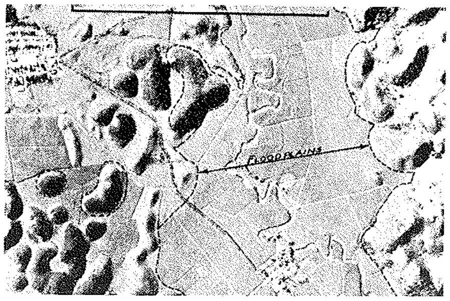

Figure 17. Advanced stage of weathering of limestone in the humid tropics. Valleys between parallel ridges were once limestone caves. Extensive sinkhole development and subsequent collapse of the caves created valleys. The hills are described as pepinos and mogotes—cucumbers and haystacks because of their shape. Related soils are plastic silty clays.

Figure 18. An oblique view of a gravel terrace in New Zealand illustrating the wide application of the major elements of analysis. Not only is the land form apparent but the absence of surface drainage, source of the material, vertical stream banks, and color pattern (arrows) are clearly shown. The checkered field pattern is caused by a variety of crops. Reproduced by permission of New Zealand Aerial Mapping, Ltd.

climate and now occupy the valleys. The tremendous terraces and fans at the foot slopes of many mountains (Figs. 18 and 21) are of glacial gravel just as the kames, eskers and river terraces of our northern States and Canada are products of the continental ice sheets.

Figure 19. The slopes assumed by weathered materials indicate the relative clay content of the soil mantle. These "soft" slopes are a contrast to those characteristic of more weather-resistant rock. Reprinted from Erich F. Schmidt, Flights Over Ancient Cities of Iran (Areal Survey Expedition, Mary-Helen Warden Foundation) 1941. By permission of the University of Chicago.

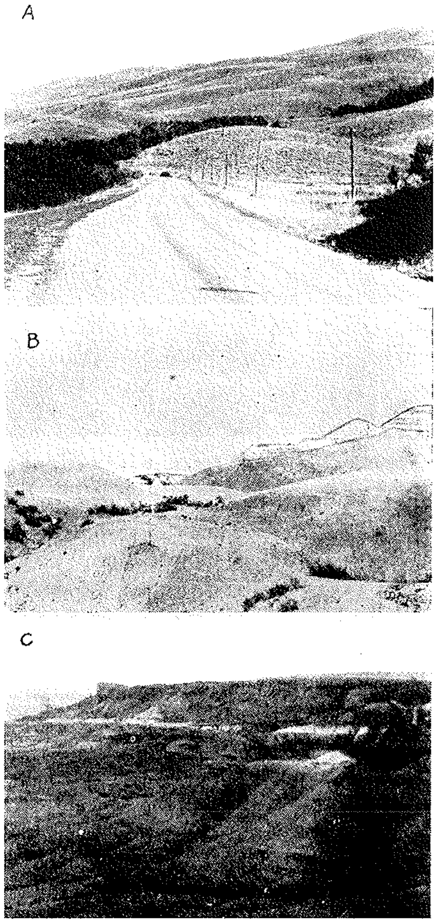

Figure 20. A: The slopes of these mountains are the key to the soil texture in the filled valley at their foot. Gravels and sands are not as available in this area as in areas of more resistant rock while the increased clay content of the soil makes the use of granular material more desirable. B and C: Clay-shale slopes in South Dakota and in Arizona indicating a No. 10 to No. 11 material. Note resistant caprock in each.

Texture, composition and origin largely determine the resistance of a material to erosion and weathering, and under similar conditions of weathering the same type of parent will respond in a similar fashion. It is reasonable to assume that, regardless of distance the same type of rock will produce similar soils under similar climatic conditions. Figures 19 and 20 show the "soft" slopes produced by the weathering of granites in the relatively dry climates. Similarly the weathering of limestones is related to the climate. These are but the more definite examples of rock types having distinctive weathering characteristics. Both the occurrence and the weather resistance combine to aid in identification. Where slopes appear to be "soft", the soil can be expected to have a relatively high clay content and the materials washed from such slopes to form terraces will have a stratified profile grading from a granular subsoil or substratum to a silty or sandy clay overburden. The more rugged slopes produce less soil and more granular material. Figure 21 shows a well developed series of terraces forming an excellent source of granular material as well as providing a very stable location for runways or highways. In contrast

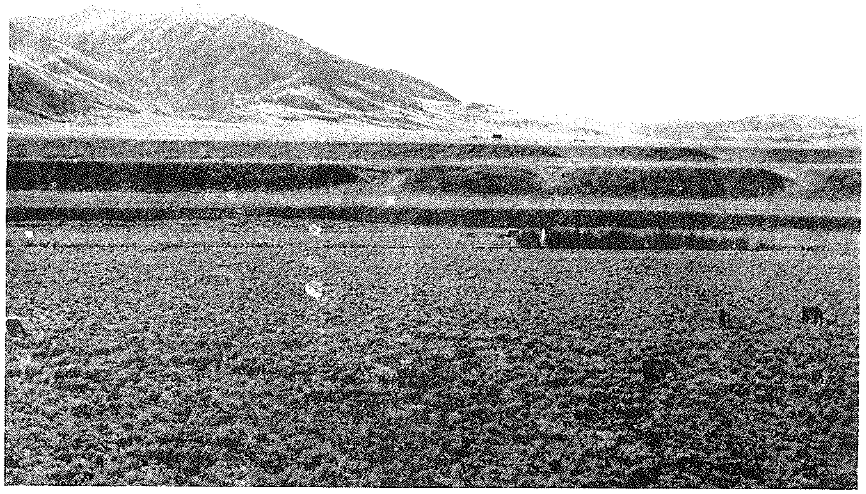

Figure 21. Glacial terraces associated with the Madison range in western Montana. These can be identified as granular material because of their forms and lack of erosion scars.

Figure 22 shows a highly dissected terrace in Palestine having a deep uniform profile in Lisian marl. The gullies' side slopes indicate uniformity, and the shape, a silty-clay material.

Slope. Prevailing ground slopes may also be considered an element of the soil pattern. In examining photographs the observer receives a general impression of the local slopes in an area. These are generally a function of texture with granular and semi-granular materials assuming the steepest slopes. The observer will find areas adjacent to streams the most productive in which to examine this feature. At bends where the current may be attacking the bank of the stream, fresh exposures unmodified by the accumulation of debris at the foot are available for inspection. However, slopes over which runoff passes are the more reliable indicators. Even the uninitiated can readily detect the difference between the prevailing slopes in areas of, No. 9 or higher, silty clay and the less plastic, No. 8 or lower, materials.

Surface Drainage. Surface drainage or runoff is the result of melting snow or ice or of rain falling on the ground. Whether it soaks in or runs off the ground surface determines the existence of a drainage pattern. The portion that runs off the surface determines the

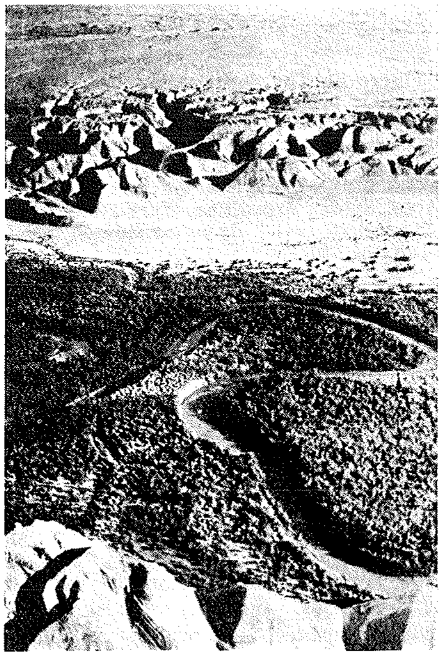

Figure 22. A land form in Palestine similar to that shown in Figure 21. In this instance erosion indicates an impervious texture and the gulleys show the existence of a deep uniform profile. The Orient Press Photo Co. (Tel-Aviv).

intensity of the pattern. In this sense surface drainage does not mean rivers and streams but the immediate and local pattern caused by runoff on an acre, a section, or a square mile of ground surface. Briefly stated it is a direct function of soil permeability and ground slope and, within rather wide limits of slope, surface drainage is a function of the permeability of the profile. Porous sands absorb the rainfall and surface drainage does not develop (Fig. 23). But plastic clays and silty clays resist the penetration of moisture, which promotes surface runoff and the development of a drainage pattern.

Figure 23. A sand plain showing no surface drainage, a uniform color pattern and sparse vegetation representing an excellent subgrade material. Muck occurs in the channel (glacial) remnant outlined.

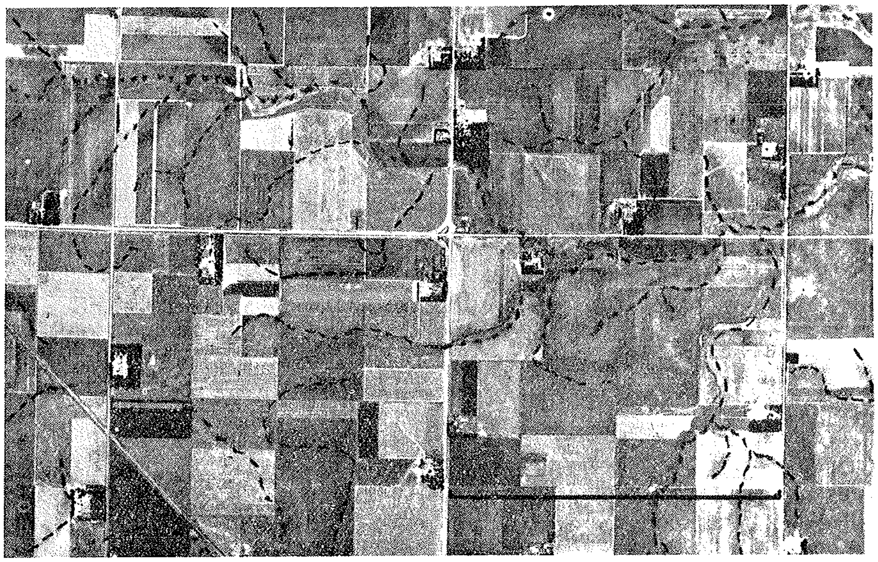

Figure 24. An air view of a plastic silty clay soil and a tracing of the surface drainage pattern. Note the transition from drainage ways to a dark color pattern. Compare the drainage pattern on these Nos. 10 and 11 soils with the sand (No. 2) pattern in Fig. 23.

A drainage system may vary in complexity. Complete absence or a simple extension of surface drainage from a stream into the upland probably indicates a pervious material. A highly integrated system with branches reaching to all parts of the area indicates poor internal drainage (Fig. 24) which for engineering use means a plastic subgrade, difficult construction, a need for an adequate base course, and provisions for drainage. Obviously on the same parent material the amount of surface runoff will be greater on the steepest slopes. This relation to slope in itself creates differences in the respective soil profiles: those on the steepest slopes are shallow and weakly developed, while those on the flat slopes are deep and less pervious. In most cases, where there is sufficient year-around rainfall the surface drainage element is highly reliable.

"Functional texture" is offered as a qualifying term for soil classification regardless of the method of survey. Aerial photographs show the effective drainage of the profile regardless of texture. The limestone soils have a well-drained profile. They are often red in color and lack evidence of complete surface drainage, indicating a porous profile. However, this is a condition not related to the common conception of texture since these soils are high in active clay content. The process of weathering and profile development produces an open structure in which the clay particles are segregated into lumps with ample space between for percolating water. The porous limestone parent material absorbs the water and prevents waterlogging of the profile, a condition which would otherwise result in a consequent swelling and closing of the soil structure. When compacted during construction this structure is destroyed and the immediate subgrade or fill reacts essentially as any other plastic clay. The qualifying term aptly applies to the slightly plastic, well drained, clay-size soil materials of the high rainfall tropics. Although the colloid content of these inactive clays is high (as much as 90 percent), they will appear porous in photographs (Fig. 25) and will act as such in engineering structures functioning as a semi-granular material.

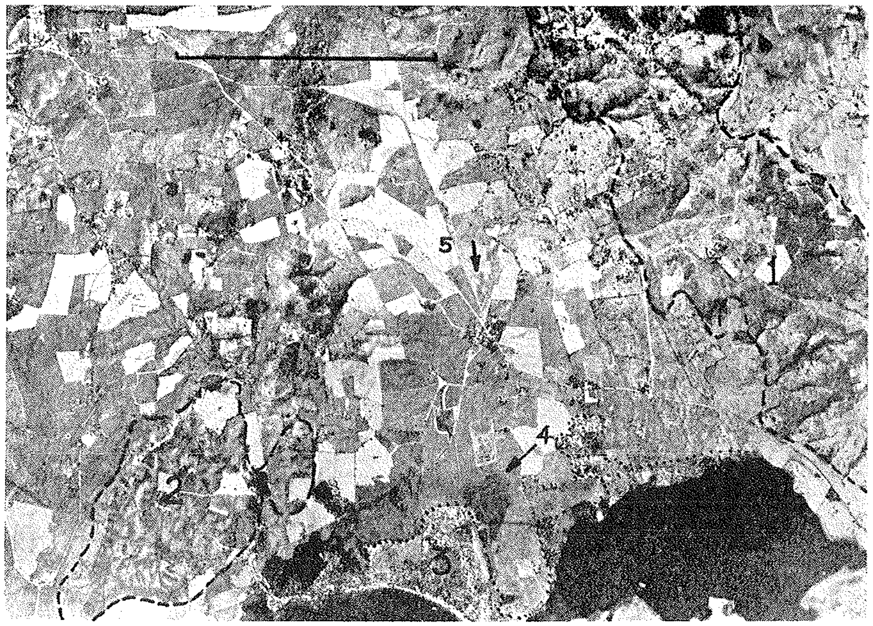

Figure 25. A vertical photograph of an area containing a lateritic soil, 1, in which clay size soils function as porous material. Laterite may develop from any type of parent rock under conditions of high rainfall and temperature. Plastic soils developed on comparable slopes, 2, from tuffaceous rock have developed a surface drainage pattern. Sand bordering the shore line is shown in dotted outline, 3. Arrows indicate, 4, a swamp area, and 5, a color pattern indicating highly plastic soil.

Logically a discussion of erosion should follow surface drainage since it is a related process. Actually erosion in gully form cuts through the profile and provides some detail on textural differences within the profile. Therefore, a discussion of the remaining elements produced by the net effect of the entire profile will be completed first.

Soil Color Tones. The color of the surface soil material is often a result of conditions that have controlled the soil-profile development. In such instances the color tones evident in photographs give indirect information on the texture and drainage of the profile. Soil color (surface) is a function of the natural vegetative cover which is in turn controlled over large areas by the climate and in local situations by the immediate ground-water condition—often regardless of climate. The climatic influence will be omitted here and considered more completely under another heading. Initially the most confusing part of photo-interpretation is that pattern created by crops. These are regular in shape and are obviously a product of human effort. The soil color pattern usually shows through most crops and can be traced upon close examination or by interpolation from adjacent fields. The color pattern is always irregular.

The color element or pattern varies from one area to another, assuming, as does drainage, different shapes and varying in actual color. Fig. 11 is an example of a highly developed color pattern (Indiana—glacial drift) faithfully reflecting slight changes in elevation and ground water conditions. The black areas are deep, wet, plastic silty clays while the slightly higher light areas have a better water condition, a shallow profile and a higher silt content. A comparison pattern in red and black occurs in Tanganyika and Somaliland (8). Red, white and black are the common colors found in surface soils. In humid areas temperate or tropic, the black color is related to soils existing in low, poorly drained situations. Since this applies equally to sands it can be seen that reliance on color alone is as erroneous as dependence on any other single element. This continuity of color often carries over long distances since the "mbuga" of Tanganyika and the "vlei" of South Africa are wet, black clays. The following description of depression soils in the Uganda Protectorate applies precisely to the black soils in Fig. 11. They "consist typically of an intensely black topsoil overlying a gray or bluish-gray waterlogged clay" (9). These soils regardless of their location will have a similar soil pattern in aerial photographs and will present the same difficulties in engineering construction. The so-called black soils or chernozems are a product of climatic influences that are favorable to grass cover. When these are viewed from the air they are found not to be uniformly black but to contain a variety of shading with a distinctly black soil in depressions.

Red in soils often indicates a well-drained profile having a low water table. In ordinary photography red filters used to remove haze give the red areas a dark value in the prints. Many soils in the south have a red color and almost all limestone soils except under special rainfall conditions, are red.

Red is also a dominant color in many clay shale deposits and the outcropping of "red beds" that weather to rounded slopes (Fig. 15) are inevitably associated with landslides and fill failures. In these cases the color is not indicative of good drainage.

White or light gray colors in soils of the humid regions are usually an indication of extremes in moisture variation. They are subject to seasonal saturation and drought; saturation during long rainy periods because of retarded internal drainage and dryness because of a favorable position. Obviously sands are an exception to this and can be distinguished from a light colored silty clay by other elements of surface drainage and dune shapes (if present).

With the co-operation of the Army Air Forces, experimental photographs are being flown in five sections of the country. These aerial photographs (transparencies) in color, exposed at various altitudes give remarkable details of the vegetative cover as well as the natural colors of the various horizons in the soil profile. Where erosion is active, the colors of the major horizons can be seen by noting their sequence from the headward ends to the mouths of gullies. Likewise, the color bands of the horizons can be seen on the slopes of highway cuts.

The value of color in this work lies in the added detail that it furnishes with respect to these two elements of the soil pattern. The cost of color film, while somewhat higher, is justified in special work and particularly in remote areas because of the separations by color of many minor details.

Vegetative cover is perhaps the most difficult of the elements of the soil pattern for the engineer to interpret. Only the more obvious details required for interpretation on the basis of vegetation is to be had in high-altitude (12,000 ft.) photographs. Various types of trees are difficult to identify but drastic changes in soil conditions create vegetative contrasts that mark the boundary between soil areas. This is especially true in the vast northern swamp areas represented by Figure 26. Within a swamp area where the water table is sufficiently high to obliterate other elements of the soil pattern, vegetation alone remains. Muck and peat bogs have separate and distinguishing patterns of their own but the so-called tamarack swamps have proven difficult to decipher. In forested areas, forest fires complicate the pattern although the fires are often confined to the dry land. Lumbering operations also tend to influence the pattern. In general wet and dry positions are distinguishable by the vegetation that they support, giving the observer a general impression of cover type. Although the presence of poplar indicates dry ground, jack pine implies sand and gravel beds; tamarack, muskeg, and willow, wet ground. It is also true that many species such as white pine and aspen are tolerant of drainage and soil conditions and will grow on sandy as well as clay soils and in wet or dry positions.

Location work on the Alcan highway was based on photo interpretation of this element. Low altitude photographs and experience would improve the reliability of this type of interpretation. Since some types of vegetation grow over a wide range of soil conditions it is well to avoid placing too much emphasis on this one factor without supporting evidence from other elements.

Vegetation also acts as a partial indicator of perennially frozen ground in northern latitudes. Within the general region of frozen ground there are small areas of thawed soil that are probably caused by circulating ground water (19). These are marked by contrasts in vegetation since the unfrozen ground promotes the growth of larger plants, shrubs, and bushes, having deep root systems.

Another characteristic of these frozen areas observable in aerial photographs is the polygonal pattern probably developed best on the silt soils of the wide flood plains and terraces of the river valleys. This pattern, also found in other positions, is created by ground ice forming more or less vertical veins in the soil mass, extending in some instances to depths of 30 or more feet. Marked by vegetational changes and micro-relief these immense polygons (20 to 70 ft. in diameter) fore-warn of extraordinary subgrade conditions.

Figure 26. A northern peat-bog area. This unusual pattern occurs in a glaciated area. Flowing water has obviously influenced the shaping of the pattern. The area is extremely difficult to explore and the variations in relief are so slight as to escape detection on the ground.

Erosion is probably the most valuable index of subsurface conditions of the soil profile. Generally speaking two types of soil erosion occur, one in the form of gullies and the other as sheet erosion. Although certain chemical properties of soil influence the degree of erosion it is controlled largely by texture.

Gullies, being the most significant, merit the principle consideration. Cut by surface runoff, they often occur on sloping ground between the shallow upland drainage-ways and the flood plains of established streams. The cross-section shape of a gulley is controlled by the cohesive properties of the soil. Silts, sands, and sand-clays develop vertical sides or U-shaped gullies.[5] Examples of these are found in sandy coastal plains areas. Figure 27 shows a ground view of a gully of this type. They are characterized by a sharp drop-off, from the ground surface to the bottom of the gulley, at the headward end. They are often stubby, extending only a short distance into the upland. V-shaped gullies indicate a deep uniform profile in a semi-plastic to plastic soil; where the V-gulley becomes very broad and shallow (Fig. 27) a silty or fine sandy material on a claypan is indicated. This same shape may indicate a shallow soil on bedrock but the presence or absence of rock outcrops in the vicinity will confirm or deny this alternate choice. These latter two types will progress for long distances into the upland. Thus we may say that the gully is a partial key in recognizing the plastic unstable silty clays or the sands, in distinguishing between well-drained and poorly-drained soils, and in anticipating dirt excavation or rock excavation. Unfortunately airphotos cannot be used satisfactorily to illustrate gulley shapes since they often appear in minute proportions requiring magnification of stereoscopic pairs. Silt gullies have the additional feature of vertical fins or columns preserved by sod or brush. Other erosion features of silt occurring in north China (12) take the form of chimneys and pinnacles. "Catsteps", another form of erosion common in some areas characterize loess on steep slopes. These contour-like shelves resulting from the slipping of the loess are clearly visible with magnification.

Figure 27. An illustration A, of gullies in sandy soils and, B, in claypan soils. The U-shaped gullies are short and begin abruptly—photo taken at head of gully. V-shaped and flat angle-shaped gullies in the more plastic soils extend well into the upland on a more uniform gradient. C: A typical gully found in arid regions where "flash floods" attack dry soil banks and often create U-shaped gullies in clay soils.

Land use and other human influences are included as an element of the soil pattern. The pattern of contour plowing, terracing, and strip cropping are forms of erosion control signifying a friable soil on a less pervious subsoil. Check dams, levees, crops, crop boundaries, plow lines and many others carry some special significance depending upon the locality. "Dead furrows", the inevitable sign of plastic, poorly-drained soils, are the farmer's attempt to obtain surface drainage in an impervious profile. Orchards thrive in well-drained locations and therefore, when observed on level ground, good subdrainage is implied.

These then are the major elements of the soil patterns, the land form, surface drainage, color, vegetative cover, erosion, and land use. Created directly or indirectly by physical properties of the soil they form a basis of interpreting the engineering characteristics of the soil and of fore-seeing problems that affect the

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[5] This relationship does not carry over in the same degree to arid climates (See Fig. 27c).

cost of construction and maintenance of pavements.

Climatic Effects on Soil

It is evident that in applying photographic interpretation to soil surveys in unfamiliar areas lack of experience may require investigation of available information concerning the area. In the eastern and midwestern States a good coverage of soil information exists. The more recent reports are usually excellent and can often be used without supplementing photographs. Unfortunately, a large number of these were completed between 1900 and 1925. The methods then used, the accuracy of mapping, and the descriptive matter make them difficult to use effectively for engineering purposes. Outside of the area mentioned there are few extensive areas that are mapped in detail.

The bulk of the published information on the soils of the western States (10) Europe (5) and Africa (7) is based on the Russian system of classification or some variation of it. Where pedology contains many phases that are directly applicable to engineering the climatic classification conceived in Russia has only a few minor applications in some areas. In the event that this type of information is available it is well to realize that it is based on climatic influence, chiefly rainfall. The names given the various soils are the Russian terms for soil colors or other general distinguishing features. The chernozems are black earths or the prairie soils; black because of the restricted rainfall that promotes the growth of grass which in turn produces a deep (12–24 in.) organic development in the profile. The podzols are soils having an ash-colored layer immediately below the surface; these are developed in cool climates usually under pine forests. There are also the gray brown podzols, the red and gray desert soils, the chesnut soils and the laterite.

In comparing these soil areas with the parent material areas it is impossible to escape the conclusion that they are not related. Examining the chernozem belt that roughly parallels the Mississippi River from central North Dakota to Texas leads to the conclusion that all types of soil exist in that area—clays, silts, sands, and gravels. The same variations occur in the other classifications. An example of this occurs in an area of Liberia mapped as laterite soil. Actually the area consists of "occasional swamps and stretches of clay soil that necessitate the hauling of laterite gravel for a few miles for road surfacing, but the supply of this ideal road building material is inexhaustible. It occurs in all parts of the country, often in a layer 3 or 4 ft. thick just beneath the topsoil . . . " (11). Even the term laterite is so broad as to include many forms of soil and does not always indicate gravel or

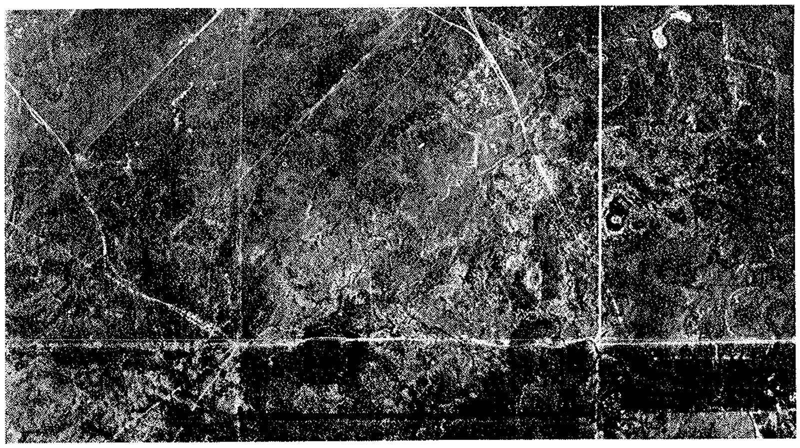

Figure 28. Soil pattern of sands and clays under arid climate (3 to 10 in. rainfall) near the central portion of a filled valley. Fine sands have the lighter color, are slightly higher in elevation, and bear the channel marks of the outwash from the mountains. The clay settles out as lacustrine material in relatively quiet waters giving a contrasting dark tone compared to the sand. These areas may be under water for short periods each year.

brick-like material used for road metal in parts of Africa, India and the Malay States.

A soil area that would be classed as a Gray Desert soil (Sierozem) is shown in Figure 28. Here sands and clays occur as indicated by the color and drainage patterns. This is the general pattern of the central or low-gradient areas of the arid, filled, intermontane valleys variously described as "bolsons", "playas", or "chotts".

THE SIGNIFICANCE

Obviously the significance of the soil pattern lies in its relationship to engineering problems affected by the soil. Currently the soil problem resolves itself into two parts, one in which the soil in place is satisfactory as subgrade, and the second, where the soil is unsuitable. In areas of unsuitable soils some form of improvement, by stabilization or insulation, is required. Insulation involves the economic location of granular materials in the form of rock to be crushed, cinders (volcanic), or sand and gravel. The preceding discussion has dealt with each element of the soil pattern; therefore, some grouping of these elements will illustrate the common soil patterns not already described.

Inasmuch as gravel and sand or other granular deposits exist to some extent in nearly every county in the country the significance of soil patterns indicating granular materials is of considerable economic importance to engineers.

Because of differing origin, granular deposits occur in various forms in various sections. Regardless of the area, isolated deposits of gravel and sand are related to present or past drainage systems. On the basis of soil areas the glacial drift has a variety of interesting gravel and sand deposits. Each has the usual elements that indicate the presence of granular material.

Kames and eskers are gravel deposits dumped by the glacier onto the unassorted till or drift of the surrounding area. They bear no necessary relation to the general soil texture of the surrounding terrain and, fortunately, often occur in areas of plastic soils. Kames are round, usually symmetrical, hills of gravel that have been dumped from holes in the bottoms of rivers flowing on or in the glacier. Eskers, formed in a similar way, often resemble abandoned railway fills. Because of their shape and abrupt slopes these two forms are readily distinguished in aerial photographs. Figure 29 shows eskers occuring in a northern area. They are, as yet, undeveloped sources of excellent gravel in the particular areas shown. Figure 30 shows a characteristic drumlin pattern that should not be confused with eskers since they furnish a semi-granular material unsuitable for commercial aggregates.

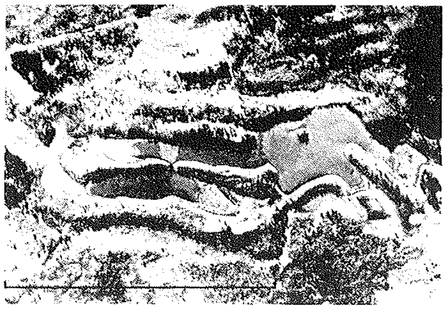

Figure 29. A series of parallel eskers in a glacial drift area. While the eskers (ridges of gravel) themselves indicate a glacial area the associated muck deposits and general pattern are also indicative of glaciation.

Figure 30. Drumlins, a glacial form that should not be mistaken for eskers. Examination of the elements of this pattern will indicate a material less pervious than the sands and gravels in kames and eskers.

Other formations in glacial areas containing sands and gravels are directly associated with stream channels. These take the form of outwash plains (sand), granular drift, and river or stream terraces. Outwash plains are also found in mountainous country, and they represent areas in which water moved with sufficient velocity to carry sand or larger size material. They are usually level plains, having a rather uniform color pattern, an absence of surface drainage, and a sparse vegetative cover (Fig.

23). Sands develop a color tone that with experience becomes unmistakable in aerial photographs. Gravelly drift plains have the same form of relief and lack of surface drainage but they can be readily distinguished from sand because of their color pattern. Figure 31 is an air view of such a plain. Close observation shows the presence of an infinite number of small irregular black spots. The general impression is that the area has a worm-eaten appearance. The difference in composition of sand and sand-gravel mixtures accounts for this. The sand, being chiefly silica, is highly resistant to weathering while the gravels, whether igneous or calcareous, weather and form a silty or sandy clay horizon at the surface. This horizon development partially retards the downward percolation of water and insignificant sinks or solution basins form where sufficient water concentrates to make a moisture condition more favorable to vegetation which in turn promotes a slight increase in organic material. This difference creates the pattern that identifies this class (No. 3) of material in gravel plains throughout the humid areas of glacial drift.

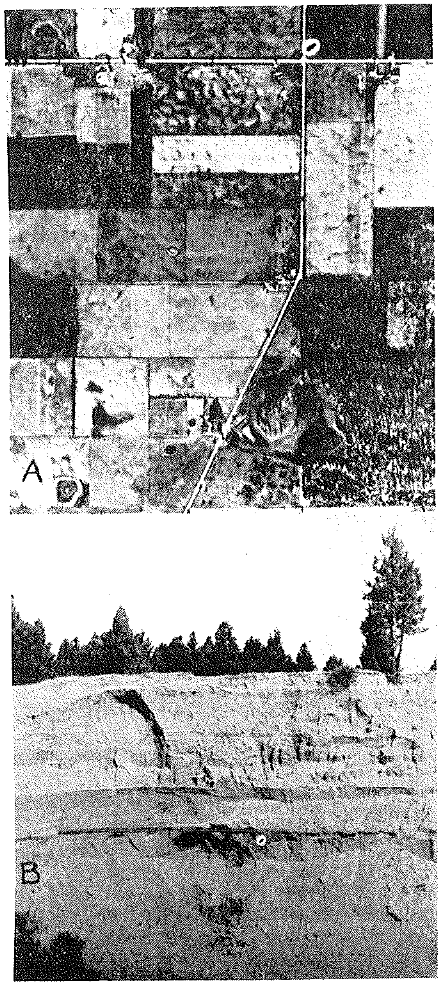

Figure 31. A: An air view of a gravel plain. These plains although porous have a pattern that distinguishes them from sand (See text and Fig. 25). B: Granular material in a glacial terrace in Washington state.

Gravel terraces occur in these areas in association with streams both large and small. Figure 18 shows this type of land form. These granular terraces are usually high above the present floodstage of the stream. They are level, they vary in width, and they may or may not be continuous. The adjoining uplands are dissected with many gullies emptying water onto the terrace, while the stream border of the terrace usually drops abruptly to the flood plains. The truly granular terraces absorb the water that they receive from the upland and remain undissected.

Glacial lake beds (See Fig. 3.) present one of the most unsatisfactory subgrade soil areas. Despite their plastic properties most have a series of beach lines that often serve as the only source of gravel and sand for many miles. Fortunately beach lines are clearly visible from the air since they present a striking pattern in contrast to the adjacent areas. Figure 32 shows the pattern of a small section of an ancient beach line striking across the bed of a glacial lake; its light color, vegetative cover, and form make it as a source of granular borrow material so necessary for subgrades in these areas.

Since water transports and assorts these granular materials, washing away the fine particles, it is possible to generalize and apply to most of the other areas of the country the rule that granular deposits occur where the velocity of water decreases. This is true along the fall line in the east, at the base of mountains in the west and at the junctions of streams in nearly all areas. If the watershed of a stream contains rock, sand, or gravel, then assorted deposits of these materials will occur in or near the channel. Abrupt changes in channel direction are caused by a body of resistant material that may either be rock or buried gravel and sand. Figure 33 shows a remarkable series of gravel terraces occurring in New Zealand near the junction of two rivers.

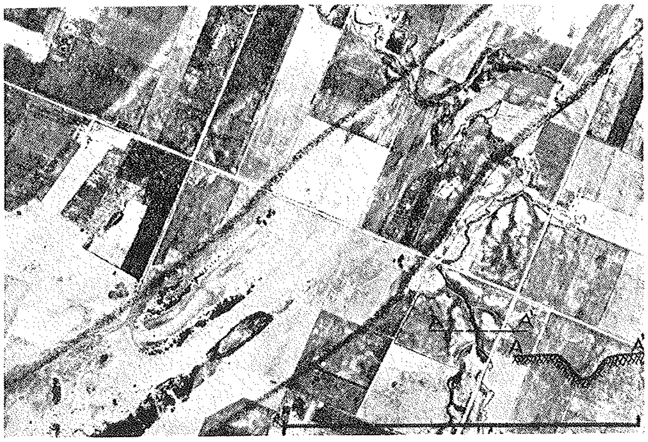

Figure 32. A beach line of sand and gravel marking the border of one stage of a glacial lake. These ridges of granular material, in a level area of fine-textured soils, are readily detected in aerial photographs. Continuous dark lines mark the general boundaries of the beach line. The stream flows through a gap. A cross-section sketch of the drainage-way is shown at lower right.

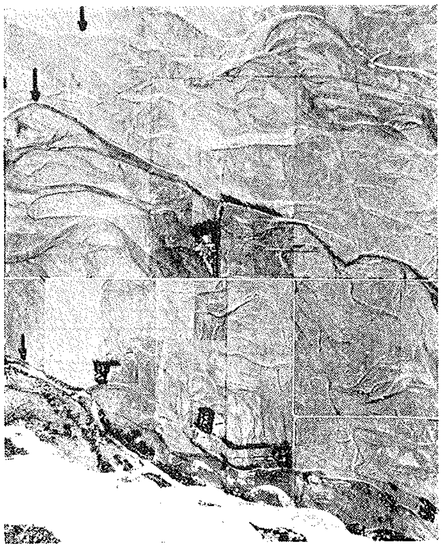

Figure 33. Gravel terraces at the junction of two rivers in New Zealand. Braided stream channel at left. The continuous lines (arrows) mark definite stages of terrace development while the less distinct scars are channel marks. On each terrace the surface is sufficiently level for a safe landing by airplanes. Being gravel, these soils are stable in all seasons. Courtesy of New Zealand Aerial Mapping, Ltd.

Figure 5 illustrates an unusual source of granular material peculiar to the coastal plains in Arkansas and Texas. The small white spots appearing in the picture are natural deposits of "gas-well sand". These occur in many of the clay areas of this region and form the only source of granular borrow in many localities. They often have a texture of coarse sand and fine gravel, are round in shape, 10 to 50 ft. in diameter, and vary from a few inches to several feet high.

These modes of occurrence apply also to areas where mountains rise abruptly from the sea. In Figure 34 a slightly dissected granular terrace stands above the sea level at the base of mountain slopes in a hot, arid climate.

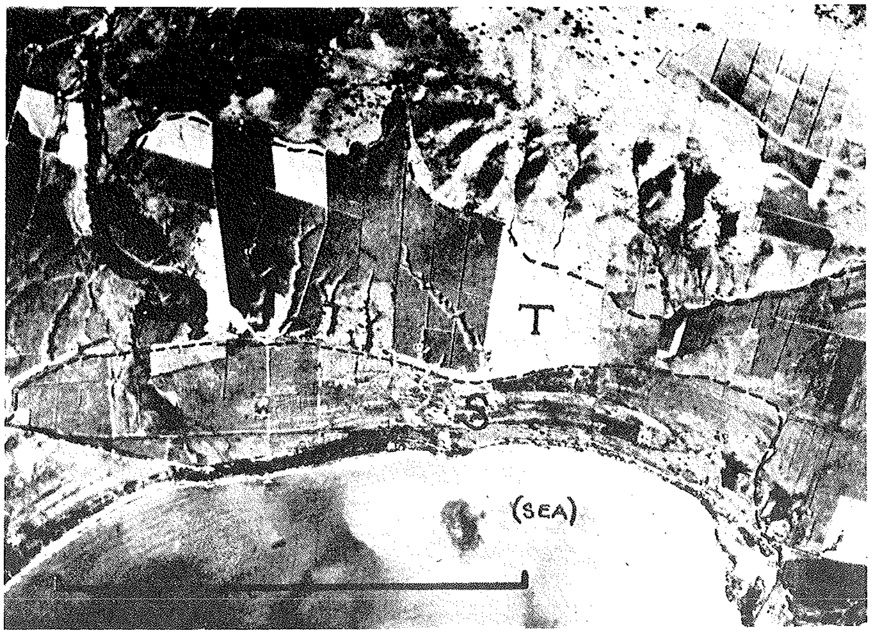

Figure 34. A gravel terrace, T, at a shoreline transition from mountainous country to sea level. Simple gullies are beginning to dissect this terrace. A belt of loose sand, S, separates the terrace from the sea.

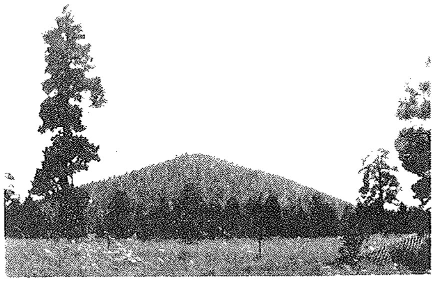

Figure 35. A ground view of a typical cinder cone. The symmetrical peak and side slopes mark this type of granular deposit.

Gully erosion in arid areas is more severe, since the total annual rainfall often falls during a few violent storms. Here the terrace, the parent stream, and the steep slopes are included in a small area.

In areas showing signs of past volcanic activity, cinder cones furnish, in most instances, a source of granular material suitable for base construction. These are recognizable from the air as well as from the ground by their distinctive cone shape. The cinder cone in Figure 35 is typical of this type of deposit. In dry areas where vegetation does not cover the slopes their form is more obvious. From the air an observer has the added advantage of detecting lava flows that stem from the base of the cone and form a pattern having fluid outlines.

HIGHWAY RESEARCH BOARD

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SOIL EXPLORATION AND MAPPING

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1949

HIGHWAY RESEARCH BOARD
DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH
NATIONAL RESEARCH COUNCIL

Washington 25, D. C.
November 1950

CONTENTS

MAPS FOR CONSTRUCTION MATERIALS[1]

Frank E. Byrne, Geologist, United States Geological Survey

SYNOPSIS

The basic materials that the engineer needs for construction are the rocks and sediments of the earth's crust. The geologist, because of his experience in mapping these same rocks and sediments, is well qualified to prepare the maps the engineer needs in his search for construction materials. The completion of short- and long-range construction programs requires great quantities of these basic materials. The use of the geologist in preparing materials maps will result in considerable reduction in the cost of engineering construction.

The three principal kinds of construction-material maps are discussed: material-site, mateerial-distribution, and surface-geology.

Material-Site Maps - The material-site map is the least expensive of the three kinds to prepare. It is an excellent inventory of materials that have already been found and tested, but it includes only those known to the compiler by reason of the basic data with which he has been supplied. It does not show other construction materials that may be present in the same area but have not previously been needed and tested. It is a poor basis for the search for additional materials.

Material-Distribution Maps - The map is based on the geologic maps available for a region. Each outcropping formation shown on a geologic map is classified as to the kind of construction material that can be produced from it. The area of outcrop of that geologic formation, then, is the area of distribution of that material.

The cost of a material-distribution map is only moderate. The map is an excellent inventory of all kinds of material available in a region, and it shows the potential production areas for each material.

Surface-Geology Maps - The surface-geology map combines many of the useful features of the other two kinds. It is constructed to a relatively large scale; it shows the outcrop areas of all geologic formations and the locations of existing pits and quarries in the area.

A field party maps the geologic formations, both consolidated rocks and unconsolidated sediments, usually on aerial photographs. The party plots the locations of all existing pits and quarries, locates additional materials, and collects samples for laboratory testing.

The surface-geology map is the most expensive of the three to prepare. The expense, however, is a self-liquidating one and the money expended is returned many times over. The map itself serves indefinitely as a completely adequate base for the efficient search for materials, and is also a valuable source of information for the planning engineer, for the design engineer, and for the engineer estimating the cost of construction.

Basis of this Evaluation - This paper is based upon experiences as a geologist assigned to the mapping of engineering construction materials in Kansas and the preparation of maps to be used in the search for materials in the western part of the United States. The work in Kansas is a cooperative project of the Geological and Materials Departments of the State Highway Commission of Kansas and the Engineering Geology Branch of the United States Geological Survey. It is a continuing project that was started in 1946. The work in western United States is in cooperation with the Military Geology Branch of the Geological Survey.

Definition of Engineering Construction Materials - As the term is used in this paper, engineering construction materials are defined as the naturally occurring materials of the earth's crust that require no more than inexpensive processing before use in construction. Sand, gravel, silt, limestone, and granite are some of the materials included in this restricted definition. Products derived from the rocks of the earth's crust that must be given expensive processing or

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[1] Published by permission of the Director, US Geological Survey.

manufacture before they can be used in construction are excluded.

Need for Construction Materials - The basic materials for engineering construction, such as sand-gravel, limestone, and granite, are needed in greater quantities than ever before. They are needed under short-range programs to repair the damages resulting from the shortages in manpower and materials prevailing during the war years. They are needed under long-range programs in ever greater quantities to complete the construction already far along in the planning stage.

These basic materials are a major item of cost in every construction project, whether it be a highway, an airport, or a dam. Through the preparation of adequate maps and by the effective use of those maps in the field exploration for materials, the nearest source of acceptable materials to the project can be located. Haulage costs, therefore, can be reduced to the minimum. In many cases this saving alone will repay the expense of map preparation many times over.

Kinds of Materials Maps - There are three principal kinds of materials maps: (1) material-site, (2) material distribution, and (3) surface-geology. The material-site map is a familiar one; maps of this kind have been prepared for many regions of the United States. The other two, the material-distribution and surface-geology maps, have been adapted for use in material exploration as the result of the work now being carried on in western United States and Kansas.

MATERIAL-SITE MAPS

Description - The material-site map shows the location of pits and quarries that are now being operated or that have been operated in the past. (See Fig. 1, Example of a Material-Site Map.) The map is usually prepared to a relatively small scale, 1 in. equals 10 or 15 mi., but may be constructed to a much larger scale if it is to be used as a part of the construction program of a single project. Although generally constructed in the office from available pit and quarry data sheets, and not field checked, this kind of map can be checked very thoroughly in the field and amplified by that field work.

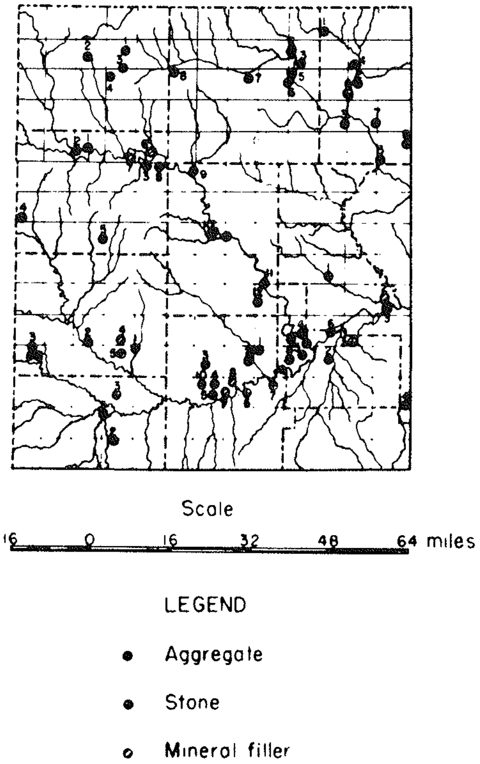


Figure 1. Example of a Material-Site Map

Most material-site maps show the kind of material available at any one place by the use of identifying symbols, which may be black and white or may be colored. In addition, each one of the pit and quarry locations shown is keyed through an index number to a source of basic data on the test properties of that material.

Advantages of Material-Site Maps - Among the advantages inherent in a material-site map is that of the relatively low cost of preparation. The basic data needed by the compiler are already available in the files of the materials department. Probably the cost of such a map for Kansas would range from $10,000 to $15,000, and would include the expenses of compilation, drafting, and publication. It would not, however, provide for collecting and testing additional samples of materials.

A material-site map is of great value in a short-range construction program. It serves as the record of materials known to be immediately available in every part of a wide area, and also indicates the existing pits and quarries from which these materials can be produced. The statistical data correlated with the map will show the quantity and quality of the material available at each site as of the date of compilation of the map. It is a useful inventory of construction materials.

In some circumstances, the material-site map is the only kind that can be prepared for a region. During World War II, for example, material-site maps were prepared by the US Geological Survey to show the available sources of construction materials in enemy-held territory. Even though the maps were prepared from no more than library data, they were found to be very useful to Army engineers after invasion had been accomplished.

Disadvantages of Material-Site Maps - Several disadvantages are inherent in a material-site map. It includes only those material-site locations known to the compiler by reason of the basic data with which he has been supplied. It is entirely possible that some agency unknown to him has opened pits and quarries in the region. Data on such sites are not available for his use and, therefore, his inventory of construction materials cannot be complete.

Nor does a material-site map show all of the kinds of construction materials available in a region; it shows only the sources of materials used in past construction. In one year, for example, a field party may explore an area for sand-gravel. This party, seeking only sources of acceptable sand-gravel, probably would take little note of other construction materials in the area. But five years later a new construction project in the same area might require limestone for use as riprap. A second materials party would then have to go over much of the area covered earlier by the first party. And with each new material requirement there would be the accompanying expense of re-exploring the area. A material-site map is not a complete record of the past exploration for materials.

MATERIAL-DISTRIBUTION MAPS

Description - The material-distribution map can be used as the basis for materials exploration in regions in which little exploration has yet been done or for which data are inadequate or are not available. The map is usually prepared to a small scale, one in. equals 10 or 15 mi. However, it is entirely possible to prepare such a map to a larger scale, one in. equals one or two mi., if there is an adequate source of information.

The map is generally prepared in the office, but a field check may be undertaken if the circumstances indicate its advisability. Maps of this kind are now being prepared for a number of states in the western part of the United States.

The material-distribution map is constructed on the basis of whatever geologic maps are available for the region. Each outcropping formation shown on the geologic map is classified as to the kind of material that can be produced from it. The area of outcrop of a geologic formation, therefore, is the area of outcrop of that construction material. Instead of depicting the outcrop areas of geologic formations, the map shows the outcrop areas of sand-gravel, limestone, granite, and other basic materials needed for engineering construction.

In one part of western Montana (see Fig. 2, Geologic Map of a Part of Western Montana), the geologic map shows the areas of outcrop of deposits laid down by present-day streams (Qa),

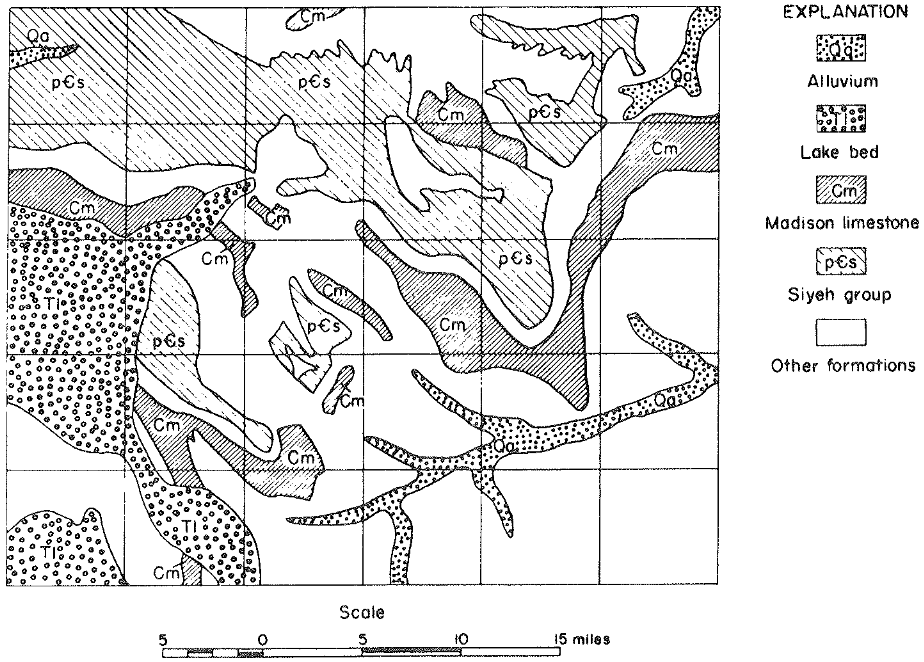


Figure 2. Geologic Map of a Part of Western Montana

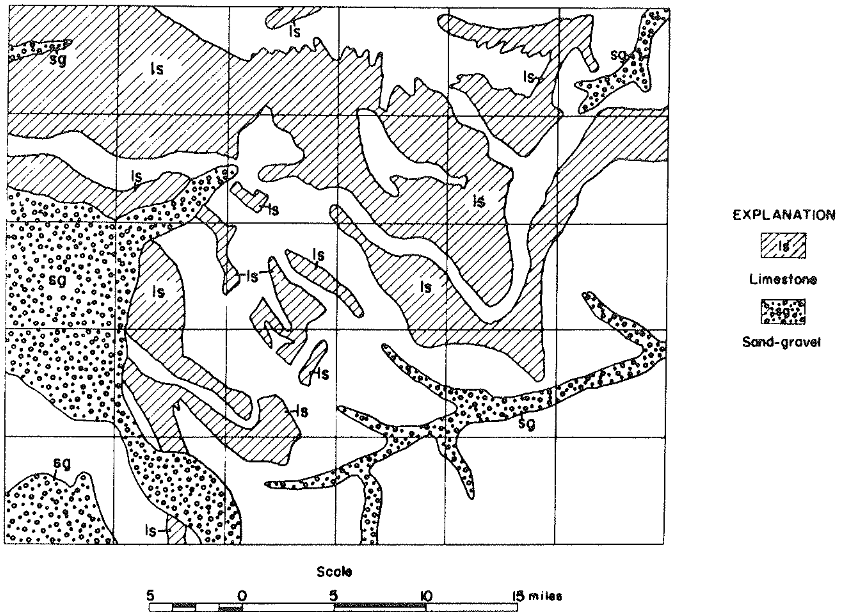


Figure 3. Material-Distribution Map of a Part of Western Montana

somewhat older deposits laid down on the floors of ancient lakes (Tl), the Madison limestone (Cm), the Siyeh group (pꞒs), and the outcrop areas of still other geologic formations not designated by symbols on the map. The stream and lake deposits are known to be composed predominantly of sand and gravel, and would be classified as a single materials unit, sand-gravel. The areas in which the stream- and lake-deposited sediments are shown on the geologic map would be the source areas for sand-gravel shown on a material-distribution map. (See Fig. 3, Material-Distribution Map of a Part of Western Montana.)

The Madison limestone shown on the geologic map would be classified as limestone and so, too, would the Siyeh group of formations, although the latter includes some thin beds of shale. (See Fig. 2.) The outcrop areas of the two formations, when transferred to a material-distribution map, would then show the potential production areas of limestone in this part of the State. (See Fig. 3.)

Advantages of Material-Distribution Maps - The example described above demonstrates the principal advantages of a material-distribution map. It shows the areas from which all kinds of construction materials in the region might be produced. Further, the map shows also the areas in which any one material cannot occur. A materials party, using this map as the basis for its field exploration, knows exactly the areas to search for a specified material, areas of outcrop of other materials can be eliminated from the exploration program even before the party goes into the field. Time and money are saved.

As another point in its favor, the material-distribution map serves as an adequate inventory of all the construction materials in the region it depicts, in which respect it is an improvement over the material-site map. The material-distribution map shows the areas of outcrop of all available materials, not just the places from which materials have been produced for past construction.

Although the preparation of a material-distribution map is more expensive than that of a material-site map, its final cost is still moderate. Unless a field check is undertaken, the only expenses are the salaries of a geologist to make the materials conversion and a draftsman, and the cost of publication. Using Kansas as the basis for the estimate, the total cost of the project probably would be about $20,000, including publication of the map.

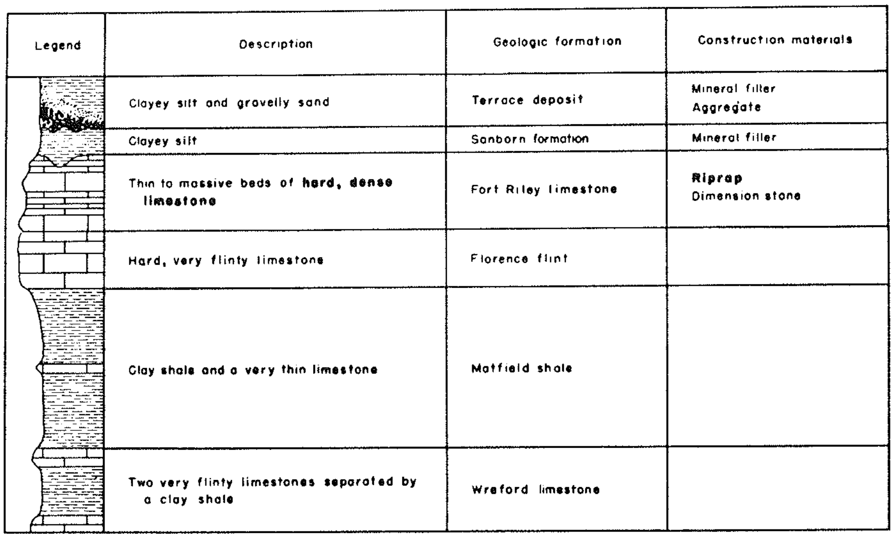
Disadvantages of Material-Distribution Maps - The principal disadvantage inherent in a material-distribution map is the possible inadequacy of the geologic maps available for a region. If the geologic map is not adequate, the material-distribution map cannot be adequate. And, unfortunately, adequate geologic maps are available for only a small part of the United States, although various State and Federal agencies hope to remedy this deficiency by completing a series of long-range mapping programs.

The map does not have in it the basis for correlating test and performance data with the materials it shows. Some limestones are sound and wear-resistant; they are acceptable sources of riprap. Other limestones are unsound, or wear or slake rapidly. The acceptable limestones are not distinguished from the unacceptable on a material-distribution map. Whatever their test properties, all limestones are shown by the same map symbol and pattern.

SURFACE-GEOLOGY MATERIALS MAPS

Description - A surface-geology materials map combines many of the useful features of the other two kinds. However, it is by far the most expensive of the three to prepare. The map is usually constructed to a relatively large scale, one in. equals one mi. or two in. equal one mi. It shows the areas of outcrop of all geologic formations, both the consolidated rocks and the unconsolidated sediments. And its scale is large enough that all pits and quarries can be clearly and accurately shown and indexed.

About 20 counties in Kansas have been mapped with the materials objective as the primary one. Surface-geology maps have already been published for an even greater number of counties by the cooperating Ground-Water Divisions of the Kansas and United States Geological Surveys; each of them can be readily adapted so as to show the areal distribution of sources of construction materials.



Legend	Description	Geologic formation	Construction materials
	Clayey silt and gravelly sand	Terrace deposit	Mineral filler Aggregate
	Clayey silt	Sanborn formation	Mineral filler
	Thin to massive beds of **hard, dense limestone**	Fort Riley limestone	**Riprap** Dimension stone
	Hard, very flinty limestone	Florence flint	
	Clay shale and a very thin limestone	Matfield shale	
	Two very flinty limestones separated by a clay shale	Wreford limestone	

Figure 4. Geologic Formations of Northeastern Kansas

Materials mapping in Kansas is done in this way: A two-man field party is sent to a county in which there is a known shortage of materials for construction already in sight. One man is employed by the Geological Department of the Kansas Highway Commission, and the other is a member of the Engineering Geology Branch of the US Geological Survey. The party generally uses large-scale aerial photographs as the map base. Experience has demonstrated that the photos serve as a means of reducing field time without sacrificing map accuracy. The outcrop areas of all geologic formations in the county are drawn directly on the photographs.

As the field men map the distribution of the geologic formations, they also visit all pits and quarries reported in the files of the State Highway Department's testing laboratory. The location of each one is plotted on a map, and the geologic formation from which the material was obtained is noted for future correlation. They also collect samples from new prospective material sites and send them to the testing laboratory.

The materials inventory for each county consists of a combined surface-geology and material-source map, a tabulation of materials tests, and a written text. The text describes the geology of the county and the construction materials available in the county. The correlation of the test characteristics of the various materials with the geologic formations from which they can be produced is also a part of the text.

Disadvantage of a Surface-Geology Materials Map - One dubious disadvantage is inherent in a surface-geology map: it is expensive to prepare. This kind of a materials inventory costs about $5,300 for the average county in Kansas. But this sum is close to the minimum; the total cost might be several times greater for many regions in the United States in which more complicated geology is

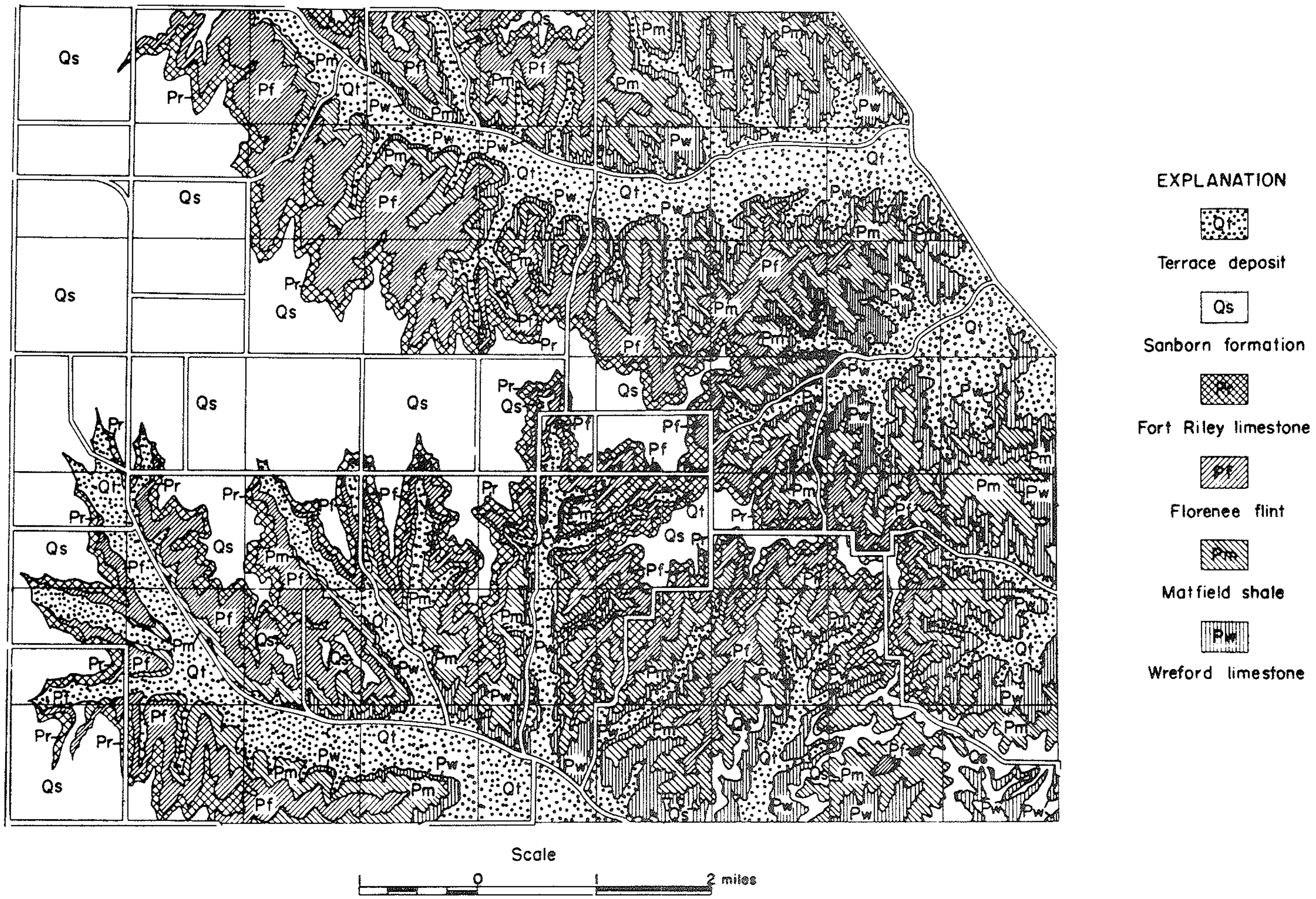
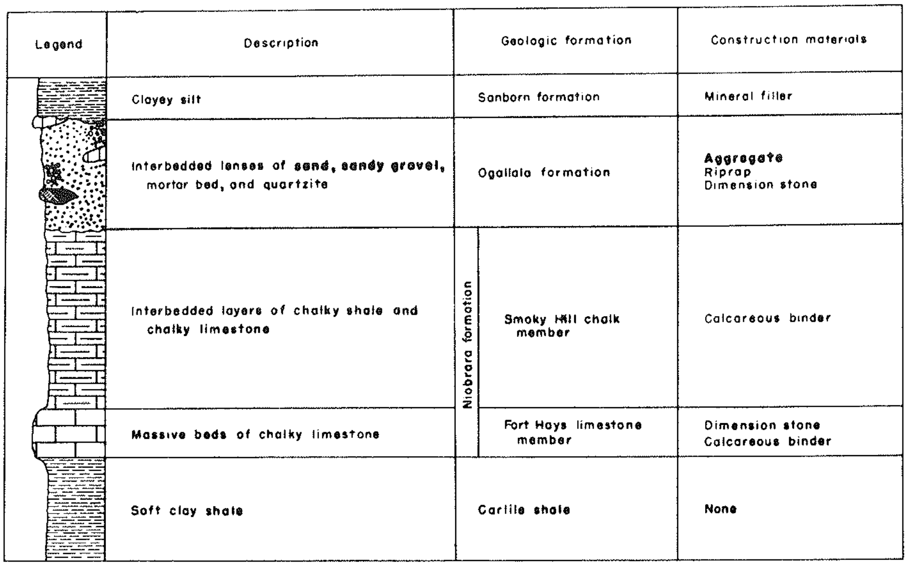


Figure 5. Surface-Geology Map of a Part of Northeastern Kansas

encountered. In preparing a cost estimate for the average Kansas county, $2,500 is allotted for the salaries and subsistence of the field men; $900 for transportation and other field expenses, $200 for laboratory tests of additional samples collected in the course of field work; $900 for the expense of drafting illustrations and writing the report; and $800 to defray the cost of publication.

possible sources of riprap. No one of them contains a material useful as riprap, as is shown in the descriptions of these formations.

However, the two limestones and the flint formation are potentially productive of acceptable riprap. The Florence flint and the Wreford limestone are flinty limestones and test data already at hand show that they are unsound and therefore fail to meet specifications.



Legend	Description	Geologic formation		Construction materials
	Clayey silt	Sanborn formation		Mineral filler
	Interbedded lenses of sand, sandy gravel, mortar bed, and quartzite	Ogallala formation		**Aggregate** Riprap Dimension stone
	Interbedded layers of chalky shale and chalky limestone	Niobrara formation	Smoky Hill chalk member	Calcareous binder
	Massive beds of chalky limestone		Fort Hays limestone member	Dimension stone Calcareous binder
	Soft clay shale	Carlile shale		None

Figure 6. Geologic Formations of Northcentral Kansas

Advantages of a Surface-Geology Materials Map - Two examples illustrate the usefulness of a surface-geology map in the exploration for construction materials. In one part of northeastern Kansas, outcrops of the following geologic formations occur: alluvium and terrace deposits in the valleys of streams, the Sanborn formation on the tops of the interstream areas, and the Fort Riley limestone, the Florence flint, the Matfield shale, and the Wreford limestone. (See Fig. 4, Geologic Formations of Northeastern Kansas.)

If it is assumed that stone for riprap is needed in construction planned for this area, the alluvium, terrace deposits, Sanborn formation, and the Matfield shale can be eliminated immediately as But tests of the Fort Riley limestone indicate that it is sound, develops little abrasion loss, and has a specific gravity of 2.6; obviously it is the best local source of stone for riprap.

Using the surface-geology map of the area as its guide, the materials men locate the quarry site in an outcrop of the Fort Riley limestone at the most accessible point nearest the construction project. (See Pr on Fig. 5, Surface-Geology Map of a Part of Northeastern Kansas.) The absolute minimum of field time and expense is required, and the engineer can be confident that riprap produced from the Fort Riley limestone will give good service in the construction.

Another example selected from an

entirely different geologic setting demonstrates the same usefulness of a surface-geology map. The Sanborn and Ogallala formations, the Smoky Hill chalk member and the Fort Hays limestone member of the Niobrara formation, and the Carlile shale outcrop in a part of north-central Kansas. (See Fig. 6, Geologic Formations of North-Central Kansas.) Sand-gravel for use as mixed aggregate is needed for nearby construction. The descriptions of four of the geologic formations show that they are not potential sources of sand-gravel. The Sanborn formation is composed of clayey silt, and if not too clayey, might be a source of mineral filler; the Smoky Hill is a chalking shale and is a source of calcareous binder; the Fort Hays is chalky limestone and is a source of binder and dimension stone; and the Carlile is a clay shale. But the Ogallala formation contains numerous beds of gravelly sand, and the test characteristics of the Ogallala material indicate that it probably will be acceptable for use as mixed aggregate.

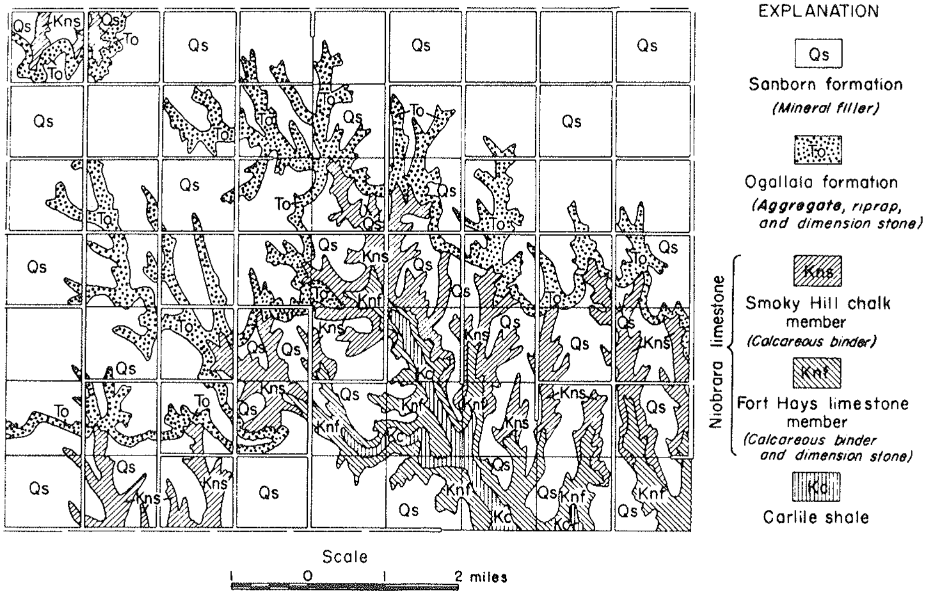


Figure 7. Surface-Ceology Map of a Part of Northcentral Kansas

Basing its exploration on the surface-geology map of the area, the materials party eliminates the outcrop areas of the Sanborn formation, Smoky Hill chalk, Fort Hays limestone, and Carlile shale from the field program. (See Fig. 7, Surface-Geology Map of a Part of North-Central Kansas.) The areas nonproductive of sand-gravel are avoided, and the search is confined to the outcrop areas of the Ogallala formation as shown on the surface-geology map. The most economic source of sand-gravel is then located with the least expenditure of field time and money.

It is possible also to estimate the quantity of material available at any one place and the overburden to be expected there from information contained in the surface-geology map and the report that accompanies it. The physical characteristics, including thickness, of a geologic formation composed of consolidated rock are fairly consistent over a moderately extensive area; unconsolidated sediments vary more rapidly. If a layer of limestone is known to be 10 ft. thick, the approximate quantity of it available at any one place can be estimated by determining the areal extent of its outcrop, as shown on a surface-geology map, at that place.

The character and thickness of overburden also can be interpreted from a surface-geology map. A geologic formation composed of consolidated rock that overlies a potentially material-productive formation probably will prove more difficult and expensive to remove than an overburden formation composed of unconsolidated sediment.

The surface-geology map is not only useful as the basis for materials exploration, but it can be employed also to advantage in engineering planning and design. A flinty limestone, for example, often discharges significant amounts of water. Knowing that, the engineer may want the alignment to avoid as many of the outcrops of that limestone as possible, or will specify that appropriate drains be designed for those places where avoidance is not possible. Then, too, the engineer can determine the kind of excavation to be expected at all places along an alignment from the information presented to him by the surface-geology map. Some geologic formations require rock excavation, others require common excavation, and the kind can be interpreted from the geologic map. Such a map, therefore, serves a multiple purpose in civil engineering.

SUMMARY

A material-site map serves as a useful inventory of construction materials immediately available in a region. A material-distribution map provides an excellent base for the exploration for construction materials, and is a complete inventory of all materials available in a region.

A surface-geology map, although expensive to prepare, is the most satisfactory of the three kinds of materials maps because in itself it is a complete inventory of all available construction materials and provides the best possible basis for the search for a material to meet certain specifications. It is useful also for estimating available quantities of material, the character and thickness of overburden, the existence of possible causes of failure of construction, and the kind of excavation to be expected at any one place.

Compendium 6 Text 4

LATERITE AND LATERITIC SOILS AND OTHER PROBLEM SOILS OF THE TROPICS

AN ENGINEERING EVALUATION AND
HIGHWAY DESIGN STUDY FOR
UNITED STATES AGENCY FOR
INTERNATIONAL DEVELOPMENT
AID/csd 3682

by W.J. MORIN
PETER C. TODOR

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DNER

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CHAPTER 11

AIR PHOTO-INTERPRETATION

INTRODUCTION

The technique of interpreting imagery obtained from remote sensors is becoming more important as the pace of worldwide development increases. The technique is particularly useful in developing generalized maps of existing ground conditions in regions where either existing documented data is not available or where ground surveys are impractical because of time and budgetary constraints.

Clearly documented data is preferable. For example, standard geological maps and agricultural (pedological) soils maps along with their supporting reports are useful to the engineer, since he can rely on past experience to identify the probable engineering and construction problems associated with the different ground conditions identified on these maps. However, when these maps are not available the engineer must depend upon generalized reports to establish his preliminary plans and to set up his detailed surveys. Under these conditions imagery from various remote sensors can be very useful to the engineer, especially if the imagery is to a fairly large scale and it is already available at a relatively low cost.

Types of Imagery

The imagery that has been most often used in the past and will undoubtedly continue to be the most widely used by soil engineers for mapping purposes has been aerial photography. Most of the aerial photography available today is the monochrome or black and white format. It is usually available in a variety of scales ranging from 1:5,000 to 1:100,000. Scales on the order of 1:15,000 to 1:25,000 are generally the most useful for detailed interpretation of terrain characteristics. Nevertheless, smaller scale photography in the range of 1:50,000 can also be utilized to great advantage if nothing larger is available. Numerous publications have appeared in the last 15 to 20 years on the interpretation of black and white aerial photography. One of the most useful is now being revised. It is the *Manual of Photo-Interpretation* published by the American Society of Photogrammetry.

Color photography has become more widely used also, particularly in the last ten years. In some areas of the world today, color photography may be available at about the same scales as mentioned above. The *Manual of Color Aerial Photography* has also been published by the American Society of Photogrammetry. Where color photography is not already available, it may be flown for a specific project for often its cost is only slightly higher than panchromatic, because a major portion of the aerial photography cost is related to the cost of the aircraft and crew time expended in obtaining the photography.

Color infrared (IR) of "false color" photography is also frequently used. There are indications that in many cases IR photography is of greater value than natural color for the interpretation of the geologic situation. IR photography is usually exposed in approximately the same range of scales as panchromatic also, but the film is not readily available in most areas of the world. Therefore, it would be necessary to contract for this special photography.

Cloud cover severely limits all types of photography in tropical countries especially during the long wet season. Thus, the periods when aerial photographs can be taken are limited and may be at variance with project requirements. It is undoubtedly for this reason that recently, more and more use has been made of radar imagery since it can be obtained in all but the most severe weather conditions. The Radam project in Brazil has been working for several years with radar imagery at a scale of 1:250,000. In some respects, radar imagery interpretation is similar to aerial photography interpretation. It is especially useful in making topographic maps where cloud cover exists during much of the year. The extensive use of the information obtained from their Radam Project in Brazil will be discussed again in another section of this chapter.

Another relatively new type of imagery is now available from the multispectral scanner located in the Earth Resources Technological Satellite (ERTS-1) which is currently in polar orbit around the earth. The multispectral scanner operates in various wave bands and scans continuously as it orbits the earth. It produces tremendous amounts of data which can be utilized for various interpretation purposes. Each image scanned by the satellite covers an area about 100 by 100 nautical miles (185 by 185 kilometers) so that the scale of the imagery is on the order of 1:750,000. This imagery, however, can usually be enlarged several times with little loss of definition. Furthermore, the available information can be analyzed without actually being transformed into an image. This is accomplished by working directly with the computer compatible magnetic tape (CCT). The scanner cannot penetrate cloud formation so much of the imagery coming back from ERTS-1 is useless as far as terrain analysis is concerned. On the other hand, all portions of the earth's surface are scanned every 18 days. In addition there is also a considerable overlap of adjacent scanning orbits, thus the opportunity to obtain almost cloud-free imagery even during the rainy season is possible. The utility of this imagery is limited primarily by the ability to retrieve it from the satellite and to process it. At the present time, only United States and Canada have receiving stations which can retrieve the information and make it available to the rest of the world. However, Brazil is now in the process of building a receiving station while Italy and perhaps central Africa will have stations in the near future. These additional stations will greatly speed the processing time of imagery in all regions. It can therefore, be anticipated that more and more emphasis will be placed on interpretation of satellite imagery, especially as its capabilities are recognized outside of the United States and Canada.

PREVIOUS IMPORTANT WORK

Numerous terrain classifications based primarily on terrain evaluation procedures have been developed in the last decade or so. All of these depend heavily upon the interpretation of remotely sensed imagery, usually aerial photography. For example, in South Africa, the National Institute of Road Research (1971) has developed a system of land classification largely patterned after the British scheme. The Institute is collecting information in the form of a data bank to correlate with the various land classification patterns. Similar work has been carried on in Australia under what has been called a "pattern, unit, component evaluation" (PUCE) again utilizing primarily a land classification scheme based on the study of aerial photographs with particular emphasis on vegetation and rock type (Aitchison and Grant, 1968). Lawrence (1972) has also described the use of aerial photography in the tropical situation of West Malaysia.

In addition to the Radam project previously mentioned, a great deal of work has been done which pertains directly to terrain evaluation in South America. Ray (1963) cited its usefulness in making geologic maps. Vera (1964) described the experience on an aerial photographic project conducted through the cooperation of the Pan-American Union in Chile. Liang (1964) summarized the characteristics for the interpretation of tropical soils in a special report for the United States Air Force. The system developed by Liang is shown in Table 11.1. Ricci and Petri (1965), described the principles of airphoto interpretation from the geologic standpoint and Condori (1967) gave an up-to-date description of the principles of photo-interpretation. One of the most recent publications is that of the Brazilian Coffee Institute, Photo-Interpretation Service of the Executive Group of Rationalization of Coffee Culture (IBC-GERCA, 1972). The techniques which are commonly employed in the photo-interpretation procedure are outlined very well in this latter publication and for this reason will be only briefly reviewed here.

Techniques Employed

In the procedure commonly followed, the first step of the geologic analysis was to look at the photo mosaic of the area and to delineate regions of similar geomorphology, drainage patterns and land use, since these are normally related to pedologic aspects. In the pilot area of Minas Gerais (IBC-GERCA), photos were 1:60,000 panchromatic.

The second step was to sketch the major lithologic units which correlated with known soil types. This was done by studying all available geologic literature for the area, mapping out the major units from the characteristics mentioned above; and then locating appropriate field sampling sites from visible outcrops and situations which require boundary clarifications. The IBC group stated that particular emphasis was given to geomorphic features, drainage patterns, structural features, evidences of lithology, such as stratification of sedimentary rock, and other criteria, such as type of vegetation and methods of cultivation.

The third step was to take the map into the field and revise it so that it correlates with field observations and findings of rock samples analysis.

Finally, the fourth step was to prepare a geologic map initially at a scale of approximately 1:50,000, and later reduced to 1:200,000 on the basis of the correlations between the field studies, the photo-interpretative mapped units and the information concerning the geologic periods.

The second analysis in the process was to prepare a sketch of the vegetation situation. First, various vegetative areas were identified on the 1:60,000 photography. The four units mapped were the forest; the cerrado, which is essentially a twisted or stunted forest and grass; the grassland areas; and the cultivated fields. These were delineated on the basis of image structure, image texture, qualities of the shapes of the boundaries, color tones, and the topographic position. Finally on the basis of the field investigation, the vegetation map was prepared and finally corrected.

The final analysis was to prepare the soils interpretation map. Photo pattern elements, particularly those observed with stereo-pairs, were utilized in order to identify the following map units in the pilot area: (1) soils with a latosolic B, (2) soils with an argillic B, (3) weakly developed soils, (4) soil associations and (5) a lowland complex. Each unit was described in accordance with Tables 11.2 and 11.3 which are commonly used in photo-interpretation to describe the geomorphology, drainage and pedology of the area.

Next, a preliminary soil legend was prepared through a soil exploratory survey which was made along all existing roads and lanes throughout the area under investigation. Numerous soil profiles were studied, samples were taken of both soil and rock and then brought to the laboratory for testing.

Next the corrected soil map was prepared by revising the preliminary map based on photo-interpretation techniques and then by delineating the new map units on the 1:60,000 photography.

Finally, all data was transferred to an uncontrolled mosaic, again to an approximate scale of 1:57,000. From this a manuscript map at a scale of 1:100,000 was prepared.

Significant conclusions were drawn on the basis of this pilot study. They are very similar to those which have been previously enumerated:

1) photo interpretation allows for an almost global planning of field activities;
2) the field control conducted with the use of aerial photographs and of photo-interpretation techniques is highly satisfactory and allows for the preparation of a considerably detailed survey map;
3) time saving and precision which are gained in delineating the mapping units have been adequately confirmed through field investigations;
4) rock and vegetation photo-interpretation provide useful information for mapping the soil;
5) the interaction of photo-interpretation with field and laboratory activities lead to a sound mapping precision.

The authors of the pilot study concluded finally,

"It is our opinion that the methodology here used has presented sound results and therefore met the proposed objectives for its application."

TABLE 11.1

Airphoto Interpretation of Tropical Soils – Summary (after Liang, 1964)

Soil Groups	Topography (land Form)	Drainage	Erosion	Gray Tone	Vegetation	Remarks
1. Laterite Crust LC	Cap rock (relatively flat hilltops): Ledges on Slopes	Little surface drainage	Little; rockfalls on edges of cap	Light	Grass or low shrubs	
2. Laterite Gravel LG	Flat hilltops to rolling ground	Little surface drainage	Little; gullying erosion starts on slopes below the gravel layer	Light	Grass or low shrubs	
3. Laterite (Hardening upon exposure) LH	Subdued to rolling ground intervened by flat valleys at high to intermediate slopes	Little surface drainage	Little erosion	Light	Variable; Plantations; Swidden agriculture	General absence of landslides; suitable for golf course or cemetery development; possibility of excavation pits
4. Lateritic Soil LS	Rolling ground, at high to intermediate slopes	Variable; less surface drainage with more advanced stage of and deeper laterization	Variable; less erosion with more advanced stage of and deeper laterization	Light to medium	Variable; Plantations; Swidden agriculture common; Intensive agriculture in high rainfall areas	Termite hills are common
5. Red and Brown Clays CR	Variable; all forms except in basins	Considerable surface drainage development	Gullying erosion; depth of gullying indication of depth of soil to rock; slides	Medium to dark	Variable; intensive agriculture common	
6. Black Clays CB	Gentle lower slopes and flat depressions	Little surface drainage; high water table	Little erosion	Dark	Intensive agriculture	Quality of clay depends on source of material and mode of deposition
7. Desert Soils SD	Variable	Dry drainage channels	Wind erosion	Light	General absence	
8. Saline Soils SS	Low, coastal land; water table near surface	Tidal drainage channels	Little erosion	Light patches (dark in special cases)	General absence	
9. Swamps SW	Low, flat land; water table at surface	Tidal drainage channels	Little erosion	Dark	Mangrove and other swamp vegetation	
10. Alluvium SA	Low, flat land bordering stream	Little surface drainage	Little erosion	Light to medium	Recent–little vegetation; Old–intensive agriculture	
11. Rock and Thin Soils SR	Rolling to hilly, at high slopes	Variable	Variable	Light to medium	Variable; no agriculture development	

TABLE 11.2
Main Characteristics Used to Determine Physiography

Relief	Geomorphology	Drainage Pattern		Depth of Weathering Cover	Probable Texture	Permeability	Probable Lithology	Vegetation	Land Use
		Standard	Characteristics						
Flat	Hill	Basic	Integration degree	Deep	Coarse	High	Igneous	Field	Little – used
Subdued to rolling	Ridge	Modified	Density	Medium	Fine	Medium	Sedimentary	Savannah	Moderate
Rolling	Plain	Special	Degree of uniformity	Shallow	Medium	Low	Metamorphic	Forest	Intense
Strongly rolling	Valley	Internal	Orientation	Outcrops	–			Meadow	
Mountainous	Basin		Degree of control						
	Mountainous		Angle of junction						
	Plateau		Angularity						

TABLE 11.3
Drainage Characteristics

Systems	Drainage Patterns					
Basic	Dendritic	Parallel	Rectangular	Trellis	Pectinate	Circular
Modification	Contoured Dichotomic	Pincer like Assymetric	Sub-dendritic Angular	Pinnate Subparallel	Pectinate Colinear	–
Special features	Disorderly	Lagoonal Braided	Illusory Anabranched	Kettle-hole –	Yazoo stream –	–
Internal	Sink-hole	Infiltration pits	–	–	–	–

IDENTIFICATION OF LATERITES AND OTHER TROPICAL SOILS

The highly weathered lateritic soils occur in a part of the world where most of the other soils have high clay contents. Thus, these soils containing concretionary material are distinctive because of their generally coarser texture, greater permeability, and inability to retain water and nutrient ions. Areas with such soils are usually suitable agriculturally as poor pasture or are not farmed at all. Surrounding areas may be forested but the coarse-grained or indurated area will only support scattered scrubby trees and sparse grass. In addition the high permeability characteristic applies even to well-indurated lateritic crusts.

True laterite crust, LC (Table 11.1) often appears in association with the remnants of ancient peneplain surfaces. Dowling (1968) describes several occurrences in northeastern Nigeria where the soils have developed over very different geological parent materials. Liang (1964) states that this association is a general characteristic of lateritic crusts and cites examples with illustrations in Brazil, Uganda and Australia. Nearly all of the peneplain remnants appear to be of rather small size. At the most they are a few square miles in area. Bates (1962) suggests that as erosion encroaches upon the peneplain remnant, it permits a substantial lateral flow of groundwater and results in the segregation of iron and aluminum oxides. The iron is transported in solution to the exposed sides of the remnant where it is precipitated as the groundwater enters a strongly oxidizing environment. The interior of the remnant is found to be less consolidated and to contain less iron oxide and more aluminum oxide than the outside fringe. This observation is confirmed by Brammer (1962) in discussing the agricultural soils of Ghana. Apparently, laterite crust occurs typically as a ring surrounding a flat-topped peneplain remnant rather than as a caprock covering the peneplain surface. Airphoto frequently shows only sparse vegetation and no surface drainage features because remnant surface soils have a high permeability. Slopes leading downhill away from the mesa usually present concave profiles. Encroaching gullies appear suddenly, often at the bottom of almost vertical headwalls, tens of feet in height. Liang (1964) notes the danger of confusing the LC pattern with that of basalt or sandstone; which often form a caprock over a base of less permeable, more easily eroded material.

The fact that each peneplain surface was formed only a few stages in geologic time is another clue to the identification of terrain areas with possible laterite crusts. Often the approximate elevations of these surfaces may be known or can be inferred from elevations of the surrounding areas. For example, the Voltaian basin of east-central Ghana has several surfaces, which are discontinuous, but similar enough in elevation to make a reliable correlation. The most noteworthy correlations occurs in the higher hills i.e. elevation of 42o to 760 m (1,400 to 2,500 ft) above sea level (Brush, 1962).

Ferricrete is a laterite-like material formed by the cementation of the sands and gravels in stream banks and terraces. The formation of ferricrete is a continuing process which takes place in areas close to present day stream levels, which is where iron oxide is precipitated from emerging groundwater. Ferricrete may also be associated with terrace systems located above present day stream systems, where the previously stream regimen was stable for a long period of time. In the Voltaian basin terraces are frequently found at levels of 18-23 m (60-75 ft), 30-36 m (100-120 ft) and 75-91 m (250-300 ft) above present base levels. The two lower terrace levels often contain well-cemented ferricrete deposits.

Laterite gravel, LG, like the laterite crust, may occur as a result of weathering in-situ or by other processes which produce accumulations of particles high in iron oxide. LG is often found on high-lying ancient erosion surfaces where the formation of LC is not complete. Erosion surfaces tend to be flat-topped and show evidence of high surface permeability, local aridity and infertility. The sharply defined break at the heads of encroaching gullies which is common in LC areas is usually subdued or missing in LG areas as is the concave profile of the slopes.

In northern Ghana some concretionary gravel is usually present in the subsoil a foot or two below the surface in welldrained areas. In such areas, the vegetative cover is usually grass and shrub rather than forest. A concentration of gravel, analogous to a laterite crust, may be found near the upper convex portion of hillsides. If a crust is present, an accumulation of detached talus material may be present. Apparently, concentrations of gravel are least likely to be found near mid-slope. Near the bottoms of the slopes, soil aggregations may be enlarged or cemented by additions of iron which has been precipitated from groundwater. If the underlying material is quite impermeable, the enriched material may remain permanently moist and become plinthite, LH. At the bottom of the slope, deposits containing lateritic detritus are usually buried by fine-grained colluvium, sheet wash material or alluvium.

Even those lateritic soils which do not contain appreciable coarse material are generally poor agricultural soils. Liang (1964) states that such areas are often devoted to "swidden" agriculture, in which an area is cleared, farmed for a few years, and then abandoned to native vegetation for many years. The resulting land pattern is often quite apparent in aerial photography which shows scattered small fields, some of which are under cultivation and others which are in various natural vegetation regrowth stages. In contrast, some nearby uncultivated areas are not farmed because of their coarse lateritic soils and still other areas show patterns of intensive perennial agriculture use because of their weathered clay or alluviated soils.

Although sources of sound gravel are rare near the ground surface in the tropics, materials other than laterite may sometimes be found. For example, layers of quartz fragments concentrated at or near the ground surface can be found in terrain where there has been a deep residual weathering of rocks which contain veins or inclusions of quartz. In spite of its convenient location, it is unfortunately, often too thin and scattered to be of much use.

If a fairly thick layer is present it can sometimes be identified in aerial photography. It appears in areas of tonal lightness and in areas with discontinuous vegetative cover. Identification is easier on sloping terrains to identify where sheet erosion has washed the finer material from the surface. It is also easier when the location of underlying country rock which contains large veins or lenses of quartz is known. Occurrences of this type are more likely to be present in youthful terrains.

Surface drainage conditions are often of considerable engineering importance. Natural color aerial photography provides one useful means for evaluating drainage systems especially when combined with considerations of the topographic position of the drainage system. Also variations in the state of oxidation and hydration of iron compounds are strongly reflected in soil color. Therefore, soil colors should be observed where land has been cleared for agricultural use and where other occasional bare spots are found. Brammer (1962) reports a change in color in typical forest soils of Ghana from red for the best drained soils in which the iron is completely oxidized and not hydrated; to brown and yellow in imperfectly drained soils in which the iron becomes increasingly hydrated; and finally to gray or white in poorly drained soils which are perennially waterlogged so that the iron has been reduced to the ferrous state or completely leached from the soil.

Tropical black clays rich in montmorillonite have attracted considerable interest because of the special engineering problems which they present. They are discussed in detail in Chapter 10. Where black clays occur as residual soils, they are nearly always associated with basic bedrock materials. Topographically, occurrences are generally located in positions where soil drainage tends to be impeded. Thus, black clays are found in areas of gently rolling topography or in flat depressions, but seldom in areas of mountainous relief. Natural vegetative cover is usually savannah and not forest even if the soil is located in a region where forest cover is common. In many tropical areas these soils are farmed intensively. Even though shrinkage cracks may attain considerable size under dry conditions, Liang reports that they were not apparent in photographs at a scale of 1:20,000 of areas in Colombia and Burma. In areas of Africa with longer dry seasons and sparser vegetation photo identification may be easier. Certainly the use of larger-scale color photography should make it easier to locate black clay soils.

In most tropical areas unweathered country rock is seldom found near the surface, but there are exceptional occurrences of isolated rock outcrops of inselbergs. Such features frequently appear as isolated "rock castles" which rise many feet above the surrounding terrain and present a relatively unweathered surface of bare bedrock. In most cases, these features seem to bear little relation to the surrounding deeply weathered terrain. They are useful sources of aggregates and coarse material if they can be found. Most inselbergs can be easily identified in aerial photography by their light appearance which constrasts with their shadows.

GENERAL CONCLUSIONS REGARDING TERRAIN EVALUATIONS

The preceeding discussions indicate that a considerable amount of work is required in order to perform an adequate terrain evaluation of a particular area. The three major steps are the interpretation of the remote sensor imagery, a review of all available bibliographic information regarding the soils and geology of the region, and a selective field investigation of the geologic, vegetation and the pedologic situation of the region.

In the conduct of the present investigation, it was impossible to carry out such a comprehensive procedure. It is important, however, to note that it can and has been done. The degree of the detail involved will always depend upon the purpose for which the evaluation is being conducted. As far as engineering requirements are concerned it will not be necessary to make a detailed pedologic survey, such as that reported by the IBC. Nevertheless, the survey must be sufficiently detailed to allow for the sampling of typical soils and for the verification of the map units. Once a map is completed a great deal would remain to be done in actually correlating typical patterns as seen in the imagery with such on-site items as the type of rock, depth of residual soil, location of laterite crust, location of lateritic gravels, and the identification of soil profiles which have special implications from the engineering performance standpoint.

In this respect, the great significance of field correlation is indicated by the statement which appeared in several of the Radam project reports:

> "Initially, intention was to use data of previous work and then to transpose the information to the radar imagery. However, the complete failure of this procedure led to direct field investigation to determine the correspondence of imagery-geologic features."

From the beginning of this present project, it was hoped that more time might be devoted to developing procedures of photo interpretation through the correlation of available imagery, particularly, black and white panchromatic aerial photography with both available geologic data and field investigation. Some IR photography was also available for study. Unfortunately, it was impossible to carry out this preliminary objective because of the short time available and because of the difficulties in obtaining necessary background data, photography and field mapping. Thus, the present project has depended primarily on the available geologic and pedologic maps as a basis of locating and classifying laterite materials. There seems no doubt, however, in view of the Radam report, the success of the Radam project and the work done by the Brazilian Coffee Institute in cooperation with the Brazilian Ministry of Agriculture, that it is feasible to use aerial photography as well as the imagery obtainable from other types of remote sensors to classify the terrain. Furthermore, various map units can be developed from the imagery and correlated with the characteristics of soil profiles which are important to engineering projects, especially those related to transportation.

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TECHNIQUES FOR THE INTERPRETATION OF REMOTE SENSING IMAGERY FOR HIGHWAY ENGINEEERING PURPOSES

by

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CONTENTS

TECHNIQUES FOR THE INTERPRETATION OF REMOTE SENSING IMAGERY FOR HIGHWAY ENGINEERING PURPOSES

ABSTRACT

Traditionally the interpretation of black-and-white aerial photographs has played a significant role in highway engineering. Recent increases in the availability of different forms of remotely sensed data and improvements in interpretative techniques have now resulted in recognition of remote sensing as a valuable tool for the highway engineer. This report summarises some of the new forms of image data and specialised interpretative techniques now available which can be selectively employed to provide more information than that previously gained from standard photo-interpretation procedures.

Proper use of these techniques requires a basic understanding of how the imagery is obtained, what it represents and its limitations with respect to spectral, spatial and brightness resolution, so that the best remote sensor data may be selected, processed and analysed for a particular problem to obtain the maximum amount of information with the least expense.

Various forms of image enhancement or computer studies may be employed to assist image discriminations and classifications. Some enhancement techniques involve visual image analysis such as colour additive/subtractive viewing, stereoscopic and pseudo-stereoscopic photointerpretation. A few procedures are ordinarily accomplished through computer analysis (brightness ratioing, atmospheric correction etc), but others are effective with either imagery or numerical data. This latter group includes density slicing, contrast stretching, cluster analysis, pattern recognition, frequency analysis, and edge enhancement.

Most procedures can be accomplished in several ways, with the accuracy of the results and efficiency of the operation largely dependent on the equipment used. Consequently, the economics of a project may often be the final consideration in the implementation of most interpretative techniques.

1. INTRODUCTION

Increasing availability of remotely sensed data and advancements in interpretative techniques have resulted in recognition of remote sensing as a valuable tool for the geotechnical engineer. Technological development of remote sensing systems, however, has at present outstripped corresponding development of interpretation techniques which are needed to convert remotely sensed data into usable information. Increasing attention must therefore now be directed towards the interpretation and analytical phases of remote sensing and the application of these techniques for solving specific problems such as those common to highway engineering.

Traditionally, black-and-white aerial photographs have been used in combination with ground investigations for the preparation of base maps, route location and the presentation of geotechnical information. The location of a highway route requires consideration of very many complex and interrelated factors (Fig 1). Image interpretation techniques have consequently been more extensively applied to highway location surveys than to any other stage of highway engineering and have proven of value in each of the steps as the survey progresses from reconnaissance of an area to the final detailed investigation on the ground.

Recent developments in photography and instrumentation have now produced a variety of new remote sensing systems capable of providing a wide range of different forms of imagery. The acquisition of data useful in planning, design, construction, maintenance and operation of highway facilities can be attained from these various types of imagery by applying traditional photointerpretative techniques, but substantially more information may be gained if specialised interpretative techniques are selectively employed. A basic understanding of how the imagery is obtained, what it represents and limitations such as its spectral, spatial and brightness resolution are essential requirements if proper use is to be made of the new interpretative techniques. With these considerations in mind the most appropriate type of remote sensor data that will best apply to a specific problem can be selected and then processed and analysed to obtain the maximum amount of information with the least expense.

Information contained within an image produced by either photographic or electronic means has consistently proved to be of major importance for many engineering investigations of terrain. The image data available include high and low altitude aerial photography, thermal infrared imagery, radar imagery, microwave data, and a full range of multispectral imagery, although the more 'exotic' remote sensor data may only be available for a few sites. However, earth resources satellite programmes (ERTS, LANDSAT and EREP) have been particularly effective in focusing attention on the potential use of small-scale imagery, the broad coverage provided by the satellite systems being freely available through the EROS Data Centre in Sioux Falls, South Dakota. Consequently anyone can now obtain photography or multispectral imagery for almost any place in the world.

Figure 2 summarises the spectral ranges of common imaging sensors and illustrates some of the basic distinctions. Non-imaging sensors can provide information for some specific, and usually highly specialised, applications, but practical considerations limit most users to an analysis of photography and readily available scanner imagery. In the location and design of new roads, any technique which can provide the engineer with quantitative information on the factors affecting the cost of alternative routes and construction at the reconnaissance, feasibility and (later) detailed survey stages will help to increase the efficiency of the site investigation. Consequently, the more recently developed photointerpretation techniques outlined in this report should further assist the geotechnical engineer to fully utilise and attain the maximum amount of terrain information from any form of imagery available over the area of investigation.

A thorough discussion of all interpretative techniques used in remote sensing is beyond the scope of this report, which will be limited to a brief outline of non-standard interpretative methods which may be employed in routine analyses. Reference should be made to the literature for more detailed and technical coverage of the wider field[1]. The interpretative methods will be discussed as they apply to forms of common imagery readily available to engineers, such as visible and near infrared multispectral photography from aircraft and multispectral scanner imagery from the LANDSAT satellite.

2. CHARACTERISTICS OF REMOTE SENSING IMAGE DATA

In order to appreciate the use of remote sensor data, it is primarily necessary to understand the basic characteristics of the image data, especially with respect to how the image is formed and what it represents. In general, a brightness value recorded on a photograph or scanner image represents the total intensity of electromagnetic radiation entering the receiver at a particular point. This energy consists of imaging radiation received directly from the target or ground surface and non-imaging radiation that is scattered into the receiver by molecules and particulate matter in the atmosphere. The non-imaging radiation appears as haze and is generally detrimental to the recorded image.

Until recently, black-and-white photography was the only form of remotely-sensed data generally available to the engineer. Now black-and-white, infrared, false colour infrared and colour photography, multispectral photography, and multispectral scanner imagery are widely available. Colour photography is more useful than black-and-white photography since it contains hue and chroma data in addition to tonal and textural information and the human eye is capable of separating one hundred times more colour combinations than grey scale values[2,3]. Utilisation of the photographic visible and near infrared spectrum, however, may be best accomplished at present by means of multispectral aerial photography which probably offers the optimum means of providing the most cost-effective information for engineering surveys. Significantly, in many terrain investigations the standard techniques of airphoto interpretation are now being most effectively complemented by the use of colour and infrared false colour films in multispectral photography for detailed investigations.

A multispectral camera system records separate photographs at a single point in time and space representing several spectral bands. These are generally obtained by a combined system of cameras, each having a different film/filter combination (Plate 1). For example, one camera might be fitted with a Kodak Wratten filter 25 and panchromatic film so that the 600–700 nm band (red) would be recorded, while a second camera, fitted with a Wratten 87 filter and infrared film, records the 720–900 nm band (infrared). A suite of multispectral photographs need not cover the entire photographic spectral range and the different 'bands' may or may not overlap. Multispectral photography may contain all the information available from colour and colour infrared photography but, owing to its inherent greater flexibility, is better suited for the application of both traditional and non-standard interpretative techniques since the image data can be more readily manipulated. The camera and film/filter configuration is commonly dictated by a particular need or preference, such as the discrimination of construction materials or natural drainage within the site investigation area.

A multispectral scanner receives energy through a small, moving aperture (Fig 3). The incoming energy is split into its various spectral components and converted into electric signals by means of photoelectric detectors. Each individual signal can then be recorded on magnetic tape or displayed immediately on a cathode ray tube. Multispectral scanners can record radiation in the visible and photographic infrared range and in spectral bands extending through the ultraviolet and thermal infrared (Fig. 2). Imagery obtained from the scanners generally covers a complete spectral range in discrete wavelength increments. Although scanner imagery is very much like multispectral photography it has the additional advantage that spectral bands outside the photographic range can be included. In addition to imagery covering complete spectral ranges in discrete wavelength increments, other configurations are possible, but special requirements are commonly left to some later phase of data manipulation.

Imaging radar and microwave radiometers produce images much like a scanner image but in spectral bands well beyond the thermal range (Fig. 2). These longer-wavelength sensors employ antennae rather than optical detectors as receivers (Fig. 4). The imaging capability of radar is dependent upon the reflected return from the target of electromagnetic energy supplied by the radar system itself, the nature of that energy returned to the radar sensor being dependent upon both the properties of the transmitted electromagnetic energy and the properties of the surface phenomena that are being sensed. Properties of the electromagnetic energy include wavelength, polarization and direction, whilst characteristic properties of surface phenomena that must be considered are dielectric and conducting properties, surface roughness in wavelength units, physical resonances, surface slopes, subsurface effects and scattering area[4].

Multispectral photography, radar and scanner imagery may be interpreted in the same manner as a standard photograph. The image interpreter can derive most of the information normally available from black-and-white photography from a single band of multispectral imagery, but the interpreter who wishes to employ the additional capability of the multispectral imagery must understand both the potential and the limitations of the data and the techniques that are available to help him in his interpretations[5].

The chief potential of multispectral imagery lies in the increased recording range and the broad range of applicable interpretative procedures. Recording a scene as a set of multiband images effectively spreads the information normally recorded on a single photograph over several photographs. This increases the effective dynamic range of the recording system so that smaller increments of scene contrast can be recorded. Recording a scene as a group of images, each representing a specific wavelength band, allows subsequent presentation of the information to be tailored to the application. The user can employ selected portions of the spectral data or combine various image bands in such a way as to enhance the significant contrasts or minimize interfering contrasts.

3. FACTORS AND LIMITATIONS INFLUENCING INTERPRETATION

The information required to undertake the wide range of engineering studies associated with a highway site investigation is derived from an analysis of the patterns present on either the available photography or relevant imagery. These patterns reflect the influence of the type of parent material; the geologic processes undergone; the climatic, biotic and physiographic environment; and man's activity. The variety of patterns developed due to the interplay of these various factors form the basis for the techniques of image interpretation. The basic premise for this technique is that materials developed under the same geologic and environmental conditions will have similar patterns on the imagery; dissimilar materials will have dissimilar patterns[6].

Image interpretation techniques applied to engineering studies involve the recognition of basic landforms and geomorphological processes as indicated by the pattern elements on the photography or imagery. The elements comprising the pattern include: image tone – colour or shade of grey, texture, uniformity, sharpness of boundary; topography – size, shape, elevation; drainage – form, type, texture; erosion – form, type;

vegetation – type, associations, indicator communities; and culture – man's influence on landscape and adjustment to variations in landforms and environment.

In addition to the equipment and analysis techniques used, success in the application of image interpretation to engineering studies is dependent on photographic and imagery parameters, experience of the interpreter and natural factors. Interpreter qualifications and basic properties of imagery pose few unique problems in engineering studies as they are well documented in the literature,[7,8,9] but an understanding of the factors influencing each of the above-listed items and the limitations imposed by these factors is important to the proper planning and utilization of interpretation techniques for engineering inventories and analyses.

No single scale of imagery will satisfy all of the requirements for the variety of engineering studies performed. Indeed, it is customary for medium and larger scale aerial photography to be stereoscopically examined in association with specially constructed controlled or uncontrolled photomosaics at scales of 1:80,000 to 1:150,000. Scales of 1:2,400 to 1:6,000 have been used for pavement-condition surveys; scales of 1:8,000 to 1:12,000 for detailed soils mapping; scales of 1:15,000 to 1:50,000 for terrain analyses; and scales of 1:60,000 to 1:1,000,000 obtained from high altitude aircraft photography and satellite imagery have been used for route selection and regional planning studies. Another imagery parameter requires sufficient coverage of an area to determine the extent of local conditions and the expected variations. Numerous instances have occurred where limited area coverage has been obtained for analysis of a selected route location. Some condition was then uncovered which required shifting of the line outside the limits of the original route, and sufficient coverage was not available to make a study of the new alignment. This caused a delay in the project and required reflying of the route at a much greater cost than if sufficient area coverage had been obtained originally. Sufficient breadth of coverage should therefore be obtained initially to cover all possible contingencies.

In considering natural factors, landforms and the soils developed on them are relatively stable, but surface features resulting from moisture conditions, vegetation cover and land use may change rapidly and affect the pattern elements discerned. For example, in a humid-temperate climate, spring is the best time of the year to obtain aerial coverage, as the water-table is usually at its highest level and the tonal contrasts between coarse-textured and fine-textured soils are greatest. Similarly, the presence of high water feeds the springs and seepage areas and emphasises the most critical zones for locating unstable slopes. Thermal infrared imagery would probably be flown at night to detect the seepage zones since at that time, maximum temperature contrasts would occur between the warmer surface waters and the cooler seepage waters, and the terrain would be cooler than both. If coverage were obtained for these studies later in the year, the features the interpreter wishes to evaluate might be masked by vegetation and would be difficult to recognise. Time of year is of critical importance when interpreting satellite imagery, for repeated coverage often exists over an area of interest and seasonal differences in sun angle and vegetation may have a considerable effect on the distribution of different patterns on the final imagery.

Limitations of remote-sensor data are largely dictated by characteristics of the recorded radiation and target materials and by system resolution factors that reflect the combined physical limitations of the sensor system[10]. In the case of multispectral camera systems, spatial resolution is a function of altitude, scene contrast, the lens system, film, ground speed, and platform stability. Spectral resolution depends upon scene brightness, lens and filter transmission characteristics, film sensitivity and processing. Brightness resolution is dependent upon the sensitivity of the optical and recording systems and upon the ratio of imaging/non-imaging electromagnetic radiation received by the sensor. These three resolution factors combine to limit the information available from the imagery and each must be considered separately with regard to its influence and the intended use of the imagery. For most photogeologic and engineering applications, absolute brightness and spectral resolution factors are not critical so long as the relative values are accurately represented. However, the spatial resolution of the system directly affects the information detail and the image utility. When more sophisticated interpretative techniques are invoked, the importance of brightness and spectral resolution parameters increases because of the increasing reliance on subtle changes in band-to-band response.

These same resolution parameters also govern the utility of multispectral scanner imagery[11] and even radar imagery. The significance of spectral and brightness resolution factors, and the need to carefully maintain quality control in data gathering and processing, will become apparent in later discussions of the various interpretative procedures. Appropriate quality-control measures may involve gathering of field calibration and reference data prior to and during data-gathering operations, and painstaking, step-by-step control of the image processing. Once more however, the quality-control procedures must be dictated by the intended application and economics.

4. INTERPRETATION OF LANDSAT SATELLITE IMAGERY

Since its launching in 1972, the ERTS – 1 satellite (now re-named LANDSAT–1) has acquired some 150,000 images of the earth's surface, so that at the present time good cloud-free imagery of over 90 per cent of land areas is readily available. This satellite has so successfully achieved its objectives that a second, LANDSAT–2, was launched in January 1975 and a third, with an extra range of sensors, has now been approved for 1977.

The satellites revolve around the earth at an altitude of 915 km in a near-polar, circular, sun-synchronous orbit so that with successive orbits each area is viewed every 18 days at the same sun angle and therefore the same local time of day. This cycle of complete global coverage allows the onboard sensor system to acquire repetitive imagery under constant observation conditions of any area from 81° north to 81° south, the satellite crossing the equator at about 9.30 am local time on the north-to-south leg of each orbit. Previous experience with aerial photography has shown that shadows cast on the ground at this time of day provide the greatest assistance in interpretation of surface features. Repetitive coverage of land surface areas by satellite imagery provides significant potential for monitoring time-dependent changes in surface features and may be useful for the transport planner and highway engineer in monitoring construction or the visible induced benefits brought about by a road construction programme.

The satellite payload consists of the Return Beam Vidicon (RBV) and the Multispectral Scanner (MSS) imaging systems and a data collection system (DCS) that relays telemetered information from about 100 stations located in remote regions of North America collecting data on rainfall, water quality, seismic activity etc. The most successful imagery has been acquired by the MSS system which is a line-scanning device that operates in four bands (labelled bands 4 to 7) of the electromagnetic spectrum: 0.5–0.6 microns (green-yellow), 0.6–0.7 microns (orange-red), 0.7–0.8 microns (red/near infrared) and 0.8–1.1 microns (near infrared). An oscillating mirror in the scanning system causes electromagnetic energy from a 185 km swath perpendicular to the satellite's path to be swept across the focus of a small telescope. At the focus is a four-by-six array of 24 optical fibres, six for each band monitored. The fibres carry the energy from each imaged spot through spectral filters to detectors that convert it to an electrical signal. Each detector observes a spot on the ground nominally 79 metres square. The oscillating mirror is timed so that when it returns for the next sweep, the satellite has advanced 474 metres and the next six lines are adjacent to the preceding six (Fig 5). Thus while the system is operating, it produces a continuous strip image of the ground below the satellite. The series of scan signals produced by the detectors is multiplexed and encoded to give a digital bit stream (a bit is a logical unit of information, ie 0 or 1) which is either recorded on one of the satellite's wide band tape recorders and subsequently telemetered to a ground receiving station or directly telemetered as it is produced (in real time) if the satellite is within range of a ground receiving station.

All of the recorded imagery is available from the EROS Data Centre in America, either in the form of computer compatible magnetic tapes (CCTs) or photographic products, all of which, at least for the present, are extremely cheap to purchase. The imagery is initially processed by NASA, using the computer tapes, to provide the 70 mm Bulk Images at a scale of 1:3,369,000 which are available as black-and-white film transparencies or prints of single bands and can also be purchased as 1:1,000,000, 1:500,000 or 1:250,000 enlargements. According to scale and product required the cost may range from $3.00 US to $15.00 US per image, whilst a computer compatible tape including all four bands may be obtained for about $200 US. Additional information may be obtained from the black-and-white images by assigning a different colour by the use of filters to each of the three or four spectral bands and superimposing them to produce highly detailed false colour images. Using black-and-white positive transparencies, band 4 is generally assigned blue, band 5 green and either band 6 or 7, red. False colour composite images may also be purchased (for any scene) direct from Sioux Falls at reasonable cost.

The interpretation of data obtained by the LANDSAT scanners may be carried out by visual inspection of the film transparencies or prints; by automated methods using the digital data directly; or by a combination of the two, utilising interactive computer facilities with visual display devices. Tape-recorded digital data is often preferred for analysis and interpretation since transferring the satellite data on to film results in a loss of accuracy in recording the radiometric information, which is also further degraded by duplication. When film is used, the final product available for interpretation may often be as much as 5 to 7 generations removed from the original. Other advantages of using the tapes for analysis include easier removal of errors and image distortions, considerable analytical flexibility including radiometric enhancement and geometric correction, reproducible results, and relatively reasonable costs. The CCTs, however, require specialised equipment in addition to a computing facility in order to extract the image data.

Although the resolution of the satellite scanner is limited to a pixel size (a pixel is the smallest element making up a picture) of 79 metres square on the ground, significant surface features are revealed without loss of definition when the images are enlarged to scales of 1:250,000 and above. Where tonal contrasts are high between surface phenomena, features as small as 10 metres wide have been identified; for example, highways whose linearity also assists in delineation. The imagery obtained from LANDSAT is orthophotographic because of the satellite's height above the earth and consequently of great value as a base map, especially as it is up-to-date and, in many areas of the developing world, map coverage is inadequate or totally non-existent[12].

A disadvantage of multispectral scanner imagery is that it does not provide the endlap necessary to produce a true stereoscopic model since the scanner does not image an entire scene from a single vantage point as does a camera but rather builds an image line by line, as the scanner platform progresses along the flight path (Fig 5). However, some sidelap stereoscopic analysis has been accomplished with LANDSAT imagery as the overlap of images increases with latitude so that at the higher latitudes 50 per cent or more sidelap occurs. Such stereoscopy is not optimal however, since it is unidirectional rather than omnidirectional as are conventional photographs, and also the stereopairs are acquired one day or more apart. The interpreter, however, may use the pseudo-stereoscopic effect produced by viewing two different bands of a scanner image as a stereo pair to produce the parallax necessary for stereoscopic viewing[13,14]. Although the impression of relief is seldom great, ability to view images stereoscopically, or at least to obtain binocular fusion, greatly reduces the signal-to-noise ratio. This is so partly because twice as many silver grains are used to form the composite image, and partly because of the benefits that result from 'binocular reinforcement' which occurs when one assigns one eye to the study of an image and the other to a study of its stereo-mate. The end-overlap of 10 per cent between images along the satellite path can only be used to advantage by binocular reinforcement although stereo parallax may be obtained by using MSS images of an area taken at different times, which is of particular benefit in that each image has its particular look-angle with respect to the sun's rays.

Film transparencies are generally superior to paper prints for purposes of interpretation because they offer high resolution and present a greater range of brightness values. They also allow greater flexibility in illumination and image combination, since viewing facilities are often equipped for variable intensity illumination so that the interpreter can make adjustments for optimum viewing over a broad range of image densities. The Carl Zeiss Jena Interpretoscope is such an instrument particularly well suited for stereoscopic study of satellite transparencies with its x 15 zoom magnification, differential magnification ability allowing images at different scales to be fused without effort, and rotating optical axes for easy orientation of the images (Fig 6).

Temporal studies may also be undertaken with this instrument. These enable images of different dates to be perfectly superimposed and changes examined by either switching the viewpoint from eye to eye or using stereoscopic (or binocular) examination techniques. Another important aspect of satellite temporal data is that under a stereoscope the parallax exhibited by a shadow on repetitive images taken of a site during different seasons of the year enables a useful indication of relief to be obtained. Thus, by fusing overlapping images of an area taken at different times of the year in order to obtain shadow parallax, there is a marked increase in the ease of interpretability of terrain features, even though often very little parallax is discernible in the features themselves[14,15]. Combination of true stereo parallax plus shadow parallax consequently offers many possibilities to interpreters for making meaningful analyses of orbital imagery.

4.1 Uses of LANDSAT image interpretation for regional inventories

The need to develop a regional master plan is common to many engineering programmes, especially for transportation systems, the accomplishment of which requires a comprehensive and continuous inventory and analysis of existing conditions. Additionally, regional transportation plans must be coordinated with other governmental and community planning organizations, and, in the third world countries, with the overall national development programme.

The use of satellite data offers unique advantages for preparing regional inventories of importance to engineering planning functions since the satellite imagery provides a broad view of an area (185 km square on one image) depicting conditions existing at a given time; indicates the interrelationships between climate, geology, and cultural and environmental factors that are of particular importance in evaluating the impact of a new engineering facility; provides a method for monitoring changes occurring in a region by comparison of sequential coverage; and provides a common base for comparison of analyses prepared by investigators of various disciplines in a coordinated planning effort[16,17,18]. LANDSAT imagery may be interpreted for regional inventories of constructional materials; preparation of regional engineering soils maps and terrain evaluations; route selection and highway corridor studies; regional slope stability evaluations; inventories of drainage networks and watershed areas; land use and natural resource inventories; and regional urban analyses.

Satellite imagery is of value to the engineer in that it presents the regional physiographic setting from which the various landforms can be delineated by their characteristic photo patterns. Geomorphological knowledge of the landforms enables the interpreter to predict the types of materials to be expected and to select the most favourable sites for field investigation. The capability to discriminate surface materials and landforms is improved as energy from the ground is recorded within four specific wavelength bands. The level of energy reflected or emitted from objects normally varies with wavelength throughout the electromagnetic spectrum and consequently a unique tonal signature (spectral characteristics) of an object or material may often be identified if that energy is broken down into selected wavelength bands. Synoptic views provided by satellite imagery also enable interpreters to determine regional geologic structure and regional trends not noticeable on larger scale imagery or mosaics. This results in a better understanding of the origin of the various landforms and the regional landscape, making it possible to predict with more confidence the types of materials that might be encountered and the possibilities of locating buried deposits.

A major construction project is controlled by the natural terrain conditions, optimum location requiring a minimum disturbance of the natural landscape as the cost of moving natural materials is usually the largest in engineering construction. To minimize construction costs, engineering soil maps are often prepared on a regional basis for planning and location purposes. Satellite imagery can play a vital role in acquiring such knowledge as the greater range of tonal signatures available from the four bands of imagery improves discrimination of surface features over a very large area providing a base for optimum route selection in relation to the physical and cultural environment and also for the selection of areas to be studied in more detail either by aerial and/or ground survey methods. The scanner images from the LANDSAT satellite are consequently proving to be invaluable as an initial reconnaissance tool. As with conventional airphoto interpretation, a detailed study of all of the pattern elements that comprise the landforms is critical in determining the soil and terrain characteristics. Analysis of topography gives some indication of massiveness or hardness of rocks or texture of unconsolidated materials, whilst characteristics of the drainage, erosion, vegetation and cultural patterns also provide clues to types of materials and to surface and subsurface ground conditions.

Satellite imagery is of immense value for the regional interpretation of drainage networks, an evaluation of the overall pattern, in addition to assessing the water resources of an area, providing information on general porosity, dip of the rock strata and types of material present. The presence of a very dense drainage pattern is generally indicative of an impervious, fine-grained material, whereas sparse drainage patterns are associated with porous, coarse-grained materials. A detailed study of drainage pattern, including such items as shape, texture, density and orientation, provides indication of extent and location of materials having significant differences; degree of uniformity of materials; location and extent of localised changes and factors of control; existence of, and depth to, bedrock or hardpan, and origin of underlying bedrock. Near infrared radiation is strongly absorbed by water so that land and water surfaces can be easily interpreted and discriminated on the infrared wavelength band 7 of the satellite imagery and regional drainage maps prepared.

Regional drainage maps have many applications in engineering and have been used for determining the size, shape and number of drainage basins in a region. Individual drainage basins, or portions of basins, can be evaluated for calculating drainage structure requirements for various engineering facilities – eg number of drainage structures required based on number of drainageways crossed, or size of a drainage structure for a given drainage crossing. Other applications include determining the location, definition and measured area of entire stream systems for use in design of flood control projects, location of water supply and evaluation of terrain and soil conditions for identifying regional structure and landforms for preparing engineering soil maps.

Some of the most obvious applications and uses of LANDSAT imagery have been briefly outlined. However, no single technique, or combination of techniques is applicable to all the various stages of highway engineering for, where large regional areas are to be evaluated, satellites, radar and other sensors providing broad coverage are applicable whereas aerial photography and other sensing systems operated from aircraft are more suitable for specific detail. As both regional and detailed information are needed in almost every stage of highway engineering, it is apparent that combinations of these two groups of coverage will be required to completely evaluate all the pertinent factors.

The main advantages of LANDSAT satellite imagery to the interpreter of highway engineering information lies in the synoptic view provided; the uniform illumination and tonal quality; the repetitive coverage; the digital computerized output; the ready availability, relatively low cost and up-to-date character of the data and finally the multispectral nature of the imagery. It is this latter characteristic which has a significant potential value with respect to the wide range of applicable interpretative procedures available for providing information relevant to highway engineering investigation.

5. INTERPRETATIVE TECHNIQUES FOR IMAGE ANALYSIS

Equipment and techniques have changed as fast as advances in remote sensing systems. For many years interpreters accomplished most of their work with pocket and mirror stereoscopes and occasionally use was made of a photogrammetric plotter to identify and map a particular formation, slope or boundary. Today, major reliance is still placed on this equipment but a wide variety of powerful tools that permit rapid extraction of more information are available. Among these tools are techniques of image enhancement and density slicing, and computer techniques for handling, classifying and analysing masses of data, as for example through pattern recognition.

5.1 Density analysis

Density analysis refers to techniques by which film densities (representing logarithms of scene brightness values) are accurately measured or subdivided in order to detect and delineate subtle variations in the image tone.

The analysis can be accomplished through photographic processing, photometric measurement and video or digital processing, a typical procedure resulting in a density contour map or density slice.

5.1.1 Photographic density slicing A set of density slices can be produced photographically by making a sequence of negatives, positives or prints with various exposures on high-contrast paper[19]. The resulting high-contrast photographic products each represent a distinct band of equal density (with lighter areas washed out and darker areas underexposed) and each image will consequently be a contrast-stretched version of the original. The various tonal values represented within the reproduced density slice will be stretched across the entire density range of the photographic paper and the relative contrast between subtly different features should be more apparent.

A set of density slices are illustrated in Plate 2 for the infrared band 7 image of a LANDSAT satellite scene of central Sudan, which was utilised in a TRRL materials investigation of a proposed road alignment connecting the towns of Wad Medani and Sennar on the Blue Nile with Kosti, to the west, on the White Nile. The infrared band 7 image (a) has been sliced to reveal more clearly in (b) the distribution of available road building materials comprising areas of red clayey quartzitic gravel, river sands and calcareous concretionary material and Jebel outcrops of bedrock protruding from the plainlands. In slice (d) the occurrence of surface water in rivers, abandoned drainage courses and irrigation canals is enhanced, whilst slice (c) emphasises the distribution patterns of vegetation and various land use practices.

Satellite imagery proved valuable in this region for initially identifying areas where construction materials were likely to be available for the proposed road alignment. Sands and gravels of varying properties, often reflecting differences in mode of origin, were interpreted to be associated with the White and Blue Nile river systems, deposits occurring either on old terraces and meander scars or as banks in the present river channels. In addition to the outstanding Jebel outcrops of bedrock, the most clearly discerned and important materials to be identified were the distinct red soil areas of clayey quartzitic gravel clearly distinguished in the field by their characteristic vegetation dominated by the *Combretum* tree. These areas of red soil, within which are found the clayey gravels that are likely to be the main source of pavement material for the Sennar-Kosti section, contrast markedly both on the satellite imagery and ground surface with the main black clay soil types which cover most of the region traversed by the road alignment.

The satellite imagery also clearly shows the different areas occupied by the two road sectors. Low-lying alluvial soils irrigated by water from canals flowing from the Sennar Dam are characteristic of the Wad Medani-Sennar section along the Blue Nile, whilst, to the west of Sennar, an area of uniform grey clay is only broken by the Jebels and their surrounding soil aureoles that protrude from the plain. At the western end of the road alignment that is proposed to follow the line of the visible railway track, the predominance of sand is clearly distinguished, especially to the west of the White Nile which appears to act as an effective barrier for deposits blown from the west.

The objectives of enhancement modifications such as density slicing are to improve the interpretability of the image, usually for a specific purpose, even though the process may completely destroy its aesthetic, visual qualities. On the Sudan image, slices of the density or tonal range have been selected to emphasise selected features such as materials, drainage and vegetation. Interpretation of these features is improved as the various tonal values within each slice have been extended across the entire density range of the photographic paper and the relative contrasts between subtly different features are more apparent than on the original.

5.1.2 Electronic and microdensitometer techniques for density slicing Various instrumentation systems are available that allow image densities to be measured and then coded or grouped according to some predetermined programme, the coded data then being redisplayed in the form of a density contour map. Subtle film-density variations are displayed on the density contour map in strongly contrasting shades or colours so that the interpreter can detect and map features that are ordinarily obscure[20].

Video analysis systems (eg Spatial Data Systems Model C703–32 Datacolour density analysis system) utilise a television camera to scan the image, the resulting analogue signals being subdivided into intensity groups which are individually coded (assigned a specific tone or colour) and redisplayed on a video monitor as a density contour map[21,22]. Video displays may lack the spatial and brightness resolution of sophisticated computer systems or scanning microdensitometers but provide by comparison a 'real time' analysis capability for a relatively modest cost. They also provide the interpreter with greater flexibility than the simple optical-photographic processes, which consume much time and do not guarantee reproducible results. Density slicing using a video system has been used previously with a fair degree of success to map soil conditions and, specifically, dense claypan subsoils[23].

Density analysis by computer is readily applied to data in digital form, such as LANDSAT satellite CCTs and multispectral scanner tapes, and provides the least loss in brightness resolution for such data. Photographic and other forms of image data must be scanned and digitized before being input to a computer, but once the system has been set up it is very flexible, easily calibrated, extremely rapid and results are easily reproducible. A digital system enables any level or levels of tone to be selected and displayed on a black-and-white or colour monitor or alternatively output on a line printer, a flat-bed or drum plotter, or directly on to a photographic film writer.

An example of a microdensitometer trace across the Blue Nile River region on the LANDSAT infrared satellite image (Plate 2) of the Sudan, shown in Fig 7, illustrates how this method of image analysis quantifies the tonal values occurring along a designated line. In addition to quantifying tonal values, the scan depicts a far larger range of tones than would be separable by eye, and consequently a better understanding can be obtained of how and why tones change in relation to ground conditions, especially if traces are made along actual transects measured and studied in the field. Relative ordering of the microdensitometer readings for natural targets such as soils, vegetation and rock types furnishes a type of spectral signature which can be used as a discriminating functional property to enable extrapolation over larger areas. The trace across the Blue Nile River region in Fig 7 clearly reveals the characteristic tone or spectral signature of the areas of red clayey quartzitic gravel, black alluvial clay soils, the river channel zone of the Blue Nile and the areas of intense, canal-irrigated cultivation.

Scanning microdensitometers, often equipped with colour filters for use with colour images, are able to measure systematically density values over an entire scene. The Joyce-Loebl Image Quantizer allows both prints and transparencies to be converted into an isodensity plot with up to 20 different isodensity contours. Density slicing is accomplished by changing the threshold level of the instrument, the range of isodensity contours being varied so that only features of the required density are recorded, thereby simplifying the image for subsequent interpretation.

The Joyce-Loebl four-colour Isodensitracer can plot up to 64 different density contours as the instrument automatically scans and measures the density of all points in a film transparency and plots the values as a quantitative, four colour, two-dimensional density map of the scanned area. This density output is in the form of a dropline chart, for, as density increases, the first coloured pen scribes a sequence of space, then dots, then dash and, with continuing increase, the second colour pen is activated and produces space, then dots, then dash and so on. The large magnification ratios available (from 1:1 to 1,000 : 1) makes this instrument ideal for studying in detail the tonal variations on orbital images, as the visual – but quantitative – recording output lends itself to easy field checking to determine the significance of the tonal variations.

Microdensitometer density studies, often involving computer processing of the measured data, have been applied to classification and analysis of terrain and should prove to be a useful analytical technique for the interpreter involved with an engineering investigation of natural ground conditions. Examples of densitometry for feature extraction include using colour infrared film for maximum likelihood function identification of terrain types[24,25] and multispectral satellite photography for crop, soil and geological mapping[26].

5.2 Contrast stretching

This technique is a widely employed image preprocessing function, which is used to make subtle greyscale tonal differences, not readily detectable with the naked eye, more obvious for interpretation. Any low contrast image or, as outlined for density slicing, any portion of the greyscale of an image may be enhanced by this procedure. Low contrast images may arise for various reasons; for example, certain scenes may be of inherently low contrast in a given wavelength, or a contrasting scene may be viewed through a hazy atmosphere. Contrast may be improved by producing new negatives and positives through repeated processing with high-gamma film or by using a log-etronic processor.

The greatest control in stretching is maintained in digital processing which is undertaken most effectively on LANDSAT satellite CCTs and multispectral scanner tapes. On the LANDSAT satellite the MSS system is designed to cover a large dynamic range in scene brightness to respond to the effects of sun angle and albedo variation as the spacecraft covers the globe. Consequently the brightness range of any one image will generally occupy only part of the dynamic range, resulting in a low-contrast image. In reconstructing an image from the digital data, it is therefore desirable to stretch the DN range to increase the contrast. The digital numbers (DN) on the computer compatible tapes (CCTs) represent data values that are linear with brightness and range from 0 – 127. For convenience in using existing computer programmes, the MSS data have been expanded into eight bits, resulting in a DN range of 0 – 255.

Stretching begins by forming a histogram plot of the number of pixels per DN value (Fig 8) so that brightness values above and below which no appreciable data exist can then be located and used as stretch limits. The stretch may be either linear or nonlinear, a linear stretch increasing the scene contrast uniformly over the dynamic range of the output product. Limits to the stretch, determined from the histogram, are placed at the extreme points of the dynamic range (that is, 0 to 255 DN values) and the other points are spaced linearly between these end points (Fig 8). In a nonlinear stretch, the cube root of each DN value is taken and the resulting DN range linearly stretched as above. This procedure increases local scene contrast in the dark areas at the expense of contrast in the brightest areas. In an exponential stretch, the inverse occurs.

On most images the peak of the histogram occurs towards the lowest brightness values with a long tail of relatively low values on the brightest pixel side which has the effect of greatly reducing the detail in all but the brightest pixels (Fig 8). Stretching consequently produces more detail for interpretation and is especially useful before colour combination of multispectral imagery in order to enhance the colour contrast. Although there does not seem to be a general rule of thumb that can be applied to all images in determining the required stretch parameters, it is essential that useful raw data at the extremes of the brightness range are not saturated and lost.

5.3 Image masking and combination

Masking is a procedure in which one image is superimposed on another to enhance certain image features. Probably the most commonly employed form of image masking is colour-additive image composition, a technique by which false-colour images are constructed from various bands of multispectral imagery (Plate 3). Colour composite images can be produced electronically from digital or analogue tapes through a flying spot recording device or cathode ray tube. If the data are available in image form, other devices can be used to produce false colour composites[27]. For example, the four bands of black-and-white LANDSAT imagery can be transformed into a false-colour image using diazo equipment[28], a colour additive viewer[29,30], a multiple exposure printing system[31] or video equipment.

A multiple exposure of colour film process for multispectral colour enhancement involves various combinations of positives and negatives being produced from a number of multiband images. A colour is then assigned to each combination by exposing it on to colour photographic material through an appropriate filter[32]. The various steps in the process are indicated in Fig 9.

Colour additive viewers are projector systems which allow several images to be simultaneously projected on a viewing screen, the black-and-white images being able to be filtered, brightened and scaled independently so that the hue and brightness of the resulting false colour composite image can be adjusted to suit a particular need. In highway engineering studies this may involve enhancing the distribution of a particular soil type or construction material, areas of poor drainage, landslides and unstable ground or any other aspect of the terrain which is visible on the combined multispectral images and which is likely to affect a proposed road construction. On more sophisticated additive viewers the saturation of the individual filters can also be independently controlled.

Additive viewing equipment may be assembled by simply combining a set of standard slide projectors and filter wheels[33] or alternatively a number of specially designed enhancement viewers are commercially available from such firms as Fairey Surveys Ltd, International Imaging Systems, USA, etc. A specially designed additive viewer has been constructed at TRRL in order to analyse and enhance imagery obtained from the LANDSAT satellite and a multispectral camera system (Plate 1) designed for operation in a light aircraft used for highway engineering surveys in developing countries. Three multispectral images are able to be superimposed in register on a photographic base-board by using a separate independently scaled colour enlarger projection system equipped with a dichroic filter head for each image (Plate 4). The colour tone of each channel is controlled by exchangeable filters and the two outermost enlargers are fitted with X-Y and rotation registration controls for exact image superimposition. A set of complementary filters in each enlarger head enables both subtractive and additive colour principles to be used[30] with either film negatives or positives to achieve a full range of colour tones and control over colour saturation. Brightness is controlled by an aperture setting for each enlarger projection lens. The final colour composite or enhanced image may be exposed directly on to colour film on the base-board or alternatively photographed by the specially positioned camera to produce hard copy records. An example of a satellite colour composite and further enhanced image obtained by this technique on the TRRL system is shown in Plate 3.

The colour composite (Plate 3) forms a portion of the LANDSAT satellite scene immediately north of the image density sliced in Plate 2 and shows the region around the confluence of the Blue Nile and Rahad rivers. This false colour composite image was formed by projecting the 70 mm black-and-white film positive of green band 4 through a blue filter with the red band 5 image through a green filter and the infrared band 7 image through a red filter. The resulting image closely resembles Infrared Ektachrome false colour photography in which the outstanding feature is that living vegetation, which strongly reflects near infrared radiation is visible in shades of red.

The satellite imagery of this area, especially the colour composites, has been used to interpret where suitable road construction materials may be found for road development associated with a project to extend the irrigated area east of the Blue Nile and Rahad rivers. Interpretation of the satellite imagery was based on experience and extrapolation from the materials investigation undertaken in the region immediately to the south of this area. The characteristic spectral signature of the red clayey gravels which form some of the best road-making material in the area can be identified in several localities to the east of the Blue Nile and Rahad rivers. High reflectance from the sand, quartzitic material and red soils, in addition to the very sparse vegetation cover, is probably responsible for the characteristic yellow/white signature of these areas which contrast with the darker tones of the black clay soils and striking red-toned pattern of the irrigated areas.

The colour composite is easier to interpret as the human eye is capable of discriminating more hue (colour) values than values of grey. In addition to the potential sites of red clayey gravels, the colour composite indicates more clearly the extensive deposits of sand in the major river channels within which layers of calcrete gravel may be found and the Jebel outcrops of bedrock protruding from the black clay plains. Although interpretation has yet to be confirmed in the field for this area, it is highly likely, based on previous field experience and interpretation of the satellite imagery, that an engineering materials inventory can be put forward with some confidence.

The soil for the road development is a heavy clay, which beneath a sealed road would have a minimum CBR of 4 per cent, and under most conditions would have a typical CBR of 7–8 per cent. Materials for construction consist of old terrace deposits consisting of clayey gravels, which are ideal for gravel roads or sub-base but need stabilisation for base beneath a bitumen surface; calcrete gravels from the Nile and Rahad which would provide sub-base and could be stabilised for base beneath a bitumen surface; sands from the Nile and Rahad would provide sub-base material; and weathered rock from the Jebels would provide sub-base and base material for gravel roads but is unlikely to be suitable for a surfaced road base construction. In some cases the rock outcrops could be quarried to provide stone.*

The enhanced colour composite in Plate 3 has been produced by varying the colour filter combinations, saturation and brightness in each channel to produce the desired effect of discriminating clearly the distribution of red soil areas where suitable clayey gravels may be found. Using this enhancement technique, spectral differences between individual images taken in different parts of the electromagnetic spectrum are distinguished in the form of colour and characteristic spectral signatures associated with ground surface features, which may not otherwise be apparent, can be emphasised and identified more clearly. In interpreting imagery covering

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*Since writing this report subsequent field investigations have confirmed the interpretation of the satellite imagery.

a proposed road construction project, natural features of the terrain of interest to the highway engineer, such as poorly drained areas, potentially unstable ground, soil conditions, etc, may be enhanced using these techniques so that they may be studied in more detail and possibly related to other controlling environmental parameters.

Repetitive-exposure printing on colour film or sandwiching of diazo colour film provides an economical alternative to the colour-additive viewing but is dependent upon the scale-stability of the recording system and may be more difficult to control with regard to the colour balance and tone of the final product. Diazo sandwiching may be the least flexible colour-additive technique, in that it allows no means of scale-change and very little control of colour tones, but it is certainly one of the most economical ways to construct a hard-copy, colour composite image. Recently, the capability of experimental video equipment has been increased by the addition of auxiliary equipment to allow density analysis, edge enhancement, image-calibration, and image combination[34]. Colour addition is just one function of such analysis systems.

Colour-additive systems can be employed both in positive/positive image masking and in other forms such as positive/negative masking which is accomplished by placing a negative of an image over the positive of another image of the same area for a different season or by placing a negative of one spectral band over a positive transparency of another band. In either case, the image mask should serve to enhance differences between the images. When a positive and negative of the same image area are used, the features enhanced should represent changes in contrast and overall brightness related to temporal changes in the scene while the band-to-band image mask enhances features that differ in their spectral reflectance characteristic. If the positive and negative of a single image mask are processed so that the brightness and contrast values are complementary, the resulting composite should appear totally grey. Any variation from the reversed contrast should stand out sharply from this grey background.

Innumerable image-mask combinations are possible, since, with proper flexibility built into the equipment used in constructing the image masks, masking techniques allow enhancement of the most subtle contrast in hue and tone. Computer processing can produce image ratios, image products or other complex combination functions in addition to direct additive or subtractive masks.

The most recent advances in results obtained from digital computer processing of remotely sensed data, especially those contained on the LANDSAT satellite CCTs, have been obtained using the technique of image ratioing. In this process, two spectral band images that have been corrected for atmospheric effects are divided pixel by pixel, the resultant image showing the variations in the slopes of the spectral-reflectivity curves between the two wavelength bands. Differences in albedo and topography are suppressed so that, using this method, one type of material will appear the same or similar in a ratio image regardless of the local topographic slope angle. One of the most successful studies has combined the use of digital computer processing and colour compositing of LANDSAT images to detect and map hydrothermally altered areas and to discriminate most major rock types in a semi-arid environment[35].

The technique used is based on enhancement of subtle visible and near infrared reflectivity differences associated with variations in bulk composition of the rocks. The LANDSAT spectral bands are ratioed, picture element by picture element, by computer and are subsequently contrast stretched to enhance the spectral differences. These stretched-ratio values are used to produce a new black-and-white image which shows the subtle spectral-reflectivity differences and concurrently minimizes radiance variations due to albedo and topography. Additional enhancement is achieved by preparing colour composites of two or more stretched-ratio images. Colour variations seen in these colour-ratio composites, representing spectral reflectance differences, enable hydrothermally altered areas and most major rock types to be discriminated[35]. The significance of this technique is emphasised by the fact that the altered areas are not apparent on the individual satellite image bands, colour-infrared composites or even colour photographs of the area obtained from NASA's Skylab mission.

The repetitive coverage of the LANDSAT satellite, in another study, has provided sequential image scenes of the playa lakes in Iran, from which, using digital computer processing techniques, hydrologic and morphologic changes have been monitored with respect to an evaluation of their economic and engineering significance[36]. In north-central Iran, the Great Kavir is a vast desert with extensive salt crusts and swamps. During the period of maximum inundation and lowest bearing strengths, as inferred from the LANDSAT satellite imagery in 1973, a preliminary road alignment was selected across this area. The selected route was able to avoid the wettest or roughest areas, take advantage of the best terrain, and reduce the road distance between northern and central Iran by as much as 700 km. In addition to the great savings in cost, this route would also reduce the travel time by as much as ten hours[36]. Data derived from the analyses of LANDSAT satellite images can thus provide a rational basis for planning the economic utilization (salts or water extraction and agriculture) and engineering development (roads and airfields) of these playa areas.

Computer processing of remotely sensed data, as referred to in the two previously outlined studies, provides the capability for the interpreter to have even more flexibility in his image enhancement procedures[37–40]. The interpreter may selectively remove unwanted image contrasts and increase residual contrasts which may be more 'meaningful' in a particular application. Feature detection is limited only by the image resolution and proper selection of spectral bands.

5.4 Edge enhancement

Edge enhancement procedures aid the interpreter in defining trends and area boundaries. Techniques for producing edge enhancement are many. Density slicing may be used if the individual image density values included in a coded group are restricted to very narrow limits, the coded density values then producing a line, or series of density contours, corresponding to any significant contrast change or 'edge'. A single-image mask (two positives of the same image) can also be used simply by shifting one positive slightly with respect to the other. Varying the direction of shift results in enhancement of different edges, the enhanced edges being those that are largely perpendicular to the direction of shift. Mis-registration allows excess amounts of light to pass through the image mask along the edges of highly contrasting objects. By shifting the superimposed image in all directions relative to the other image, edges of all orientations can be observed.

Digital or analogue image analysis systems may produce edge enhancement by sampling consecutive data points and displaying the resulting density curves or by determining whether or not the rate-of-change of brightness values exceeds a threshold value. Those values where the brightness change is sufficient to exceed the threshold may then be re-displayed in the form of an edge-enhanced image. These edge enhancement procedures help the interpreter to define area boundaries regardless of the shape or orientation of the contrast changes defined as edges. Other edge enhancement procedures can help an interpreter define only trends or linear anomalies on an image.

One such technique consists of superimposing pattern grids on an image in various orientations. The interference patterns formed between the image and the patterned grid may cause linear and/or curvilinear features to stand out strongly as they become coincident with the grid patterns. A somewhat more sophisticated form of edge enhancement can be accomplished through frequency filtering using an optical bench. In this process, the image is illuminated with coherent light (laser), and the resulting transmitted beam, which has been altered by its passage through the image, is made to interfere with a reference beam. The resulting interference pattern represents a frequency transform of the original image. Selective filtering of the transform image, by blocking or masking selected elements, can remove unwanted elements of the photograph[41]. An edge enhanced or other special purpose image, especially useful to the highway engineer for interpreting regional or local structural geology, can then be reconstructed by a reverse optical process.

5.5 Clustering, pattern recognition and frequency analysis

The digital computer provides the interpreter with a capability for automatic discrimination and mapping of features that are recorded on multispectral imagery. The relatively new need for rapid processing of remotely sensed data has been created by the explosive growth in volume of earth resources imagery now available from LANDSAT satellites, other space programmes such as Skylab and from numerous aerial surveys. The magnitude of this need can be appreciated when it is realised that the LANDSAT satellite circles the earth every 103 minutes or roughly 14 times per day and that each multispectral scanner image, containing 8×10^6 picture elements (pixels) in each of 4 wavebands, can be recorded in only 25 seconds.

It is therefore evident that rapid processing and analysis necessitates an automatic system if data are not merely to accumulate. Particularly for environmental, hydrological and land use problems, immediate analysis and assessment are often essential. Automatic image analysis involves the use of selection criteria programmed into the computer and can vary from single image density analysis to extremely complex functions[1,42]. Useful functions commonly take the general form of three basic styles of classification: clustering, pattern recognition, or frequency analysis.

The conventional description of image classification techniques can be broadly divided into two types: supervised learning, which involves the initial generation of a spectral signature for each class to be recognised, and unsupervised learning, which usually involves some form of cluster analysis. In the supervised method the computer is trained by supplying it with spectral information for certain predetermined areas (the training samples) from which the spectral signatures are determined. The highway engineer, in this context, may choose characteristic areas of poorly drained ground, areas of suitable construction material or any other terrain parameter that is visible on the imagery. Disadvantages of this method of image classification are that the reference signature may only apply at any one instant in space and time; the success rate of the final classification depends on the quality of the training sets and so may be low if these are not representative of the required classes; and the ground truth information relating to the training areas must be acquired beforehand.

Clustering is a procedure in which band-to-band comparisons are made for individual image points or sets of points. Each point is assigned a position in an array on the basis of the relative response recorded on the various bands of multispectral imagery or individual layers in colour film emulsions. All points with identical or similar response on each spectral band or film layer will fall into a single group or 'cluster'. When all image elements have been assigned, the clusters can be coded and printed in the form of a computer map[25,43]. The map may represent a finished classification or may be used as an aid in image interpretation. Different cluster maps can be produced by changing the boundary selection criteria for the clusters or by using different sets of image bands. The principal disadvantage of using clustering methods lies in the fact that they may require a considerable computer store and processing time.

An automatic computer analysis which uses a clustering procedure to classify an aerial false colour infrared image covering an area to the north of Maiduguri in North East Nigeria is illustrated in Plate 5 (analysis by Owen Jones of Bedford College). The computer classification map has been derived from an analysis of microdensitometer data taken from the individual layers in the false colour infrared image which is shown accompanying the classification in black-and-white on Plate 5. This simple example indicates how such techniques can be used in highway engineering to predict ground conditions for road location. The classification has identified well-drained sandy areas, silty clays waterlogged for part of the year and expansive black clays, making it relatively easy for the interpreter to select the most suitable road alignment. Although this simple classification could just as readily be interpreted by eye from the original image, the computer system offers the advantage of speed with quite often a more accurate delineation of boundaries and usually almost an instantaneous measurement of the actual ground area covered within each class.

Some procedures use both the relative band-to-band response of data points and rates-of-change of brightness values as selection criteria[44]. Consequently, maps produced through these analyses can represent both spectral and spatial relationships of the original data. The general procedure is much the same as in cluster analysis except that the groupings take into consideration the value of each point relative to its neighbouring points, as well as similarity of response in each spectral band.

Frequency analysis is a further modification of procedures which employ the spatial relationships of the data in classification[45]. The relationship of each point is considered with respect to many of its neighbours, both rates-of-change of brightness values and repetitive aspects of these brightness changes being considered. Fourier analysis of image values is a frequency analysis procedure comparable to the optical bench procedures described previously under 'edge enhancement'. Both techniques can be used to enhance particular features by increasing certain frequency components relative to others.

Computer classification schemes can be used for automated discrimination and mapping or as aids to the interpreter in making objective decisions. In general, features that are displayed in regular and predictable relationships to one another, such as the regular pattern of well-drained sands and expansive, poorly drained black clays in North East Nigeria, are best suited to automatic classification. The engineering geologist, however, must often make decisions on the basis of characteristics of a particular data point, its relationship to other points, and its context, while ignoring certain image elements which are considered to be noise. These combined decision criteria are generally too complex and variable to be programmed at present, and consequently the engineering geologist's use of computer classification procedures has seldom gone beyond applications where the computer serves as an aid in making objective decisions or as a means of preliminary analysis to define general areas of interest. The technology for using digital computer techniques in image and remote sensing data analysis, however, is at the threshold of development and expanding so rapidly that continuous reassessment of the potential application and cost-effective benefits of new digital techniques for the engineering geologist will be necessary.

6. CONCLUSIONS

Until recently, black-and-white aerial photography was the only form of remotely sensed data generally available to the highway engineer. Now new forms of image data are becoming increasingly available from the multispectral scanners on board the LANDSAT satellites, airborne radar and scanner systems and infrared, colour and multispectral photography. Although much can be gained from applying traditional photo-interpretive techniques, in order to realise the full potential of these new tools, the highway engineer and geologist must understand and employ some rather specialised interpretative techniques. The application of new interpretative techniques, such as those outlined in this report, is becoming increasingly important for the interpreter involved with highway engineering projects because of the advent of multisensor missions collecting a great volume and variety of data[46–52].

The inundation problem facing the interpreter, owing to the large volumes of data collected by new remote sensing systems, has been highlighted by recent studies in Kansas, where 140 different sets of data were collected over 5 investigated test sites[46], and in Nepal where over 3,000 multispectral images were obtained over a proposed road alignment of 55 km[52]. Analysis of this volume of data by traditional visual methods is long and tedious. Consequently, various methods of data extraction and image analysis techniques have been developed and, although many systems are not used operationally at present for engineering programmes, it is significant that they do provide some unique capabilities that may greatly assist future highway engineering projects.

Fortunately many of the most useful techniques can be accomplished in several ways, but some methods are quite expensive and require special equipment whilst others can be undertaken for a very modest investment and employ equipment that is widely available. The cost of a procedure may generally reflect the speed or flexibility of the analysis rather than its quality or utility. It is important, however, that the interpretative procedures employed and the equipment used should be governed by need and economics. The highway engineer and user of remote sensing data must know the analysis alternatives that are available to him in order to select those that will give him the greatest return for his investment.

The technology for acquiring remotely sensed data and the interpretation techniques required for converting these data into usable information are being continuously developed. Research is continuing so that the potential application and cost-effective benefits of new techniques for the highway engineer can be fully evaluated. The potential benefits of using new types of imagery and associated analytical interpretative techniques have been demonstrated, but it will only be after more successful applications of these new tools in active highway engineering situations or road construction programmes that their use will become fully operational.

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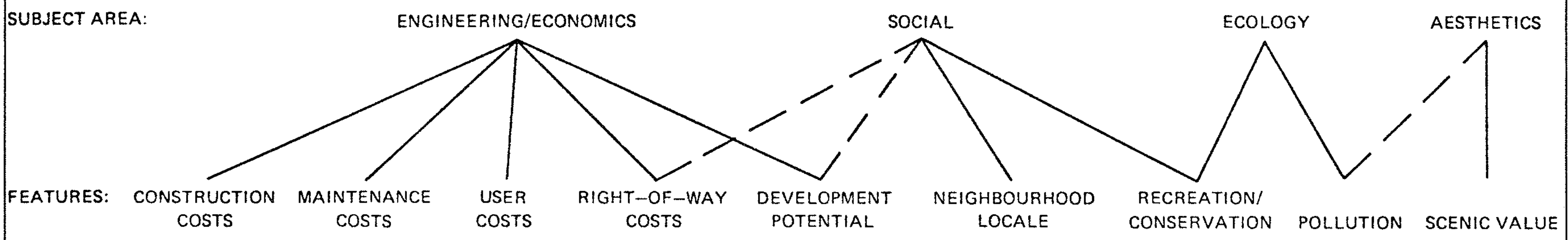


FEATURES:	CONSTRUCTION COSTS	MAINTENANCE COSTS	USER COSTS	RIGHT–OF–WAY COSTS	DEVELOPMENT POTENTIAL	NEIGHBOURHOOD LOCALE	RECREATION/ CONSERVATION	POLLUTION	SCENIC VALUE
FACTORS:	Topography	Climate	Traffic	Land Values	Agriculture	Population	Land Use	Noise	Scenic Areas
	Geology	Traffic	Topography	Land Use	Forestry	Culture	Vegetation	Air	View from Road
	Geomorphology	Soils	Travel Time	Replacement Costs	Mineral Extraction	Land Use	Fish Life	Water	View of Road
	Soils	Materials	Safety	Traffic	Trade/Industry	Tax Rate	Scenic Areas	Spillage	'Eye Sores'
	Materials	Topography		Design Criteria	Tourism	Land Value	Wildlife	Thermal	Topography
	Vegetation	Drainage		Utilities	Personal Mobility	Institutions	Drainage	Chemical	Vegetation
	Drainage	Geomorphology		Tax Base	Political Strategy	Transportation	Topography	Waste	Drainage
	Design Criteria					Historical Sites	Erodibility		
	Safety					Utilities/Services	Sedimentation		
						Community Boundaries	Land Marks		
						Traffic			
						Employment			
						Dynamic Change			
						Tax Base			

Fig. 1 COMPENDIUM OF FACTORS CONSIDERED IN HIGHWAY ROUTE LOCATION
(Based on RIB 1975)[49]

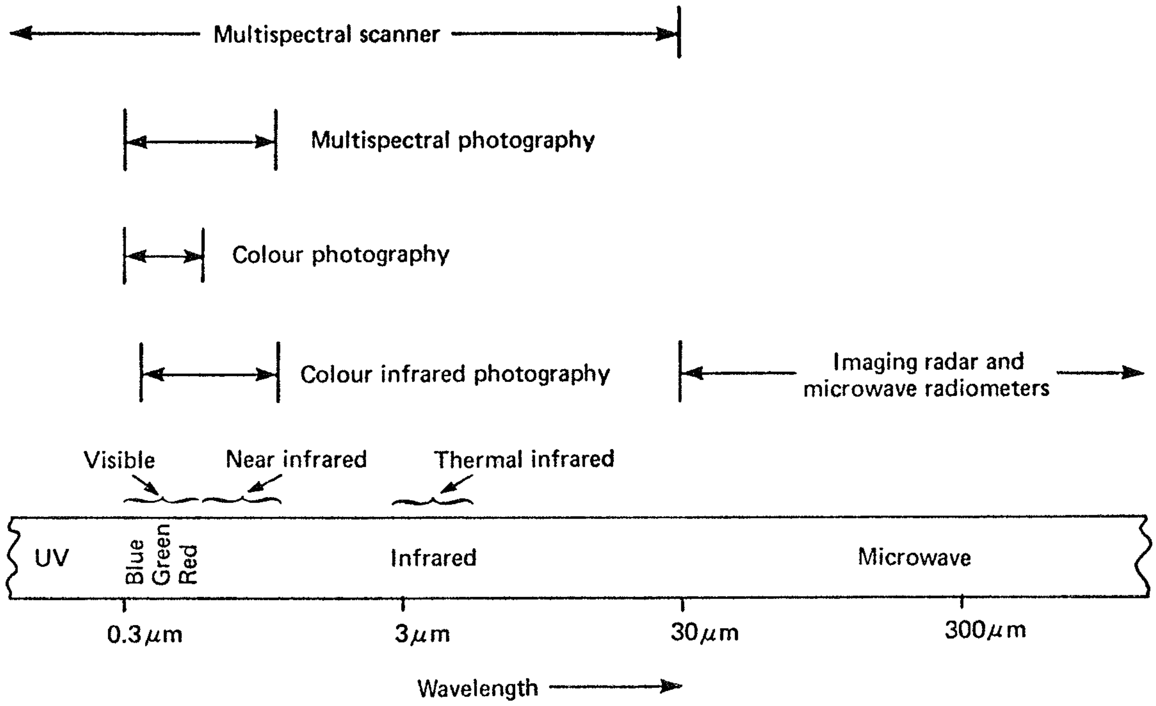


Fig. 2 SPECTRAL SENSITIVITY RANGES OF IMAGING SENSORS

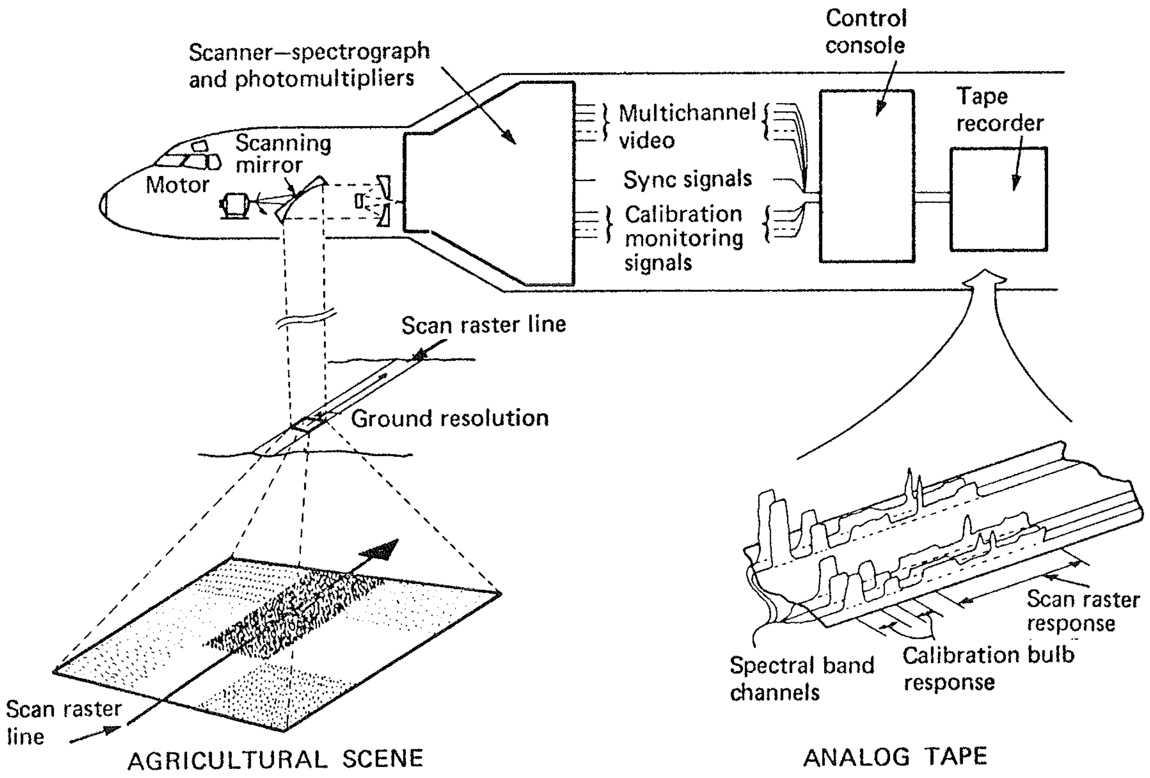


Fig. 3 DIAGRAM OF A MULTISPECTRAL SCANNER SYSTEM
(After Estes and Senger 1974)[1]

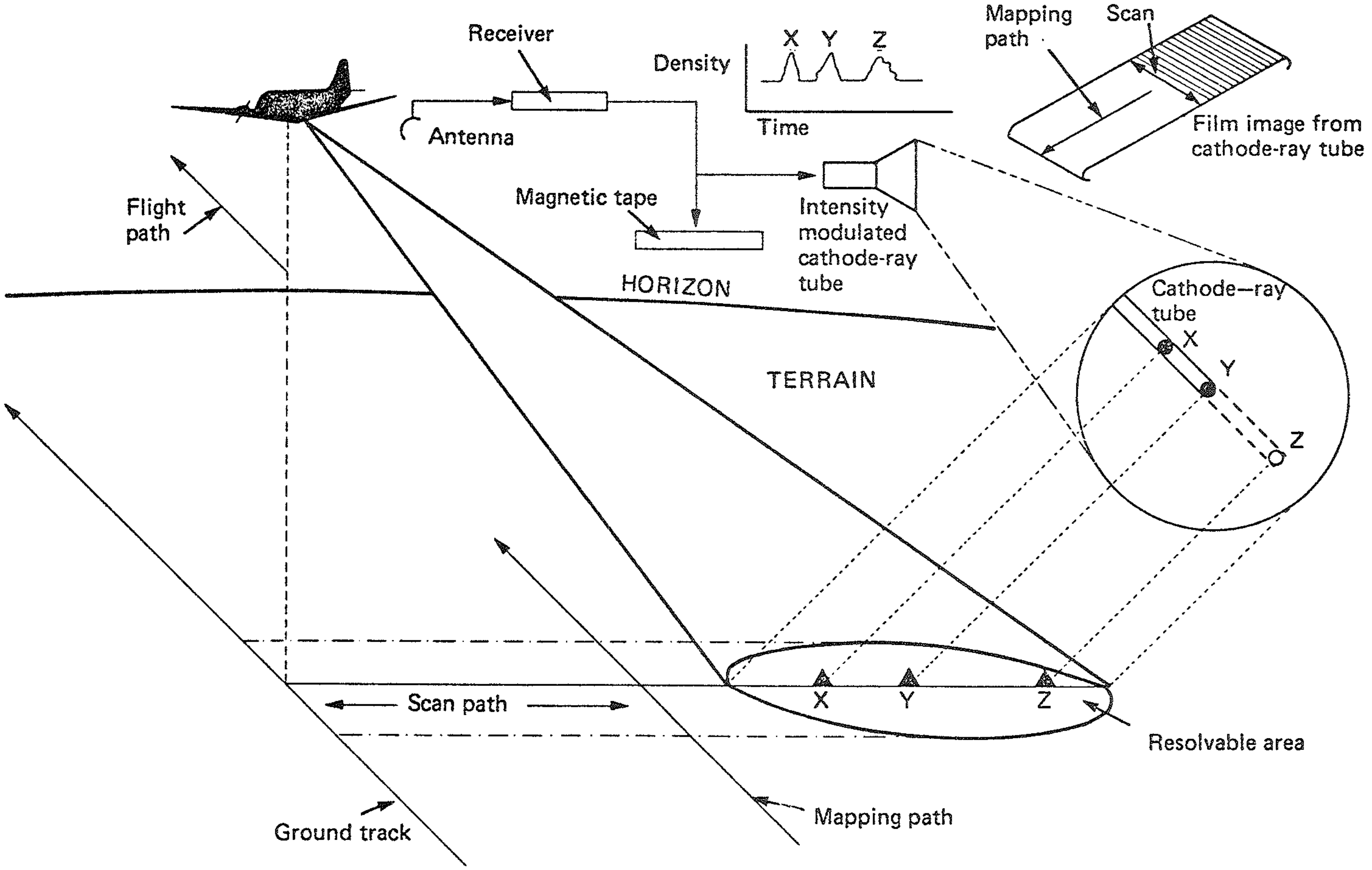
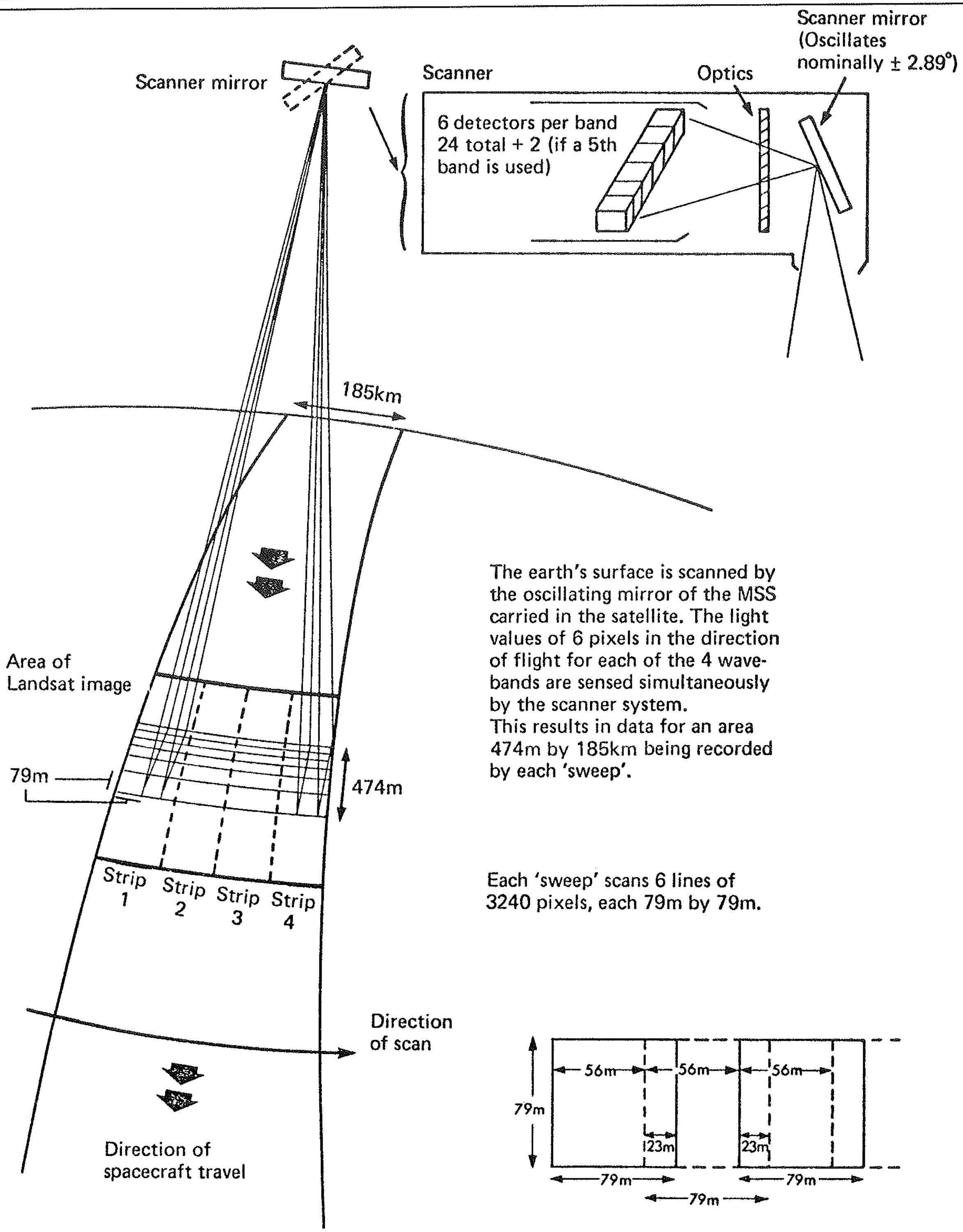


Fig. 4 DIAGRAM OF A SIDE–LOOKING AIRBORNE RADAR (SLAR) SYSTEM
(After Estes and Senger 1974)[1]

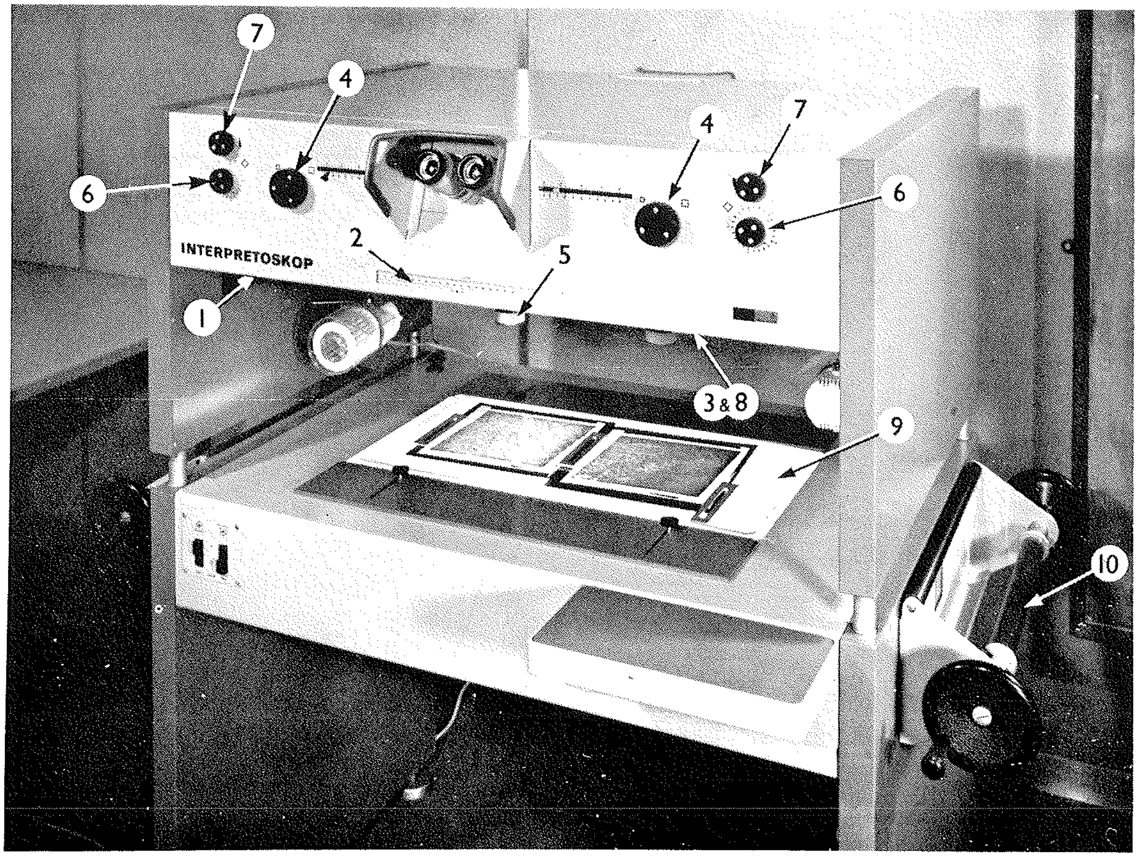


The earth's surface is scanned by the oscillating mirror of the MSS carried in the satellite. The light values of 6 pixels in the direction of flight for each of the 4 wavebands are sensed simultaneously by the scanner system.
This results in data for an area 474m by 185km being recorded by each 'sweep'.

Each 'sweep' scans 6 lines of 3240 pixels, each 79m by 79m.

PIXEL DISTRIBUTION ALONG SCAN LINES
The multispectral scanner continuously records the light values from a field of view 79m by 79m along each scan line. The signals are sampled at 56m intervals so that there is an overlap of 23m in the ground area viewed.

Fig. 5 IMAGING OF THE EARTH'S SURFACE BY LANDSAT SATELLITE



Neg. no. B2022/76

1. Incident (reflected) light equipment.
2. Scale for reading horizontal parallax differences.
3. Handles for shifting the objective lenses in x and y directions.
4. Panchratic system for stepless magnification variations; elimination of scale differences between left and right images.
5. Change-over objectives for the magnification steps x 2 to x 6 and x5 to x15 respectively.
6. Optical rotation of left and right images.
7. Brightness control of transmitted and incident light for left and right images.
8. Parallax elimination.
9. Image stage for putting on photographic material. Beneath the glass plate is the transmitted light equipment.
10. Removable roll-film holders

Fig. 6 THE CARL ZEISS JENA INTERPRETOSCOPE

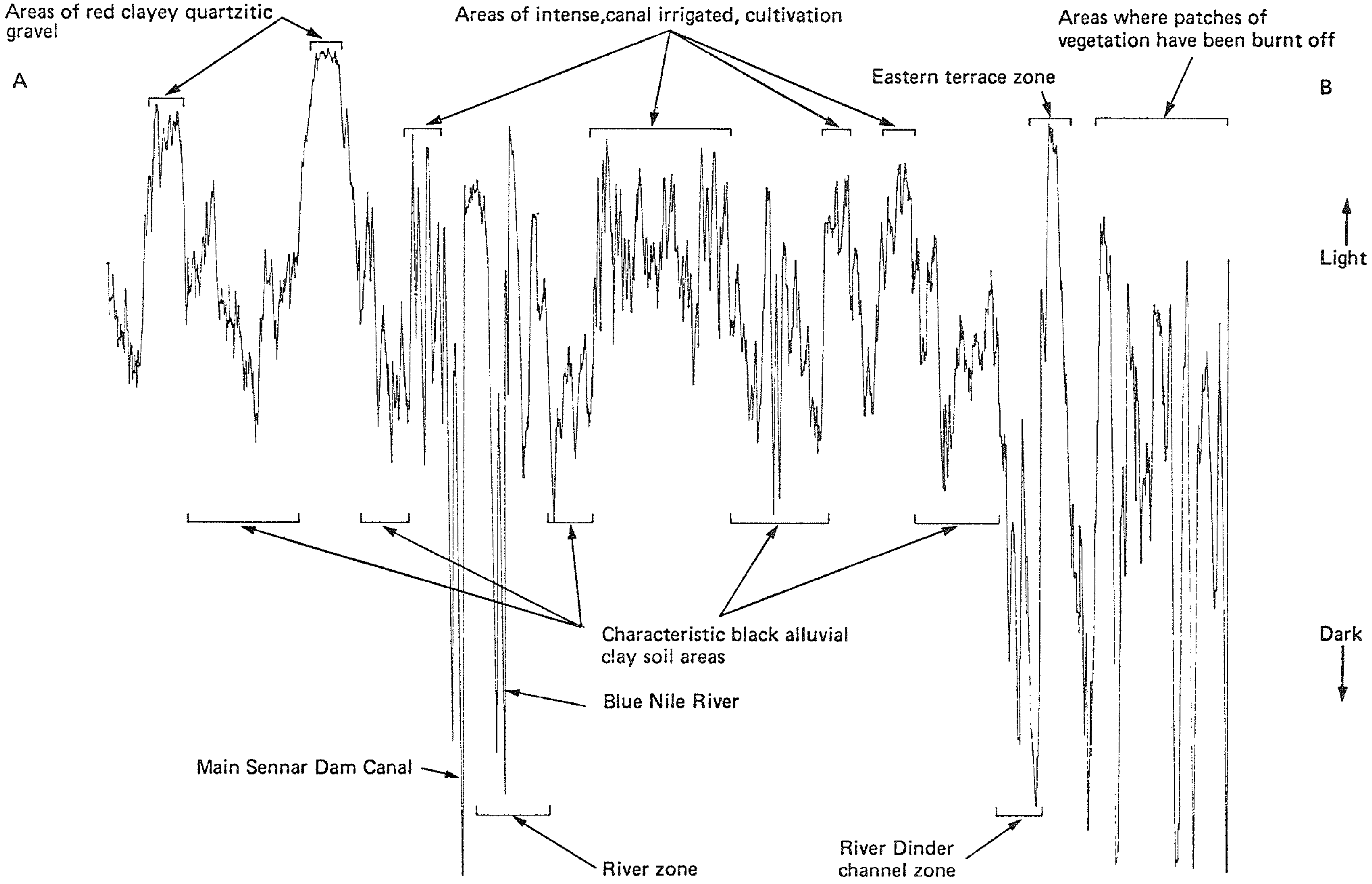


Fig. 7 MICRODENSITOMETER TRACE OF THE LANDSAT INFRARED BAND 7 IMAGE ACROSS THE BLUE NILE REGION SUDAN

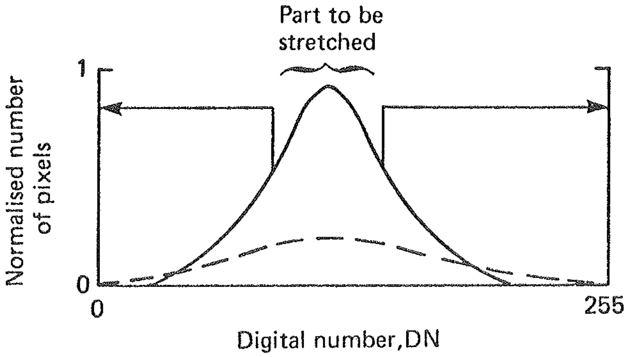


Fig. 8(a) SCHEMATIC HISTOGRAM SHOWING THE DISTRIBUTIONS OF DIGITAL NUMBERS (DN) FOR A TYPICAL LANDSAT MSS SCENE BEFORE CONTRAST STRETCHING (SOLID LINE) AND AFTER LINEARLY STRETCHING (DASHED LINE) A PART OF THE DN RANGE (After Rowan 1974)[35]

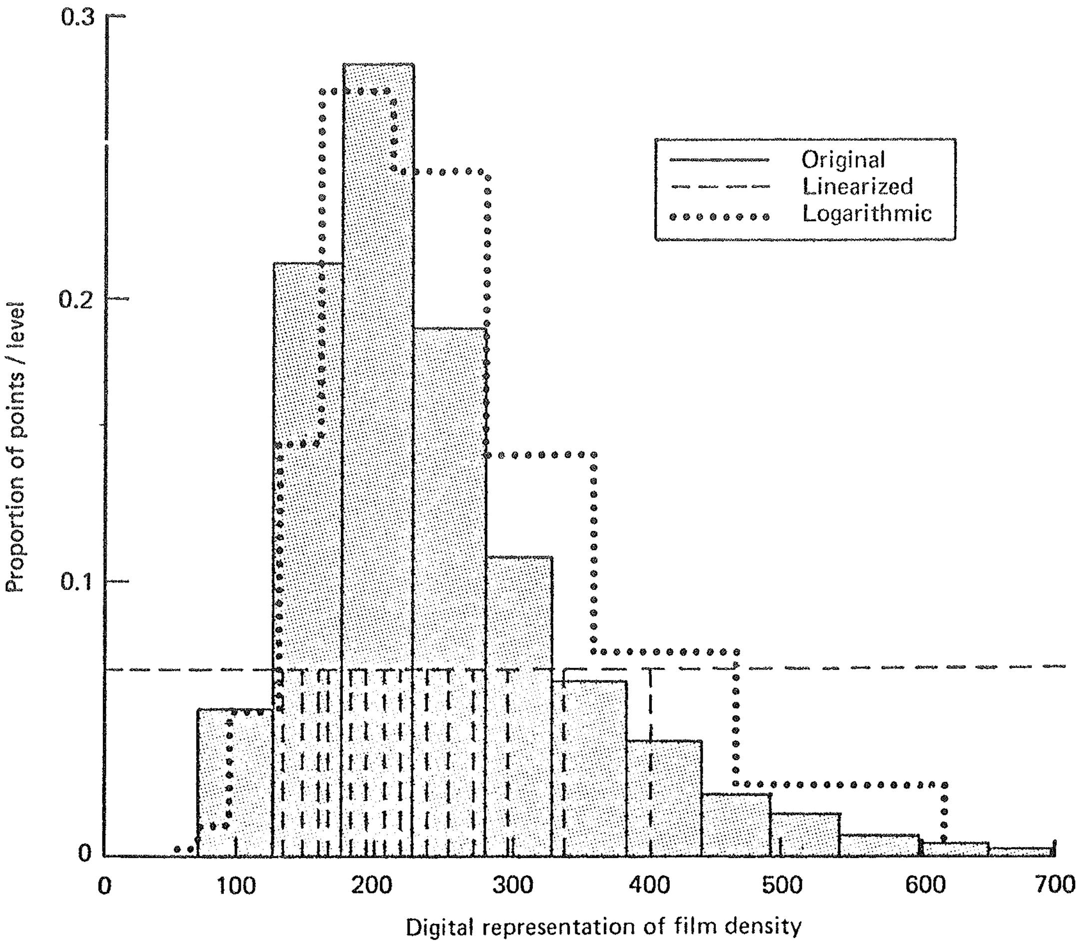


Fig. 8(b) EXAMPLE OF VARIOUS TRANSFORMATIONS WHICH CAN BE CARRIED OUT TO CONTRAST ENHANCE DIFFERENT DENSITY REGIONS OF AN IMAGE (After Carter et al 1975)[53]

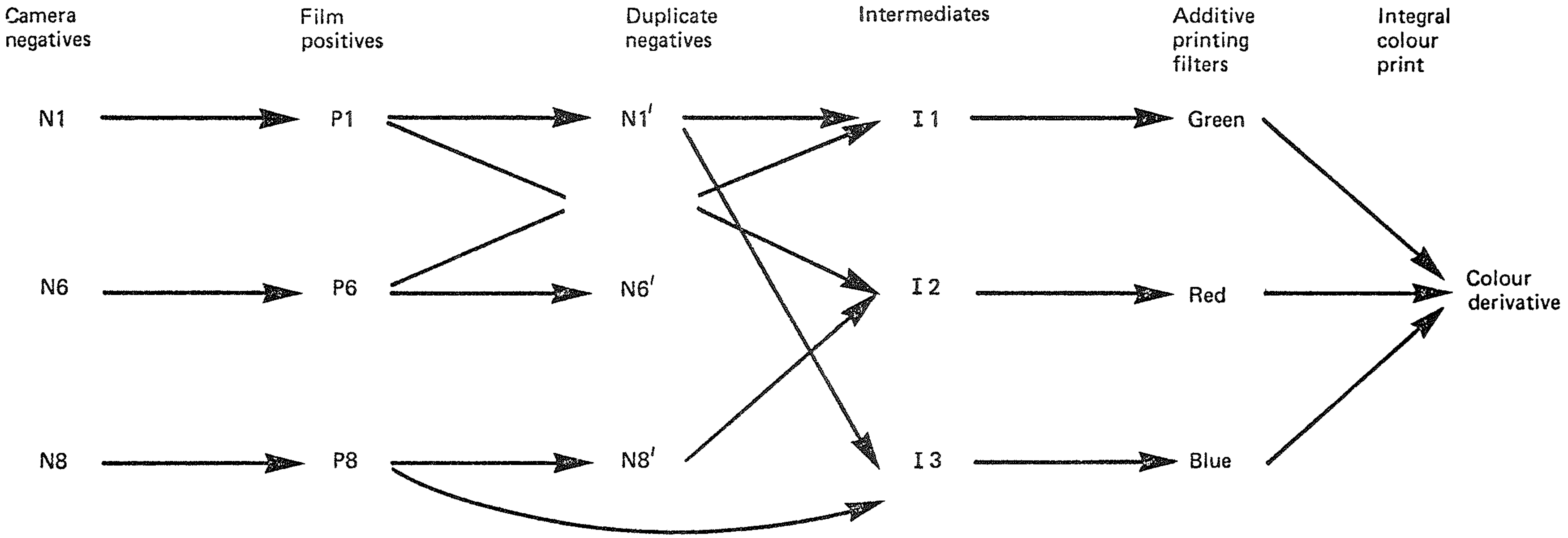


Fig. 9 PHOTOGRAPHIC METHOD OF COLOUR ENHANCING MULTISPECTRAL IMAGES BY CROSS–COMBINING POSITIVES AND DUPLICATE NEGATIVES (After Molineux 1965)[32]

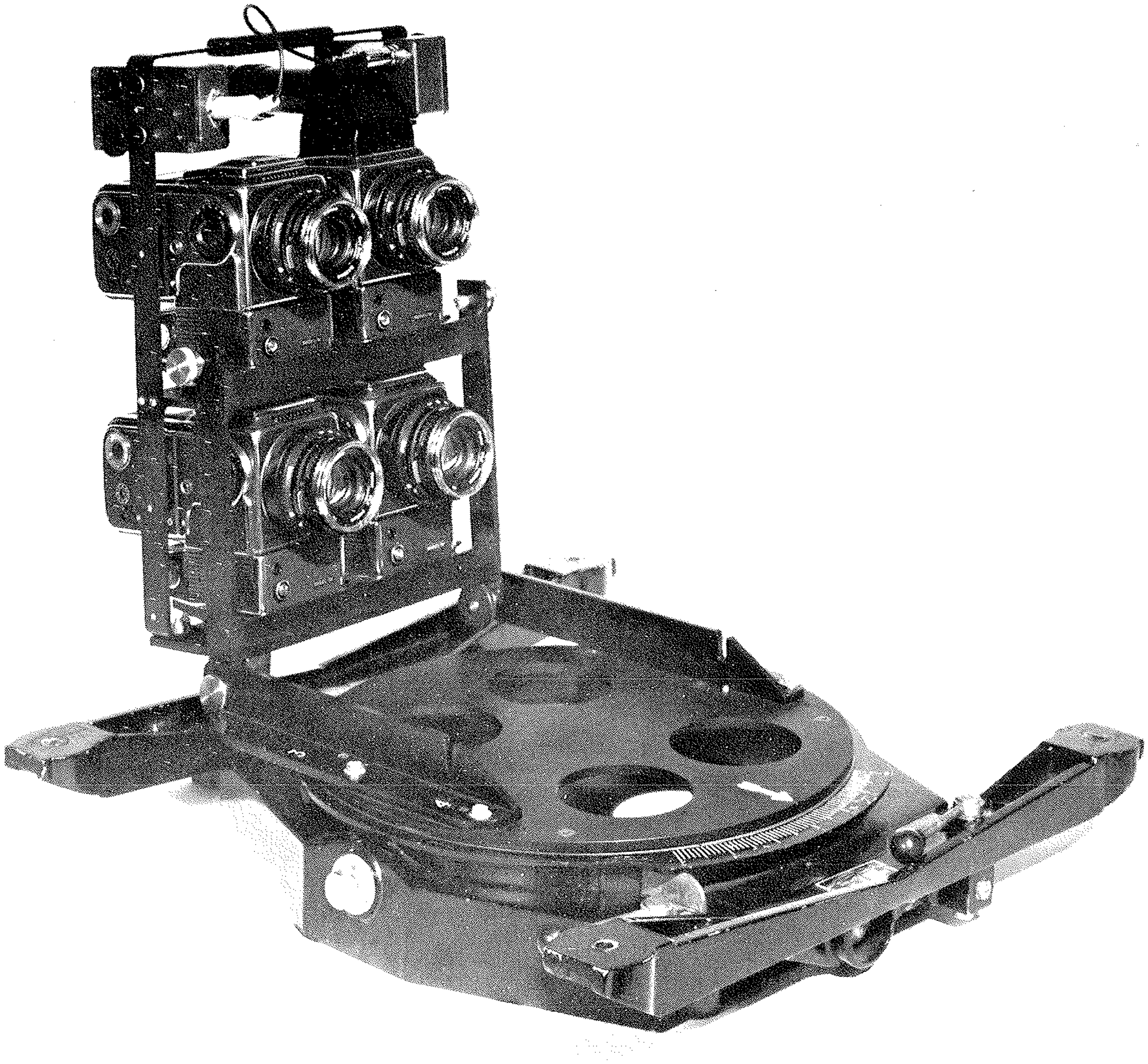


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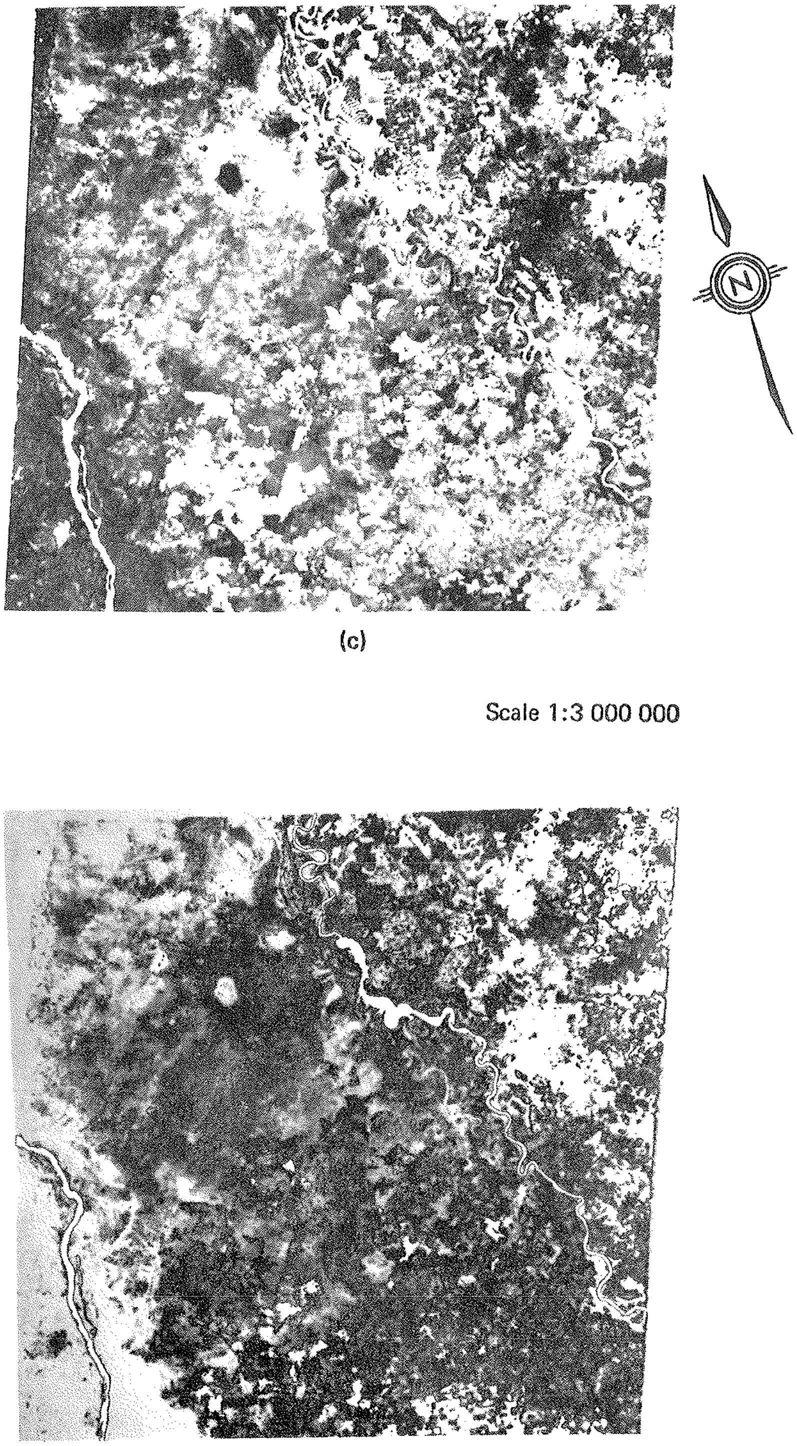
Plate 1 THE TRRL MULTISPECTRAL CAMERA SYSTEM

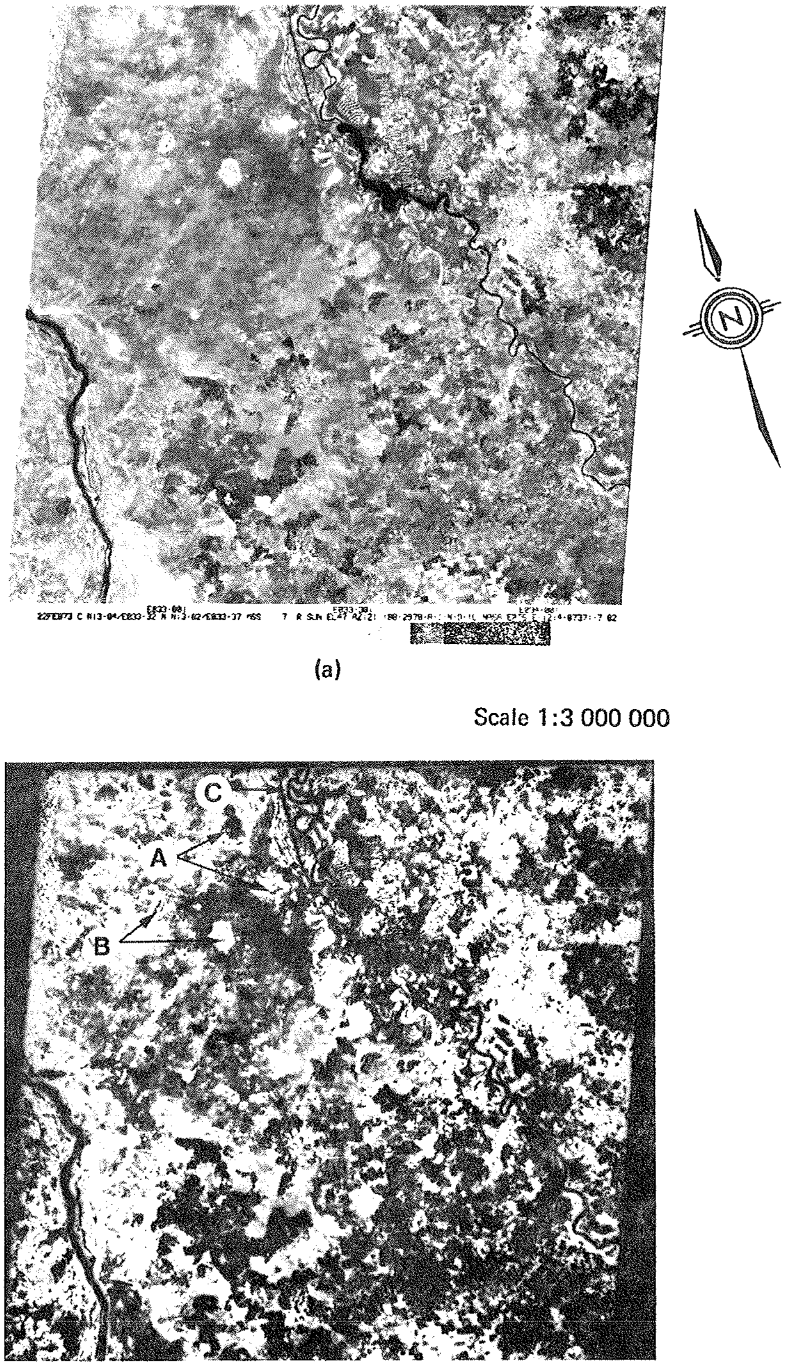


(c)

Scale 1:3 000 000

(d)

Plate 2. (cont.) DENSITY SLICES (c) and (d) FOR A SCENE OF CENTRAL SUDAN TAKEN FROM THE 'LANDSAT' SATELLITE INFRARED BAND 7 IMAGE (a)



(a)

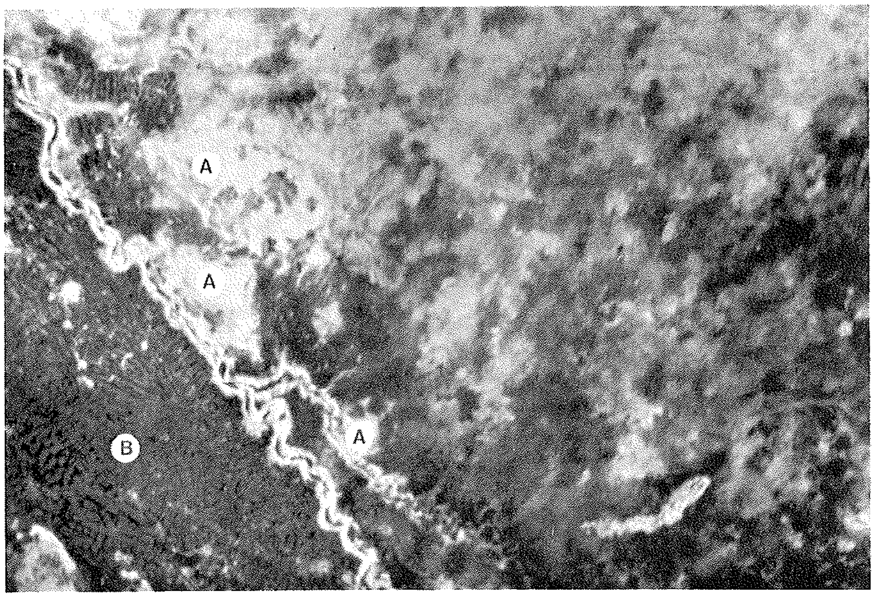
Scale 1:3 000 000

(b)

A Red clayey quartzitic gravel
B Jebel outcrops of bedrock
C River sands and calcareous concretionary material

Plate 2. A 'LANDSAT' SATELLITE INFRARED BAND 7 IMAGE (a) AND DENSITY SLICE (b) FOR A SCENE OF CENTRAL SUDAN

NOTE: The original photographs on this page are in color.



(i)

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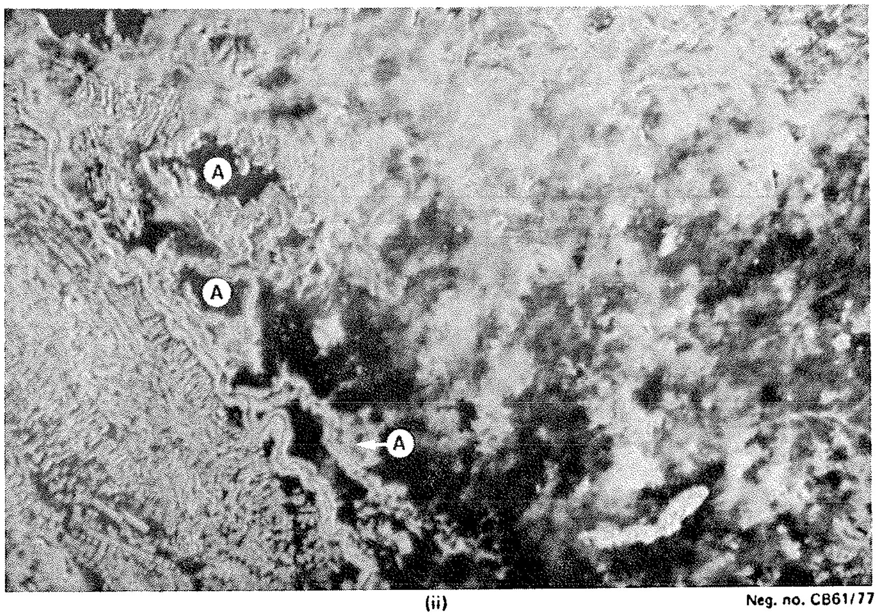
A – RED CLAYEY QUARTZITIC GRAVEL
B – AREA OF INTENSE, CANAL IRRIGATED, CULTIVATION



(ii)

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PLATE. 3. A COLOUR COMPOSITE (i) AND ENHANCED COLOUR COMPOSITE (ii) GENERATED FROM BANDS 4,5 and 7 OF THE 'LANDSAT' SATELLITE MULTISPECTRAL IMAGERY,CENTRAL SUDAN

LR 753. Pl.3

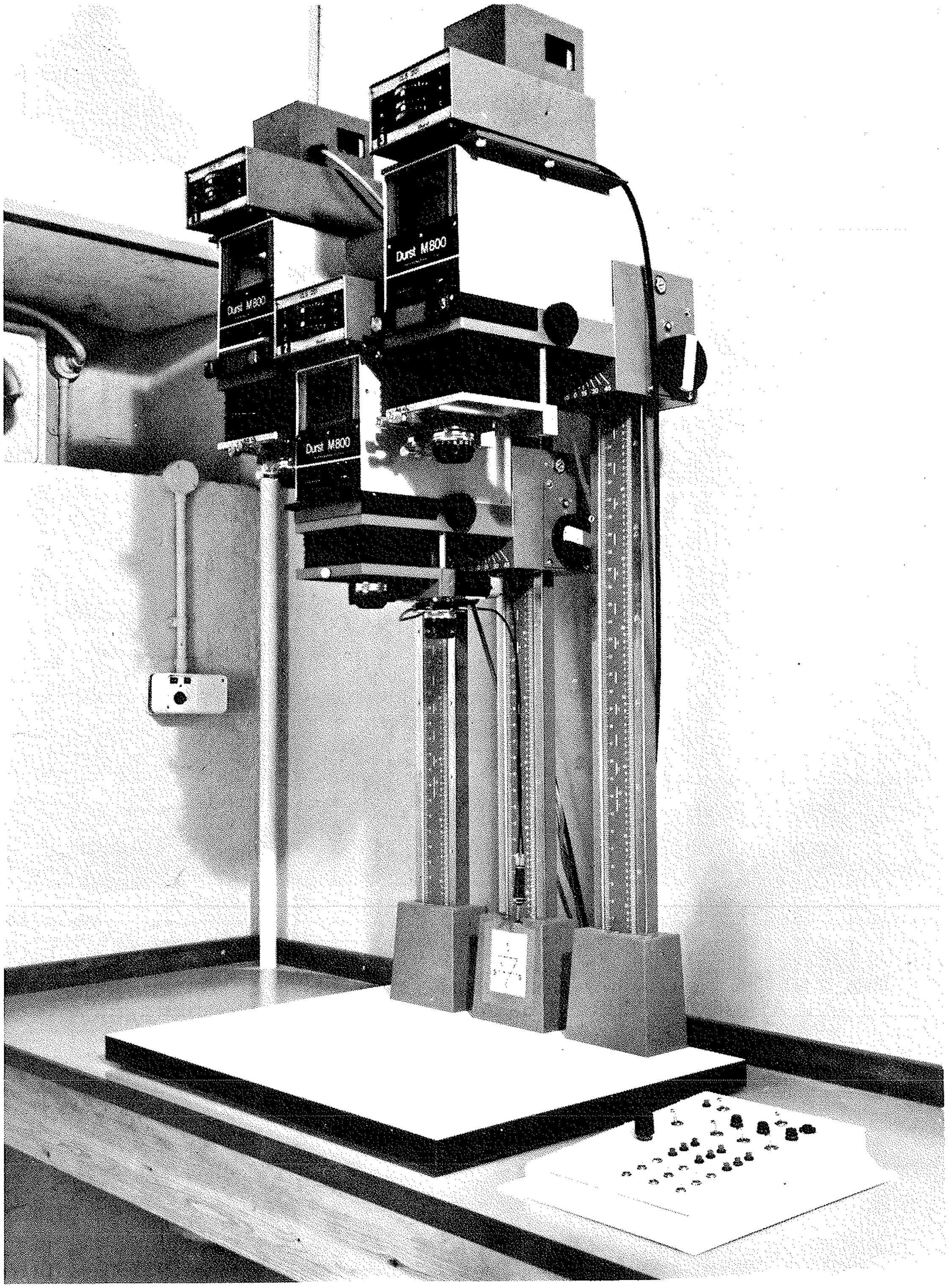

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Plate 4 THE TRRL CONSTRUCTED ADDITIVE VIEWER

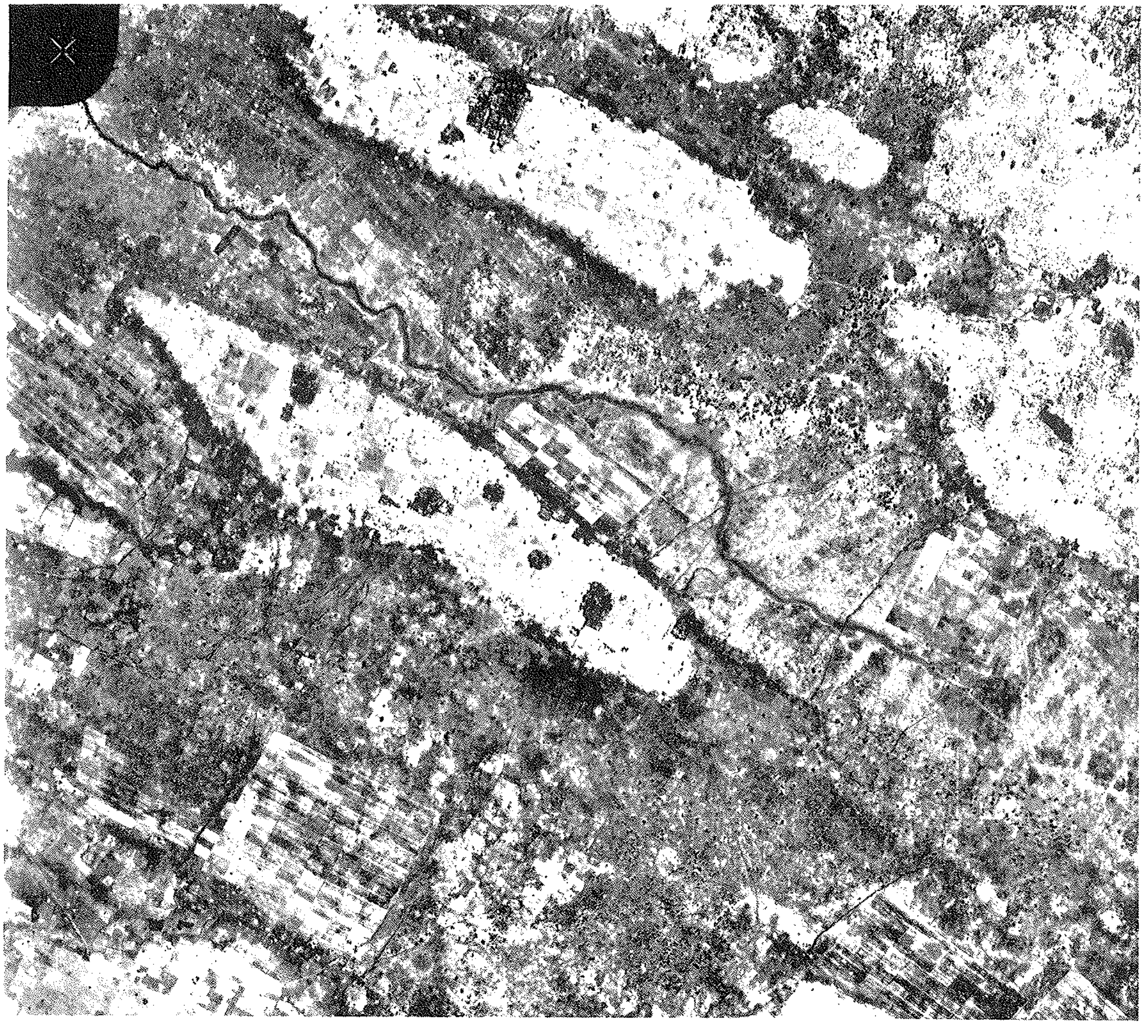

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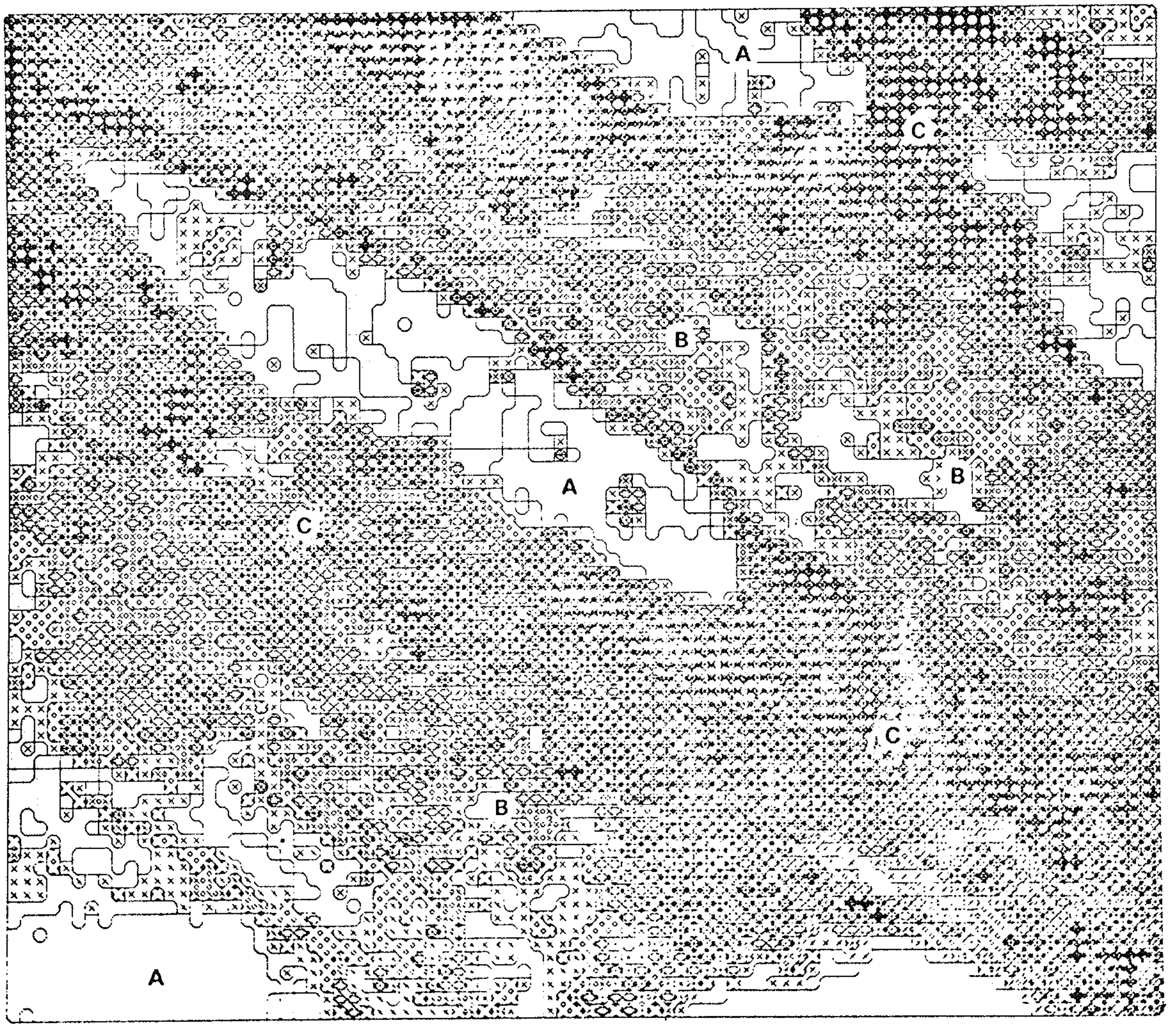
Plate 5 (a) THE BLACK–AND–WHITE IMAGE OF A FALSE COLOUR INFRARED AERIAL PHOTOGRAPH OF AN AREA IN THE MAIDUGURI REGION OF NORTH EAST NIGERIA



A – Sand soils
B – Sand-silt-clay soils
C – Black clay soils

Plate 5 (b) AN AUTOMATIC COMPUTER ANALYSIS MAP OF AN AREA IN THE MAIDUGURI REGION OF NORTH EAST NIGERIA, DERIVED FROM USING A CLUSTERING PROCEDURE

Land forms in Ethiopia.

AUSTRALIAN ROAD RESEARCH BOARD

PROCEEDINGS – FOURTH CONFERENCE

MELBOURNE, 1968

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TERRAIN EVALUATION SYMPOSIUM

SESSIONS L2, M2, N2, and O2

Papers presented for discussion:

Paper No. 515T **THE USE OF LANDSCAPE CLASSIFICATION IN PLANNING ENGINEERING WORKS**
A. O. BARRIE, Ministry of Defence, United Kingdom

Paper No. 514T **THE RELEVANCE FOR ENGINEERING OF PRINCIPLES, LIMITATIONS AND DEVELOPMENTS IN LAND SYSTEM SURVEYS IN NEW GUINEA**
H. A. HAANTJENS, Division of Land Research, C.S.I.R.O.

** Paper No. 513T **TERRAIN EVALUATION FOR CIVIL ENGINEERING PROJECTS IN SOUTH AFRICA**
B. A. KANTEY, Kantey and Templer, Cape Town, South Africa
M. J. MOUNTAIN, Kantey and Templer, Cape Town, South Africa

Paper No. 512T **LAND CLASSIFICATION AND DATA STORAGE FOR THE ENGINEERING USAGE OF NATURAL MATERIALS**
A. B. A. BRINK, Department of Geology, University of Witwatersrand, South Africa
T. C. PARTRIDGE, National Institute for Road Research, South Africa
R. WEBSTER, Department of Soil Science, University of Oxford, United Kingdom
A. A. B. WILLIAMS, National Institute for Road Research, South Africa

Paper No. 452T **PROPOSALS FOR THE APPLICATION OF THE PUCE PROGRAM OF TERRAIN CLASSIFICATION AND EVALUATION TO SOME ENGINEERING PROBLEMS**
G. D. AITCHISON, Chief, Division of Soil Mechanics, C.S.I.R.O.
K. GRANT, Senior Research Scientist, Division of Soil Mechanics, C.S.I.R.O.

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Paper No. 452Ta **ENGINEERING EXPECTATIONS FROM TERRAIN EVALUATION**
G. D. AITCHISON, Chief, Division of Soil Mechanics, C.S.I.R.O.

Paper No. 453T **STORAGE AND RETRIEVAL OF INFORMATION IN A TERRAIN CLASSIFICATION SYSTEM**
K. GRANT, Senior Research Scientist, Division of Soil Mechanics, C.S.I.R.O.
G. D. LODWICK, Scientific Services Officer, Division of Soil Mechanics, C.S.I.R.O.

Paper No. 525T **SURVEY OF HIDDEN CALCRETE IN ALLUVIAL PLAINS OF INDIA BY AIRPHOTO INTERPRETATION**
H. L. UPPAL, Central Road Research Institute, India
R. L. NANDRA, Central Road Research Institute, India

DISCUSSIONS and SUMMARY CLOSURE (p. 1683)

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Kantey and Templer, Consulting Engineers, Cape Town, South Africa
M. J. MOUNTAIN
Consulting Geologist, Kantey and Templer, Consulting Engineers, Cape Town, South Africa

TERRAIN EVALUATION FOR CIVIL ENGINEERING PROJECTS IN SOUTH AFRICA

(Paper No. 513T)

The developments in terrain classification, data storage and soils engineering mapping in South Africa are traced, and some comments tendered on the possible advantages and drawbacks of the current trends of development. It is suggested that more emphasis should be placed on geological and geographical concepts for classification systems, as a system based on local names is rather meaningless. It is further suggested that the project level approach to soils engineering mapping provides much valuable information, applicable to any form of data storage. The standard method of mapping and presentation of data in the production of soils engineering maps at project level is described and the unexpected benefits that have accrued indicated.

THE DEVELOPMENT OF CURRENT APPROACHES TO TERRAIN EVALUATION IN SOUTH AFRICA

1. The terrain classification system as it exists in South Africa has come about as a logical development of advances made in the techniques and requirements of soils engineering for roads. In South Africa suitable construction materials have had to be found in areas where the engineer has had very little basic information from which to work. Pedological maps, the basis of information in other countries such as the United States of America and Europe, are not available and geological maps are mainly of a regional nature.

2. With the introduction of proven techniques of airphoto interpretation to mapping for road projects a new and valuable tool became available for the engineer's usage. Brink (Ref. 1), Kantey and Williams (Ref. 2) and Brink and Williams (Ref. 3) have described the development of soil engineering mapping for roads in South Africa, based on the application of airphoto interpretation. Not long after this it became evident that two trends of development in terrain evaluation were taking place depending upon circumstances surrounding the individuals concerned with soil engineering mapping. On the one hand, a data storage system was proposed which would be based on physiographic classification of terrain as developed by Beckett and others (Ref. 4). Its development in South Africa to the present stage is described by Brink and Partridge (Ref. 5). On the other hand a number of soil engineering mappers were working in close association with engineers on many varying practical projects and in these cases the accent was concentrated on producing the specific requirements of the engineer as efficiently and as quickly as possible. The fact that the information could also be used for data storage purposes was of secondary importance.

3. Whether the long term approach, that of an adequate data storage system, satisfactorily developed for the whole country, is actually better than the short term project approach, is a highly debatable question. The fact remains that while a terrain data classification system has been getting under way, soil engineering mappers have continued to perform a most useful function on civil engineering projects. It is suggested that the project approach, with its increasing popularity amongst practising civil engineers, is the more likely to be generally accepted although it has not received the same publicity as that the terrain data classication system.

4. The development of the project approach has been due to a growing realization that aerial photography provides a picture of the terrain in adequate detail. Equally important is the growing recognition by the engineer of the importance of the interpreter as the link between aerial photography and himself. Most practising engineers accept the specialist interpreter without concern as he can be adequately replaced by another person of similar training and experience. It is accepted that a particular interpreter is not the 'end of the line'. What is of vital importance to the successful functioning of the aerial photograph-interpreter-engineer approach is a mutual understanding and acceptance of the capabilities and limitations of the system. Assuming there is aerial photography of a reasonable scale available, which in fact is the case in South Africa, it will show most of the significant detail that could be discerned from the ground as well as much information that is normally indiscernible from the ground. The interpreter, to quote Lueder (Ref. 6), 'must be convinced that these details can be successfully evaluated to provide an intelligent, reliable estimate of ground conditions by using the process of deduction and induction in conformance with logic and physical laws'. Lueder states further that the interpreter should have a conviction that failure to obtain reliable information is due to interpretation failure, or lack of proper selective field work (or both) rather than to a deficiency of the photography within the limitations of equipment and material. The writers are in accord with these views of Lueder as it is their experience that the degree of reliance that can be placed on information is directly related to the extent of experience of the interpreter. There appears to be little doubt that the amount of information obtained from interpretation is proportional to the amount of the interpreter's experience beyond his basic training.

5. Apart from the relationship between the interpreter and aerial photography a further important factor in the aerial photograph-interpreter-engineer approach is that of communication between the interpreter and the engineer. This aspect has to date not presented a great deal of difficulty since the very nature of the development of the technique has arisen out of a mutual understanding of the requirements and limitations of the method. It is the duty of the interpreter to inform the engineer of a possible weakness in the link which may lie in either the lack of the desired information on the aerial photographs, or in his own inability to adequately interpret the photographs, or in the lack of clarity as to what the engineer himself requires. Complete integrity is required on the part of the interpreter. The requirements of the engineer may vary considerably from the straightforward case of possible sources of underground water to the more complicated case of a complete inventory of all materials in an area, in order to form an assessment of foundation conditions and sources of construction materials.

6. It is against this background that the aerial photograph-interpreter-engineer approach to terrain evaluation in South Africa has developed. Firstly, the combination has

proved itself as a working team and secondly, because of the economic necessity of consulting work, it is sufficiently flexible to adapt itself to a specific requirement, without wasting effort on unnecessary detail. Further, it is important to realize that the method can be equally adapted to the exploration geologists', the agriculturists', the pedologists' or the military engineers' requirements although more than one interpreter may be required to act as the links between the aerial photography and these earth sciences. By the same token it is doubtful if a single terrain classication and data storage system could adequately store all the information on all the various earth sciences.

7. The terrain classification and data storage system in South Africa as envisaged by Brink and Partridge, recognizes the value of the interpreter. In their system is built around the land facet, is the smallest area which can be delineated on aerial photography of the available scales is the land facet. Their entire concept, of extending information from a type area to the site under consideration, depends on the ability of the user to recognise at the site the same facets that were described and classified in the type area. This is a 'tall order' for the average practitioner not well versed in airphoto interpretation and this is a weakness in the system. It is also clear that if incorrect information is fed into the data store at any level of classication, the system will not operate successfully, whereas in the airphoto-interpreter-engineer approach the incorrect placing of a boundary is not likely to have a lasting effect on an individual project. It is clear therefore that, in the land system classication, the services of the expert interpreter cannot be eliminated when used for engineering projects.

8. However, the greatest weakness in the concept of the land system classification as now being developed lies in the fact that it is not readily assimilated within the normal experience of the intended user. It tends to mystify with new terminology and requires extensive reading and study to grasp the detail that is available to the experienced. The project level approach on the contrary, records and reports the necessary information in terms of the terminology and experience of the intended user because that user has himself dictated the terms of reference.

A NEW APPROACH TO STORAGE OF TERRAIN DATA

9. In spite of the successful functioning of the airphoto-interpreter-engineer method at project level, the need for terrain classification and data storage is fully recognized. Although much valuable work is being done in this respect, the authors believe that it will still be some time before any proposed system is sufficiently advanced to result in valid information becoming readily available for use at project level. It seems logical therefore that maximum encouragement should be given to techniques which will lead to the rapid development of a fully functional terrain classification and data storage system.

10. In this respect it is surprising that the various classification systems proposed apparently overlook or ignore so much of the valuable work that has already been carried out on terrain evaluation, particularly by geologists and physical geographers. This work has long been considered as a science of terrain evaluation, to which a wider interpretation is now being given. For virtually all modern projects concerned with terrain evaluation, it is the recognised practice to obtain information on such factors as geology, soils, vegetation and land use prior to the interpretation study. It seems logical to assume that a readily accepted classification system should be based to some extent on these existing sources of information.

11. In South Africa, where soils are thin and pedologically immature, the importance of geology is recognized by the soils engineering mapper but does not appear to be accorded sufficient emphasis in the land system type of classification, which places maximum emphasis on physiography.

12. An experienced interpreter can recognize on aerial photographs, nearly all the different rock types known to the engineer that occur in South Africa, no matter what climatic conditions prevail. Geology should thus form the starting point for any classification system in this country. Further, as geology is the most important factor influencing variations in physiography, it should be placed before physiography in a classification system.

13. Accepting the contributions of previous workers, a terrain classification system, based on their work, could immediately be put into operation. It is suggested that the broadest framework for terrain classification would be the geological map of a country with the boundaries of the physiographic regions superimposed upon it. *Fig. 1* illustrates the combination of the major Southern African geological systems, after du Toit (Ref. 7), combined with the main physiographic regions, after Wellington (Ref. 8). The small scale of the map used to illustrate the concept indicates the principal in broadest outline only, whereas for data storage or project level mapping a larger scale could be easily chosen. For data storage purposes selected annotated stereograms

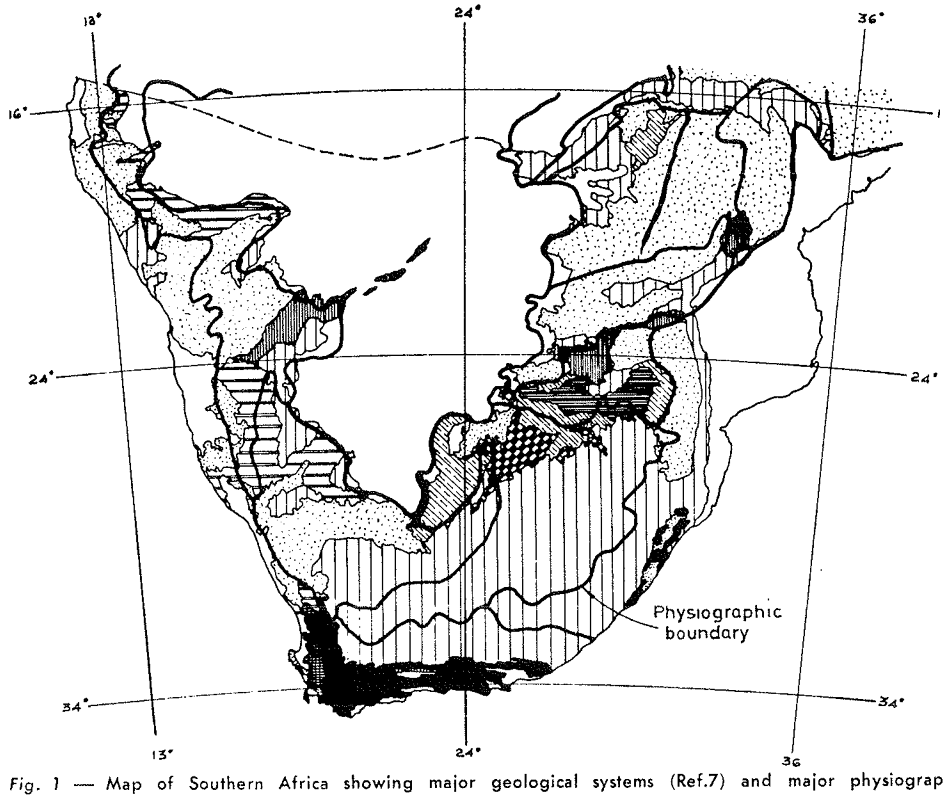

Fig. 1 — Map of Southern Africa showing major geological systems (Ref.7) and major physiographic regions shown by thick lines (Ref. 8)

showing typical mapping units could then be kept for each geological/physiographic region. The degree of detail could eventually lead to annotated stereograms for individual rock types of a particular geological series in a particular physiographic subregion. For retrieval of data, for example, one could request the annotated stereograms for the Table Mountain sandstone series of the Southern Cape, Folded Belt region.

14. In essence, this proposal is not unlike that of Brink and Partridge. However, it suggests that the generally accepted physical (geologic/physiographic) division of a country forms the logical framework in which to build a classification system. These divisions are preferable to the rather ill-defined land system boundaries and also, as suggested by Floyd (Ref. 9), preferable to the usage of rather meaningless local names for land systems. Further, the system does not claim that the typical stereogram will contain a type example of every mapping unit likely to be found in the given division.

FORMS OF PRESENTATION OF ENGINEERING INFORMATION

15. Presentation of information in the airphoto-interpreter-engineer system may take several different forms depending on the specific requirements of the engineer. The currently standard form, which will itself yield data for storage purposes, is the normal soils engineering map, as understood in South Africa. However, for some projects, the time and finances available and the information required, do not in themselves justify the production of a fully detailed soils engineering map. In such cases, it is obviously a more practical approach to carry out the work in accordance with the terms of reference than to lose the opportunity of proving the validity of the technique and widen the experience of the interpreter. A typical example arises when, on a specific project, a contractor finds himself apparently short of construction materials and is experiencing difficulty in locating additional sources of supply. Further possible sources of supply may often be located from airphoto interpretation and the locations pointed out to the contractor, with the result that he is satisfied and places greater confidence in the methods used. This is a type of service which no existing terrain data storage system can supply but the results of this service can usefully be fed into the data storage system direct from annotated airphotos, without any map having been prepared. While the writers strongly favour the production of soil engineering maps wherever possible, and particularly in little known areas, it is obvious that it would be unwise to adopt the viewpoint that a map must be produced at all costs. On the other hand, the production of detailed soils engineering maps, at an early stage, has often been shown to be of great benefit in the final route location and has thus fully justified the cost of production. However, it is considered vital that, irrespective of the scale or scope of the project, any information obtained by airphoto interpretation should be recorded for subsequent transmission to a data storage system.

16. Where soils engineering maps are not prepared, the engineering information may usefully be added to an existing base map, whether or not the base map has itself been photogrammetrically compiled. It is a relatively simple matter to transfer information from a set of airphotos even though there may be a difference in scale between the photos and the base map. If time and cost justify the desired accuracy and the base map has been photogrammetrically compiled,, the same stereoplotting instruments may be used to plot the additional information.

17. It may also be that the airphotos themselves could be regarded as the principal source of information for data storage in which case the use of overlays could usefully be developed to present a great mass of data on the different earth sciences, in forms which could be easily assimilated by the intended user. Using an airphoto mosaic as a base map, overlays, used singly or in combination, could give information on physiography, geology, soils, natural vegetation, land use and project study data. This method is not new, being an accepted part of photo-geological studies, particularly in petroleum exploration.

18. For civil engineering purposes, however, it may well be that the soils engineering maps themselves may become the base maps to which overlays, showing additional information, may be added.

THE SOILS ENGINEERING MAP, ITS PREPARATION AND APPLICATION AT PROJECT LEVEL

19. It has been stated above that terrain classification and mapping in South Africa has developed basically from the experience gained in the preparation of soil engineering maps for specific highway projects and various references have been given which indicate the pattern of development in the preparation of soil engineering mapping. The earlier work discussed in these references has generally been connected with the preparation of contract documents for construction purposes but this work has now been extended to the preparation of soil engineering maps for projects which are still in the planning stage. The programme of work differs materially between the preparation of a map for contract purposes and the preparation of a map for planning purposes although the two maps, as presented, should virtually be identical. This arises from the fact that, in the preparation of the map for contract purposes, the interpreter has available in the field, a working party which is engaged in the detailed sampling of selected borrow pits as well as the routine sampling of the in situ materials along the centreline of the proposed highway, all of which information is required for the materials design. When preparing a soils engineering map for planning purposes, however, all necessary information has to be obtained from preplanned field trips and the efficiency of the project will then depend on the efficiency of this preplanning. The experience gained in these later projects has been of considerable value for soil engineering mapping and has led to the development of a standard method of mapping and presentation of data with some variations dependent on the project itself.

20. The method is described below and, while it is probable that further experience will result in modifications of the techniques, it has led to a high degree of efficiency in the preparation of soils engineering maps.

(a) The first step is the obvious one of ordering two sets of aerial photography of the area to be mapped. In some cases, it may be found that more than one set of photography is available due to the area having been flown on different occasions and sets are consequently ordered of all such coverage. These photographs are ordered on semi-matt paper since this type of print is more amenable to annotation than the glossy type with resultant greater accuracy in the annotation which is carried out directly on the photographs.

(b) While awaiting the arrival of the photographs, a search of the literature covering the area involved, is carried out and information on local geology, soils. natural vegetation, land use, topography, communications, cadastral boundaries and farm names collected. If large scale topographic maps of the area are available, copies of these are ordered.

(c) On the arrival of the photographs, an uncontrolled airphoto mosaic is compiled, using alternate photographs from one set of the most recent coverage. This mosaic should always cover a greater area than that to be mapped in order to obtain an overall picture of the area involved.

(d) The mosaic is now studied from all angles in order to obtain a picture of the regional trends. At this stage, the experienced interpreter will have recognized to some extent the bulk of the rock and soil types of the area and many preliminary boundaries may be sketched on the mosaic. In addition, certain basic information such as roads, tracks, watercourses, farm boundaries and the approximate position of a proposed road centreline may also be sketched or defined on the mosaic.

(e) From the basic knowledge of the general geology and soils of the area, an approximate assessment of the probable construction materials is made, i.e. alluvial terraces, talus deposits, etc. are noted and the possible occurrence of pedogenic materials considered. The rocks, whether in the weathered or fresh condition are also assessed with a view to their probable use. All the above is considered as an extension and revision of the earlier literature search, revised in the light of the preliminary airphoto study.

(f) The stereoscopic study is now commenced directly on the mosaic. Depending on the experience of the interpreter, a considerable amount of preliminary annotation can be done. At the stage where unreliability is suspected various localities are pinpointed for field identification. These localities are selected such that they are accessible, will yield information on geological and/or soil boundaries and cover potential sources of construction material. All such localities are marked on the second set of airphotos and the preliminary annotation similarly marked.

(g) The interpreter is now in a position to make his field trip and takes with him the second set of airphotos and a stereoscope. In the field, trial holes are dug at the selected localities and a more detailed stereoscopic study of the airphotos made in the light of the information obtained from the trial holes and on the spot examination of exposures, gully sides etc. Samples are selected for laboratory testing in sufficient detail to obtain information on the performance of the available construction material. In most instances, it will be found that sufficient information is obtained from this single field trip for the work to be completed but, in some instances, the results of the laboratory testing may dictate the necessity for a second field trip to define in greater detail suitable materials within economical haul distances.

(h) A statistical analysis of the test results of the samples taken from various mapping units is carried out in order to indicate the probable performance characteristics and variability of the various significant construction materials as a guide to final route location and preliminary design.

(i) The final map and report can now be completed. If large scale topographic maps of the scale of 1:50,000, 1:36,000 or 1:18,000 are available, such maps form the base map for the soils engineering map, and topo features, farm boundaries, etc. are used for orienting the annotation made on the airphotos.

TABLE I

SUMMARY OF ENGINEERING PROPERTIES OF LEGEND UNITS

<table>
<tr><th rowspan="5">Symbol</th><th rowspan="5">Material</th><th rowspan="5">Subgrade</th><th rowspan="5">Subbase</th><th rowspan="5">Basecourse</th><th rowspan="5">Aggregate for Bitumen Carpet and Concrete Coarse Aggregate</th><th rowspan="5">Binder</th><th rowspan="5">Concrete Sand</th><th colspan="12">Typical Grading</th><th colspan="3" rowspan="4">LL</th><th colspan="3" rowspan="4">PI</th><th colspan="3" rowspan="4">LS</th><th rowspan="5">Quantity</th><th rowspan="5">Overburden</th><th rowspan="5">Thickness</th><th rowspan="5">Degree of Weathering</th></tr>
<tr><th colspan="12">Percentage passing on total sample</th></tr>
<tr><th colspan="3">¾"</th><th colspan="9">Soil Mortar</th></tr>
<tr><th colspan="3">0.742"</th><th colspan="3">0.078"</th><th colspan="3">0.0164"</th><th colspan="3">0.0029"</th></tr>
<tr><th>x̄</th><th>s</th><th>c</th><th>x̄</th><th>s</th><th>c</th><th>x̄</th><th>s</th><th>c</th><th>x̄</th><th>s</th><th>c</th><th>x̄</th><th>s</th><th>c</th><th>x̄</th><th>s</th><th>c</th><th>x̄</th><th>s</th><th>c</th></tr>
<tr><td rowspan="2">A</td><td rowspan="2">Alluvium and Alluvial Wash</td><td rowspan="2">—</td><td rowspan="2">—</td><td rowspan="2">—</td><td rowspan="2">—</td><td rowspan="2">—</td><td rowspan="2">Possible small occurrence in Hluhluwe Rv. west of main road.</td><td>100</td><td>0</td><td>0</td><td>98</td><td>1</td><td>1</td><td>96</td><td>49</td><td>51</td><td>57</td><td>12</td><td>21</td><td>40</td><td>13</td><td>32</td><td>23</td><td>9</td><td>42</td><td>11</td><td>5</td><td>41</td><td rowspan="2">—</td><td rowspan="2">None</td><td rowspan="2">Up to ± 10ft.</td><td rowspan="2">—</td></tr>
<tr><td colspan="21">Results from 5 samples</td></tr>
<tr><td>H</td><td>Hillwash Soils</td><td>These soils in close proximity to S areas possibly suitable</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—</td><td colspan="21">Results of the hillwash soils, given below, are grouped with the parent material over which they occur.</td><td>Large</td><td>None</td><td>0 to ± 4ft.</td><td>—</td></tr>
<tr><td rowspan="2">S</td><td rowspan="2">Aeolian Sand (Windblown)</td><td rowspan="2">✓</td><td rowspan="2">Unsuitable as is Requires modification</td><td rowspan="2">—</td><td rowspan="2">—</td><td rowspan="2">✓</td><td rowspan="2">Too Fine</td><td>100</td><td>0</td><td>0</td><td>100</td><td>0</td><td>0</td><td>87</td><td>3</td><td>4</td><td>13</td><td>4</td><td>2</td><td>14</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td rowspan="2">Unlimited, only in southern portion</td><td rowspan="2">None</td><td rowspan="2">Up to 20 ft.+</td><td rowspan="2">—</td></tr>
<tr><td colspan="21">Results from 5 samples</td></tr>
<tr><td rowspan="2">CR</td><td rowspan="2">Cretaceous deposits</td><td rowspan="2">Generally too plastic and variable</td><td rowspan="2">Generally too plastic and variable</td><td rowspan="2">Too plastic and variable</td><td rowspan="2">—</td><td rowspan="2">—</td><td rowspan="2">—</td><td>100
94</td><td>0
13</td><td>0
13</td><td>93
84</td><td>12
23</td><td>13
27</td><td>86
74</td><td>16
22</td><td>20
30</td><td>41
39</td><td>8
12</td><td>18
31</td><td>38
43</td><td>9
9</td><td>21
21</td><td>21
24</td><td>4
7</td><td>18
30</td><td>10
11</td><td>3
3</td><td>29
25</td><td rowspan="2">Unlimited</td><td rowspan="2">0 to ± 20 ft.</td><td rowspan="2">0 to ± 50 ft.</td><td rowspan="2">High</td></tr>
<tr><td colspan="21">Results from 5 samples in each case. N.B. See remarks below</td></tr>
<tr><td rowspan="2">R</td><td rowspan="2">Rhyolite</td><td rowspan="2">Residual soils probably suitable</td><td rowspan="2">Fresh residual probably suitable esp. if stabilized with non-plastic binder or lime.</td><td rowspan="2">Fresh crusher run material suitable from selected areas</td><td rowspan="2">Crusher run material probably unsuitable for chips due to glassiness</td><td rowspan="2">—</td><td rowspan="2">Quarried product</td><td>96
100</td><td>0
0</td><td>0
0</td><td>79
71</td><td>31
27</td><td>39
38</td><td>67
56</td><td>31
33</td><td>47
59</td><td>38
33</td><td>19
22</td><td>49
65</td><td>39
42</td><td>12
12</td><td>31
29</td><td>19
23</td><td>8
12</td><td>41
50</td><td>9
10</td><td>5
5</td><td>52
51</td><td rowspan="2">Unlimited</td><td rowspan="2">0 to ± 20 ft.</td><td rowspan="2">50ft. +</td><td rowspan="2">Weathered zone of up to ± 30 ft.</td></tr>
<tr><td colspan="21">7 Hillwash samples, 5 Residual samples</td></tr>
<tr><td rowspan="2">B</td><td rowspan="2">Basalt</td><td rowspan="2">Residual soils probably suitable</td><td rowspan="2">As above, but less suitable material due to active days.</td><td rowspan="2">As above</td><td rowspan="2">Crusher run material suitable for chips</td><td rowspan="2">—</td><td rowspan="2">Quarried product</td><td>100
94</td><td>0
13</td><td>0
14</td><td>74
46</td><td>26
18</td><td>35
40</td><td>58
30</td><td>29
13</td><td>44
44</td><td>33
16</td><td>20
11</td><td>60
66</td><td>42
45</td><td>7
12</td><td>16
28</td><td>23
24</td><td>5
10</td><td>22
40</td><td>11
11</td><td>3
4</td><td>23
33</td><td rowspan="2">Unlimited</td><td rowspan="2">0 to ± 20 ft.</td><td rowspan="2">50 ft. ±</td><td rowspan="2">As above</td></tr>
<tr><td colspan="21">Results from 5 samples in each case.</td></tr>
</table>

$\bar{x}$ = Actual Mean: S - Standard deviation: C = Coefficient of variation: v Suitable as is.

NOTE: Homogeneity was POOR for A, H and CR. and GOOD for S, R and B.

REMARKS: For A: severe heaving conditions may be expected, especially in A B areas.

For H: as for A, however deposits generally thinner than A.

For S: sand becomes clayey with depth, or in vicinity of certain drainage depressions.

For CR, R and B: the upper set of results are from hillwash soils, while the lower are from the residual or weathered rock.

TABLE II

FIELD DESCRIPTION OF LEGEND UNITS

Symbol	Colour	Consistency	Structure	Soil Type or Rock Texture	Mineral/Rock Composition	Variability 1 = Uniform 5 = Highly Variable
A	Dark brown to almost black	Firm	Shattered (dry)	Sandy clays, sandy silts, some sand lenses	Variable	4–5
H	Various shades of dark brown	Firm	Shattered	Sandy clays, sandy clay-silts.	Variable	4–5
S	Light brown to brown	Loose	————	Fine to medium sand.	Sand, siliceous	1–2
CR	Yellow, buff, grey	Variable, firm, stiff, dense	Sedimentary bedding	Fine grained sandstones, sandy clays (shales) gravels	Aggregate mainly slate, quartzite, shale. Fines variable	4–5
R	Whitish pink, buff, red	Firm (weathered) to dense, compact (fresh)	Fractured (weathered) to jointed (fresh)	Porphyritic, banded, brecciated tuffaceous	Orthoclase, andesine quartz, augite	3–2
B	Yellow-brown, olive green, grey	As above	As above	Crystalline, cryptocrystalline amygdaloidal, vesicular	Labradorite, andesine, augite, olivine, magnetite + zeolites	3–2

Where such maps are not available, the soils engineering map is traced direct from the annotated mosaic on to which all the additional information obtained from the field trip/s has been placed. In such a case, any prominent features which can assist the user to locate himself in the field, are noted and mapped. Typical examples of the type of information supplied with the soils engineering map are shown in TABLES I, II and III.

21. The above procedure has been found to be efficient in the preparation of soils engineering maps for planning purposes, but where such a map is required for the materials design for an actual contract project, the procedure has of necessity to be altered to allow for the minimum of delay in the detailed location and testing of borrow pits for construction materials. In such cases the planning of the field work is varied as described below while, in addition, the interpreter has available in the field, not only a party which can rapidly obtain any additional information he may require, but also a small mobile laboratory which can carry out preliminary indicator tests on selected samples from various mapping units.

TABLE III

POSSIBLE BORROW PITS

Strip	Photo Number	Possible Borrow Pit Location	Material	Use	Remarks
6	2058	1	Residual Rhyolite	Subbase	Material plastic near surface but quality improves with depth.
6	2058	2	As above	Subbase	As above
6	2058	3	As above	Subbase	As above
5	2108	4	Hillwash and residual rhyolite	Subbase	See test results
4	2483	5	Residual Rhyolite	Subbase	Material probably improves upslope
9	1915	× (off area mapped)	Coarse Chrystalline Basalt	Basecourse and chips	Amygdale free material, suitable exposure for quarry face

For precise field location use aerial photographs from Job 442 in conjunction with soils engineering map.

22. Under these circumstances, as soon as the interpreter has made a preliminary assessment of the possible sources of materials as described in (d) and (e) above, under the guidance of the engineer responsible, desirable spacing of borrow pits is agreed upon. Several of the most promising sources of materials are then selected and pinpointed on a spare set of airphotos. The field party can now leave and commence sampling and testing possible sources while the interpreter commences his stereoscopic study. He does not carry this interpretation as far as indicated in (f) above but follows the field party a short time afterwards, having allowed sufficient time for the field party to obtain much valuable information. He then continues his stereoscopic study in the field, making use of the findings to date and

indicating further possible sources of construction material. In this way, annotation of the photographs and an inventory of the available materials proceeds hand in hand. The interpreter can then leave the field before the full materials investigation is complete having a party in the field to whom he may send individual airphotos on which he has marked any locations from which he requires more detailed information, thus obviating the necessity for a further field trip.

ENGINEERING BENEFITS DERIVED FROM THE USE OF SOILS ENGINEERING MAPS

23. It should be obvious that the use of the above techniques will enable the location and testing of construction materials to be proceeded with in a logical and preplanned manner which will not only result in a high degree of efficiency but also ensure that, as far as is possible, all possible sources of supply have been located and tested. It follows too, that the existence of a detailed picture of the materials availability and the characteristics of the in-situ soils, allows a more accurate assessment of the problems that may be encountered to be made, thus leading to a possibly more efficient final route location. This aspect is most marked in areas where potential slope instability may occur as the location and mapping of such areas forms an integral part of the study. But this is not the complete picture and experience has revealed several unexpected benefits not envisaged in the original concept of an efficient materials survey.

24. An unexpected dividend has, on several occasions, been reaped by an intelligent study of the soils engineering map and its accompanying reports by contractors who plan to tender for the construction of the project. The availability of a complete picture of the soils and materials position along the entire project has, in such instances, allowed the contractor to preplan his works programme so as to balance his requirements for short and long haul earthmoving equipment and thus reduce his unit rates. In arid areas too, the availability of the map has allowed the contractor to plan his desirable water points and obtain the assistance of the interpreter in locating possible borehole sites in reasonable proximity to his desired location. But possibly the greatest unexpected benefit that has accrued from the production of soils engineering maps has been its value for communication purposes on construction projects.

25. The soils engineering map presents, on the spot, a valid picture of the materials and soils position. This picture is available in the field office and the head office of all parties concerned. When unexpected difficulties arise, their location can be pinpointed on the map and, in many instances, the problem resolved by telephone without the necessity for a hurried field trip to a remote area of the country.

26. It has been shown above, that the development of soils engineering mapping in South Africa arose out of the development of an efficiently designed highway system. It is considered, however, that the principles involved can apply to the bulk of civil engineering development. In many instances, such endeavour will not require the full detail shown on a soils engineering map but the desired information can be readily and efficiently obtained from airphoto interpretation. For example, on a recent railroad project, where route location and grading were dictated by other factors, a partial study was undertaken and a partial map produced which depicted areas of potential slope instability, areas of potential seepage problems and areas of potentially erodible soils. This map was sufficient for the users' requirements but, at the same time, much additional information of value was automatically obtained which could be fed into an established data storage system.

CONCLUSION

27. It is apparent that an acceptable system of terrain classification and data storage must automatically lead to the more efficient planning of developing areas. Such a system is vitally dependent on the quality and validity of the information fed into the system. In the long term view, it is not difficult to envisage that vital civil engineering information could be retrieved from such a system but in the short term view, development must proceed. The authors believe that in the overall global view far too much emphasis has been placed on the long term picture of terrain classification and data storage to the neglect of the short term project level approach. It is believed that the approach described above provides valuable information in a form that could be readily recorded in any agreed form of classification and data storage and provides a valuable tool to the civil engineer while the overall picture is being clarified.

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Rock excavation in a cut section, Mexico.

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NATIONAL RESEARCH COUNCIL

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CONTENTS

DEVELOPMENT OF GEOPHYSICAL METHODS OF SUBSURFACE EXPLORATION IN THE FIELD OF HIGHWAY CONSTRUCTION

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Since 1933 the Bureau of Public Roads, through its Physical Research Branch, has had in progress a study of geophysical methods of exploring the substrata as applied to highway engineering problems, including the development of instruments and of methods of interpretation of the data obtained. Early developments were reported in papers published in 1935 (15)[1] and in 1936 (17). Both earth resistivity and refraction seismic apparatus were adapted or developed for use in the shallow subsurface explorations usually associated with highway construction. Special attention was given to the necessity for portable units capable of being transported by hand into areas where reconnaissance surveys might be required. Figures 1 and 2 show respectively the seismic equipment and earth resistivity apparatus now in use.

A large amount of data has been obtained by the Bureau of Public Roads with this equipment applied to such problems as slope design, classification of excavation materials on grading projects, foundation studies for bridges, buildings and other structures, investigation of tunnel sites, location of sand, gravel, solid rock and special soils for use in construction, determination of depth of peat and muck in swampy areas, and studies of existing and potential slide areas.

These field studies have been carried out in the following States: Washington, Oregon, California, Montana, Idaho, Colorado, Arkansas, Missouri, Iowa, Michigan, New York, Connecticut, New Hampshire, New Jersey, Pennsylvania, Maryland, Virginia, North Carolina, Tennessee, Georgia, Florida, and in the District of Columbia.

In general, the data obtained have shown that both the seismic and the resistivity methods of test have merit, particularly as rapid and relatively inexpensive methods of exploration for use in preliminary surveys. As a result of demonstration work done in the States of New York, Connecticut and New Hampshire, the Corps of Engineers, US Army, adopted the seismic test as a more or less standard procedure in preliminary subsurface explorations in connection with investigations of possible dam sites for flood control. Hundreds of dam sites have been investigated by this method since the latter part of 1938 (19, 21, 23).

World War II caused curtailment of the use of the geophysical methods of exploration with the general decrease in civilian construction, but an increased interest is being manifested at the present time. The New York Department of Public Works has purchased equipment of both types and has assigned personnel to a continuing program of geophysical test as a part of a regularly instituted program of subsurface exploration. The geophysical work has been in progress since the early part of 1948, and it is hoped that reports of the successful application of both seismic and resistivity tests to the solution of construction problems within the State of New York will be made available in the near future. The Pennsylvania Turnpike Commission has kept two earth resistivity parties in the field since July 1948 in a systematic resistivity survey of well over 100 mi. of right-of-way for extensions to the present Turnpike system. The Michigan State Highway

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[1] Numbers in parentheses refer to a list of references at the end of this paper.

Department has purchased resistivity apparatus for use in locating construction materials and on other construction and maintenance problems of that State. The Massachusetts Department of Public Works has had in progress since 1944 a program involving the use of refraction seismic tests in studies of highway grading projects and structure sites in Massachusetts. A report on this work was made at the 27th Annual Meeting of the Highway Research Board (29). The States of Wisconsin, Minnesota, Missouri, California, Texas and Illinois have each had some experience in the application of earth resistivity tests to highway construction problems (5, 9, 10, 14). The State highway departments of Georgia and Arkansas have expressed an active interest in an early application of earth resistivity tests to construction problems peculiar to their respective States.

With this brief summary of the present status of geophysics as an integral part of our highway construction program, it may be of interest to review briefly the theoretical aspects of the two methods of test and to consider in more detail their application in the field.

BRIEF DISCUSSION OF THE THEORY INVOLVED IN THE GEOPHYSICAL TESTS

Refraction Seismic Test[2] - The seismic method of subsurface exploration consists of creating sound or vibration waves within the earth, usually by exploding small charges of dynamite buried three or four ft beneath the surface, and measuring the time of

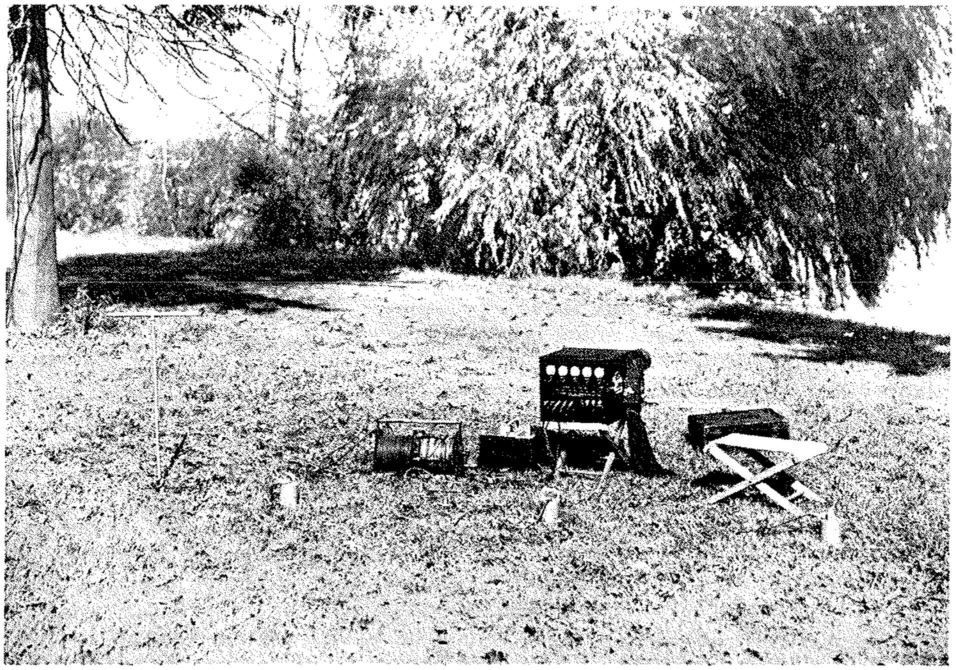

Figure 1. Refraction Seismograph Developed by the Bureau of Public Roads for Use in Shallow Subsurface Explorations

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[2] For a more detailed description of the apparatus see reference 15, and for additional discussion of the interpretation of refraction seismic data, together with their application to various field problems see references 19, 21 and 23.

travel of these waves from their point of origin to each of several detectors placed at known distances from the source. The variation in mechanical energy transmitted to the detectors, or "seismic pick-ups" are converted into variations in electrical energy which, in turn, are used to deflect light rays reflected from small mirrors that are a part of sensitive galvanometers and these deflections are recorded photographically on rapidly moving film. Electrical circuits are so arranged as to obtain one impulse at the instant of firing the shot and another as the first wave reaches each detector. Figure 3 shows typical seismic records, the small break in the righthand trace on each film indicating the start of the wave and the three separate breaks in the three traces on each of the films shown indicating the arrival of the wave front at each detector. The space between the transverse lines on the film corresponds to a time interval of 0.005 sec. It is usually possible to estimate to one-tenth part of this time interval.

Figure 2. Apparatus Used by the Bureau of Public Roads in Shallow Earth-Resistivity Operations

The time lines are placed on the film by means of a suitably placed light source and a tuning fork operating at 100 cycles per sec and equipped with thin phosphor-bronze plates on each tine having narrow slots which cause 200 flashes of light to reach the film during each sec of time.

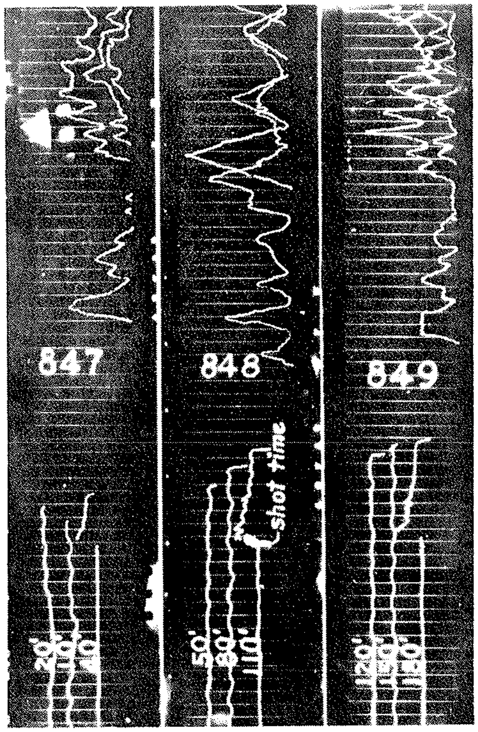
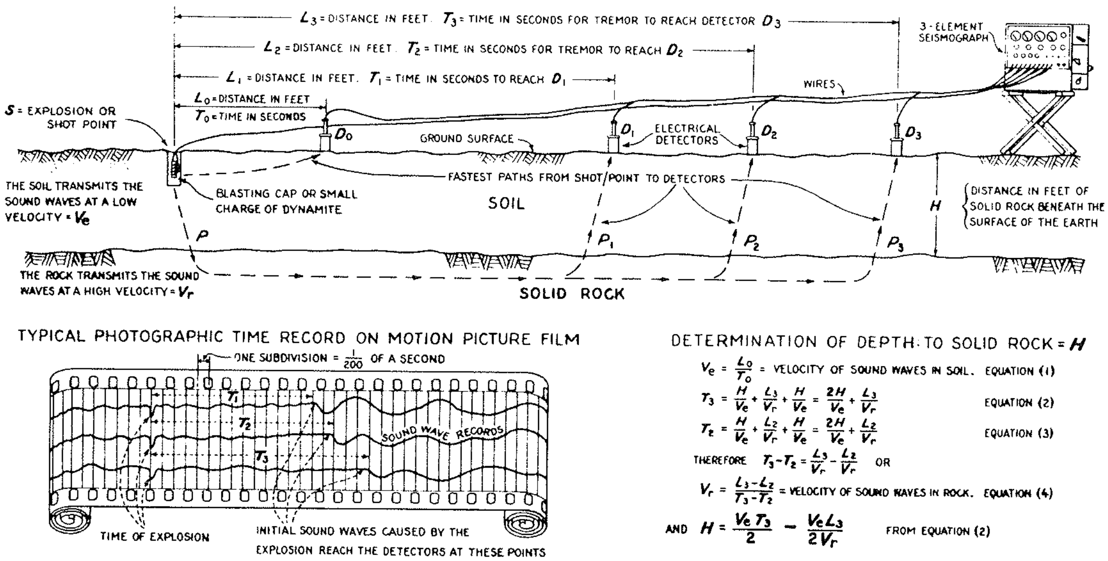


Figure 3. Typical Seismic Records - Note: For clarity in illustration the light traces were inked in before this print was made.

The time data obtained from film records and the measured distances along the ground surface, between the shot point and the detectors, are plotted in the form of time-distance graphs from which the depth and probable character of the various subsurface formations are determined. Wave velocities range from approximately 600 ft per sec in light, loose soils to about 18,000 to 20,000 ft per sec in dense solid rock. This wide range in wave velocities makes possible determination of the general character of the materials encountered and by use of simple formulas the average depth to the various substrata can be calculated. A knowledge of the local geology helps materially in a more accurate identification of the formations encountered.



DETERMINATION OF DEPTH TO SOLID ROCK = H

$$V_e = \frac{L_0}{T_0} = \text{VELOCITY OF SOUND WAVES IN SOIL.} \quad \text{EQUATION (1)}$$

$$T_3 = \frac{H}{V_e} + \frac{L_3}{V_r} + \frac{H}{V_e} = \frac{2H}{V_e} + \frac{L_3}{V_r} \quad \text{EQUATION (2)}$$

$$T_2 = \frac{H}{V_e} + \frac{L_2}{V_r} + \frac{H}{V_e} = \frac{2H}{V_e} + \frac{L_2}{V_r} \quad \text{EQUATION (3)}$$

$$\text{THEREFORE} \quad T_3 - T_2 = \frac{L_3}{V_r} - \frac{L_2}{V_r} \quad \text{OR}$$

$$V_r = \frac{L_3 - L_2}{T_3 - T_2} = \text{VELOCITY OF SOUND WAVES IN ROCK.} \quad \text{EQUATION (4)}$$

$$\text{AND} \quad H = \frac{V_e T_3}{2} - \frac{V_e L_3}{2 V_r} \quad \text{FROM EQUATION (2)}$$

THOD.

Figure 4. Sketch Showing Fundamental Principles of Seismograph Method

The theory of refraction shooting and the derivation of approximate working formulas for depth determinations are shown in Figure 4. These equations, as will be seen, are developed on the assumption that the path of the seismic wave is vertical from the shot point to the rock or other dense stratum, thence along the rock to a point directly beneath the detector and thence vertical to the detector. Although this assumption gives satisfactory values for the shallow depths involved in most highway problems, it is preferable to use a more exact formula for tests to greater depths such as are encountered in exploring locations for dams and certain other structures. The derivation and application of these formulas may be found in published papers (18, 19) and will not be discussed further.

Although four detectors are shown in Figure 4 to better illustrate the wave travel for short distances involving the low velocity soil and the longer distances in the rock stratum, only three detectors are required for the three-channel seismograph used by the Bureau of Public Roads. The usual procedure when using this type of equipment is to place the three detectors on the ground in a line and at intervals of 25 to 50 ft apart. Shots are then fired successively at increasing distances along the detector line extended, beginning with a point 10 or 15 ft from the center detector and extending the shooting distances by increments to some greater value as, for example, 50, 85, 125, 165, 225 and 300 ft from the center detector. There is an approximate relation between shot distance and the effective depth of the test such that this depth is about equal to one-third the shot distance. The relation depends somewhat on the relative wave velocities in the materials involved. If the depth to rock were more than about 80 ft, additional shot distances greater than the 300 ft mentioned above would be required to adequately show a rock formation. A duplicate line of shots is usually placed in the opposite direction from the center detector to expand the data to allow depth determinations to be made when the interface between the overburden and the rock is not parallel to the surface but on a slope.

A theoretical time-distance curve is shown in Figure 5. As shown, a straight line through the origin will result so long as a uniform homogeneous material comprises the surface layer. The velocity of wave propagation is constant in such a medium and time of wave travel is proportional to travel distance. The reciprocal of the slope of the line, OC, passing through the origin, represents the velocity in the medium, since velocity is equal to distance divided by time.

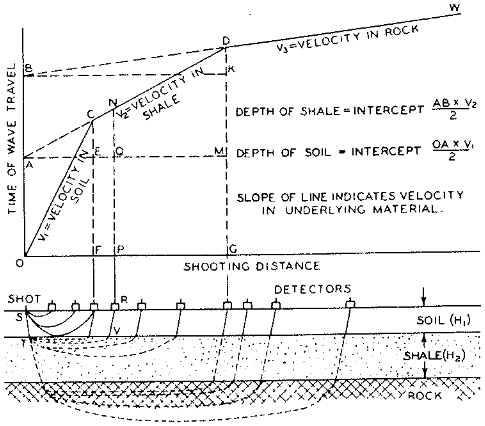


Figure 5. Time-Distance Curves from which Soil Profile Determinations are Made

If, at some greater depth, a second layer of homogeneous material of greater density is present, such as that designated as shale, there will be a point, F, at which there is a simultaneous arrival of a slower wave through the less dense surface soil and one traveling over the longer but faster route along the top of the shale stratum. Beyond this "critical distance", OF, a new slope, CD, exists, the reciprocal of which represents the faster wave travel in the shale, and for a path, STVR, the time, PQ or OA, is that required for the wave to travel through the surface soil from S to T and again from V to R. QN represents the time of travel from T to V in the shale. If H_1 is the thickness of the surface soil , we have the relation:

$$H_1 = V_1 \times \frac{OA}{2}$$

Similarly, for a third layer having an even greater density, such as that designated as rock, there will be a second "critical distance". OG, and a second break in the curve to a new slope, DW, the reciprocal of which will give the velocity in the rock. The time intercept MK or AB in this instance represents the time required for the wave to travel down through the shale and back again. If H_2 is the thickness of the shale then:

$$H_2 = \frac{V_2 \times AB}{2}$$

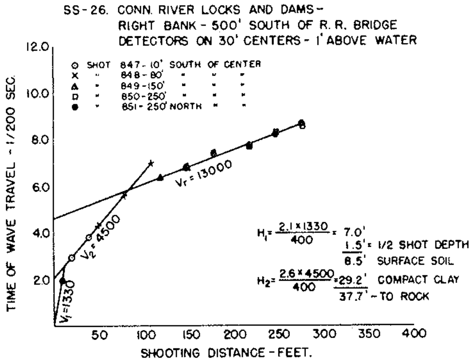


Figure 6. Time-Distance Graph for Seismic Records Shown in Figure 3

Usually in plotting the time-distance data, the time units of 1/200 sec, as taken directly from the film records, are used and the denominator in the foregoing equations becomes 400 instead of 2.

When the geologic conditions existing at a particular test location actually approach those assumed in a theoretical analysis of the data obtained from refraction seismic tests, there is a remarkable similarity between the field curves obtained and the theoretical curve as it appears in Figure 5. This is illustrated by the time-distance curve shown in Figure 6 which was prepared from the field data shown in Figure 3, supplemented by two additional shots placed at greater distances from the detectors. The data for this graph were obtained in New England where a relatively thin layer of loose soil was underlain by glacial till which rested upon solid rock.

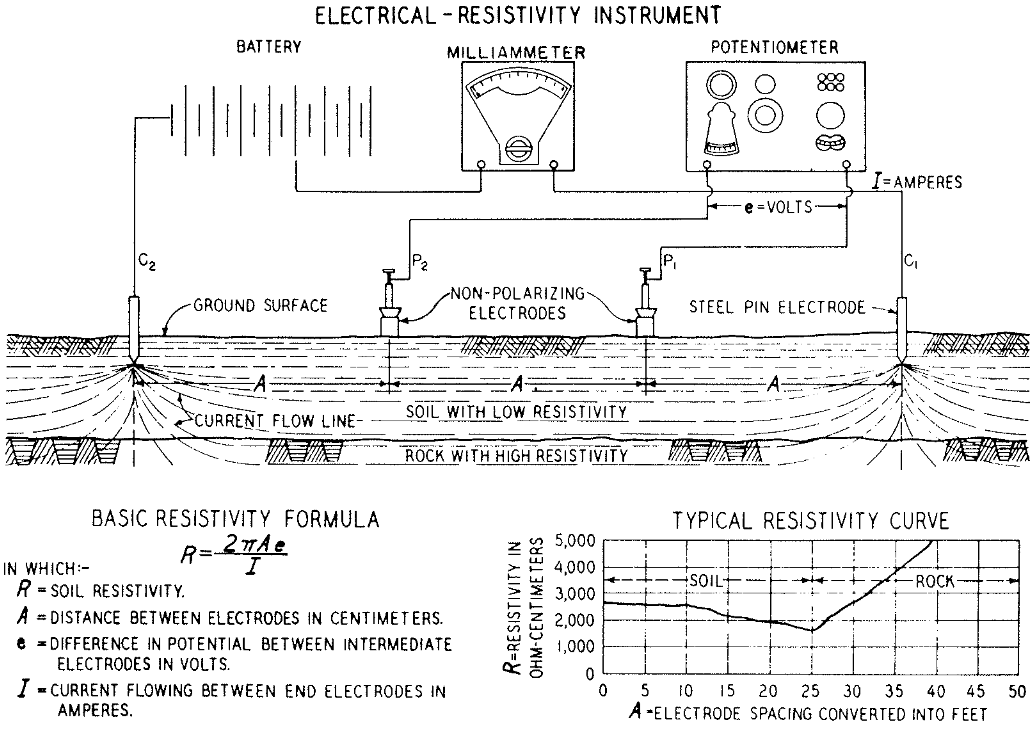


Figure 7.

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Earth Resistivity Method [3] - Experience has demonstrated that many of the materials making up the earth's crust can be identified, in some degree at least, by their reaction to the flow of a direct current of electricity. This is an action of electrolytic nature in which the moisture in the soils and rocks together with the dissolved impurities give to the several materials characteristic resistances to a current flow. These characteristic resistances or resistivities may be used for locating and, to some degree, identifying subsurface formations. Figure 7 illustrates diagramatically the earth resistivity test and the Wenner electrode configuration (1) used by most investigators. In this test a prediction of the character of the subsurface materials is attempted by measurements indicating the magnitude of the resistance to direct current flow. Ordinary moist soils containing moderate amounts of clay or silt with some electrolytic agent more or less active, have a comparatively low resistance. In contrast, sand, gravel, extremely dry, loose soils and solid rock usually have

[3] For a detailed description of the apparatus and a more comprehensive discussion of the earth resistivity method of test see references 1, 3, 7, 15, 25 and 26.

relatively high resistivity values. However, these classifications are too general to be useful and it is very necessary to calibrate the instrument with tests made on local materials which can be identified by exposed faces, test pits, drill logs or other means. Curves obtained later for unknown conditions may then be compared with those for known conditions and a prediction can be made as to the materials lying below the surface.

Referring to Figure 7, an electric current is passed through the ground from a direct current supply, usually one or more radio "C" batteries, using the two outside electrodes. Measurement is then made of the potential drop between two intermediate points symmetrically spaced at the third points between the current electrodes as shown. The current flow is determined with the milliammeter and the voltage or potential drop with the potentiometer, from which the resistivity of the material is computed by use of the formula:

$$\rho = 2 \pi A \frac{E}{I}$$

in which A is the electrode spacing in centimeters, E is the potential drop in volts, and I is the current, in amperes, flowing in the circuit.

There is an empirical relation such that the "effective" current flows within a depth below the surface equal to A. That is to say, if A = 10 ft, the resistivity obtained with the formula represents an average of all material existing with 10 ft of the surface. Thus, as the electrode spacings of the system are expanded the current flow lines encounter the deeper portions of the underlying formations as, for example, a rock formation, as shown. This material, having an appreciably higher resistivity than the overlying soil, affects the average resistivity values, the effect of the lower bed increasing progressively as the test is carried to greater depths.

When using the empirical method of interpretation proposed by Gish and Rooney (2) the apparent resistivity, ρa, obtained by inserting the measured values of A, E, and I, from the field tests in the formula for resistivity as given above, is plotted as the ordinate against the electrode spacing, A, as the abscissa. The inflections in the resulting curve are interpreted as indicating changes in the materials underlying the surface. Where clay overlays rock a curve similar to that shown in the lower right-hand portion of Figure 7 is usually obtained. The depth of the surface soil is taken as the value of A (electrode spacing) at which the upward inflection of the resistivity curve occurs. This empirical solution has been used in analyzing data from many tests in the past. Cases were found, however, where the plotted curve was smoothly rounded with no inflection point, affording no criterion for predicting the depth of the surface material. Another empirical method of analysis has been proposed (25) for interpreting such curves, a brief summary of which follows.

In Figure 8 the smooth rounded Gish-Rooney curve is shown as a dash-line curve determined by the plotted crosses. The same field data are shown below this curve in the form of a cumulative resistivity curve determined by the plotted circles. When the values of apparent resistivity are plotted as a cumulative curve, a straight line or a curved line of gentle curvature is usually obtained so long as the "effective" current flow remains within the surface layer. When the electrode spacing is expanded to include increasing amounts of the deeper lying rock formation the cumulative curve shows an increased curvature upward, reflecting the influence of the higher resistivity of the rock formation. It has been found that straight lines drawn through as many points as practicable on the cumulative curve and intersecting in the region of increased curvature will give a good approximation of the thickness of the surface material if the point of intersection of the straight lines is projected to the horizontal or dimensional axis. This is a purely empirical relation with no theoretical basis whatsoever. It has given rather close approximations of the depth of the surface layer in simple two-layer formations, however.

Referring to Figure 8, it will be seen that the relatively shallow depth of 14.0 ft to rock, as determined by the test pit, affects strongly the measured values of apparent resistivity beyond an electrode spacing of about 10 ft. For this reason the plotted values of cumulative resistivity continue to show a rather marked degree of curvature well beyond what might be termed the "critical point" in the curve. The trend of the Gish-Rooney curve is used to determine the approximate "critical point" which in this curve appears to be at an electrode spacing of 10 to 12 ft. Guided by the indications of the Gish-Rooney curve and such other correlating data as may be available from test pits or borings in the general area, the additional tangent intersections beyond the "critical point" may or may not be disregarded.

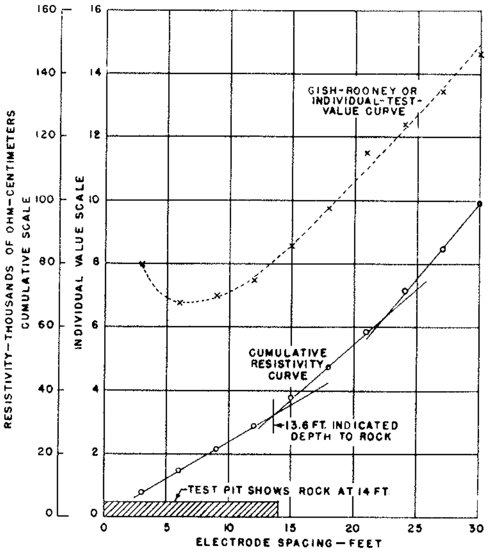


Figure 8. Typical Resistivity Data and Method of Analysis Using the Cumulative Resistivity Curve

Other methods of analysis of earth resistivity data based upon theoretical studies have been presented by Tagg (7), Hummel (4), Roman (6, 22), Wetzel, and McMurry (20), and others. Sets of theoretical curves for various assumed resistivities and thicknesses of materials involved have been prepared for use by the operator as control for interpreting the field curves obtained. In some instances the field data are plotted to the same scale as that used in the theoretical curves and on identical sheets and are superimposed upon the theoretical curves and where a "fit" is obtained the depths of the layers involved as well as the resistivities of each layer are obtained. Attempts to use these methods in analyzing the data obtained in the relatively shallow work done by the Bureau of Public Roads have been discouraging due to the time required for such studies and the frequency with which the field conditions failed to conform to those assumed in developing the theoretical curves. The empirical solutions heretofore described have been found to be more practical from the standpoint of time and cost in connection with a given exploration. This might be, in some cases, a deciding consideration between the geophysical tests and the direct methods of exploration ordinarily used.

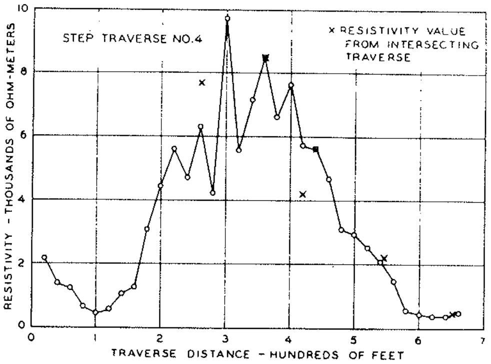
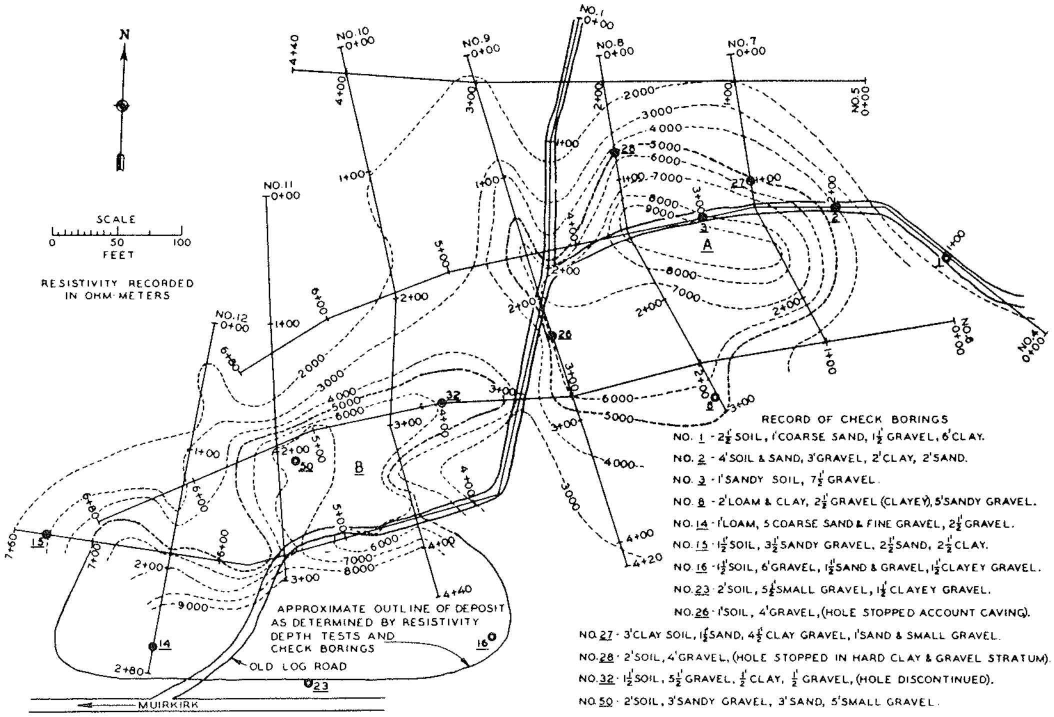


Figure 9. Step Traverse Over Deposit of Sandy Gravel - Electrode Spacing 20 Ft

When making surveys of areas a somewhat different test procedure, one which might be termed the "resistivity traverse" or "constant depth traverse", is often used. In this, a succession of tests using a fixed electrode spacing is made along the selected traverse line, the interval between test sites being equal to the electrode spacing. The measured resistivity values are then plotted as ordinates against traverse distance as abscissas and the resulting graph shows the variation in resistivity along the traverse line for a depth equal to the electrode spacing chosen. A typical example of such data is shown in Figure 9, the rise in resistivity between the 100-ft and 500-ft points on the traverse distance scale indicating the presence of higher resistance material within the depth explored. Traverse lines of this type carried out systematically over an area permit the preparation of a resistivity contour map, such as that shown in Figure 10. Such a map may be of considerable aid in rapidly locating and delineating critical areas that require more detailed study or that contain valuable isolated deposits of granular materials or rock in areas where such materials are scarce.



RECORD OF CHECK BORINGS

NO. 1 - 2½' SOIL, 1' COARSE SAND, 1½' GRAVEL, 6' CLAY.
NO. 2 - 4' SOIL & SAND, 3' GRAVEL, 2' CLAY, 2' SAND.
NO. 3 - 1' SANDY SOIL, 7½' GRAVEL.
NO. 8 - 2' LOAM & CLAY, 2½' GRAVEL (CLAYEY), 5' SANDY GRAVEL.
NO. 14 - 1' LOAM, 5 COARSE SAND & FINE GRAVEL, 2½' GRAVEL.
NO. 15 - 1½' SOIL, 3½' SANDY GRAVEL, 2½' SAND, 2½' CLAY.
NO. 16 - 1½' SOIL, 6' GRAVEL, 1½' SAND & GRAVEL, 1½' CLAYEY GRAVEL.
NO. 23 - 2' SOIL, 5½' SMALL GRAVEL, 1½' CLAYEY GRAVEL.
NO. 26 - 1' SOIL, 4' GRAVEL, (HOLE STOPPED ACCOUNT CAVING).
NO. 27 - 3' CLAY SOIL, 1½' SAND, 4½' CLAY GRAVEL, 1' SAND & SMALL GRAVEL.
NO. 28 - 2' SOIL, 4' GRAVEL, (HOLE STOPPED IN HARD CLAY & GRAVEL STRATUM).
NO. 32 - 1½' SOIL, 5½' GRAVEL, ½' CLAY, ½' GRAVEL, (HOLE DISCONTINUED).
NO. 50 - 2' SOIL, 3' SANDY GRAVEL, 3' SAND, 5' SMALL GRAVEL.

Figure 10. Resistivity Contour Map of a Deposit of Sandy Gravel

INCREASING NEED FOR RAPID AND INEXPENSIVE METHODS OF EXPLORING THE SUBSURFACE

Development during recent years of earth-moving equipment of ever increasing capacity has made possible the removal of huge quantities of excavation materials quickly and economically. However, operating costs of such equipment are high and a reasonably certain knowledge that the equipment selected will be able to handle all or a major portion of the materials on a given grading project, without costly delays from unforeseen adverse conditions, can be extremely helpful to contractors in establishing reasonable unit prices in bidding for the job. A thorough investigation of the subsurface formation prior to design of slopes in cut sections when preparing plans for a proposed roadway will help to avoid the confusion that results when solid rock cuts as shown on the plans actually are found to be soil or other easily removable materials. Such errors in the classification of materials may lead to increased costs and to the necessity for changes in design.

Stoney soil, talus materials and thin but continuous stringers of quartz or other hard materials extending throughout a cut may present insurmountable difficulties when attempting to explore subsurface conditions with hand or power operated auger equipment. Such troublesome conditions, although they may result in misleading data when the auger is used, will not affect the data obtained with geophysical tests to any appreciable extent. For this reason, preliminary surveys by geophysical methods can be used to considerable advantage in determining the overall character of the materials to be excavated and thus avoid errors of the type just mentioned. Complete and dependable information will make unnecessary hurried changes of alinement and grades to care for increased or decreased quantities of excavation materials, with possible delays of construction operations.

APPLICATION OF GEOPHYSICAL TESTS TO HIGHWAY CONSTRUCTION PROBLEMS DESCRIBED

It has been found that both seismic and resistivity methods of test are practical for use in the study of many highway construction problems. The earth resistivity apparatus, by reason of its simplicity of operation and the rapidity with which the shallow tests can be made is believed to have a more universal application than does the seismograph. Accordingly, when making a detailed geophysical survey of a grading project it has been the practice of the Bureau of Public Roads to make a resistivity survey first and, if necessary, to follow with a limited number of check tests with the seismograph in areas where the resistivity data have failed to adequately identify the subsurface formation. This procedure has been applied to 10 highway construction projects ranging from 1-1/2 to 12 mi. in length and located in the States of Virginia, North Carolina, Tennessee, Georgia, Arkansas, Missouri and in the District of Columbia. Reports have been received on four of these which have since been constructed and the conditions found during construction were substantially as predicted from results of the geophysical tests.

The following discussion will deal with the field data obtained with both types of apparatus. The discussion of the seismic method is rather brief in view of its somewhat limited use by the Bureau of Public Roads.

Results of Seismic Tests Described - In general, the velocity of the transmitted sound waves increases with an increase in the density of the transmission medium (soil, rock, etc.). Loose unconsolidated soil layers have wave velocities ranging from 600 to 1,500 ft per sec. More compact subsurface layers range from 2,000 to 9,000 ft per sec with the lower ranges 2,000 to 3,500 usually associated with clay materials and the higher ranges 4,000 to 9,000 with compact gravels, badly broken or weathered rock, and soil-boulder mixtures. Solid rock usually has wave transmission velocities between 10,000 and 20,000 ft per sec, depending upon the type of rock and its degree of weathering or fracture. In predicting the character of material that may be found, particularly in the intermediate velocity group (4,000 to 9,000 ft per sec), considerable judgment, as well as some knowledge of local geologic conditions, is required. Calibration tests over known subsurface formations are essential for a successful interpretation of the data obtained.

Actual identification of the materials involved is not always necessary, however. For example, broken rock or badly seamed rock, a highly compacted shale or a cemented gravel, having similar velocity characteristics, may also be expected to offer similar difficulties in excavation operations, possibly requiring some blasting and special handling and distribution. These same materials will probably show similar load carrying capacities when considered for foundation purposes, particularly where surrounded by materials which have been left in an undisturbed state. As an example, seismic tests made at Lincoln, New Hampshire, at a proposed bridge crossing of the Pemigewasset River, showed a comparatively high wave velocity for material lying only a few ft below the surface and apparently continuing to a depth of at least 40 ft. This material, with a wave velocity of 9,400 to 9,600 ft per sec, was predicted to be a tightly cemented boulder formation with excellent load carrying capacity. Figure 11 shows a view of subsequent excavation being made for one of the piers at this location. The material was so tightly cemented together that only a simple sandbag cofferdam was required. Soundings and drill holes through material of this type would be impossible or made only with great difficulty and at considerable cost.

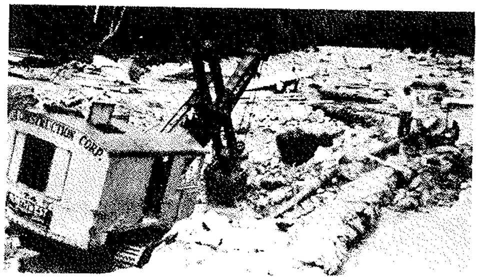


Figure 11. View Showing Tightly Cemented Boulder Formation Predicted from Seismic Tests at Pemigewasset River Crossing Near Lincoln, New Hampshire

Another bridge location, near Crater Lake, Oregon, was investigated by the seismic method in about 3 hr's time and the data obtained showed the subsurface formation to be a very dense material providing a wave velocity of 8,400 to 8,600 ft per sec. Here, again, there could be no doubt regarding the existence of adequate foundation materials. Figure 12 shows the seismic data for two of the three tests made at this location.

Experience is needed to determine the particular slope design that is adequate where certain materials within a local area are involved. With proper calibration data, the seismic method often can be relied upon to establish definitely the presence of the materials. As an example the data in Figure 13 show the presence and depth to the predominant material, shale.

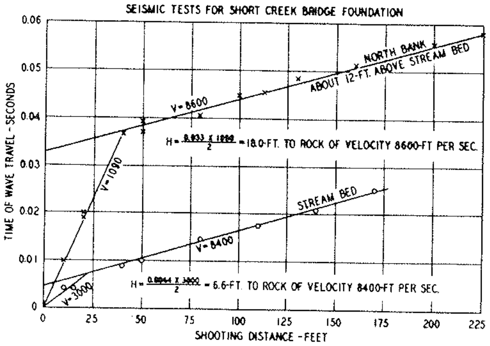


Figure 12. Time-Distance Graph Showing Results of Two Seismic Tests Made in Vicinity of Crater Lake, Oregon, While Investigating a Bridge Site on Short Creek

As mentioned previously, portability of equipment is of primary importance to the successful application of geophysical methods of test in preliminary surveys for a highway location. Figure 14 shows a view that is more or less typical of much of the terrain that is sometimes encountered in the construction of National Park and National Forest roads in various parts of the country. In designing for a modern highway through such country any information regarding the materials likely to be encountered in excavating cut sections is important. A close balance of quantities must be maintained in the interest of economy and of preserving the natural scenic beauty of the area. Unsightly borrow or waste areas are to be avoided. Therefore, a design prepared for solid rock with its 1/4 or 1/2 to 1 slopes in a cut section, such as the one shown in Figure 14, could lead to embarrassing difficulties should a comparatively loose earth or talus material be encountered. Should that happen a 1-1/4 or 1-1/2 to 1 slope reaching high up the mountainside would be required with large quantities of material to be wasted or cared for by substantial changes in alignment and grade. Conversely, where earth slopes are expected and rock is found a source of borrow would be required for adjacent large fills unless major grade changes were made.

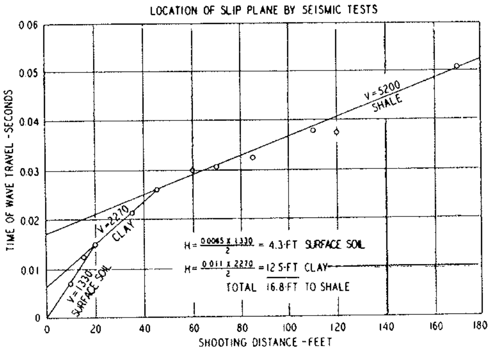


Figure 13. Refraction Seismic Test Over a Shale Formation

The ridge from which the photograph shown in Figure 14 was taken had been originally assumed to contain solid rock. A tunnel several hundred ft in length was proposed to carry the roadway through the ridge, some 100 ft below the top. Test pits dug to obtain design data for portal construction failed to encounter rock above grade. Several weeks were required for this exploration work which cost hundreds of dollars, and finally a redesign for an open cut was found necessary. Seismic tests requiring no more than two or three hr's time were sufficient to adequately establish the fact that no solid rock existed in the hill. The excavation during construction was made with the usual heavy earth-moving equipment. Studies made with seismic equipment at other sites have been of value in portal design and in indicating the probable need for lining in the tunnel.

Another problem to which refraction seismic equipment has been applied occurs in regions where slide conditions are prevalent. In some cases the loose talus material frequently involved in a slide rests upon a sloping shale formation which constitutes the sliding surface. This talus material has velocity characteristics differing from those of the more compact shales, making possible the location of the plane of separation.

Figure 14. Rugged Construction Conditions for Highway Through National Forest Area in Oregon

Although the refraction seismic test has proved of value in preliminary surveys in various phases of highway construction, as has been pointed out, it has not been used to the same extent as the earth resistivity test in recent years because of the greater time required for a seismic test. Six or 8 seismic tests per 8-hr day is about the max number to be expected and under some field conditions even this number is not possible. Fifteen to 20 resistivity tests are usually possible under similar field conditions. Seismic tests can be utilized as a completely independent check of the indications of the more rapid resistivity tests, however, and are used for this important purpose in the routine work done by the Bureau of Public Roads.

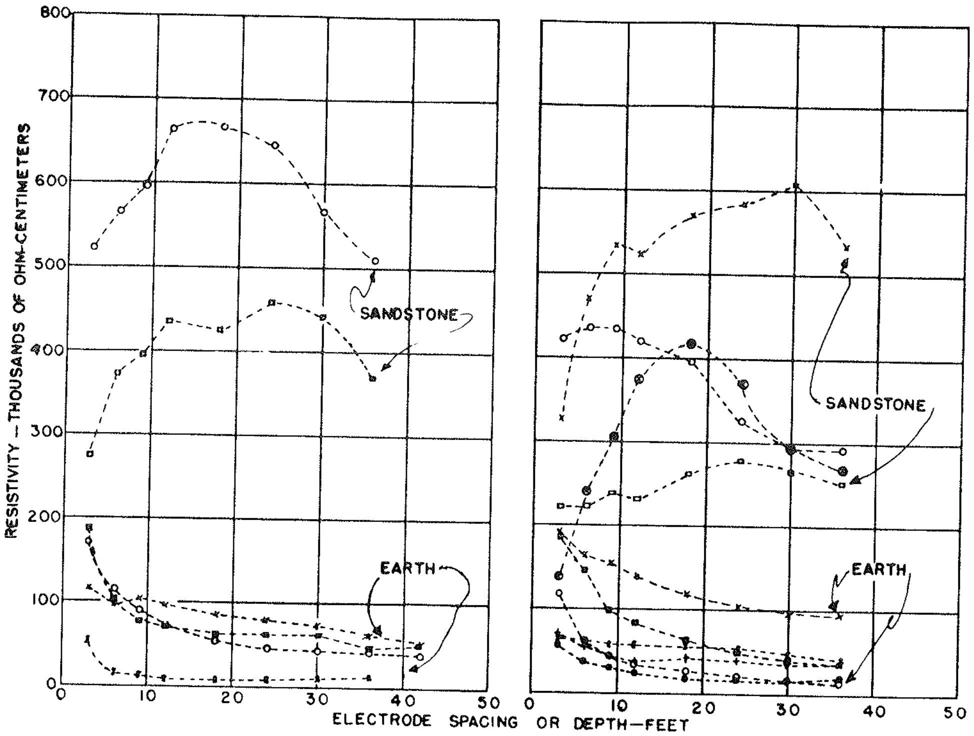


Figure 15. Resistivity Calibration Curves (Left) and Typical Field Curves Obtained in the Ozark National Forest Near Russellville, Arkansas

Earth Resistivity Tests Applied to Highway Grading Projects - In a subsurface survey in the field it is an established procedure to make calibration tests with the resistivity apparatus over exposures of formations believed to be typical of those in the area of immediate interest. Resistivity curves for the known conditions are then used for comparison with curves obtained over unknown conditions elsewhere in the area. From these comparisons reasonably accurate predictions can be made regarding the materials to be encountered below the surface and their location. Figure 15 shows typical resistivity curves obtained in Arkansas, in the Ozarks National Forest, in the course of a resistivity survey of about 22 mi. of proposed roadway. The calibration curves on the left were obtained for heavy sandstone ledges interbedded with shales and for the soils and decomposed shales typical of the region. These latter are materials that could be handled with the heavy self-loading carryall scraper. Those curves of the right-hand graph are examples of the field curves obtained in the survey along the right-of-way of the proposed roadway. Little difficulty would be experienced in predicting the type of materials involved for the several curves shown. Figure 16 shows views of the two general types of material over which calibration tests were made.

Based upon the usual methods of direct exploration, the original slope design called for rock slopes over a considerable portion of the right-of-way. Actually, earth conditions, as predicted from the results of the resistivity survey, were found in a majority of the cuts during the construction of about 14 mi of roadway thus far completed.

The entire 22 mi was investigated in about 12 working days, one 8-mi project being covered in 3-1/2 days.

In northwest Georgia, resistivity calibration tests over solid rock and over earth formations produced curves as shown in the left and in the lower right-hand graphs, respectively, of Figure 17. Here again, although the shapes obtained are quite different from those obtained for materials of the same general classification in Arkansas, the two materials, rock and earth, can very easily be distinguished one from the other. On the basis of these calibration data, the typical field curves shown in the upper right-hand corner were all interpreted as "earth" curves representing materials easily removed by self-loading "pans". Figure 18 shows the two types of material over which calibrations were made.

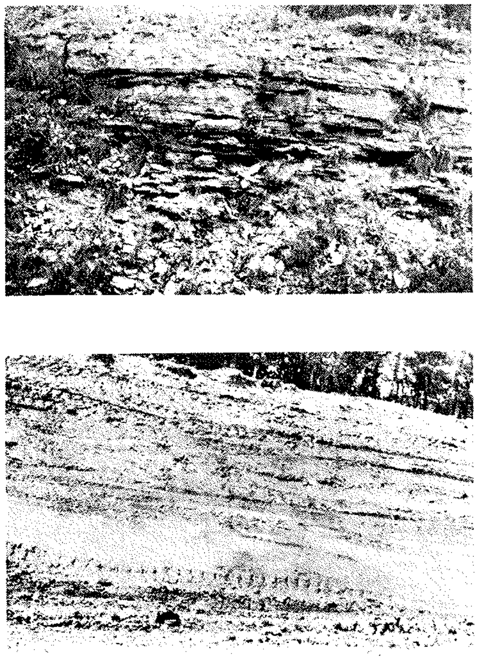


Figure 16. Views of Locations Where Resistivity Calibration Tests Were Made Over Rock (Upper) and Earth in Arkansas

In the Great Smoky Mountains National Park in western North Carolina, the dense granite rock formations typical of that area weather into a highly micaceous decomposed rock material that can be removed with self-loading "pans". As shown by the calibration curves presented in Figure 19 (solid line curves), this material has an extremely high resistivity, 1,500,000 ohm-cms, which is 10 times as great as resistivities found in some solid rock in other parts of the country. Due to the fact that the parent rock in a solid unweathered state has even higher resistivities (4,000,000 to 5,000,000 ohm-cms), it is again possible to differentiate between "earth" and rock excavation. The appearance of the materials over which the calibrations were obtained is shown in Figure 20. That section of the Blue Ridge Parkway on which the resistivity survey was made has not yet been built and no confirming correlations are available at the present time.

In southeast Missouri, the porphyry rock found in the vicinity of Farmington has a resistivity as indicated by the upper curve of Figure 21, while a calibration test over the soil common in the same area produced the lower curve of the figure, indicating almost no resistance to direct current flow. No difficulty was encountered in determining the type of material present in all but one cut of all those investigated on a 4-mi project.

Other resistivity surveys on construction projects in Tennessee, Virginia, Maryland, and in the District of Columbia have developed information regarding the subsurface formations that has been found to agree closely with conditions as actually found during construction.

Resistivity Tests Applied to Foundation Problems - Earth resistivity tests can be of assistance also in a subsurface study of the foundation conditions existing at proposed building sites, bridge locations, and in other areas where solid rock foundations are required or desirable.

In 1942, at the request of the Navy Department, a resistivity survey was made of a 150-acre tract at Carderock, Maryland, where a model testing basin is situated. The site is underlain with rock and information was desired as to the depth to rock throughout the reservation. Altogether, over 500 depth tests and upwards of 10-1/2 mi of constant-depth resistivity traverse were made in carrying out the survey. From the information obtained a rock contour map, shown in Figure 22, was drawn up showing rock elevations on 2-ft contours over the entire area. An accuracy of ± 2 ft at any point in the area mapped was predicted. In 1944 an existing building with a width of 120 ft was extended for 1,800 ft in the area that had been mapped. Cross sections of the rock surface as found, obtained at intervals of 10 ft, along the building axis, showed a difference in total amount of stripping of less than 6 percent from that computed from the rock contour map prepared in 1942. About 100,000 cu yd of stripping were involved.

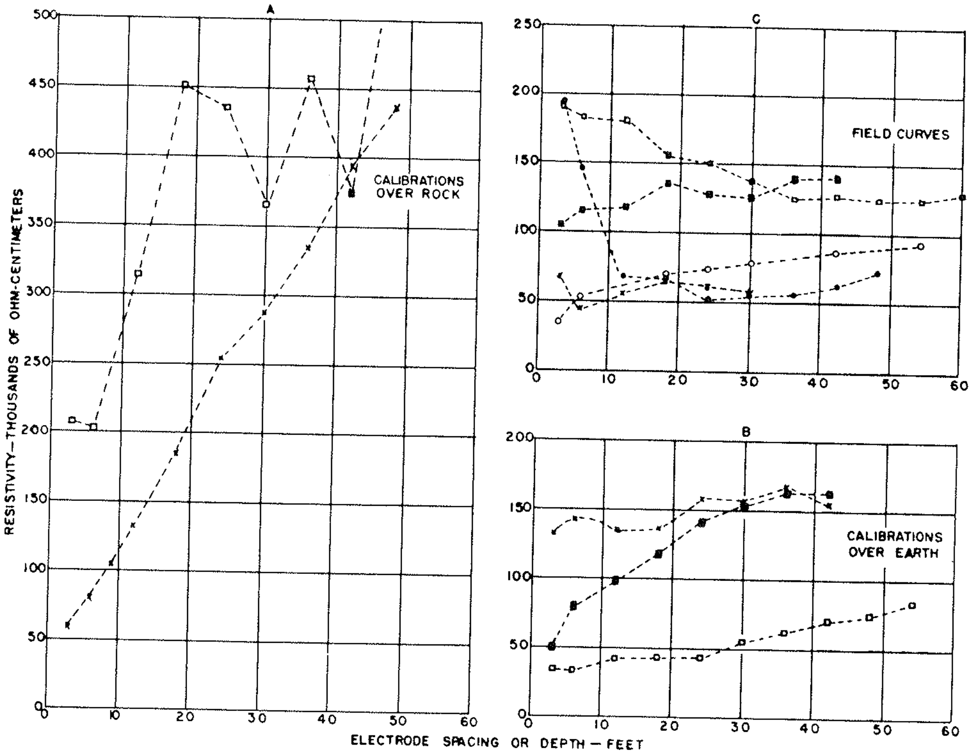


Figure 17. Resistivity Calibration Curves Obtained Over Earth and Rock Formations in Northwest Georgia and Typical Field Curves Obtained on Proposed Road Project North of Marietta

Figure 23 shows typical traverse data obtained in this study and it illustrates how the resistivity test can be used in a preliminary survey to obtain information that may be used to guide a detailed survey by borings and eliminate many unnecessary soundings or borings. The flat-lying portion of the curve suggests a uniform condition for much of the distance traversed. The peaks in resistivity indicate those areas where direct borings should be concentrated to delineate in detail the obvious anomaly. These buried ridges of rock can be traced across wide areas, indicating regions where excavation will be difficult or where foundation conditions will be excellent at shallow depth. The figures shown underlined are depths to solid rock obtained by resistivity depth tests made at 100-ft intervals along the line of the traverse. The two depth curves shown in the inset are a striking indication of radical changes in the subsurface at stations 2+00 and 13+00 of the traverse.

In bridge foundation studies there have been numerous instances when the routine subsurface survey using the usual methods of probing, wash boring, etc., has failed to disclose unusual conditions later found during construction. Piers designed originally for solid rock foundations have had to be carried to considerably greater depths than those shown on the original plans, or supported upon piling extending to rock at a lower elevation. Figure 24 shows several resistivity depth curves obtained in a post-construction survey of a bridge crossing of the Flint River in southwest Georgia. The individual graphs show the plan data for depth of rock, the depth to rock as found during construction, and the depth to rock as predicted from the resistivity data. The general agreement between the results of the resistivity tests and the actual conditions existing is apparent.

Although it is not possible to make an unqualified statement regarding the effectiveness of the resistivity test generally in all localities and under all possible combinations of geologic formations, the fact remains that one or two hr's work at a particular location will usually determine the extent of its usefulness in solving the particular problem at hand. The data from the tests made in Georgia are similar to those that have been obtained elsewhere

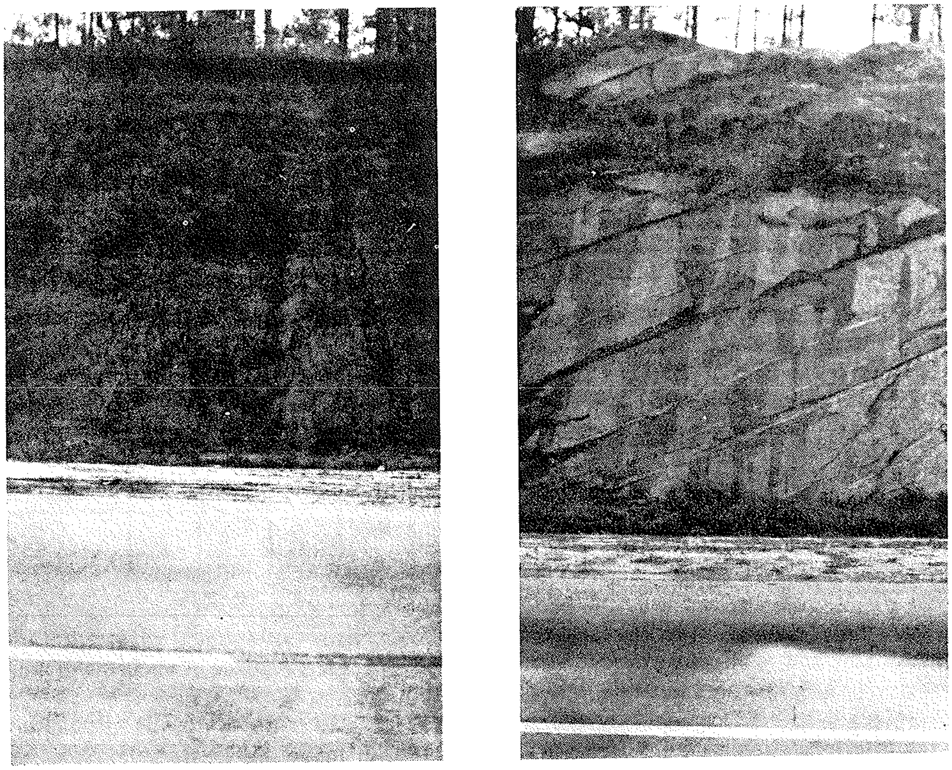


Figure 18. Locations of Resistivity Calibration Tests Made Over Earth and Solid Rock Formations in Georgia

in areas where the river deposits have shown resistivity characteristics differing from that of an underlying rock formation.

Resistivity Tests over Peat Bogs and Swampy Areas -The investigation of swamps, peat bogs and salt marsh areas by geophysical tests constitutes what might be termed a marginal application of such methods since simple probings are often effective in such areas. However, since a resistivity depth test to depths of 60 ft can be made in a period of 12 to 15 min, the deeper muck deposits can be studied economically in competition with direct probings. Where sand lenses are likely to be present within a relatively deep layer of muck or peat, probings can result in erroneous information, being stopped by relatively thin sand layers. The resistivity test, due to the large volume of material involved, will not be appreciably affected by thin sand lenses and will indicate depth to a true bottom formation.

The curves shown in Figure 25 were obtained in a study of the application of resistivity tests to determine the depth of peat bogs. This study, carried out in Michigan in 1941, confirmed earlier test results obtained in a study of peat formations in Wisconsin and reported on by Kurtenacker (9, 10) and demonstrated that resistivity tests can be used successfully in determining the depth of peat and muck layers.

Figure 26 shows results of a resistivity survey along a taxiway at the National Airport, in Arlington County, Virginia, just south of Washington, D. C. The resistivity tests not only indicated the bottom of the floating sand-gravel fill upon which the taxiway was placed, but they also rather effectively located a second horizon comprising the sand and gravel bed of the river.

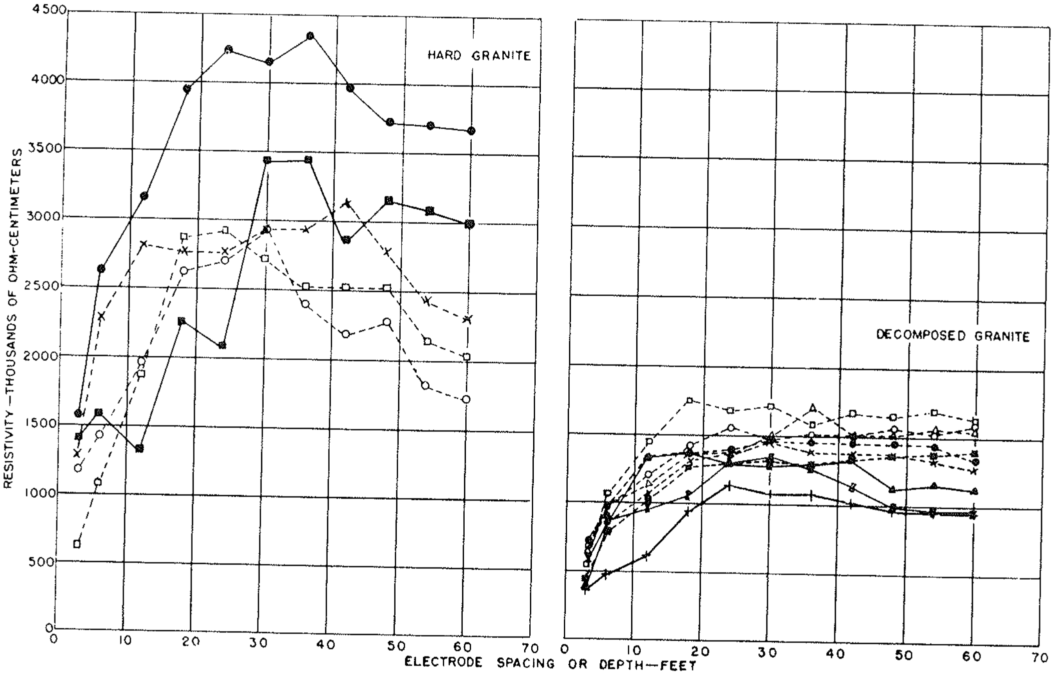


Figure 19. Resistivity Calibration Curves and Typical Field Curves Obtained Over Solid Granite and Over Decomposed Granite (Earth) in Great Smoky Mountains National Park in North Carolina - Field curves are shown by broken lines, rock curves on left, earth curves on right.

The conditions as they exist were determined by the auger holes shown in the figure. It is of interest to note the resistivity peaks occurring in the 10-ft depth resistivity traverse, shown in the lower portion of the figure, which coincide with the thicker portions of the granular fill. Even the small difference of a few ft in the overall depths of the muck from place to place had caused differential settlement sufficient to affect the pavement of the taxiway.

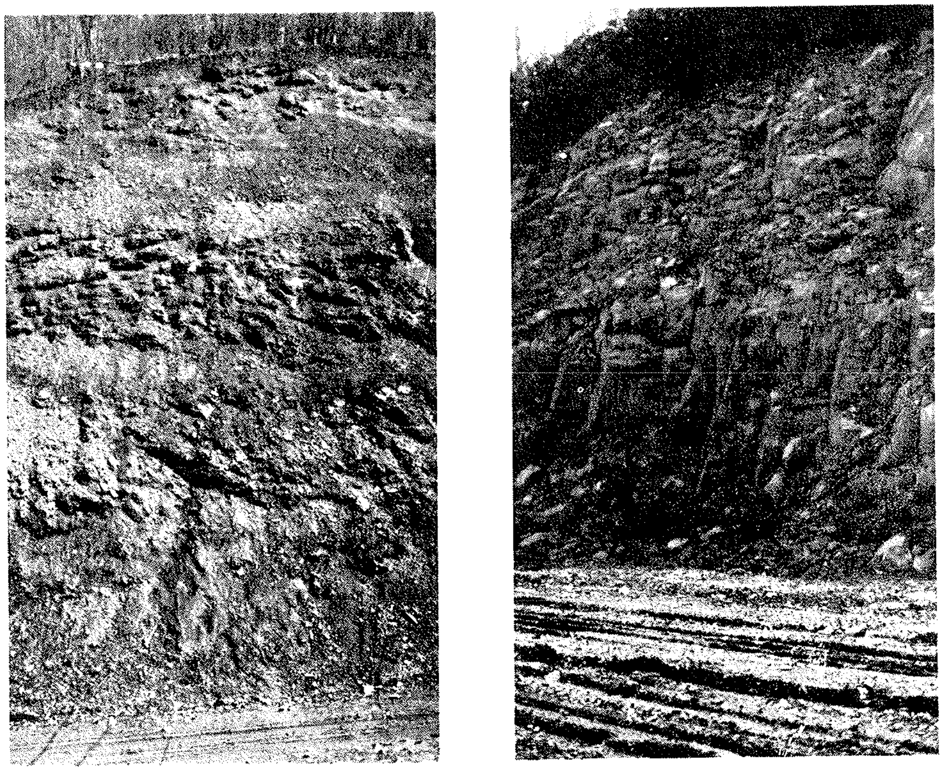


Figure 20. Views of Resistivity Calibration Test Locations on North Carolina Project Involving Earth Excavation and Solid Rock

Knowledge of Local Geology Essential to an Intelligent Interpretation of Resistivity Data - Just as with the seismic test, a working knowledge of the local geology is necessary when attempting to predict the actual character of the materials below the surface as indicated by resistivity tests. Figure 27 shows two resistivity traverses, the upper one made over a rock ridge rising almost to the surface, the lower one made over a sand and gravel deposit. The similarity of the two curves might lead to error in predicting the type of material without at least a general knowledge of the local geology. The depth tests shown on the right of Figure 27, however, offer some clue as to the actual material involved. Usually when a solid rock formation is present beneath a soil overburden a sharply rising curve is obtained similar to the curve shown in the upper right-hand graph. The dipping curve shown in the lower right-hand graph for the sand and gravel formation suggests to the experienced operator, acquainted with the local geology, that such a formation is likely to be present. However, curves of this same general type, obtained, for example, in Arkansas might involve a sandstone ledge underlain by decomposed shales. Or, in southwest Colorado a curve of this type might be obtained with talus material overlying low resistivity shales. It is necessary to depend upon a study of local geology and upon calibration tests over exposed materials in the same region when attempting a classification of the materials involved.

In Pennsylvania, a depth test was made at the location of a proposed drill hole in an investigation of foundation conditions for a bridge to carry the Pennsylvania Turnpike across the Susquehanna River. The depth test data indicated a definite change at a depth of 27. 0 ft as shown in Figure 28. The consultant geologist suggested that the underlying formation might be shale. The data for this curve were obtained in about one hr's time. In contrast, a drill crew, starting simultaneously with the resistivity test, spent 2-1/2 days in reaching the shale at 26. 5 ft.

ADVANTAGES AND LIMITATIONS OF THE GEOPHYSICAL METHODS OF TEST

The seismic test is particularly useful for determining the presence or absence of dense solid rock. The high velocity usually associated with such formations makes the determination quite dependable. Although the resistivity test will, in most instances, indicate a depth of overburden to a high resistivity formation, such as rock, it cannot, in the absence of confirming geologic data, furnish a completely dependable basis for predicting the presence of rock in all cases. As has been shown, sand and gravel under special conditions can have reasonably high resistance and show subsurface anomalies quite similar to those shown by solid rock. However, in areas where solid rock layers are interbedded with less dense materials such as shales, as occurs in Arkansas and in many other areas, the resistivity test is much the better tool since it is possible to detect the change from hard rock to softer, less resistant shales. The seismic test under such geologic conditions would be limited to an indication of the depth of overburden to the high velocity sandstone or limestone and the lower velocity shales could not be located. This results from the fact that the first wave to reach the detector will usually cause such high degree of activity in the galvanometer elements controlling the deflections of the photographed light rays as to preclude the possibility of detecting any subsequent wave arrival through the underlying low velocity formation.

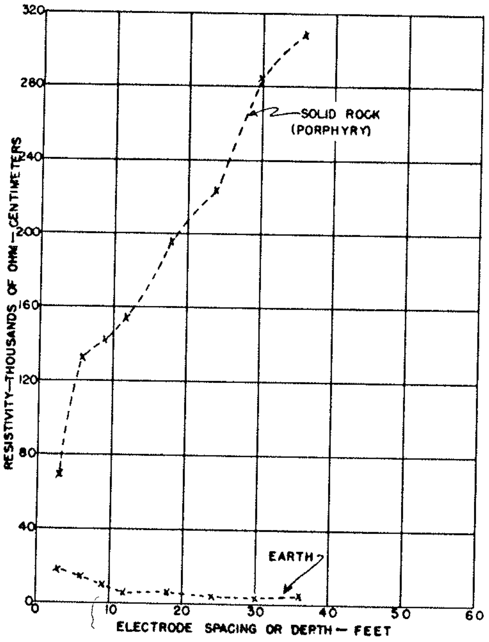
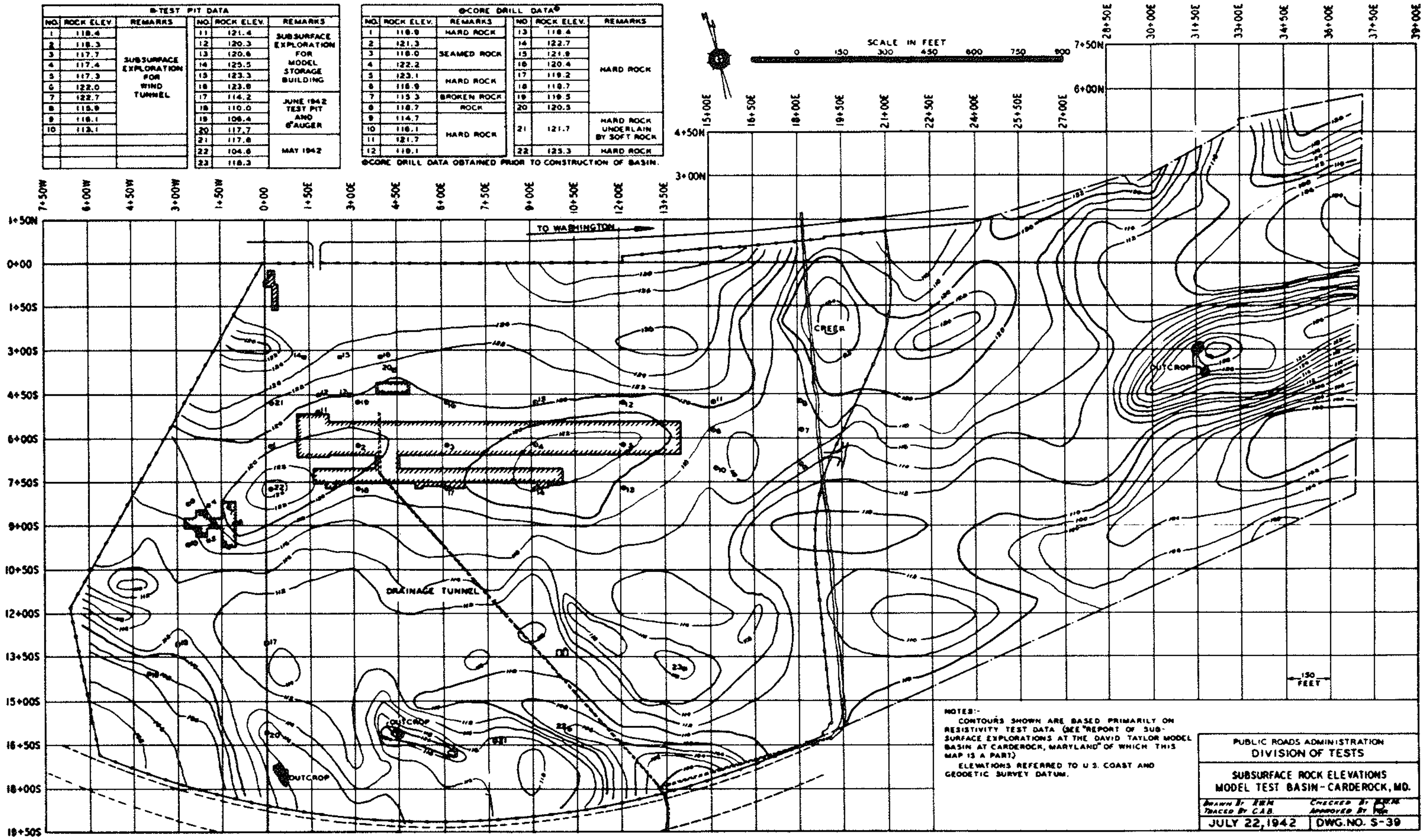


Figure 21. Typical Resistivity Calibration Curves Over Solid Rock and Earth Formations Near Farmington, Missouri

The resistivity test, particularly the resistivity traverse, offers a practical means for the rapid investigation of large areas in search of localized deposits of gravel, sand, or other granular materials useful in road construction. The method can be used also to determine the extent of special soils, such as impervious silty and clayey soils, which might be useful for earth dam and levee construction.

The seismic test is not well adapted for an area survey, but is best applied



■-TEST PIT DATA

NO.	ROCK ELEV.	REMARKS	NO.	ROCK ELEV.	REMARKS
1	118.4	SUBSURFACE EXPLORATION FOR WIND TUNNEL	11	121.4	SUBSURFACE EXPLORATION FOR MODEL STORAGE BUILDING
2	118.3		12	120.3	
3	117.7		13	120.6	
4	117.4		14	125.5	
5	117.3		15	123.3	
6	122.0		16	123.8	
7	122.7		17	114.2	JUNE 1942 TEST PIT AND 6" AUGER
8	115.9		18	110.0	
9	118.1		19	106.4	
10	113.1		20	117.7	
			21	117.8	MAY 1942
			22	104.6	
			23	118.3	

●CORE DRILL DATA*

NO.	ROCK ELEV.	REMARKS	NO.	ROCK ELEV.	REMARKS
1	118.9	HARD ROCK	13	118.4	HARD ROCK
2	121.3	SEAMED ROCK	14	122.7	
3	118.0		15	121.8	
4	122.2		16	120.4	
5	123.1	HARD ROCK	17	119.2	
6	116.9		18	118.7	
7	115.3	BROKEN ROCK	19	119.5	
8	118.7	ROCK	20	120.5	
9	114.7	HARD ROCK	21	121.7	HARD ROCK UNDERLAIN BY SOFT ROCK
10	116.1				
11	121.7				
12	118.1		22	125.3	HARD ROCK

*CORE DRILL DATA OBTAINED PRIOR TO CONSTRUCTION OF BASIN.

NOTES:-

CONTOURS SHOWN ARE BASED PRIMARILY ON RESISTIVITY TEST DATA (SEE "REPORT OF SUBSURFACE EXPLORATIONS AT THE DAVID TAYLOR MODEL BASIN AT CARDEROCK, MARYLAND" OF WHICH THIS MAP IS A PART)

ELEVATIONS REFERRED TO U.S. COAST AND GEODETIC SURVEY DATUM.

PUBLIC ROADS ADMINISTRATION
DIVISION OF TESTS

SUBSURFACE ROCK ELEVATIONS
MODEL TEST BASIN - CARDEROCK, MD.

DRAWN BY R.W.M. CHECKED BY R.W.M.
TRACED BY C.A.B. APPROVED BY

JULY 22, 1942 DWG. NO. S-39

Figure 22. Rock Contour Map of 150 Acre Tract Prepared from Data Obtained by Earth Resistivity Tests

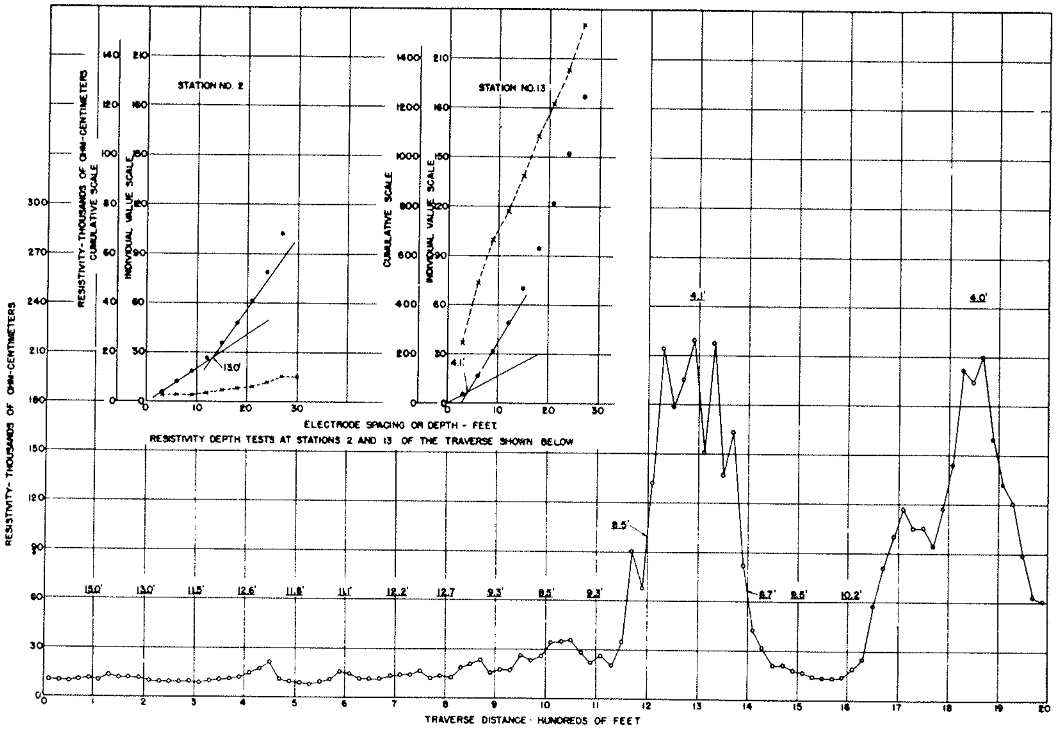


Figure 23. Earth Resistivity Constant - Depth Traverse Discloses Abrupt Changes in Rock Surface Underlying a Clay-Soil Overburden Traverse Involved a 20-ft Depth Along a 2000-ft Line - Figures shown underlined are results of resistivity depth tests for depth of overburden. Curves for two such tests are shown in inset.

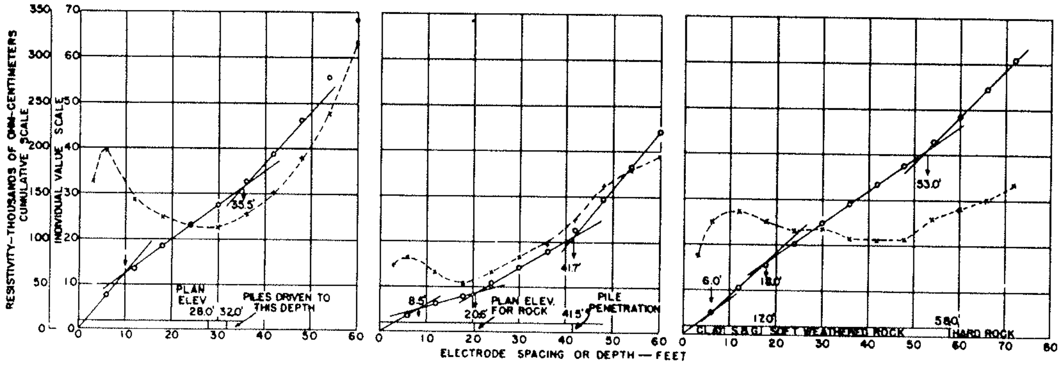


Figure 24. Earth resistivity tests at Flint River Crossing on US 19 south of Thomaston, Georgia, locate subsurface rock for bridge foundation more accurately than drill.

to the determination of conditions at a single designated spot or limited area such as a dam site, bridge location, etc. Even in the limited areas, if differential weathering has been in progress, leaving pinnacles and deep valleys in otherwise hard rock, a condition sometimes encountered in limestone formations, the resistivity test may possibly prove the more valuable of the two methods. In such cases the sharp irregularities of the rock surface present unfavorable conditions for consistent interpretation of the seismic data (24). To the writer's knowledge, however, there has been no report on results of resistivity tests carried out in such areas.

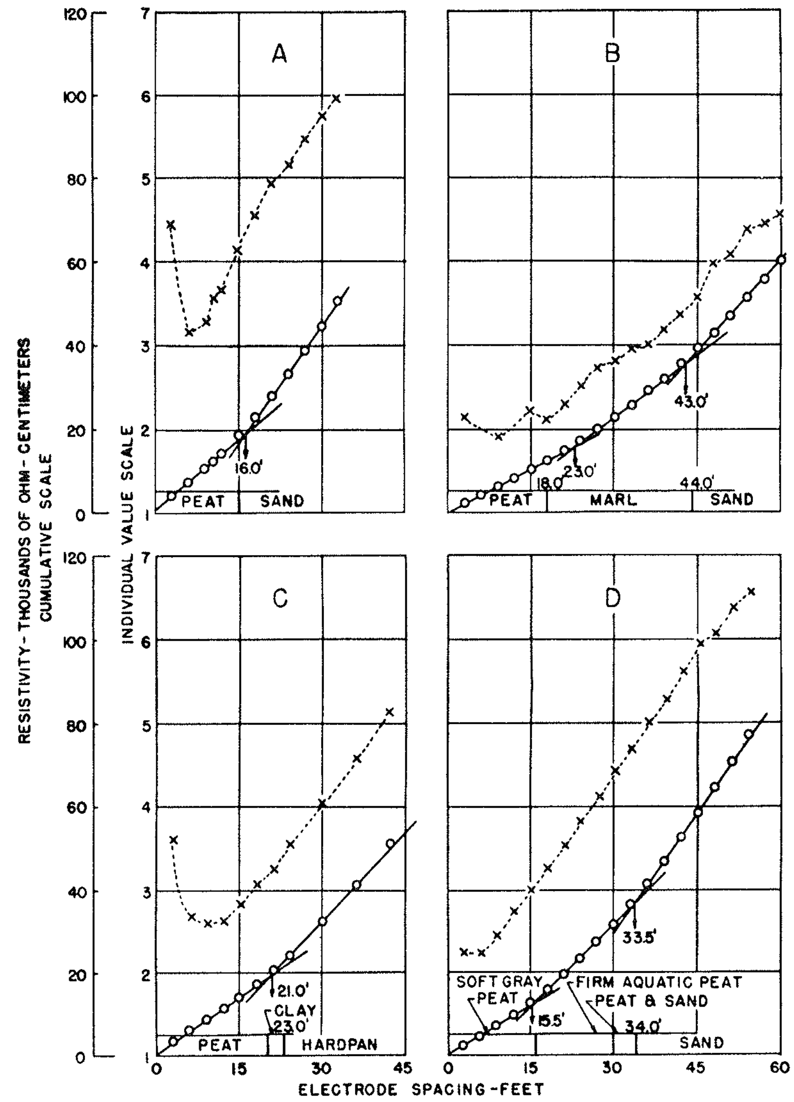


Figure 25. Resistivity Depth Tests Over Peat Bog Formations

The use of explosives as required in the seismic method is not desirable in thickly populated areas. Compliance with local regulations regarding possession and transportation of explosives, sometimes rather strictly enforced, can be troublesome and inconvenient, placing a further handicap upon seismic exploration.

As mentioned previously, the time required for conducting a seismic test can vary from one to two or three hr, depending upon local conditions, while resistivity tests can be made at a rate of three per hr to depths of 60 ft in rugged mountainous terrain. A seismic party may require one or more men than are necessary for the efficient operation of the resistivity apparatus, particularly in isolated areas where supplies of explosives and film developing equipment must be carried in by hand. However, stray currents leaving cross-county pipe lines or emanating from electric railway systems in urban areas, and buried utilities such as water and gas pipes can, at time, be troublesome when making a resistivity survey. These will not affect the efficient use of the seismograph.

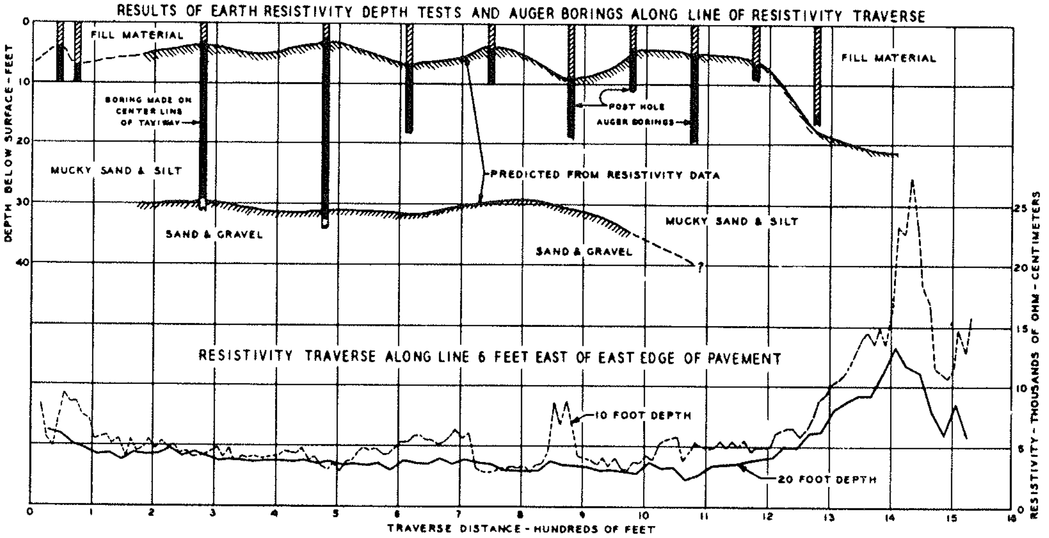
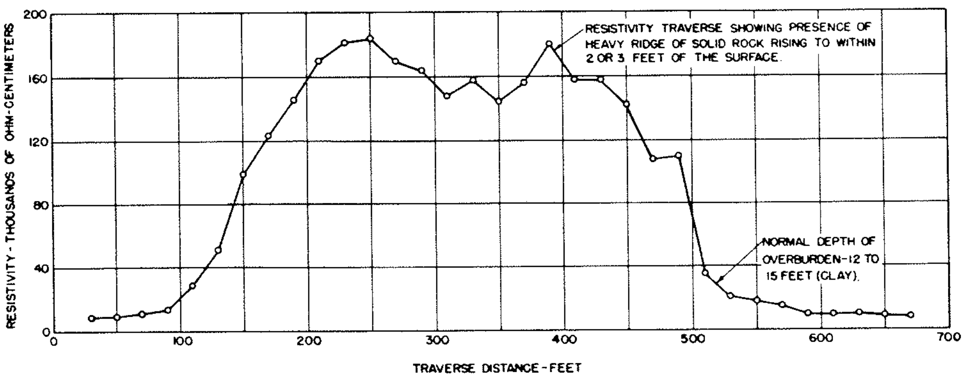


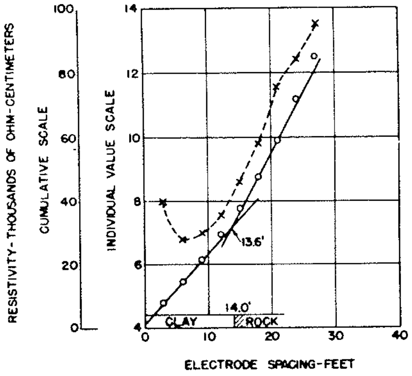
Figure 26. Results of Earth Resistivity Tests Along East Edge of Taxiway No. 4, National Airport, Washington, D. C. Traverse Station 0+00 = Station 11+17 Taxiway No. 4

CONCLUSION

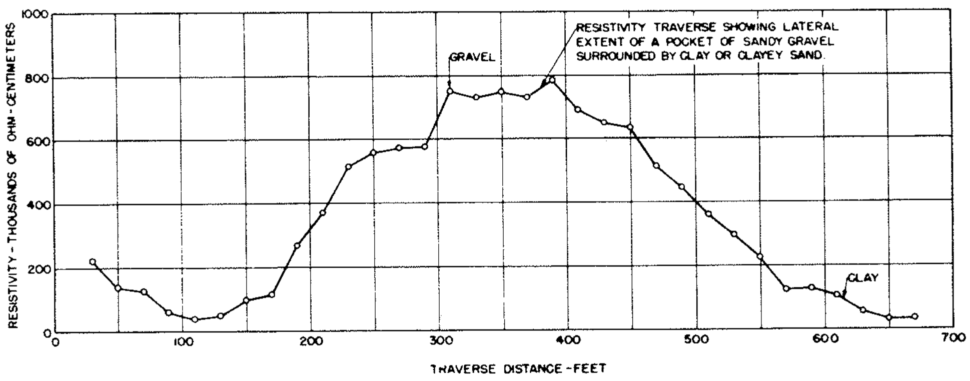
In conclusion it can be stated that, despite limitations that have been enumerated and others which may arise in future exploration work, the geophysical methods of test under consideration have definitely established their value in connection with highway work, particularly for use in preliminary surveys. Their use by the Bureau of Public Roads and other Federal agencies has emphasized the usefulness of these relatively inexpensive methods of test in shallow subsurface exploration in obtaining information to be used as control for design purposes or as control for more detailed subsurface surveys by core drilling and other commonly used direct methods. The fundamental principles of the two methods differ so widely that where both methods give concordant data they may be accepted with considerable assurance. As a result, when they are used jointly on a given project, a limited amount of confirming data from the seismic test can serve as a valuable check on a considerable number of the more inexpensive resistivity tests, at times obviating the need for test pits or auger holes for locating and identifying subsurface formations. This does not imply that test pits or auger holes may not be



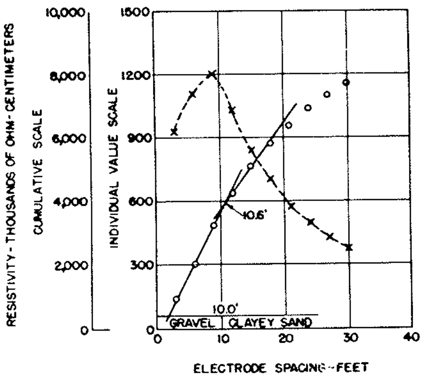
RESISTIVITY TRAVERSE OVER A BURIED GRANITE RIDGE USING A CONSTANT DEPTH OF 20 FEET.



DEPTH TEST INVOLVING CLAY UNDERLAIN BY SOLID ROCK.



RESISTIVITY TRAVERSE OVER A SAND AND GRAVEL DEPOSIT USING A CONSTANT DEPTH OF 20 FEET.



DEPTH TEST INVOLVING SANDY GRAVEL UNDERLAIN BY CLAY OR CLAYEY SAND.

Figure 27.

necessary for obtaining samples of soil and other materials for determination of their physical and other properties.

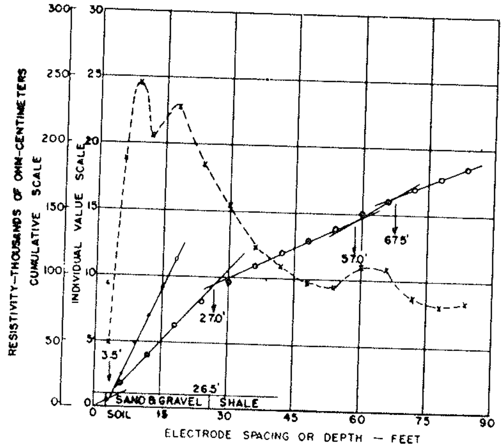


Figure 28. Resistivity Depth Test at Location of DH No. 2 19 in Right of Station 52 + 19, Susquehana River Crossing of the Pennsylvania Turnpike at Harrisburg

Even though there might exist some uncertainty that the geophysical methods of test would prove applicable to a particular subsurface condition, the simplicity, low cost and rapidity with which the tests can be made recommend their trial before resorting to the more costly and tedious methods of direct exploration ofttimes employed.

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GENERAL

1. Geophysical Abstracts, a bulletin published quarterly by the US Geological Survey, contains abstracts of currently published literature relative to subsurface exploration.

DISCUSSION

E. R. Shepard, Office of the Chief of Engineers - This paper is of particular interest to me, as we in the Corps of Engineers have been doing very similar work now for some 10 yr. The author has described very clearly the relative merits of the two methods of exploration and the particular types of problems to which each is most applicable.

Because of the relatively shallow depths with which highway construction is concerned, Mr. Moore has found the resistivity method generally preferable to the seismic method. Our explorations for the most part have been on dam sites and proposed canals, where the purpose of the test is to determine the depth to firm rock and here the seismic method has proved to be admirably suited. Best results are obtained in glaciated regions and in river flood plains where hard rock exists under alluvial or glacial deposits. Where the rock is shallow and the top deeply weathered or seamed and fractured, velocities are often no greater than those prevailing in some types of soil. Under these circumstances there is often a question as to the character of the material. Moisture is a major factor influencing velocity. In relatively dry overburden, velocities of about 1000 ft per sec or less are observed. With increasing moisture the velocity increases and in saturated sand and other coarse grained material attains a critical speed of 5000 ft per sec, or approximately that in water. In clays and other fine grained soils the critical velocity of 5000 ft per sec does not necessarily occur even though they may be fully saturated.

The fractured and seamed top zone of rock, particularly when dry and carrying only a thin overburden often exhibits a remarkably low velocity and for this reason may be mistaken for saturated sand or other unconsolidated material. A correct interpretation under such conditions may be highly important where excavation costs are concerned. Where the top of rock is at or near the water table, it is often difficult to determine whether the intermediate zone between low velocity top soil and hard, high velocity rock, is saturated sand or fractured rock. Where the top of rock is relatively deep, say 30 ft or more, the presence of moisture and the heavy load which closes up seams and fractures, tend to increase the velocity in the rock, leaving little question as to its presence and character. For these reasons better results are obtained by the seismic method at moderate and great depths than at shallow depths.

The cumulative method of interpreting resistivity data developed and used extensively by Mr. Moore appears to have been of great value in his exploration for highway construction and other shallow determinations. Seldom in nature do we find soils in layered formations to which theoretical formulae and curves are applicable. The man in the field is usually frustrated and discouraged in attempting to apply these principles to his data and is usually forced to fall back on some simple and rapid emperical method of analysis. The cumulative method, although not infallible, appears to give satisfactory results on the type of work described by the author and should receive the attention of other investigations engaged on similar projects.

Typical borrow pit (0.6 km from roadway) with gravel used as road-surfacing material, Brazil.

TM 5-332

DEPARTMENT OF THE ARMY TECHNICAL MANUAL

PITS AND QUARRIES

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DECEMBER 1967

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***TM 5-332**

TECHNICAL MANUAL
No. 5-332

HEADQUARTERS
DEPARTMENT OF THE ARMY
WASHINGTON, D. C., *15 December 1967*

PITS AND QUARRIES

***This manual supersedes TM 5-332, 7 June 1963.**

CHAPTER 1

INTRODUCTION

1. Purpose

This manual is designed as a guide for military personnel engaged in the selection and operation of pits and quarries.

2. Scope

a. This manual outlines methods and procedures used in exploration for an operation of pits and quarries.

b. It provides information on equipment required to operate pits and to supply crushed stone; however, it does not cover operation of this equipment.

c. The information contained herein is applicable to both nuclear and nonnuclear warfare.

3. References

The reader should have a knowledge of engineer intelligence, engineer geology, control of soils in military construction, explosives and demolitions, and the utilization, capabilities, and limitations of engineer equipment. Appendix A lists appropriate texts.

4. Definitions and Classifications

a. Definitions. Pits and quarries are sites where select materials and aggregates suitable for construction may be obtained in quantity.

(1) Pits are sites from which materials can be removed, generally without blasting.

(2) Quarries are sites where open excavations are made for the purpose of removing rock which is suitable in quality and quantity for construction, usually by drilling, cutting, or blasting.

(3) Overburden is that waste material which often overlies pits and quarries and which must be removed prior to excavation of the construction materials below. The term is commonly applied only to loose materials, but locally it may include solid rock lying above some desired material.

(4) Burden is the construction material on the face of a quarry. Depth of burden may be considered as the distance from a charge measured perpendicular to the nearest free face and in the direction in which displacement will most likely occur upon charge detonation.

b. Classifications. Pits and quarries are classified according to the type of material contained in them and the methods of obtaining the materials as outlined in table 1.

Table 1. Classification of Pits and Quarries

Type	Material	Primary use	Water condition	Operations and equipment
PIT:				
Borrow	Select soil other than gravel and sand.	Embankment and subgrades.	Dry	Earth moving equipment, dozer, power shovel, rooter, front loader, or dragline.
Gravel:				
(Bank-hill)	Gravel and sand with clay.	Base courses, surfacing, and fills.	Dry	Power shovel, front loader or hand.

Table 1. Classification of Pits and Quarries — Continued

Type	Material	Primary use	Water condition	Operations and equipment
(Alluvial)	Clean gravel and sand.	Aggregate for concrete and bituminous mixes.	Wet (or dry).	Earth moving equipment, dragline, power shovel, clamshell, or hand.
Miscellaneous (dumps)	Mine spoil, slag, cinders, etc.	Surfacing and aggregates.	Dry	Power shovel, front loader or hand.
QUARRY:				
Hard rock[1]	Aggregate	Base courses, surfacing, and aggregate for concrete and bituminous mixes.	Dry	Drilling tools, blasting, power shovel, crushing, screening (and washing) plant.
Medium rock[2]	Aggregate	Base courses, surfacing.	Dry	Drilling tools, blasting, power shovel and crushing, screening (and washing) plant.
Soft rock[3]	Cementaceous material	Base courses and surfacing on roads and airfields.	Dry	Rooter, power shovel, front loader, earth moving equipment.

[1] Hard rock — granite, trap, schist, gneiss, etc.
[2] Medium rock — some limestone, some sandstone, etc
[3] Soft rock — soft coral, tuff, caliche, chalk, some limestone, some sandstone, laterites, etc.

5. Suggestions and Recommendations

Users of this manual are encouraged to submit recommended changes or comments to improve the manual. Comments should be keyed to the specific page, paragraph, and line of the text. Reasons should be given for each comment to insure complete understanding and permit evaluation. Comments should be forwarded directly to Commandant, U.S. Army Engineer School, Fort Belvoir, Va. 22060.

CHAPTER 2

SITE SELECTION

Section I. PRELIMINARY AND FIELD RECONNAISSANCE

6. Reconnaissance Planning

Site reconnaissance is divided into preliminary reconnaissance and field reconnaissance. Preliminary reconnaissance is the collection and study of all information relative to possible sites before going into the field. A thorough preliminary reconnaissance saves time by limiting the areas to be searched to those having definite possibilities. The amount of planning for reconnaissance for pit and quarry sites will vary according to time limitations dictated by tactical considerations; however, in all cases, as many sources of data as possible should be used in formulating the reconnaissance plan to locate the best source of pit and quarry material.

7. Sources of Information

a. Strategic Intelligence. Information on soil types, rock formations, and on the location of existing pits and quarries is included in intelligence reports published by the Defense Intelligence Agency and the Central Intelligence Agency. These are important sources for long-range planning and can serve as a basis for the engineer to make reconnaissance plans for his sector before the area is entered. Strategic engineer analyses prepared by the Office, Chief of Engineers, and the engineer sections of specified and unit commands are also good sources of information.

b. Geologic Maps. These maps are a good aid in finding pit or quarry locations. They reveal information on existing pits and quarries and provide information on geologic formations that lie beneath the surface and the strike and dip of beds. The information depicted on these maps about an area may greatly reduce the amount of field reconnaissance necessary to locate suitable sources of construction materials. It must be recognized that geologic maps are not available for all areas of the world, nor will there be complete information on all categories of potential aggregates on the maps which may be available. Therefore it may be necessary to depend more on topographic or soil maps when available.

c. Topographic Maps. These maps indicate existing pit and quarry locations, streams, roads, railway cuts, cliffs, routes of communication, and other pertinent features. If the contour intervals of these maps are 10 meters or greater, sharp irregularities of the land surface may not appear on the map and some important features such as ravines, low escarpments, knobs, and sinkholes may not appear at all. When a topographic map is used together with a geologic map, interpretations can often be made that could not be made by using either map alone. Thus through geologic inference, topographic maps may yield considerable information other than topography to locate good quarry sites. Close inspection of the patterns of topography, such as steepness of slopes and steam patterns, can provide considerable clues to the relative nature of rocks, depth of weathering, soil, and drainage.

d. Agricultural Soil Maps. These maps are suited for use in selection of pit locations. An intent of soil maps is to show the extent of soil units that are classified on the basis of the characteristics of the different soil horizons and the texture of the surface soil. It is best to use soil maps in conjunction with geologic maps, as they can be used to clarify the details of ground interpretation.

e. Special Aerial Photographs. These may be requested when the previously mentioned maps do not present a complete or up-to-date picture of the area of immediate interest or when maps are not available. Often maps may be out-of-date, and aerial photos are needed to present a current picture of the area of interest and to supplement maps for more up-to-date interpretation. Many features such as excavations, quarries, cliffs, outcrops, roads, railroad tracks, and streambeds can be located from aerial photographs. An experienced interpreter can determine many soil facts from photographs alone, but they are most reliable when used in conjunction with other information or with ground investigation. Often aerial photographs may be the only source of information.

f. Foreign Maps and Publications. These normally will contain the same basic information as topographic maps. They may, however, contain additional information not included in our own maps; therefore, they should be used in conjunction with them wherever possible. Foreign publications can be of value in supplementing foreign maps as they often point out inadequacies or discrepancies in them. Additionally the U.S. Army Map Service and U.S. Defense Intelligence Agency produce information of both strategic and tactical nature which will complement or supplement foreign maps.

g. Tactical Intelligence. Intelligence reports compiled by intelligence and reconnaissance officers at all echelons are excellent sources of information on terrain and potential quarry or pit sites. The engineer can extract the applicable information from those reports in his continual search for construction material locations. Units located in an area of interest should be contacted if possible. Individuals who have been in the area are a good source of information.

h. Local Inhabitants. These persons, particularly surveyors, engineers, miners, contractors, and quarrymen, may provide much useful data on local geology and engineering problems that may be encountered. They normally are a quick source of information on types and kinds of rock and soil in the area, and locations of readily available exposures or deposits. Farmers are a good source of information as they are familiar with outcroppings on their land.

i. Miscellaneous Records. In areas where drilling has been conducted for wells, petroleum, or mine shafts, records normally are available showing locations and results of the exploration. These records, coupled with scientific literature available on the area in question, will constitute a valuable source of information. Active or abandoned mines can often be an excellent source of construction materials or of information.

8. Geologic Investigation

Geologic investigations are preformed at the start of the project with the objective of locating favorable sites and determining the engineering feasibility of site development. The importance of accuracy in these preliminary investigations cannot be overemphasized.

a. Research. The research phase of investigation includes a careful search through published and unpublished papers, reports, maps, and records and consultation with local authorities for information on the project or problem. From a combination of geological and topographic maps certain information can be inferred. Topography tends to reflect the geologic structure and composition of the underlying rocks. Geologic features, however, are not equally apparent on all topographic maps. It therefore becomes apparent that whenever possible, the two types should be used as a combination. Information of engineering significance that may be obtained or inferred from this study may be classified as follows:

(1) *Physiography* — Significant topographic features; physiographic history pertaining to engineering.

(2) *General rock types* — Crystalline or noncrystalline; massive or thin bedded; alternating hard or soft rocks; glacial terrain.

(3) *Rock structure* — Dip and strike Folding; Faults; Joints; Slide areas; Soil types — glacial, alluvial, or residual.

b. Topographic and Geological Aspects. Topographic and geological aspects which would affect production include the following:

(1) *Assessment.* Topographic assessment of an area will provide informa-

tion on geologic form, pattern of surface drainage, results of erosion, soil color, vegetation cover, and land use. By a careful evaluation of available data, it can be determined if it is feasible to enter the area for pit or quarry operations. The geologic composition and structure of materials of potential interest are highly important aspects of investigation. It is of utmost importance that the materials used be suitable for the construction project anticipated. Sedimentary rocks were deposited in horizontal beds, and accordingly we can infer that internal earth forces contorted them into the folds, faults, and joints to be seen in many formations.

(2) *Folds.* In regions characterized by crustal instability, the stratified rocks commonly yield to forces of earth movement by bending and crumpling. This folding occasionally is on a scale small enough to be observed in a single exposure, but more often it may only be inferred from ridges of relatively durable rock that are tilted at different angles in nearby outcrops. The position and inclination of these strata in the ground, referred to as the *attitude* of the beds, are accurately defined by two measurements called strike and dip. The term *dip* designates the maximum angular departure of an inclined bed from the horizontal; the *strike* is the direction of the line formed by intersection of the bedding plane of the rock strata with a horizontal plane. Dip, expressed in degrees, is always measured at right angles to the line of strike. The strike direction, determined by means of a compass, is always given with reference to north.

(*a*) In a series of folds, the up-arched parts are called *anticlines,* the trough-like parts are called *synclines*. An up-arched structure in which the beds dip away from a central point at its apex is called a *dome.* A local steepening of stratum which is otherwise horizontal or gently dipping is referred to as a *monocline.*

(*b*) Monoclinal structures should not be confused with *regional* or *structural* dip, a characteristic where the rocks over a large area have a gentle dip in the same general direction. Where the underlying sediments dip more steeply than the ground surface, the truncated ends of the most resistant rock layers stand out in low ridges or mountains.

(3) *Faults.* Any fractured surface along which there has been relative displacement of rock in any direction parallel to the fractured surface is called a *fault.* The magnitude of linear displacement may vary from inches to many feet or miles along the fault surface, and the lateral disturbance may be spread over a considerable area adjacent to the fault surface. This laterally fractured area, called the *fault zone,* usually contains pulverized rock or *gouge* and angular fragments of crushed rock or *breccia* that were produced during the movement of the fault blocks. Recognition of faults is of great importance to the engineer because faults represent zones of weakness in the earth's crust. In outcrops they are easy to recognize as are many that appear in aerial photographs. Faults that are not visible, however, may be determined by field observation or drill logs or from geologic maps.

(4) *Joints.* Fractures along which there has been little or no displacement parallel to the fractured surface are called joints. They cut across rock masses in different directions and various angles, forming a system of intersecting joints that divide the rock into blocks.

c. Field Reconnaissance. A geologic field reconnaissance follows geologic research and is a preliminary investigation involving one or more trips to potential pit and quarry sites for the purpose of gathering such information as is obtainable without subsurface exploration. Before plans for detailed surface or subsurface investigations are prepared, the engineer responsible for planning the investigations has obtained advance knowledge through geologic research regarding the geology, physiography, and cultural features of the potential sites involved. During the field reconnaissance, records should be made on map overlays of all the geologic and topographic features which may have a bearing on the suitability of the potential pit and quarry sites. It is essential at this time to obtain as much information as possible on landforms, soil types and thickness, bedrock types and structure, ground water conditions, volume of construction materials, and any other factors that may influence the selection of a site for the production of construction materials.

(1) *Subsurface borings.* A number of types of subsurface borings are utilized in site evaluation. Some of these are used extensively in the Army, while others require equipment normally not available to military units.

(2) *Probings.* These normally consist of driving a steel rod into the ground and noting the variations in penetration resistance. These rods may be of any size; however, they normally are round or hexagonal, between 5/8 and 7/8 inch in diameter. They may be pointed or have a driving point attached. Penetration of the probe may be accomplished by driving the rod manually or by mechanical means. Probings generally are intended to determine the presence or absence of bedrock within acceptable depths. Resistance to penetration can be roughly interpreted in terms of the character of the material penetrated. Probings are not always completely reliable because a penetration refusal, which may be erroneously interpreted as bedrock, may actually prove to be a cobble or boulder in a cemented soil condition. Probings should never be used for other than preliminary exploration and should always be checked with other investigative methods.

(3) *Wash borings.* These consist essentially of forcing a wash pipe or hollow drill rod through overburden by chopping and jetting while water is pumped through the boring device. Usually a chopping bit is attached to the bottom end of a wash pipe. Displaced soil is washed to the surface where it may be caught in a container for sampling and testing. Wash borings are used principally to advance holes through overburden materials between zones of drive sampling or to obtain a borehole through overburden to rock preparatory to rock drilling. Again, this method cannot be used as a final analysis for determining subsurface conditions. It should be used only as an expedient prior to final evaluation of an area.

(4) *Core drilling.* This process involves the cutting and recovery of core samples of the particular area in question. The term includes certain methods of soil drilling and sampling, but is most commonly applied to the drilling and recovery of continuous cores from bedrock. As core drills normally are not available to field troops, no further mention of this equipment will be made in this manual.

(5) *Wagon and jackhammer drilling.* This drilling uses percussion-type drills. As the term implies, the wagon drill is mounted on a wheeled carriage, while the jackhammer drill is handheld. Exploration with these drills consists of drilling holes in rock and observing the rate of, and resistance to, penetration of the drill as well as the color of cuttings from the

hole. These observations are interpreted in terms of bedrock condition. These explorations are useful as supplementary investigations for searching out shallow cavities, solution channels, and soft zones after overburden has been stripped from foundation rock.

(6) *Test pits and trenches.* Test pits are openings excavated vertically from the ground surface to expose the subsurface materials for examination in place. They may also be excavated as a means of taking undisturbed samples of soil materials. Test pits have their greatest use in connection with soils exploration and testing. They may also be used to study the character of the overburden bedrock content and the position, character, and condition of the bedrock surface. Trenches are similar, functionally, to test pits except that they usually are limited to relatively shallow depths below ground surface. They are particularly useful for exploring, examining, and correlating bedrock surface conditions that elude accurate identification by conventional drilling and sampling methods. Combined with test pits, exploratory trenches are a highly reliable method of determining the occurrence, composition, distribution, structure, and stability of unsatisfactory materials in deep alluvial and residual soil deposits.

9. Site Reconnaissance Planning

Once all the intelligence on potential pit and quarry sites has been assembled and evaluated, the planner establishes priorities for finalized investigations. The three priorities for these investigations generally consist of known sites, probable sites, and possibilities.

a. Known Sites. These consist of those sites currently or previously used as pits or quarries and close enough to the construction site to warrant further investigation.

b. Probable Sites. These are those sites that contain desirable construction materials as found by the preliminary investigation.

c. Possible Sites. These are sites for which available data indicates a possibility that construction materials exist. Information on these sites may have been obtained from visual or aerial photo coverages and must be confirmed by individual investigation.

Section II. EVALUATING PIT AND QUARRY SITES

10. Quality Determination

The contemplated use of the material is the determining factor in the quality required. In general, materials used for fills or subgrades do not have to meet the same specifications as materials used in compacted rock surfacing, concrete construction, or asphalt pavement. TM 5-541 provides information concerning characteristics of materials used for construction purposes and TM 5-530 discusses tests for evaluation of these characteristics.

a. Hardness, Toughness, and Durability. Hardness, toughness, and durability are related to one another, but they are not the same thing.

(1) *Hardness.* The hardness of a mineral is a measure of the ability of one mineral to scratch another. Loose particles on or just below the surface of a gravelled road must resist abrasion or they will wear away to dust. Hardness has nothing to do with the ease with which a mineral can be broken. A diamond, the hardest mineral, can be broken with the tap of a hammer. Ten minerals have been chosen, against which the hardness of all others is tested. This listing, known as Moh's scale, appears in table 2. It is difficult to measure rocks for hardness using the Moh scale. Most rocks are composed of several minerals, but only single minerals can be tested in this way. If a rock is composed of just

one mineral, or is very fine-grained in texture, the Moh scale will give an indication of hardness. The higher the number on the scale the harder the mineral. The scale does not indicate an exact hardness, that is, the number 9 is not three times as hard as the number 3. It means only that any mineral can scratch all those beneath it in the scale and can be scratched by all those above it. Two minerals of the same number will scratch each other. In the absence of this scale, tests can be made quickly in the field by substituting a few familiar objects, such as fingernail (2.5); copper coin (3); knife blade or window glass (5.5); steel file (6.5). If, for example, the mineral scratches the blade of the knife, it is harder than the blade, and since steel is near the middle of the standard scale (5.5) the mineral is hard. If the mineral does not scratch the blade, try to scratch it with the blade. Soft minerals will be scratched in this way without dulling the blade very much.

Table 2. Moh's Scale

Mineral	Hardness
Diamond	10
Corundum	9
Topaz or Beryl	8
Quartz	7
Feldspar	6
Apatite	5
Fluorite	4
Calcite	3
Gypsum	2
Talc	1

Expedient Scale

Steel file	6.5
Knife blade or window glass	5.5
Copper coin	3.0
Fingernail	2.5

(2) *Toughness.* This is resistance to fracture. Marble, used for statues and tombstones, is tough, even though not very hard. The rock on or close to the surface of a road or airstrip should be tough, so as to withstand the impact of passing vehicles, and not break easily into smaller pieces. To test a fragment of rock for toughness, try to break it by striking it with a hammer. Tough rock will be hard to break; weak rock can be broken easily. A large boulder of tough rock will cause the hammer to make a ringing sound. Without using a hammer, the toughness of a rock may be judged from the appearance of a fragment already broken from a larger piece in the field. Flat or slightly curved surfaces, sharp edges, and equidimensional shape indicate toughness. Some rocks, when they break at all, disintegrate into a powder. Resistance to powdering is desirable in addition to toughness.

(3) *Durability.* This is literally the ability to endure, but it is here restricted to resisting the attacks of temperature, moisture, and natural chemicals. A rock may be durable in one environment and not in another. A rock that fractures when alternately heated and cooled, as a cold water tumbler does when boiling water is poured into it, will not be durable in a climate where the temperature is much higher in the daytime than in the night. A rock that deteriorates when wetted or dried or alternately wetted and dried is not durable unless protected.

(*a*) *Acids.* Carbon dioxide and oxygen combine with water vapor in the air to make dilute acids that attack rocks. Surface water and ground water almost always contain such acids. Chemically inert rocks withstand such attacks. To test a rock for resistance to attack by acid, place a drop of dilute hydrochloric acid on a freshly broken surface. If there is effervescence (bubbling) the rock is being attacked. Limestone, coral, and marble will show this. So will sandstone in which the grains are cemented by calcium carbonate. If hydrochloric acid cannot be obtained, then acetic acid or vinegar locally procured from a store or a photographic supply house may be used. Do not get the acid on your clothes or on your hands. This test is a good way to distinguish dark-colored fine-grained limestone from traprock or basalt.

(*b*) *Weathering*. Deterioration from any of the above kinds of attack is called weathering. Weathering generally reduces the strength of a rock, decreases its chemical inertness, produces impurities, and causes the rock to lose its coherence.

b. *Suitability of Materials*. The engineer must be able to evaluate the suitability of materials for construction purposes. Aggregates for construction should have a hardness of 5 to 7. Materials with a hardness over 7 should be avoided as they tend to cause excessive damage to the crushers. Materials with a hardness of less than 5 may be used providing no other economical source of aggregate exists. The requirements as to shape, strength, durability, resistance to weathering, and toughness of aggregates will vary, depending on the type of construction anticipated. The shorter life spans characteristic of military construction in the theater of operations often permit the military engineer a wider choice of materials for a given type of construction.

11. Quantity Determination

The quantity of material available at a site must be carefully estimated to include a margin of safety, especially at proposed quarry sites, due to the expenditure of manpower, material, and time involved in moving into a new site. Unforeseen difficulties such as deterioration of quality of materials or the presence of water may arise which can reduce the estimated output. For this reason all estimates of quantity should be conservative. All other factors being equal, it is advisable, so far as possible, to select a site containing a greater volume of potential aggregate than is required, rather than one which is estimated to meet the immediate requirements. The volume of material is estimated by selecting a reference plane, such as a quarry floor or bottom of a pit, and computing the volume either directly or by dividing into segments and summing the volume of these segments. The thickness of a deposit is measured at right angles to the reference plane. Unusable materials such as weathered rock and overburden should not be included in the volume calculations.

a. *Pit Material*. When placed in well compacted fills, pit material can be considered to retain approximately the same volume as in its original pit state; however, when it is removed from a deposit, it has a greater volume than before excavation. The depth of pit material can be determined from hand auger boring, trenches, or test pits. There are two methods of determining the volume of material contained in a pit:

(1) *Hasty method*. Take cross sections at right angles to a convenient baseline, determine the average cross-sectional area; then determine the estimated volume.

(2) *Deliberate method*. Divide an isometric view (fig. 1) of a pit into a system of squares or rectangles, 20 to 50 feet on a side; determine the difference in elevation of the original ground level and the grade of the excavation at the corners of the squares or rectangles; compute the volume of each cube prism, or wedge, and total these volumes. It is to be remembered that the surface of usable pit material or pit floor will seldom ever be level, so this must be taken into consideration in the computations by averaging their depths. When the depth of excavation is uniform or averaged throughout the pit, the computation by this method may be expressed as follows (figure 1):

$$V = N(abd) + M\frac{(a'bd)}{2}$$

where:

V = volume in cubic yards

N = number of rectangles or squares

d = depth of excavation

a, a', b = length of sides in feet

M = number of triangles

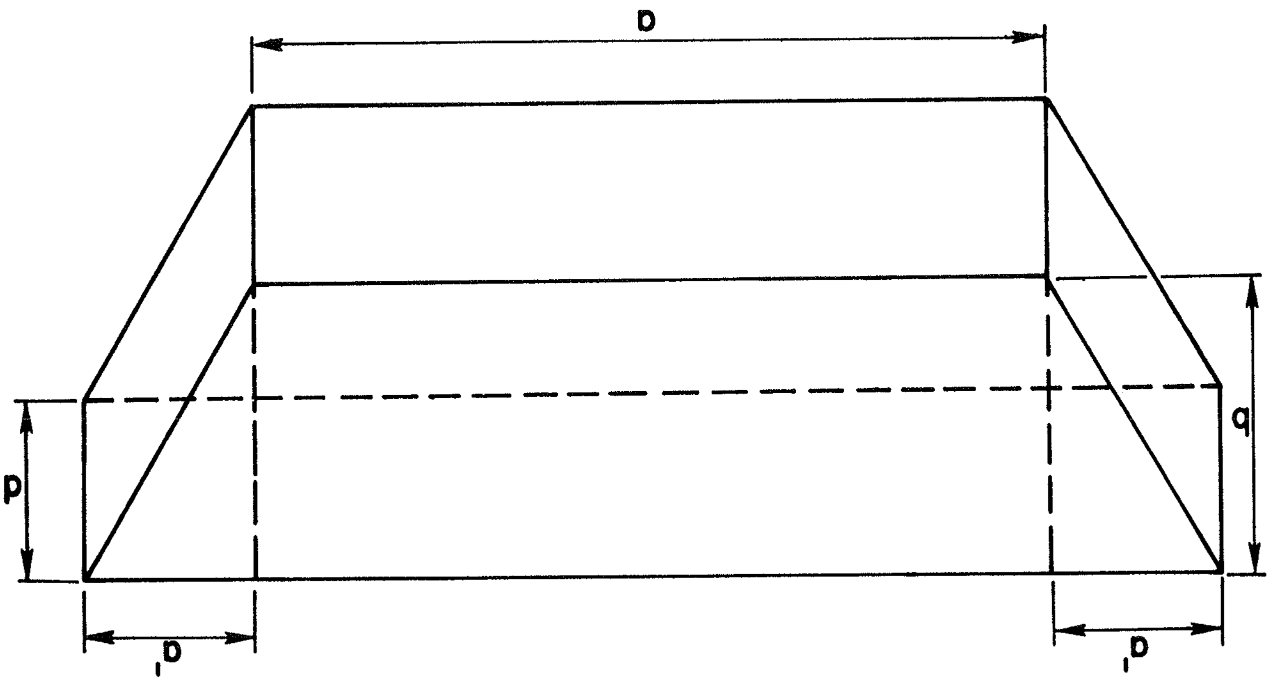


Figure 1. Layout for determining volume of pit.

b. Quarry Material. The quantity of rock may be estimated by multiplying the average depth of the face by the working area, deducting for overlying waste rock and other overburden. To convert from quantity in place to quantity when broken, a multiplying factor of 1.75 is used. To estimate tonnage in place, a multiplying factor of 2.25 tons per cubic yard may be used (table 3). Estimates of quantity of rock available are more easily made from the face of existing quarries than from new developments and generally are more accurate. When estimating quantity of materials, one must consider the possibility of encountering springs that will demand provision of drainage to the quarry; however, springs or seepage may be beneficial in the crushing, screening, and washing plants as the water may be used to wash the materials or may be sprayed on the conveyer belts to reduce dust.

Table 3. Weight of Rocks

Material	Pounds per cubic foot		Cubic feet per ton		Tons per cubic yard		Swell
	In place	Broken	In place	Broken	In place	Broken	
Andesite	181	97	11.1	20.6	2.44	1.31	1.75
Basalt	181	97	11.1	20.6	2.44	1.31	1.75
Diabase	187	94	10.6	21.3	2.52	1.27	1.75
Diorite	187	94	10.6	21.3	2.52	1.27	1.75
Gneiss	168	96	11.9	20.8	2.27	1.30	1.75
Granite	170	97	11.8	20.6	2.30	1.31	1.74
Limestone	168	96	11.9	20.8	2.27	1.30	1.75
Porphry	170	97	11.8	20.6	2.30	1.31	1.74
Rhyolite	150	86	13.4	23.3	2.02	1.16	1.75
Quartzite	165	94	12.1	21.3	2.23	1.27	1.74
Sandstone	151	86	13.2	23.3	2.04	1.16	1.76
Schist	168	91	11.9	22.0	2.27	1.23	1.75
Shale	175	95	11.4	21.1	2.36	1.28	1.85
Slate	175	95	11.4	21.1	2.36	1.28	1.85

12. Factors Affecting Operations

a. Ground and Surface Water. Test pits or earth auger borings are used to determine the approximate amount of ground water and the height of the water table. These findings may be determining factors in the selection of a site. Many existing quarries contain standing water from seepage or rainfall which, in most cases, can be drained with organizational pumping equipment; however, pumping is the least preferred method of removing water. Care should be taken to insure that rock and soil particles do not damage the pump. The feasibility of removing water may be ascertained by installing a pump and gaging the rate of fall of the water surface after a period of time. It is essential that most borrow pits be worked in a dry condition because it is difficult to move borrow material when it contains an excessive amount of moisture. Gravel pits containing little or no clay may be worked wet with little loss of efficiency, provided proper equipment for wet operations is available. Quarries are worked dry unless it is impracticable or impossible, as in operations involving coral reefs. Hillside or sloping locations simplify surface drainage problems as interceptor ditches can be opened on the uphill side to prevent drainage into the pit or quarry. Extensive drainage projects, such as diverting a stream or draining a lake, should be considered only when an extended operation is planned or when other sites are not available.

b. Location. Choose a location as close as possible to the construction site and convenient to good routes of transportation. This allows more efficient hauling by decreasing the length of access roads. Quarry haulage ordinarily is done by trucks; however, for large operations in the communications zone, railways and water transportation are sometimes used. When large quantities are being shipped by rail, a siding should be laid into the pit or quarry to eliminate trucking from source to railroad.

c. Overburden. Sites containing quality materials with the least overburden are more desirable. Stripping the overburden is sometimes as large an operation as excavating the material itself. Usually, it is not profitable to operate the site if the depth of overburden exceeds one-third of the depth of the usable material. Normally overburden should not be more than 15 feet in depth. For some types of road construction, the overburden may be removed and used together with sand and gravel. Clearing of vegetation may sometimes present hazardous conditions or even render a site uneconomically feasible. Therefore, the engineer must take this into consideration when making his decision on a site.

d. Slopes. Slopes are most desirable in all types of pit and quarry operations, with the exception of underwater gravel pits. Downhill loading is highly desirable, since the force of gravity aids in obtaining larger loads in less time than can be obtained using other directions for loading. Similarly, locating a quarry on a hillside permits a flow of material from face to crusher, crusher to storage, and storage to truck.

e. Utilities. Certain utilities are desirable to increase the operational efficiency of quarrying operations:

(1) *Electricity.* Lighting is essential for efficient, safe operations during periods of poor visibility and two-shift operations including night work. Frequently, adequate lighting is also required for maintenance, major repair operations, and security purposes. Power requirements for utilities must be included when determining sources and total requirements.

(2) *Water.* Clean water is essential in everyday operations, equipment use, and cleaning for maintenance, and is needed in large volume when the aggregate is to be washed for concrete and bituminous uses. Water and other natural resources in sufficient quantity located in the immediate vicinity of pits and quarries mean a great saving in equipment requirements.

(3) *Communications.* Communication facilities (telephone) are required for each quarry bench, maintenance area, and operational site.

f. Equipment. The availability of engineer equipment is a determining factor in both the extent and method of operation at pits and quarries. Maximum use should be made of operable equipment found in place when utilizing an existing quarry site.

g. Training. The state of training of personnel must be kept in mind at all times. It may be necessary, in extensive operations, to institute special training programs even in the theater of operations. Adequate equipment may be rendered inoperable by untrained personnel, or the logistical repair parts load may be increased to an unacceptable level. With the increase of accidents, the output decreases.

h. Security. Pit and quarry equipment is susceptible to enemy operations. Any major item of equipment destroyed at the site may close down the entire operation until a replacement is received. It is necessary to provide security for all equipment and personnel at an operational site, particularly in the theater of operations. Many items essential to the total operations are also vulnerable to pilferage which can easily cause costly damage.

i. Existing Sites. Whenever possible, an existing site should be used. For existing pits and quarries, the quantity and quality of the material are easily determined. Existing sites generally are located near good haul roads with access roads already constructed.

The amount of work required to remove the overburden is greatly reduced. Existing quarries may be found with some facilities available for use. When possible, the local operating personnel of existing quarries should be employed.

13. Final Selection

Pit and quarry sites are selected on the basis of quality and quantity of material, location of site, factors affecting ease of operation, and the equipment and personnel available. Final selection of the site is made after all reconnaissance data has been collected, analyzed, and evaluated. To determine the most suitable site, the requirements of quality and quantity must first be met. If more than one site satisfies these requirements, the ultimate choice is based on location, equipment and personnel required, and ease of operation.

CHAPTER 5

PIT OPERATIONS

43. Classifications

Any site where unconsolidated earth or rock particles suitable for engineer construction can be obtained in quantity may be called a pit. Pits are classified according to the type of material produced and the manner of operation.

a. Borrow Pit. A borrow pit is a site where material suitable for fill, surfacing, or blending can be removed with earthmoving equipment. The greatest yardage of pit material for theater-of-operations construction is taken from this type of pit. Borrow pits should be worked dry.

b. Gravel Pit. A gravel pit is a source of coarse-grained soil, consisting predominantly of particles of gravel size. Pit-run gravel is used extensively for surfacing secondary roads, in base courses for pavements for roads, taxiways, and runways, and as aggregate in concrete and bituminous construction.

(1) *The alluvial gravel pit* derives its name from the origin of the deposit, as the material is stream-deposited. The gravel or sandy gravel obtained from alluvial pits is often very clean and free of clay and humus, and therefore particularly desirable for concrete and bituminous work. This type of pit may be worked either wet or dry, depending upon whether operations are being carried on above or below stream-, lake-, or groundwater level.

(2) *A bank or hill gravel pit* produces a clayey gravel or clayey sandy gravel. Such materials are very desirable for surfacing work because of their binding qualities. Bank gravel pits are worked dry.

(3) *Miscellaneous pits* (dumps) contain mine tailings, slag, cinders, or the like, used for surfacing and in aggregates. They are usually worked dry with a power shovel, scoop loader, or by hand. Volcanic cinders are easily washed, drain well, but break down easily. Some are excellent for fill and railroad ballast.

c. Principles of Operation. The principles of pit operation take into account whether the pit is worked dry or wet, on a slope or on the level, and with what type of earthmoving equipment. For this reason pit operations will be discussed in this chapter without reference to the particular class of pit being operated. It should be remembered that in pit operations there are normal requirements to screen and crush materials to specifications for construction other than for use as fill material.

44. Site Preparation

Site preparation includes making an operations plan, clearing and stripping, removing any overburden, drainage the area, building access roads, and installing equipment and utilities.

a. Operations Plan. The operations plan is prepared before moving any earth. The limits of the area to be developed are determined; methods of excavation are chosen; equipment is selected; locations for all structures and equipment are determined; and a plan for supervision of traffic control is established.

b. Clearing and Grubbing. If the area is wooded, the first operation in preparing the site is the clearing of timber, standing and fallen. If camouflage is necessary, no more trees should be removed than is absolutely necessary. Brush may be disposed of by burning on the site, but larger timber should be moved clear of the perimeter of the site. Timbers of suitable dimensions should be stockpiled for possible use in the construction of loading ramps. All stumps and large boulders should be excavated and moved clear of the site.

c. *Removal of Overburden.*

(1) *Stripping.* The removal of overburden from pits usually is done by a continuous process of stripping. The spoil should be dumped far enough to the right or to the left of the longitudinal axis of the pit to avoid double handling. On hillside locations the waste material should be placed in spoil banks located on the downhill side, outside of the pit area. Spoil banks should be brought up evenly so they can be negotiated without difficulty by excavation equipment. Stripping by zones should be done concurrently with excavation. That is, zone 1 should be stripped before excavation starts, then zone 2 should be stripped while zone 1 is being excavated, and so on. Both stripping and excavation are usually done with the same equipment.

(2) *Bulldozers and scrapers.* Bulldozers are used to remove topsoil, humus, and other light overburden from pits up to a distance of 300 feet. Beyond this distance it is more economical to use scrapers if available. For best efficiency, dozing and scraping should be downhill.

(3) *Other equipment.* Where the shovel or front loader is the excavating equipment, it may be used to do its own stripping on small operations. On large operations, stripping with a shovel is uneconomical, since its short dumping radius makes it necessary to rehandle the overburden or to use trucks to haul the overburden away. Draglines normally strip their own pits, casting overburden beyond the boundaries of the pit or into an exhausted cut. Where the overburden is thick and the haul distance short, draglines may be useful for stripping purposes alone. For small areas with thin overburden the motorized grader may also be used.

d. *Drainage.* As pointed out earlier, borrow pits should be worked in a dry condition. Adequate drainage to eliminate surface and seepage water is an essential part of borrow-pit operation, and should be provided for as soon as possible. Hillside locations are comparatively easy to drain of surface flow or seepage by making an interceptor ditch along the uphill side with a scraper, bulldozer, or grader, or by making a single furrow with a breaking plow. Where the floor of a site generally is below ground level, both surface and seepage water must be disposed of. If open ditches cannot be dug to take advantage of gravity flow, then all water should be directed to a sump in the lowest part of the floor, preferably in an area out of the way. Here the water may be left to seep into the ground or if necessary be removed by pumps.

e. *Access Roads.*

(1) *To borrow pits.* Access roads to borrow pits should be graded and compacted to reduce rolling resistance for both tracked and wheeled vehicles. Where motorized scrapers and other pneumatic-tired vehicles are used on the haul, the roads should be kept smooth by constant shaping with a grader. Unless the roads traverse wet ground or low CBR soils, there is very little need for surfacing as borrow pits ordinarily are not workable during wet weather. If the pit is to be worked in wet weather, consideration should be given to surfacing the road. Dust should be controlled during dry weather, with application of water, membrane, or asphalt.

(2) *To gravel pits.* Construction of access roads to gravel pits should start as soon as the operational plan is completed to take advantage of any usable surfacing material in the overburden and to permit hauling in crushing and screening equipment if required. These roads should follow the shortest and easiest route with

a minimum of sharp curves and steep grades. They must be of all-weather construction. The maximum grade for truck operation is 10 percent, but tractors with scrapers can climb 20-percent grades for short distances. With the exception of the loop at the loading site, the access roads should provide for two-way traffic.

f. Choice of Equipment. The choice of pit equipment is largely determined by whether the pit material is to be used for concrete or bituminous aggregate, for earth fills, or for road and airfield surfacing. In the case of alluvial gravel, choice of equipment further depends on whether the pit is worked wet or dry and whether materials for aggregate require washing. Additional factors to be considered are whether or not the pit is to be started on flat ground or from a bank or hillside location, and the extent of stripping required.

g. Traffic Control. Traffic control includes routing traffic to and from the pit and regulating traffic flow within the operational area. To avoid traffic delays, all pit roads are designed for loop traffic so that routes of loaded and empty vehicles do not cross.

h. Pit Maintenance. Depending on the size of the operations, one or more bulldozers should be kept near the pit to strip overburden, maintain pit roads, and keep the floor of the pit free of holes and depressions in which surface water may accumulate. Humps, ruts, and ridges must also be avoided in scraper-operated pits, as they interfree with loading scrapers. In shovel-operated pits, a bulldozer is also used to start initial cuts and to windrow spillage. The bulldozer can be used with a dragline to level travelways and heap up material scattered from stockpiles.

i. Supervision. Pit operations should be properly supervised. Pit foremen, consisting of one or more officers or noncommissioned officers, are required, the number depending on the size of pit, amount and kind of equipment, and the nature and magnitude of operations. Duties include controlling stripping equipment, spotting scrapers, directing pushers, supervising rooters, spotting trucks, designating digging locations and moves for shovels and draglines, directing stockpiling and hopper loading, maintaining the pit, controlling traffic, and coordinating these various operations. Generally the greatest delay in pit operation is the loading of hauling equipment.

45. Excavating With Scrapers

a. Types and Use of Scrapers. Tractor-drawn and motorized scrapers are the most efficient items of equipment available to military units for moving large quantities of pit material in the minimum length of time. The maximum efficient one-way haul for tractor-drawn scrapers is about 1,500 feet. Motorized scrapers haul efficiently over good roads up to 5,000 feet, one way, and may even haul as far as 5 or 6 miles if the need for certain types of material is urgent. Because they have pneumatic tires, motorized scrapers operate over surfaced roads without damaging the surface. Except under unusual conditions, it is necessary for a pusher-tractor to assist a motorized scraper in loading, and sometimes in unloading. The rear of the scraper and the bulldozer blade of the pusher-tractor should be equipped with pusher blocks. The pusher-tractor, usually the largest tractor available, accommodates from four to eight motorized scrapers, depending on the length of haul. (The number of hauling units per pusher equals the hauling unit cycle time divided by the pusher cycle time.) Where it is difficult for a tractor-drawn scraper to pick up a load in a reasonable distance, a rooter should be used first. If the loading distance is still too long, then a pusher is used.

b. Use of Rooters, Rippers, and Explosives. In consolidated gravels or soft rock, when scrapers assisted by pusher-tractors will not pick up a heaping load in about 100 feet, a rooter should be used to increase the loading efficiency. A 110 to 140 drawbar horsepower tractor towing a heavy rooter can loosen 600 to 1,200 cubic yards per hour. Rooters are operated downhill and an entire zone is rooted at one time while the scrapers are hauling from another. Consideration should also be given to the use of back rippers on tractor blades. By dropping these rippers and reversing direction, sufficient material will often be available for the next pass. If the material is too consolidated for efficient rooter or ripper operation, blasting may be necessary, but for extensive operations, blasting is impractical.

c. *Excavation.* Excavation includes both the removal of material from its natural bed and its transportation to the construction site. It may also include rooting and blasting. Scrapers are loaded downhill to obtain maximum load and for ease in loading. Material is removed from the floor of the pit in successive thin layers over the entire width of the zone, using the straddle method of loading. During excavation, scrapers should be carefully spotted to maintain an even downgrade and prevent cutting holes below the general level of the floor. If the pit is much longer than 100 feet in the direction of loading, the scrapers should be staggered along the length of the cut as well as across the width of the zone.

d. *Pit Layout.* For coordinated stripping, excavation, and maintenance of scrapper-operated sites, the pit should be divided into zones at right angles to ground contours. Figure 24 shows the layout of a typical side-hill pit.

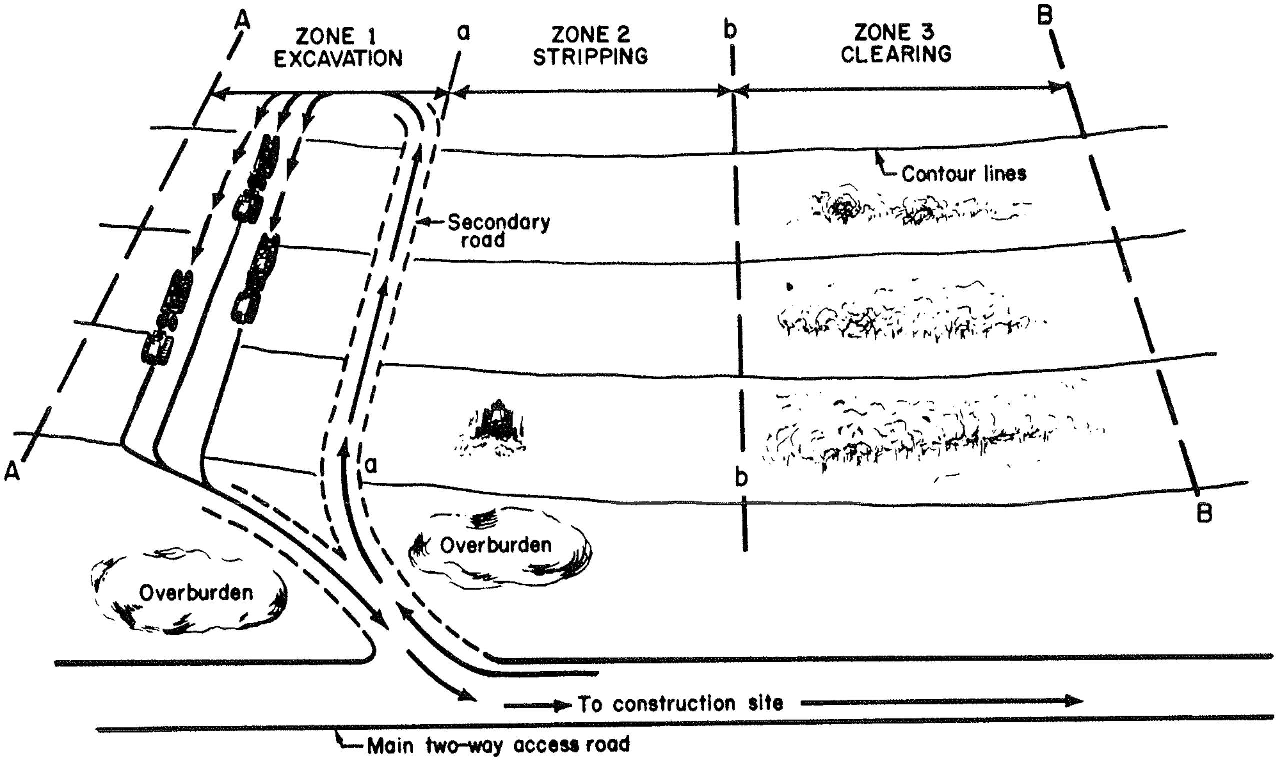


Figure 24. Layout and development of a scraper pit.

46. Excavating With Power Shovel and Trucks or Front Loader and Trucks

a. Operating Principles. The shovel-and-truck combination or front loader and truck ordinarily is used in pits consisting of above-water gravel deposits because, as a rule, required quantities are less, and hauling distances are greater than for earth borrow pits. The power shovel is particularly well adapted to hillside deposits which have slopes too great for the practical operation of earthmoving equipment. It may also be profitably adapted to horizontal deposits provided that a working face of the proper height is maintained. The minimum economical height of face or bench is about 5 feet. The maximum economical height of face for a 3/4-cubic-yard shovel is about 22 feet, and for a 2-cubic-yard shovel about 34 feet. When faces are excessive in height, a bulldozer should either be used to feed the shovel from above to prevent dangerous overhang or a multiple-face operation should be used. The shovel-and-truck combination is primarily designed for maximum efficiency in long hauls of 3,500 feet or more. The shovel cycle consists of digging, swinging, dumping, and swinging back to dig. Expert operators sometimes combine the last two operations for greater speed. A rough estimate of shovel production in cubic yards per hour is 100 times the bucket capacity. To obtain maximum production and efficiency in shovel-and-truck operation, the following rules should be adhered to:

(1) Keep a sufficient number of trucks working with the shovel so that it operates continuously.

(2) Keep the floor of the pit slightly higher at the face to aid drainage.

(3) Dig in long, thin cuts up the face of the pit.

(4) Increase digging speed by operating against a face not less than 5 feet high nor greater than the height of the boom.

(5) If the face is too high, use a bulldozer to shove off the top or work it in terraces.

(6) Keep the swing distance as short as possible, never exceeding 90 degrees.

(7) Spot trucks on both sides of the shovel, if possible, to decrease swing and to keep one truck always in position to be loaded.

(8) Keep long dimension of the truck bed tangent to the arc of swing of the shovel.

(9) Keep an alert spotter in the pit to direct the prompt and proper spotting of trucks.

(10) Keep trucks on about the same level as the shovel to aid loading.

(11) Swing over the rear of the truck, not over the cab. Never swing over the cab with the driver in the seat.

(12) Keep shovel level.

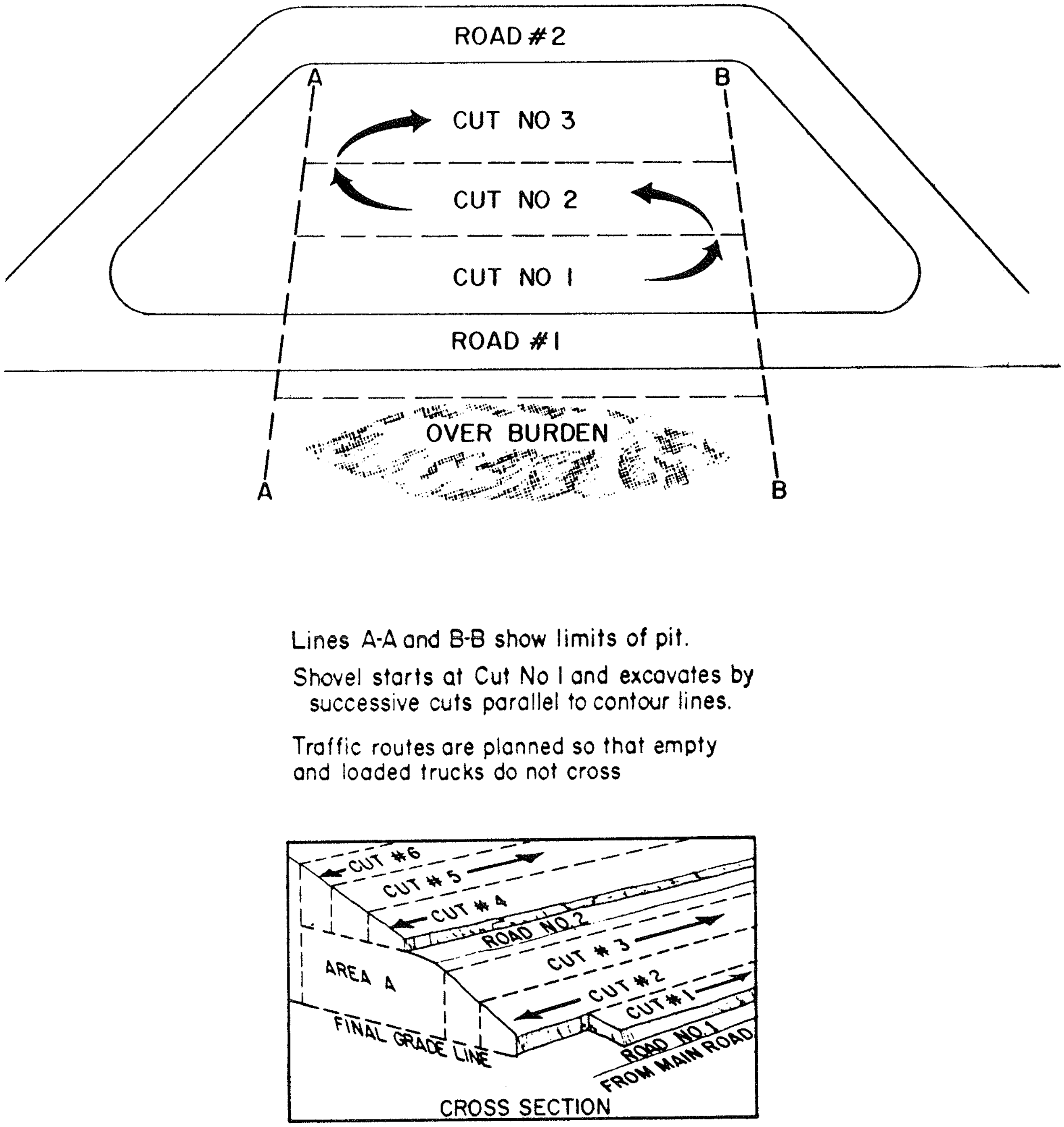
(13) When working on soft ground, support crawlers on timber mats.

(14) Keep haul roads in good shape to minimize the number of trucks required.

(15) Give constant supervision to servicing and maintenance of equipment.

(16) Keep loading area clear.

b. Hillside Deposits. Deposits are excavated by power shovels or front end loaders in benches in successive cuts *parallel* to the contour lines (fig. 25). First, a road is cut and leveled with a bulldozer along the toe of the slope of the hill. Starting from the road, the shovel is used to cut into the bank until the shovel is off the road, but still in position to reach trucks parked there. The first cut is completed and a second cut made while the trucks use the first cut as a road. When the shovel is advanced into the hill to a point where the maximum working-face height is reached, a second road is dozed above the cut and a new bench started. When the second face reaches a maximum height, a third bench is started or the shovel is moved back to the first bench and that face advanced. When more than one shovel is used, several benches may be operated simultaneously. If the benches are of sufficient length, two or more shovels may be operated on the same bench. The floor of the benches should always be kept sloping slightly away from the face to provide drainage.



Lines A-A and B-B show limits of pit.

Shovel starts at Cut No 1 and excavates by successive cuts parallel to contour lines.

Traffic routes are planned so that empty and loaded trucks do not cross

Figure 25. Layout and development of hillside pit for power shovel operation.

c. *Horizontal Deposits.* In level country it is sometimes necessary to use power shovels to excavate material from deposits below the surrounding ground level. This type of pit is particularly adaptable to gravel deposits where drainage is not a problem.

(1) *Large pits.* Where deposits are sufficiently large, pits are best developed by the circular bench method (fig. 26). The best method is to excavate an initial trench of the desired depth with a bulldozer. Another method is to begin the shovel digging on a downgrade of not over 10 percent until it is working against a face of suitable height. When the initial cut is advanced by the shovel and the face is not more than 6 or 8 feet high, trucks are kept on the surface for loading in order to keep the swing of the shovel as short as possible. When the initial cut is completed, the shovel widens the pit by making additional cuts. Trucks are spotted in the first cut for loading while the shovel is making the second cut, and so on. The shovel continues to dig deeper with each successive cut until the desired maximum height of working face is reached. In order to keep the floor of the pit fairly level, it may be necessary for the shovel to remove a second layer from the first or second cuts. As the pit widens from successive cuts, it assumes a circular shape. Either loop traffic within the pit or one-way through traffic may be established depending on such factors as gradient of entrance outside traffic pattern, trafficability of pit floor, area within the pit, and amount of equipment in the pit. If more shovels are available than can operate efficiently on the face around one level, then a second lower level is started inside the first, beginning near the middle of the first. Development of the second and succeeding levels is the same as for the first.

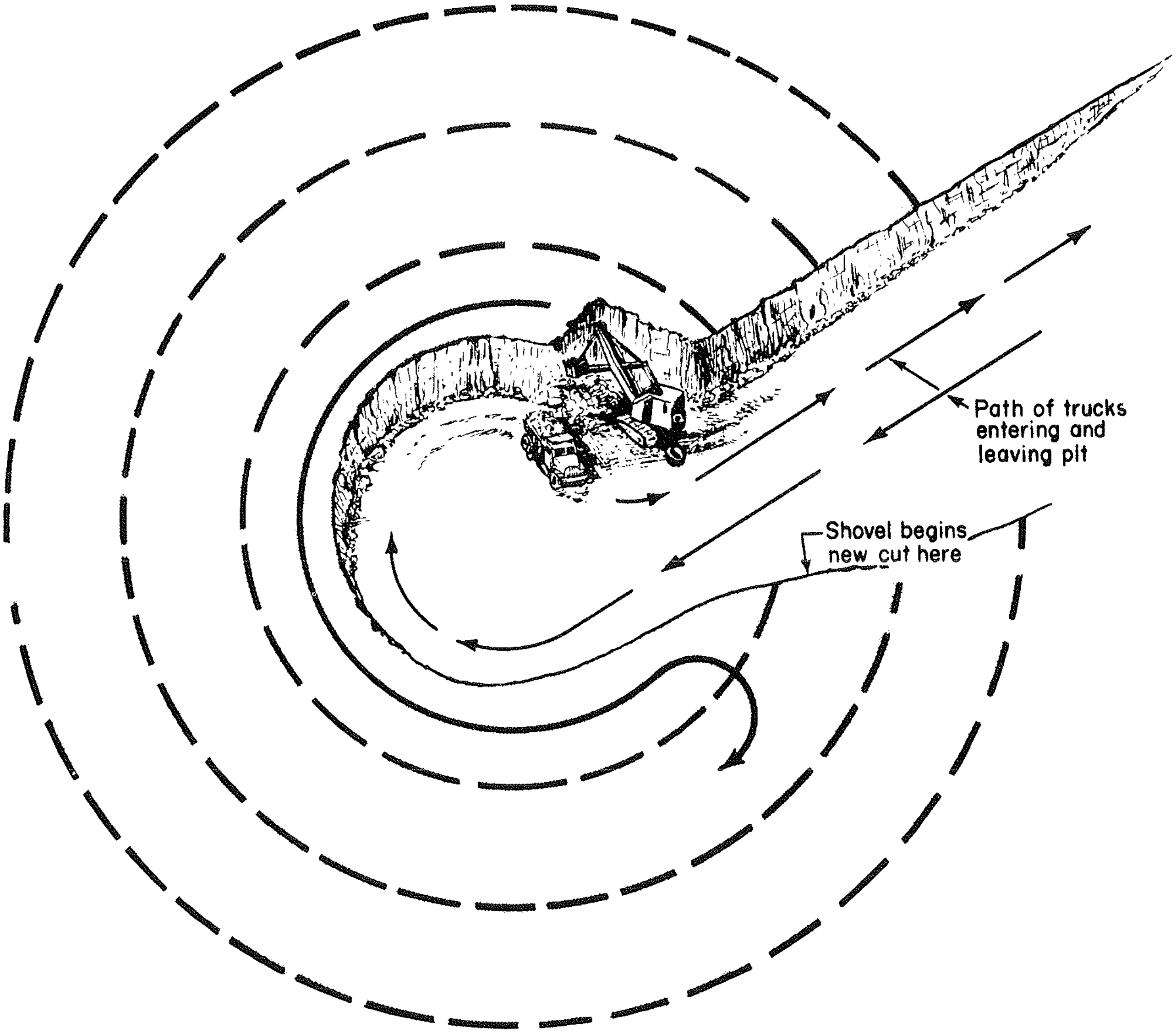


Figure 26. Layout and development of a subsurface pit using circular bench method.

(2) *Narrow pits.* Certain types of deposits, such as those of old streambed origin, are not of sufficient width for circular development. A similar method of operation involves development in straight-line benches (fig. 27). The shovel or a bulldozer digs the first cut to a depth sufficient to provide a desirable height of working face. The cut is continued at this level, loading trucks over the bank. Then the shovel reverses its direction, making a second cut alongside the first. A bulldozer is used to level the first cut for the trucks. Succeeding excavation operations are in parallel straight cuts. If the deposit is deep enough, even a second and third level are developed, beginning at one side of the pit rather than in the center. The ground water table, drainage, and area rainfall may be factors in the depth to which this deposit may be worked and the equipment to be used. Excavation of deep narrow deposits tends to develop faces of great heights. Caution must be exercised to avoid endangering personnel and equipment by cave-ins or slides.

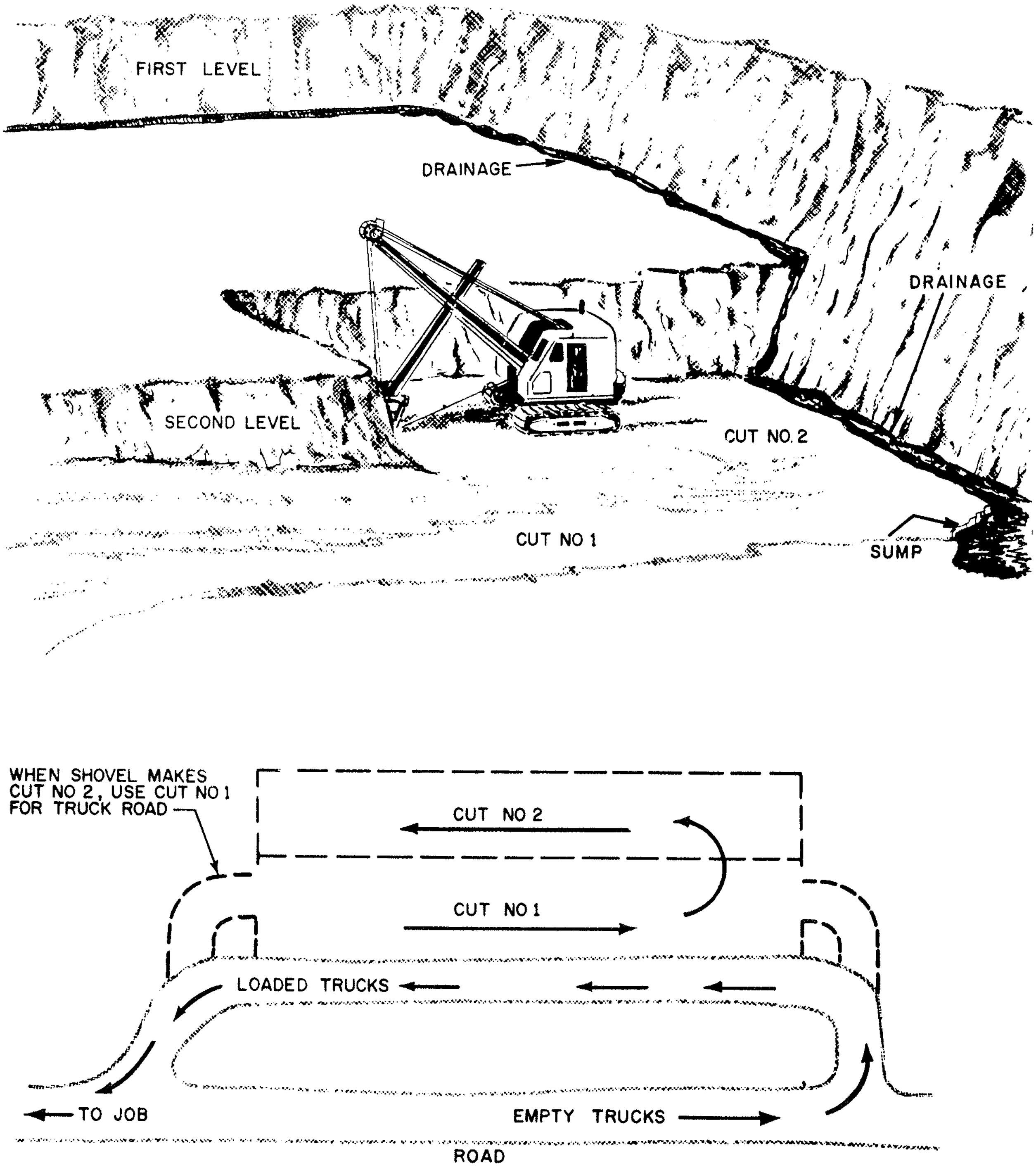


Figure 27. Layout and development of a subsurface pit using straight bench method.

47. Excavating With Draglines

a. Use. Draglines are best used to excavate loose materials below the track level of the machine. It is the most practical piece of military equipment for underwater digging and is well adapted to submerged gravel pit operations. Typical dragline jobs are recovering sand, gravel, or coral from streambeds, lake bottoms, lagoons, and beaches. The primary use of draglines is to stockpile material for other loading equipment or to load hoppers. Since draglines are slower and less accurate than power shovels, they are not normally used to load trucks. Figure 28 depicts layout and development of a pit using this equipment.

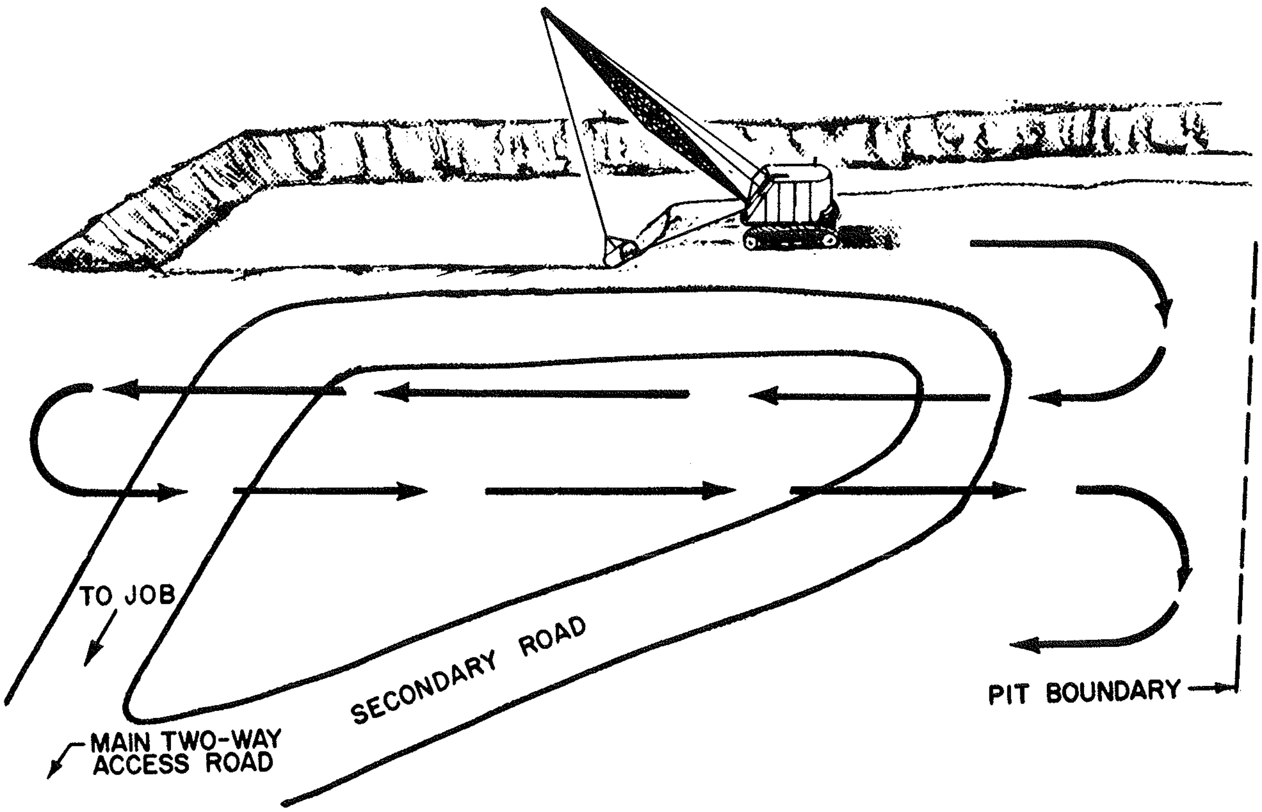


Figure 28. Layout and development of a subsurface pit using the dragline.

b. Working Range. Since the dragline has a greater reach than any type of power shovel, it usually is classed with earthmoving equipment, whereas shovels are classed with loading equipment. The horizontal casting radius for excavating or dumping may be 20 or 30 feet beyond the end of the boom, and the vertical reach may be as much as 50 feet below the machine track and 30 feet above.

c. Underwater Excavation. When removing material by dragline from streams, lake beds, lagoons, and ocean beaches, the unit should be set as close to the water as possible, with the crawlers advancing parallel to the shore line. The machine should be worked in a fan-shaped pattern, reaching out into the water as far as possible. A sector of approximately 90° should be worked from one setting, then the dragline should be advanced along the shore line to a new location. It usually is desirable to swing 180° when dumping so that the stockpiled material will be a maximum distance from the water's edge. With each new setting of the dragline a new stockpile is made. In place of stockpiling, a hopper may be moved to each location either by derrick or by rail. Hoppers should be used when possible because they eliminate handling the material a second time. There are times when waterborne dredges can be used for stockpiling suitable aggregate. The material removed when channels are made or improved often will be usable, especially if allowed to dry. This should not be overlooked if aggregate is scarce.

d. Dry Pit Work. Draglines are adpated to working entirely below the level of their tracks in deep deposits. Working down in a series of nearly horizontal layers, the dragline removes each layer by a succession of parallel straight cuts. When a layer is completely removed, a ramp down to the new floor level is built by the dragline or by a bulldozer.

e. Hillside Operations. Where a power shovel or front loader is not readily available, the dragline may be used to excavate hillside deposits. The usual procedure is to start at the top of the hill and excavate in a series of horizontal lavers or benches. Two or more machines may be used on successive horizontal benches. Although draglines can negotiate grades as steep as 20 percent, they must be level to dig. Normally draglines level their own digging positions.

f. Slag Pile Operations. In certain mining, smelting, and industrial districts, slag piles afford an excellent source of aggregates and material for surfacing. While the dragline ordinarily digs toward itself, it may be arranged to dig away from itself with comparatively simple rigging. With the machine located at the base of the slag pile, it can be employed to dig upward along the surface of the slag pile. Hoppers should be used with this operation.

48. Loading Ramps

a. Use. A loading ramp, or chinaman, is a structure built expressly for the purpose of loading pit or quarry material into hauling units with earthmoving equipment. Loading ramps are used principally in situations where trucks or other types of hauling equipment are available for transportation. For example, a small detachment equipped with only a few vehicles and a bulldozer may be required to deliver as much as 300 to 400 cubic yards of material per day to a construction or maintenance job. Loading ramps are also used when the loading equipment available is not sufficient. Such may be the case where a dump truck unit is attached to an organization that does not have the necessary extra loading equipment. Loading ramps may also be used by a battalion in charge of a large earthmoving job for the purpose of balancing the plant so that all equipment is operating at maximum output. Loading ramps are sometimes used with hillside deposits or in pit operations if the floor of the pit is accessible to trucks. They are particularly adaptable to deposits of material too shallow for economical shovel operation.

b. Types. Loading ramps are designated by the method of discharging the pit material, by the manner in which material is loaded into them, and by the manner in which hauling vehicles approach and depart.

(1) *Chute.* The simplest type of loading

ramp is the plain chute (fig. 29). Care is required in spotting trucks, especially at night. Construction of chute should allow the loading operator to visually observe the equipment bed being loaded.

Figure 29. Simple chute loading ramp.

NOTE: These descriptions and diagrams have been combined to save pages.

(2) ***Single-end trap, truck-back-in*** (fig. 30). This type of loading ramp is best adapted to a situation in which comparatively small quantities must be loaded immediately. It can be constructed in the least time and with the least amount of building material, but it is the slowest in operation. It requires only one bulldozer for operation, and is suited to bank excavation. A small excavation at right angles to the bank may be required to accommodate the rear end of trucks. When large quantities are desired and sufficient equipment and trucks are available, this type of loading ramp can be widened to permit multiple truck loading.

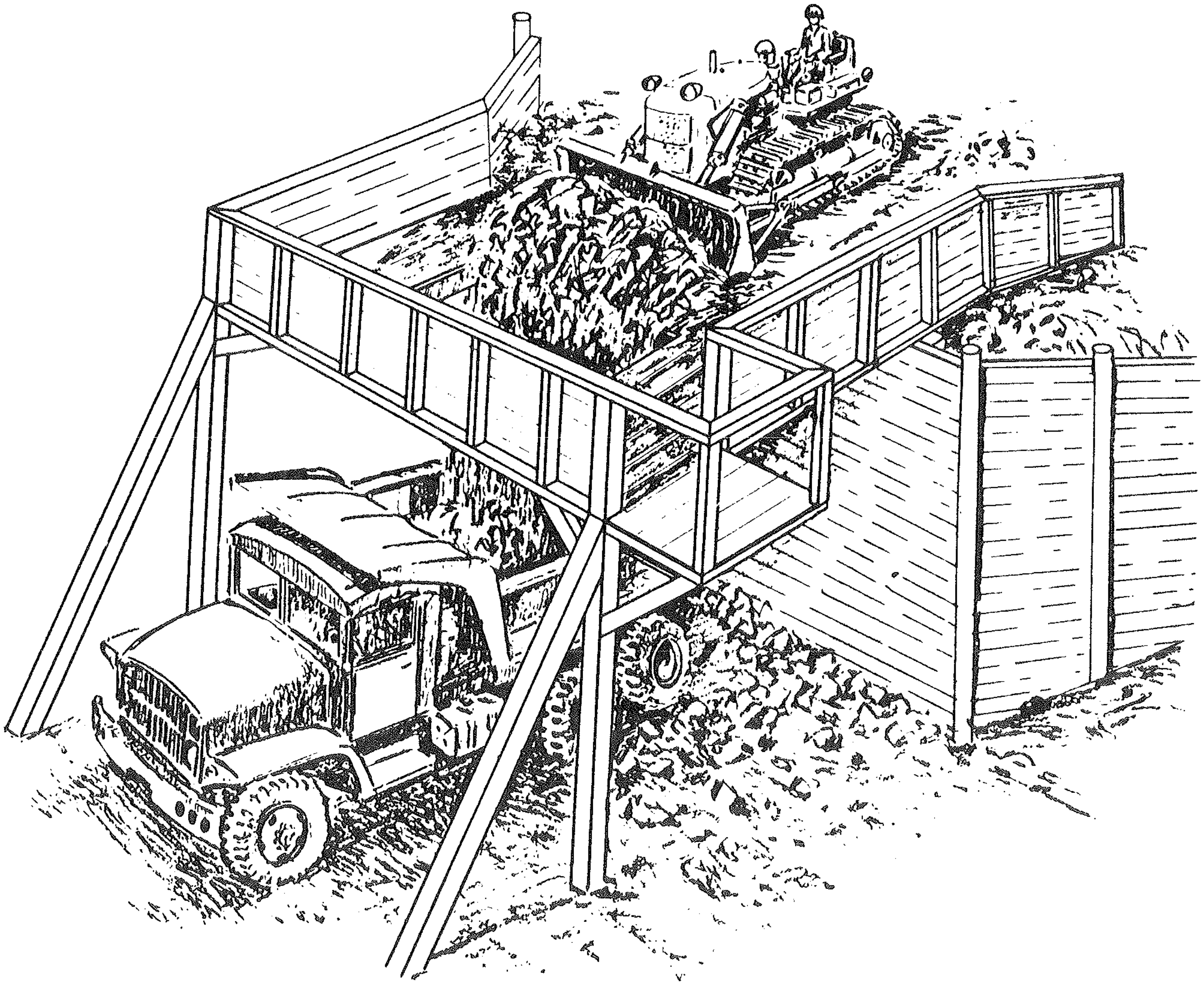


Figure 30. Single-end trap, truck-back-in, loading ramp.

(3) *Single-end trap, truck-drive-through* (fig. 31). This loading ramp is a modification of the single-end trap, truck-back-in type to permit closer control of truck loading and better traffic circulation. It requires more building materials and must be of stronger design.

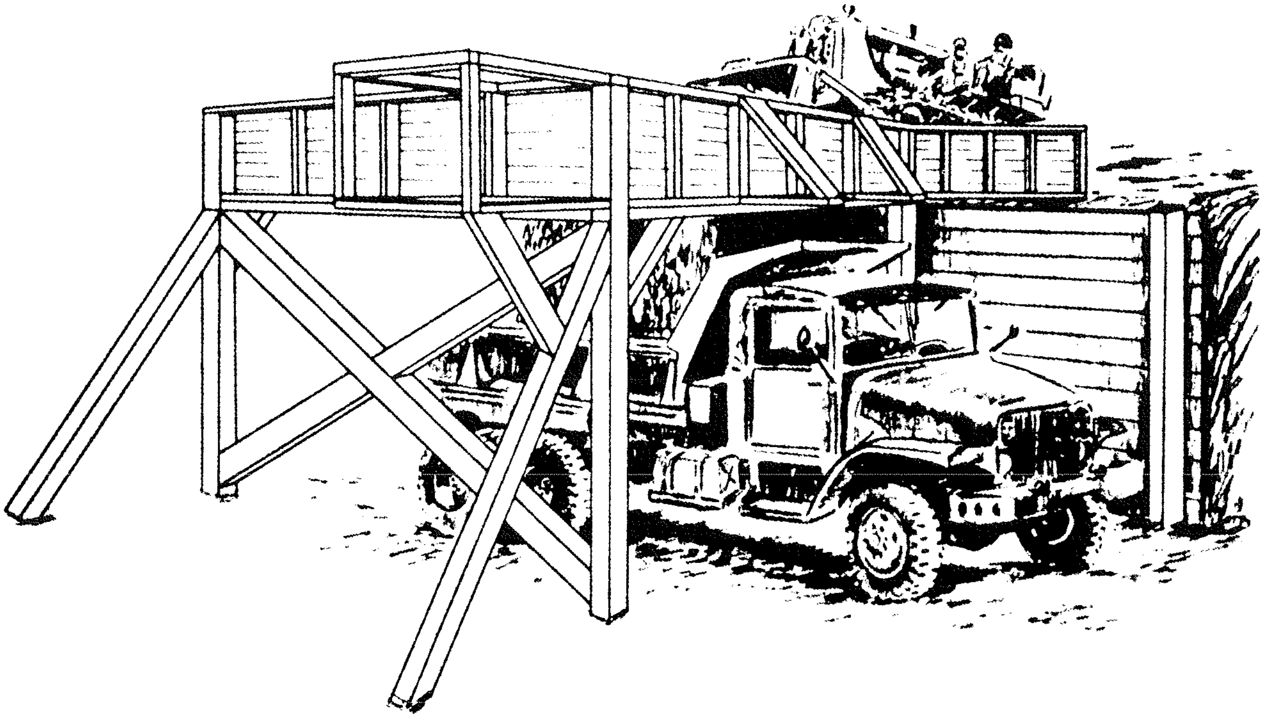


Figure 31. Single-end trap, truck-drive-through loading ramp.

(4) *Single-end trap, with grizzly* (fig. 32). This type is useful when a grizzly is required to remove rocks, lumps, or fines from material. Heavy wire mesh or pierced steel plank may be used for grizzly construction instead of 2- by 8-inch or larger lumber. The grizzly may be adapted to or combined with any other type of loading ramp.

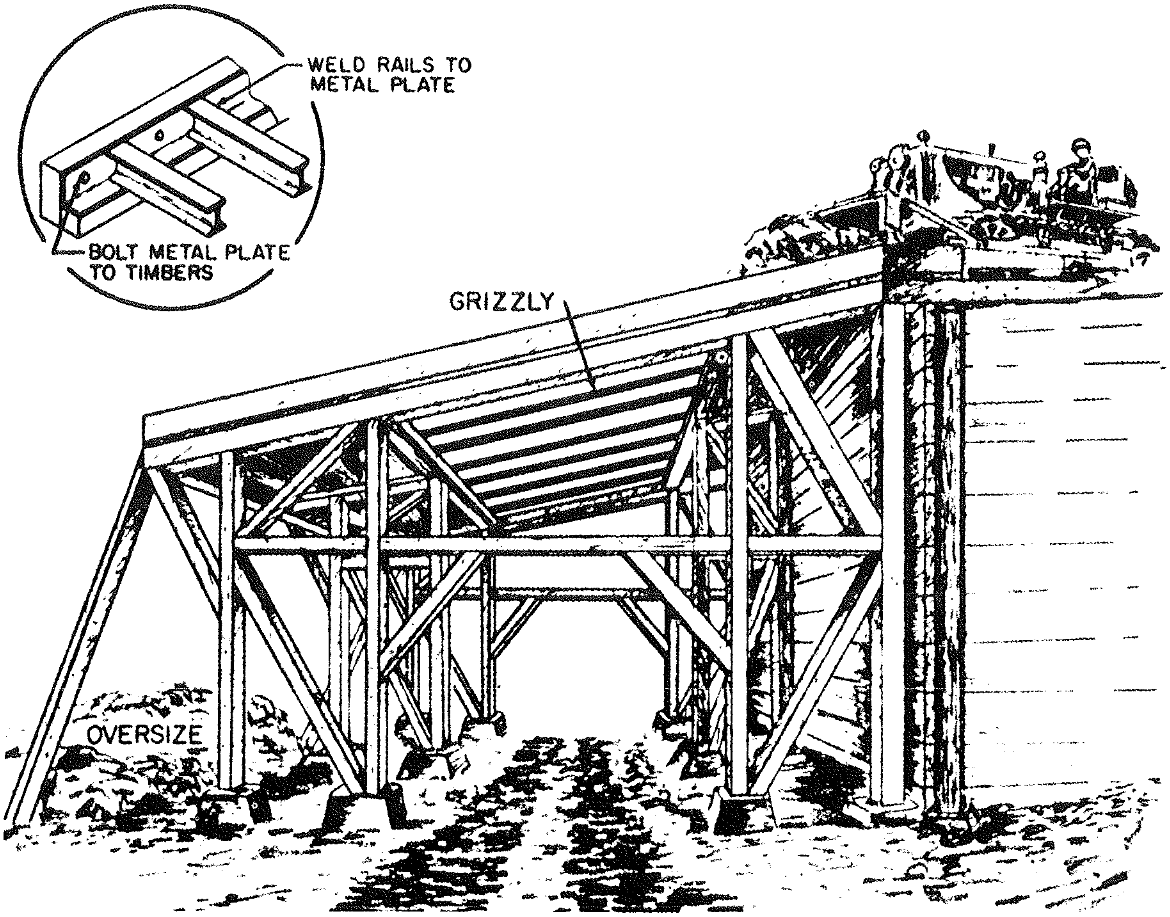


Figure 32. Single-end trap and grizzly type loading ramp.

(5) *Double-end trap, truck-drive-through* (fig. 33). This type of loading ramp can be operated with dozers, graders, or tractor drawn scrapers. It permits simultaneous operation of two faces, provided that two-way traffic is properly supervised. It requires excavation and time to install and is difficult to drain. Double loading can be done by lengthening the loading ramp similar to the overhead-with-ramp type. Additional gates permit stocking of material to allow uninterrupted movement of both hauling and earthmoving equipment.

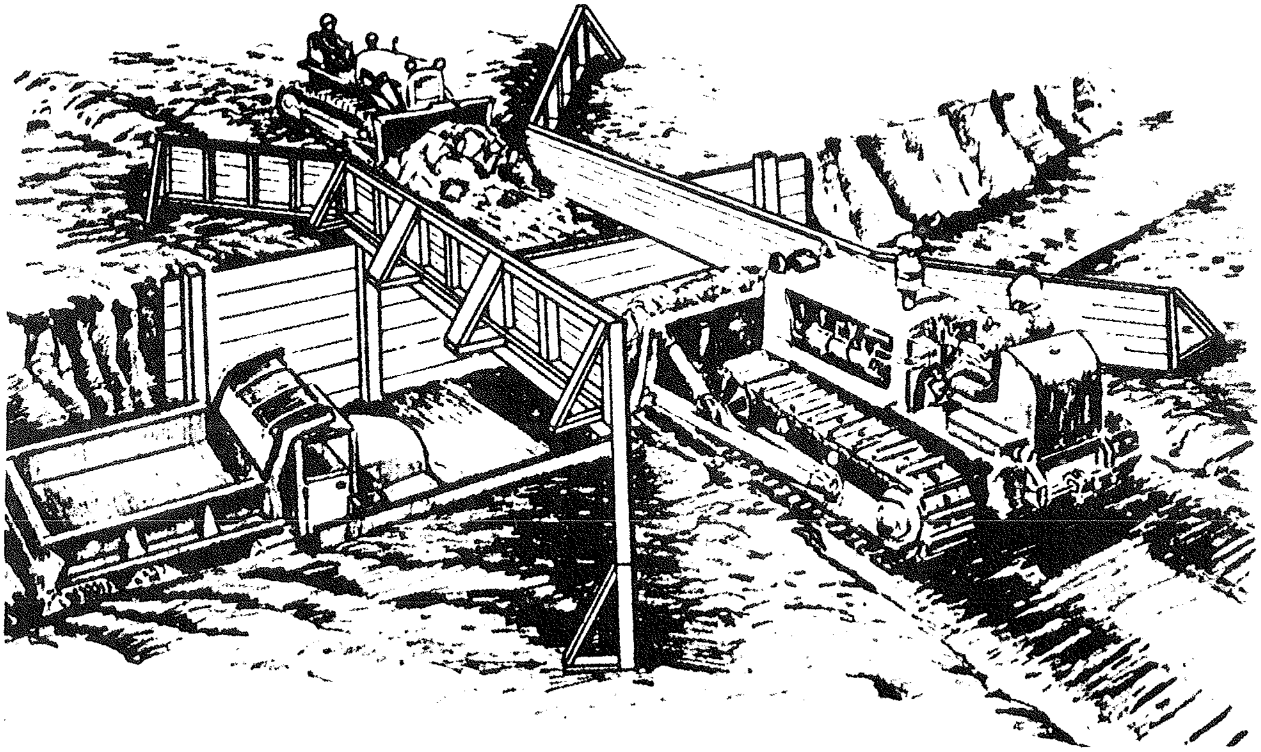


Figure 33. Double-end trap, truck-drive-through loading ramp.

6) *Double-end trap, overhead-with-ramps* (fig. 34). This modification of the double-end type allows for simultaneous loading of two trucks. It is adaptable to high ground-water conditions with restricted drainage, or other grade limiting considerations. Single or double loading can be accomplished. Distance between posts must be sufficient to clear a dozer or grader used for removing spillage in the truck roadway. Gates will provide the same advantage as mentioned for the truck-drive-through type in (5) above.

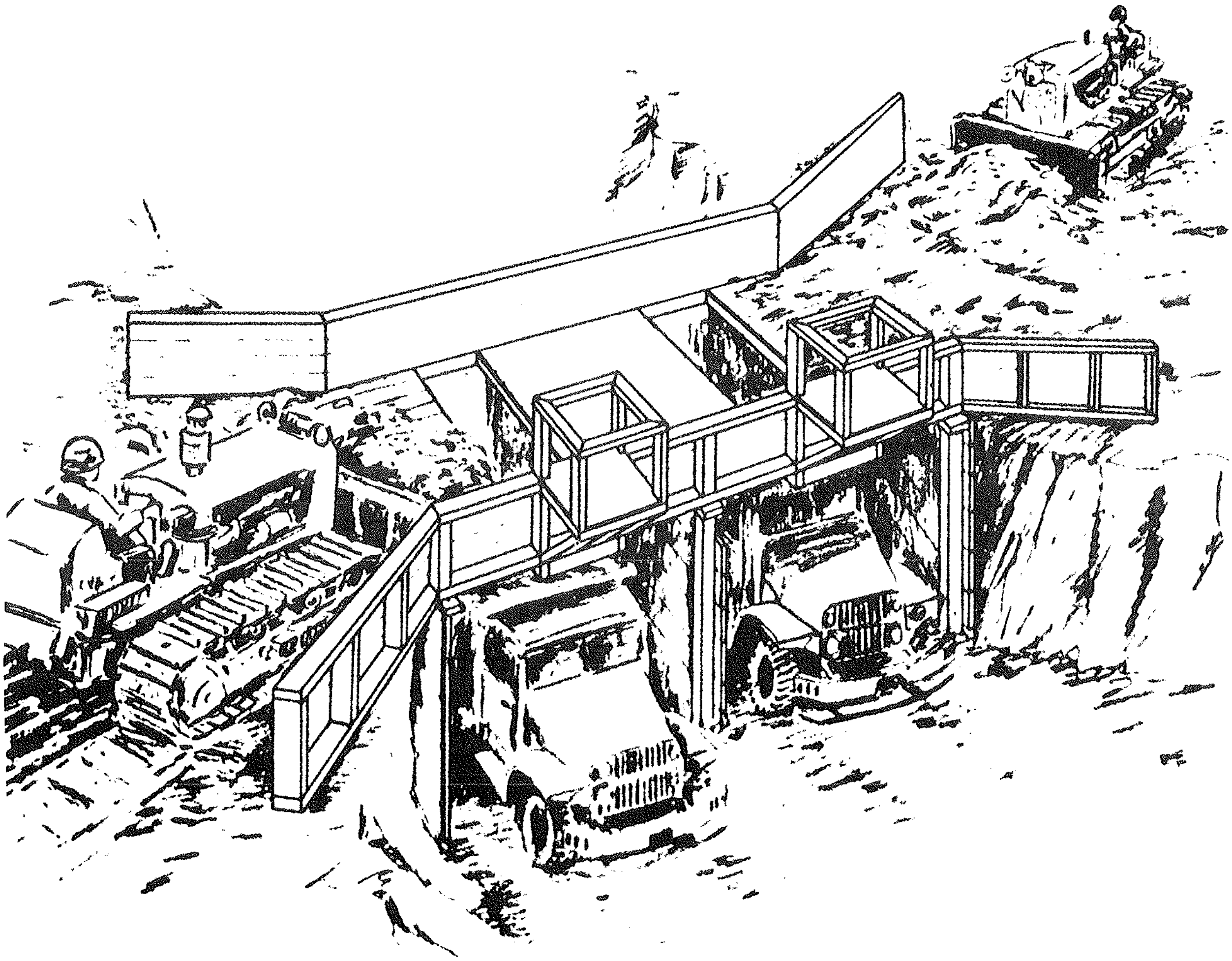


Figure 34. Double-end trap, overhead-with-ramp loading ramp.

c. Design of Loading Ramps.

(1) *Strength.* The most common error in the construction of loading ramps is inadequate strength. They must be designed to support a 20-ton tractor, plus an impact factor of 50 percent, and 20 tons of earth. Particular attention must be paid to cross and sway bracing.

(2) *Walls, floors, and wingwalls.* All walls should be amply high and well-braced. Short wings lose much material by spillage. Deck flooring must be covered with 12 inches of the excavated material to prevent dozer cleats from tearing up the flooring. Where a hopper is not used, a trap should be constructed in the floor smaller than the smallest equipment bed to be loaded. Larger traps waste material over the sides of the truck. Construction should allow for maximum visual capability by the loading operator from his operating position to see the limitations of the loading ramp and equipment to be loaded. The trap is centered over the truck bed. When the back-in type loading ramp is used, a stopblock is installed for the rear wheels of trucks.

(3) *Columns.* Columns beneath a loading ramp should be spaced wide enough apart to permit a dozer blade to pass through when clearing spillage from the roadway.

d. Location and Number of Loading Ramps.

(1) *Distance from pit.* Space must be provided for turning and return trips of loading equipment, particularly when working into a bank or hillside, but long back trips of equipment must be avoided. For a tractor-drawn scraper, distances to be traveled should be kept to about 4 to 6 minutes per round trip.

(2) *Truck loading points.* Single truck loading points limit output to about 30 trucks per hour. Multiple loading points should be provided if warranted by the size of the operation, and, if at all possible, they should be part of one loading ramp. Several loading points with a separate loading ramp for each point increases the need for loading equipment.

e. Operation of Loading Ramps.

(1) *Lighting.* For night operations it is necessary to provide adequate lighting around a loading ramp, especially at the chute or trap.

(2) *Control.* Signals between truck spotter, loading dozers, and gate operators must be closely coordinated.

(3) *Traffic circulation.* Loops to eliminate backing are laid out around loading ramps. The truck spotter must be alert to avoid traffic jams.

(4) *Operating plan.* The plan of operation is fitted to the plant. Plant sequences must be dovetailed. Where pieces of different types of equipment are used, proper coordination of their operations is essential to assure efficient performance.

(5) *Use of bulldozers.* If different sizes of bulldozers are on site, the largest are used to push material up to the loading ramp and a small bulldozer is kept at the ramp for loading. The bulldozer haul should not exceed 200 to 300 feet depending on the number available as compared to the number of trucks and their hauling distance. On long excavations two bulldozers operating with blades side by side deliver about one-third more material than two dozers operating independently.

(6) *Use of scrapers.* Scrapers may be used to haul quantities of material to the loading site. A bulldozer can then be used to feed the loading ramp. With a double-end loading ramp, if adequately designed, scrapers can be used to load material.

(7) *Use of hoppers.* By installing hop-

pers and gates on the loading ramp, material may be stored and drawn off into trucks while the loading equipment is at work. A continuous supply of material is thus maintained, independent of truck operations.

(8) *Use of miscellaneous equipment.* Make use of slips, various types of scrapers, fresnos, and any other kind of captured or improvised earthmoving equipment to supplement organizational equipment in loading ramps.

(9) *Multiple faces.* If possible, always design and lay out an installation with multiple faces and multiple truck loading points so that the maximum available equipment can be used and the greatest unit output obtained.

(10) *Downhill operation.* Always work equipment downhill if possible, letting gravity aid work instead of hindering it.

(11) *Supervision.* Loading ramp operation requires the closest supervision. Trucks must be spotted promptly and accurately in coordination with the loading bulldozer. Transportation of material from the face must also be coordinated with the loading of the ramp to insure that material is on hand when trucks arrive.

CHAPTER 7

SOFT ROCK OPERATIONS

77. General

Soft rock differs from soil in that it is consolidated and requires some method of loosening at the excavation site. It differs from hard rock in that blasting is not required for excavation. It may be loosened by rooters, bulldozers, or air hammers.

a. Construction. It is important for the quarry officer to know whether he is to deal with soft rock or hard rock, because he must know what sort of equipment will be needed. Soft rocks are not preferred for construction purposes except under special conditions which clearly make their use the economical procedure. A single family of rock may have members which are so soft as to be useless for construction purposes, while others of the same family may be quite useful. For instance, chalk is very soft limestone, made from the skeletons of small marine animals whose fleshy parts have been eaten away by chemical action Chalk is practically useless for construction purposes, yet most limestones are quite hard and tough, although generally not very resistant to weathering. So it is with coral, which may be soft or quite hard.

b. Procedures. Soft rocks that have proven suitable for use in road and airfield construction are coral, tuff, caliche, and lateriate. The general principles of operation of soft rock pits and quarries are the same as those governing the operation of any pit or quarry, but it may sometimes be necessary to vary these principles to meet local conditions. In most soft rock pits or quarries the material can be loosened with rooters and picked up by tractor-drawn scrapers or loaded into trucks with power shovels and front end loaders.

78. Coral

The majority of coral reefs occur within 25° north and south of the Equator. For military construction, reef coral is divided into two general groups — soft and hard.

a. Soft Coral consists of unconsolidated muds, sand, coral fragments, algae deposits, shell, and partially weathered hard coral. It may vary from loose to compact, being not especially cohesive when dry. In color it is white, gray, buff, yellow, brown, or light chocolate brown. It appears in lagoons or near shallow water when loose, and in a more compact state as reefs, ridges, and terraces. Usually it is easily worked in pits or on terrace slopes with rooters, scrapers, dozers, or shovels. Soft coral is much less desirable than hard coral as an aggregate for concrete.

b. Hard Coral is formed by the intergrowth of coral heads and the cementation of coral sand and fragmented reef material. It is usually white but may be gray-white, buff, yellow, or brown. It is principally calcium carbonate, but often contains chert, gypsum, and streaks of clay. It usually is hard, and its texture may range from porous to dense, depending on the degree of cementation. It occurs as reefs, ledges, or terraces. It may require quarrying for use as a structural material and, on account of fissures and veins of clay and soft coral, it may be difficult to drill and blast. It usually requires crushing. The dry weight of hard coral in a loose state is from 75 to 90 pounds per cubic foot.

c. Uses. Selected coral may be used for fills, subgrades, and base courses, the degree of selection depending upon the use. White or nearly white soft coral, with properly proportioned granular sizes compacted at optimum moisture content, will create a concrete-like surface. The wearing surface will require considerable care and maintenance. Hard coral when properly graded is a good aggregate for concrete. Soft coral makes an inferior concrete, low in strength, difficult to place, and often of honeycomb structure.

d. Quarrying.

(1) Hard coral is obtained from cuts along the construction project or from quarries. The formations contain fissures as well as large voids which, together with the porosity of the coral structure, decrease blasting efficiency. The use of high percentage dynamite, shaped charges, and bulk and cratering charges is not satisfactory. Boreholes 8 to 12 feet deep, spaced 4 to 8 feet on centers, and loaded with black powder, ammonium nitrate, or low percentage dynamite which has been well tamped, will give the best blasting results. In both pits and quarries, hard coral heads are often encountered. These heads are hazards to excavating equipment and must be blasted.

(2) Soft coral may be obtained from either wet or dry pits. The soft material should be loosened with a rooter, pushed into piles with a dozer, and then loaded into trucks with a power shovel. Where coral requires little loosening, draglines and tractor drawn scrapers can be used. Occasionally, coral from fringing reefs and lagoons can be dug with draglines or power shovels, piled as a causeway, and trucked away progressively from the seaward end to the shoreline. Whenever possible, rooting and scraping methods are preferred for working coral in pits or shallow lagoons.

79. Tuff

Tuff is weathered volcanic ash that has been compacted by natural processes to varying degrees of density and hardness. While it is commonly found in regions where volcanic action has taken place, wind action occasionally has spread a deposit from a single active source over an area of thousands of square miles. It is a soft, workable rock which easily can be excavated by handtools. In parts of Italy, tuff is quarried by sawing large blocks off the face and then cutting them into building blocks. A dozer blade cannot loosen tuff, but a tractor-drawn rooter easily cuts the surface and uproots it. After loosening by a rooter, tuff can be hauled away in scrapers or pushed into stockpiles by dozers, and later loaded into trucks.

80. Caliche

Caliche is just one of the names given to a group of formations found in arid or semiarid regions. It consists chiefly of calcium and silica in the form of clays, sands, and gravels, cemented into a conglomerate by calcium carbonate deposited through the evaporation of ascending or descending waters. The wide variation in both the content and the degree of cementation in caliche causes differences of opinion concerning its suitability for road or runway construction or as an aggregate. The suitability of each deposit should be determined by tests. Caliche is often fairly uniform over considerable areas where the surface soils, sands, or gravels are of relatively uniform character and are saturated by more or less similar cementing solutions. One quality which makes many caliches valuable for road construction is their tendency to recement after being saturated with water, compacted, and allowed to set. This is especially true of caliches which are cemented with lime or salt.

81. Laterite

Laterite is a residual soil formed when ground waters remove certain constituents of where some soils are subjected to the leaching the original soil. In areas of high rainfall action of ground water over long periods of time, certain silicate constituents may be largely removed by solution, the more insoluble residues remaining. These residues consist of either the hydrated oxides of iron, the hydrated oxides of aluminum, or any combination of these with minor quantities of other minerals. A soil so formed is known as laterite. It is referred to as ferruginous, aluminous, or a mixture of these, depending on the character of the parent material. The hardened ferruginous type is known as ironstone or tombstone, which usually is a shade of red. The aluminous type is known as a bauxite, which usually is brown, gray, or white. Laterites occur extensively in the tropics and are widely used as construction material there. Good deposits of hardened laterite can often be found near construction sites. The material often outcrops, or is found within 2 meters of the surface. Such deposits can be readily developed into a valuable source of construction material for fill, base courses, and foundations. Laterites vary in quality however, and experience in use of a particular laterite is often required to produce satisfactory results. Laterites have been used as a stabilizing material and for surfacing when other materials are not available.

Bibliography

The following bibliography contains two sets of references. The first set consists of a reference for each selected text that appeared in the preceding part of this compendium. The second set consists of references to additional publications that either were cited in the selected texts or are closely associated with material that was presented in the Overview and Selected Texts. Each reference has five parts that are explained and illustrated below.

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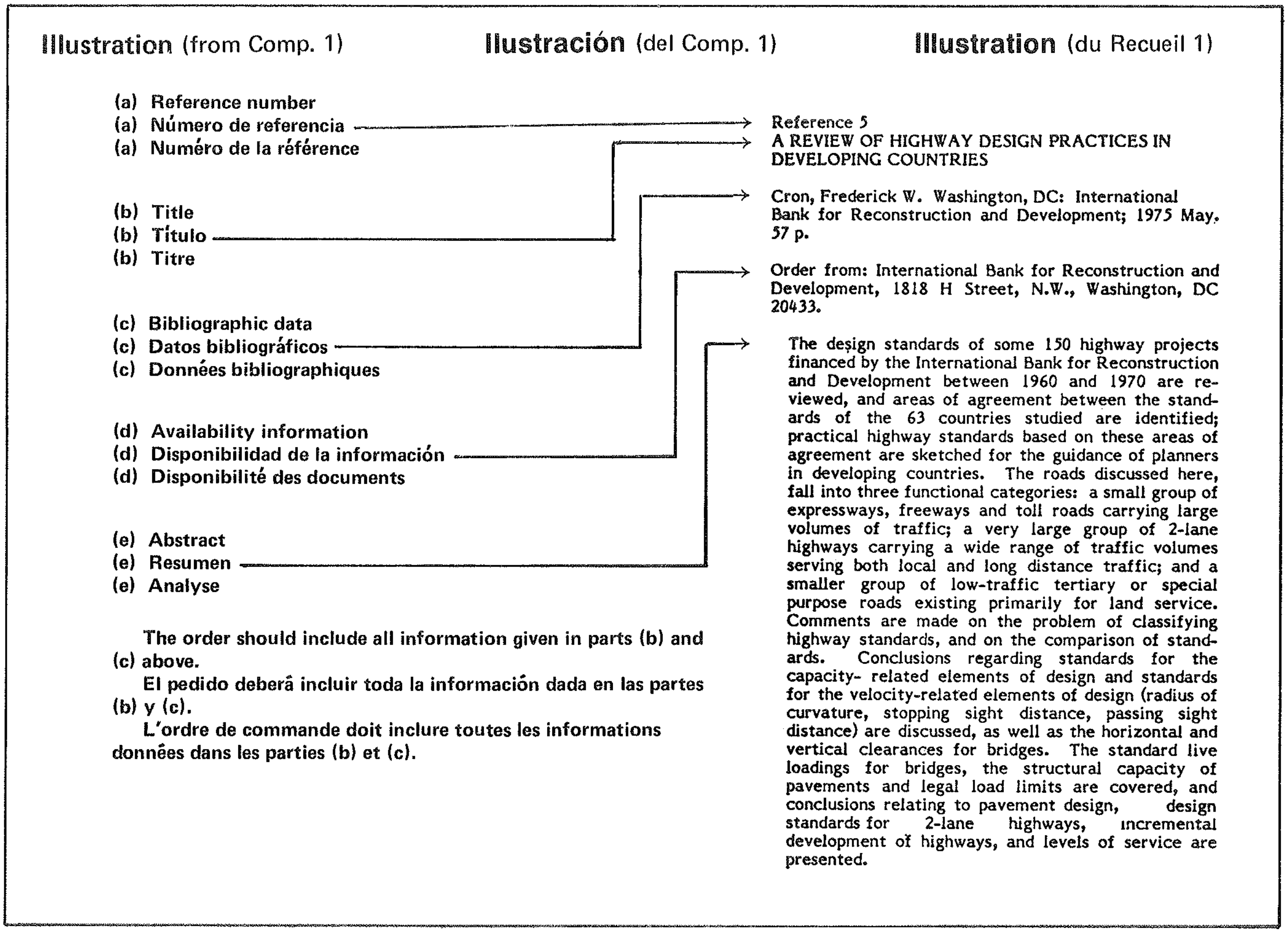

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Reference 5
A REVIEW OF HIGHWAY DESIGN PRACTICES IN DEVELOPING COUNTRIES

Cron, Frederick W. Washington, DC: International Bank for Reconstruction and Development; 1975 May. 57 p.

Order from: International Bank for Reconstruction and Development, 1818 H Street, N.W., Washington, DC 20433.

The design standards of some 150 highway projects financed by the International Bank for Reconstruction and Development between 1960 and 1970 are reviewed, and areas of agreement between the standards of the 63 countries studied are identified; practical highway standards based on these areas of agreement are sketched for the guidance of planners in developing countries. The roads discussed here, fall into three functional categories: a small group of expressways, freeways and toll roads carrying large volumes of traffic; a very large group of 2-lane highways carrying a wide range of traffic volumes serving both local and long distance traffic; and a smaller group of low-traffic tertiary or special purpose roads existing primarily for land service. Comments are made on the problem of classifying highway standards, and on the comparison of standards. Conclusions regarding standards for the capacity- related elements of design and standards for the velocity-related elements of design (radius of curvature, stopping sight distance, passing sight distance) are discussed, as well as the horizontal and vertical clearances for bridges. The standard live loadings for bridges, the structural capacity of pavements and legal load limits are covered, and conclusions relating to pavement design, design standards for 2-lane highways, incremental development of highways, and levels of service are presented.

SELECTED TEXT REFERENCES

Reference 1
A REVIEW OF ENGINEERING SOIL CLASSIFICATION SYSTEMS

Liu, Thomas K. Classification Safety Factor, Terrain, and Bearing. Highway Research Board. Washington, DC; 1967; pp. 1-22. (Highway Research Record 156).

Order from: University Microfilms International, 300 North Zeeb Road, Ann Arbor, Michigan 48106.

This paper discusses, with particular reference to transportation engineering, the nature and necessity of soil classification and the distinction between soil identification and soil classification. The soil properties suitable for classification purposes are considered. The requirements for a satisfactory soil classification system are listed as (a) distinct properties as the basis for grouping, (b) logical, simple and concise scheme, (c) meaningful grouping, (d) desirable terminology, (e) appropriate symbols, (f) sufficient flexibility, and (g) ease of application. The AASHO, Unified and FAA systems are compared in light of these requirements. Finally, the equivalent soil groups in each system are correlated on the basis of classification procedures as well as pavement design values.

Reference 2
THE ENGINEERING SIGNIFICANCE OF SOIL PATTERNS

Belcher, Donald J. Highway Research Board; Proceedings of the Twenty-Third Annual Meeting. Crum, Roy W.; Burggraf, Fred, eds. Washington, DC: Highway Research Board; 1943; pp. 569-597. (Proceedings Volume 23).

Order from: University Microfilms International, 300 North Zeeb Road, Ann Arbor, Michigan 48106.

This work stems, in a large measure, from an engineering evaluation of pedology--the science of soil formation--and its application to the problems of highway design, construction, and maintenance. Its subsequent use in airport site selection has permitted an analysis of the soil patterns and their significance in areas existing under a wide range of soil, parent material, and climatic conditions. The book discusses engineering pedology from the standpoint of subgrade problems. Since this soils engineering technique applies to large areas, a number of extensive soil areas are described in detail and test data showing their uniformity are presented. These have been chosen to illustrate the similarity of soils having a common origin regardless of geographic location. Photographs of these areas are included to illustrate their respective patterns. The individual soil areas have patterns that indicate their properties. Each of the elements that make up the soil pattern may then be studied. These elements, consisting of erosion characteristics, soil color, surface drainage, and numerous others, reflect the nature of the profile. Gullies assume various shapes and thereby reveal certain properties of the soil such as texture and claypan developments; surface drainage is a function of slope and porosity of the soil; while color patterns often reflect ground water conditions. The elements of the soil pattern change and their significance varies in differing climatic zones. The effect of climate is to change the type of vegetative cover and the significance of soil color. However, the soil pattern emphasizes the significance of land forms and weathered slopes. Evaluation of the pedologic classification of the great soil (climatic) groups indicates that it is of little value in engineering work. This assessment is necessary since, in some western states and in many foreign areas, this is the only type of soil information available. Therefore, reliance must be placed on the interpretation of the soil pattern and its engineering implications. A group of photographs shows the basic soil patterns, geologic patterns, and the occurrence of granular deposits. The geologic pattern is considered in its relation to problems of location and grading. By example and test results the properties of various strata visible in photographs are shown. The data show that the soil pattern has engineering significance and that it indicates the conditions that affect the location and construction of highways and airports.

Reference 3
MAPS FOR CONSTRUCTION MATERIALS

Byrne, Frank E. Soil Exploration and Mapping. Highway Research Board. Washington, DC; 1950 November; pp. 63-72. (Bulletin 28).

Order from: University Microfilm International, 300 North Zeeb Road, Ann Arbor, Michigan 48106.

The use of the geologist in preparing materials maps will result in considerable reduction in the cost of engineering construction. The three principal kinds of construction-material maps are discussed: material-site, material-distribution, and surface-geology. The material-site map is the least expensive of the three kinds to prepare. It is an excellent inventory of materials that have already been found and tested, but it includes only those known to the compiler by reason of the basic data with which he has been supplied. It does not show other construction materials that may be present in the same area but have not previously been needed and tested. It is a poor basis for the search for additional materials. The material-distribution map is based on the geologic maps available for a region. Each outcropping formation shown on a geologic map is classified as to the kind of construction material that can be produced from it. The area of outcrop of that geologic formation, then, is the area of distribution of that material. The cost of a material-distribution map is only moderate. The map is an excellent inventory of all kinds of material available in a region, and it shows the potential production areas for each material. The surface-geology map combines many of the useful features of the other two kinds. It is constructed to a relatively large scale; it shows the outcrop areas of all geologic formations and the locations of existing pits and quarries in the area. A field party maps the geologic formations, both consolidated rocks and unconsolidated sediments, usually on aerial photographs. The party plots the locations of all existing pits and quarries, locates additional materials, and collects samples for laboratory testing. The surface-geology map is the most expensive of the three to prepare. The expense, however, is a self-liquidating one and the money expended is returned many times over. The map itself serves indefinitely as a completely adequate base for the efficient search for materials, and is also a valuable source of information for the planning engineer, for the design engineer, and for the engineer estimating the cost of construction.

Reference 4
LATERITE AND LATERITIC SOILS AND OTHER PROBLEM SOILS OF THE TROPICS; AN ENGINEERING EVALUATION AND HIGHWAY DESIGN STUDY FOR UNITED STATES AGENCY FOR INTERNATIONAL DEVELOPMENT, VOLUME I

Morin, W.J.; Todor, Peter C. Baltimore, Maryland: Lyon Associates, Inc.; 1975. 369 p. (Performed jointly with the Brazilian National Highway Department, Road Research Institute; report #PB-267262).

Order from: National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161.

This product of 5 years of worldwide research gives a comprehensive description of tropical soils including their chemical, mineralogical and physical properties and engineering behaviors, as well as their appropriate classification. A new pavement design procedure developed in the tropics for tropical application is described, and a practical range of strength values attainable by stabilizing tropical soils is given. Specifications for common tropical materials used in highway construction, and methods of working with and using problem soils such as black clay and volcanic soils are also described. All tropically weathered red residual soils including true lateritic soils as well as those undergoing laterization were studied. The more descriptive pedological classifications are preferred, and it is noted that variations in properties among groups in different classification systems should be established in each country. Correlations of properties of red tropical soils are established that can be used in identification of soil type and preliminary assessments of engineering properties. The special pretreatments and procedures for soils over volcanic rocks, and the use of the one-point liquid limit test for tropical soils are discussed. The findings are reported and recommendations are made regarding the following: the soil compaction curve, the establishment of the CBR, maximum deflection values for standard axle applications, structural coefficients, flexible pavement design, design tables, overlay design, unpaved road design, Los Angeles abrasion and aggregate impact test, shale durability test, repetitive triaxial load tests, soil stabilization with cement, lime, and asphalt, African black clays, classification of terrain by remote sensors, and specifications.

Reference 5
TECHNIQUES FOR THE INTERPRETATION OF REMOTE SENSING IMAGERY FOR HIGHWAY ENGINEERING PURPOSES

Beaumont, T. E. Crowthorne, U.K.: Great Britain Transport and Road Research Laboratory, Overseas Division; 1977. 24 p. plus photographs and tables. (TRRL Laboratory Report 753).

Order from: Transport and Road Research Laboratory, Crowthorne, Berkshire RG11 6AU, U.K.

Traditionally the interpretation of black-and-white aerial photographs has played a significant role in highway engineering. Recent increases in the availability of different forms of remotely sensed data and improvements in interpretative techniques have now resulted in recognition of remote sensing as a valuable tool for the highway engineer. This report summarises some of the new forms of image data and specialised interpretative techniques now available which can be selectively employed to provide more information than that previously gained from standard photointerpretation procedures. Proper use of these techniques requires a basic understanding of how the imagery is obtained, what it represents and its limitations with respect to spectral, spatial and brightness resolution, so that the best remote sensor data may be selected, processed and analysed for a particular problem to obtain the maximum amount of information with the least expense. Various forms of image enhancement or computer studies may be employed to assist image discriminations and classifications. Some enhancement techniques involve visual image analysis such as colour additive/subtractive viewing, stereoscopic and pseudo-stereoscopic photo-interpretation. A few procedures are ordinarily accomplished through computer analysis (brightness ratioing, atmospheric correction, etc.), but others are effective with either imagery or numerical data. This latter group includes density slicing, contrast stretching, cluster analysis, pattern recognition, frequency analysis, and edge enhancement. Most procedures can be accomplished in several ways, with the accuracy of the results and efficiency of the operation largely dependent on the equipment used. Consequently, the economics of a project may often be the final consideration in the implementation of most interpretative techniques.

Reference 6
TERRAIN EVALUATION FOR CIVIL ENGINEERING PROJECTS IN SOUTH AFRICA

Kantey, B. A.; Mountain, M. J. Australian Road Research Board; Proceedings--Fourth Conference, Melbourne, 1968. Australian Road Research Board. Melbourne; 1968 August; Vol. 4, Part 2; pp. 1613-1623.

Order from: Australian Road Research Board, 500 Burwood Highway, Vermont South, Melbourne, Victoria 3131, Australia.

The developments in terrain classification, data storage and soils engineering mapping in South Africa are traced, and some comments are rendered on the possible advantages and drawbacks of the current trends of development. It is suggested that more emphasis should be placed on geological systems, as a system based on local names is rather meaningless. It is further suggested that the project level approach to soils engineering mapping provides much valuable information, applicable to any form of data storage. The standard method of mapping and presentation of data in the production of soils engineering maps at project level is described and the unexpected benefits that have accrued are indicated.

Reference 7
DEVELOPMENT OF GEOPHYSICAL METHODS OF SUBSURFACE EXPLORATION IN THE FIELD OF HIGHWAY CONSTRUCTION

Moore, R. Woodward. Soil Exploration and Mapping. Highway Research Board. Washington, DC; 1950 November; pp. 73-99. (Bulletin 28).

Order from: University Microfilms International, 300 North Zeeb Road, Ann Arbor, Michigan 48106.

This article summarizes the present (1949) status of geophysics in highway construction, reviews the theoretical aspects of the refraction seismic and the earth resistivity methods, and details their application in the field. It has been found that both seismic and resistivity test methods are practical for use in the study of many highway construction problems. The earth resistivity apparatus, by reason of its simplicity of operation and the rapidity with which the shallow tests can be made, is believed to have a more universal application than the seismograph. Accordingly when making a detailed geophysical survey of a grading project it has been the practice to make a resistivity survey first and, if necessary, to follow with the seismograph in areas where the resistivity data have failed to adequately identify the subsurface formation. Seismic test results are described, as well as the application of earth resistivity tests applied to highway grading projects, resistivity tests applied to foundation problems, and resistivity tests over peat bogs and swampy areas. A knowledge of local geology is essential to an intelligent interpretation of resistivity data. The advantages and limitations of the seismic and resistivity tests are also discussed. These relatively inexpensive test methods are useful in shallow subsurface exploration for obtaining information to be used as control for design purposes or as control for more detailed subsurface surveys by core drilling and other commonly used direct methods.

Reference 8
PITS AND QUARRIES

U.S. Department of the Army. Washington, DC; 15 December 1967. 142 p. (Technical Manual 5-332).

Order from: U.S. Department of the Army, Army AG Publications Center, 1655 Woodson Road, St. Louis, Missouri 63114.

This manual, which is designed for personnel engaged in the selection and operation of pits and quarries, outlines methods and procedures used in explorations for pits and quarries, and provides information on the equipment required to operate pits and to supply crushed stone. Site selection is discussed with details of preliminary and field reconnaissance as well as details of evaluation of the pit and quarry sites. Quarry layout and development are also detailed. The review of pit operations covers site preparation, excavation with scrapers, excavation with power shovel and trucks or front loader and trucks, excavation with draglines, and loading ramps. Cut design, blasting and quarry records in rock excavation are described. Soft rock operations discussed in the publication cover coral, tuff, caliche, and laterite. A sample quarry problem, information on retaining walls, and further advice on exploration and operation of pits and quarries are included in appendices.

ADDITIONAL REFERENCES

Reference 9
PCA SOIL PRIMER

Portland Cement Association. Skokie, Illinois; 1973. 39 p. (Engineering Bulletin EB007.04S).

Order from: Portland Cement Association, 5420 Old Orchard Road, Skokie, Illinois 60076.

This publication was prepared to furnish engineers with basic information on soil with regard to its influence on the design, construction, and performance of concrete, soil-cement, and other types of pavement. Definitions of soil terms are given and tests commonly employed by soil technicians are described, with particular emphasis on the particular meaning and application of these terms and tests. The importance of a clear understanding of the relation of soil identification to soil classification is stressed, and the classification systems of the U.S. Department of Agriculture, the American Association of State Highway Officials (AASHO), the American Society for Testing and Materials (ASTM) and the Federal Aviation Administration are described. The engineering properties of soils (compaction, structural strength, elasticity and compressibility, permeability and capillarity) and related tests are outlined, as well as soil surveys and soil sampling. Examples are used to illustrate the engineering application of the information presented here. These examples include a soil reconnaissance survey for an airport, a detailed soil survey, sampling, testing, and classification procedure for the same airport, and the analysis of soil tests in terms of the design and performance of concrete, soil-cement, and granular-base pavements.

Reference 10
TROPICAL SOILS: CHARACTERISTICS AND AIRPHOTO INTERPRETATION

Liang, Ta; Cornell University. Bedford, Massachusetts: U.S. Air Force, Cambridge Research Laboratories; 31 August 1974. 83 p. plus photographs and appendices. (Report #AD-613555).

Order from: National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161.

To facilitate engineering studies of tropical soils, and particularly their airphoto interpretation, a classification system is proposed which covers major groups of soils peculiar to the tropics, soils common in both tropical and subtropical regions, and soils common in all climates. The origin and formation of tropical soils and their relation to climate, parent material, topography, and age are reviewed. The physical and chemical characteristics, and engineering problems of each of the major soil groups are examined. A method of airphoto interpretation by direct recognition of soil features, and by inference gained from observation of soil-forming factors and circumstances is presented. Air and ground photographs from Central and South America, Tropical Africa, Southeast and South Asia, and Australia are included to illustrate a cross section of the major soil groups in the tropics. Recommendations are made for further study toward refining the airphoto interpretation of the major groups and subgroups of tropical soils, in addition to the supplementary use of other remote sensing devices.

Reference 11
AERIAL PHOTOGRAPHIC INTERPRETATION: PRINCIPLES AND APPLICATIONS

Lueder, Donald R. New York, New York: McGraw-Hill Book Company, Inc.; 1959, 462 p.

Order from: McGraw-Hill Book Company, Inc., 1221 Avenue of the Americas, New York, New York 10020.

This book consists of three parts which cover the principles and theories of photo interpretation, geomorphology and landforms as seen by aerial photography, and the application of aerial photographic techniques to the various fields of earth science. General features such as origin, landform and rock type, surface-drainage patterns, and erosion features are covered as well as gray tones, interpretation, and background training. Fluvial landforms, marine and lacustrine landforms, glacial landforms, glacio-fluvial landforms, aeolian landforms, organic-mineral complexes and rock types are detailed. The application of aerial-photographic techniques to engineering, to geology, to agricultural surveys, to forestry, botany and ecology, and to urban, regional and military studies is reviewed. Comments are also made on aerial photography and geophysics, and various practical considerations. Appendices provide further information on the air-borne profile recorder, a basic system for designating map units on aerial photographs, and the interpretation of photogrammetry and electronic computation in highway engineering.

Reference 12
THE USE OF SATELLITE IMAGERY FOR HIGHWAY ENGINEERING IN OVERSEAS COUNTRIES

Beaumont, T.E.; Beaven, P.J. Crowthorne, U.K.: Great Britain Transport and Road Research Laboratory, Overseas Unit: 1977. 16 p. plus tables and photographs. (TRRL Supplementary Report 279).

Order from: Transport and Road Research Laboratory, Crowthorne, Berkshire RG11 6AU, U.K.

Landsat imagery has been used on two road investigations in the Sudan to provide information on the four main factors that affect route location, i.e., soil strength, earthworks, drainage requirements and construction materials. The interpretation techniques included the production and enhancement of color composites in a purpose built additive viewer which was also used for examining photographically prepared density slices of infrared 'band 7' imagery. The work in the Sudan, together with a review outlining the advantages gained by repeated observations of the earth from space, is used to define the main techniques that can be employed and to identify the major areas where satellite imagery could assist the highway engineer. It is concluded that the present generation of imagery is most suited for the planning and feasibility stages of engineering survey for road projects, such as the preparation of regional maps and inventories of terrain characteristics or reconnaissance studies involving decisions on route location.

Reference 13
DEVELOPMENT OF AIRBORNE ELECTROMAGNETIC SURVEY INSTRUMENTATION AND APPLICATION TO THE SEARCH FOR BURIED SAND AND GRAVEL -- A SUMMARY REPORT

Russell, O.R.; Everett, J.R.; Uncapher, J.A.; Earth Satellite Corporation. Washington, DC: U.S. Federal Highway Administration, Offices of Research and Development; 1977 January. 22 p. (Report #PB-271331).

Order from: National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161.

The development of airborne electromagnetic survey systems (AEM) began about 30 years ago in Canada. To date, the systems have mostly been used in exploration for metallic mineral deposits. However, in the last 10 years there has been some use of the systems for looking at surface material types and exploring for sand and gravel. The results of this work are encouraging; although experience is as yet limited. The three systems which appear to have the greatest potential in exploration for sand and gravel are E-Phase, INPUT, and Dighem. All of these rely on radio frequencies in the very low frequency (VLF) range. Each has been used to locate sand and gravel under specific sets of conditions.

Reference 14
ACQUISITION AND USE OF GEOTECHNICAL INFORMATION

Jones, Gay D., Jr. Washington, DC: Transportation Research Board; 1976. 40 p. (NCHRP Synthesis of Highway Practice 33).

Order from: Transportation Research Board, Publications Office, 2101 Constitution Avenue, N.W., Washington, DC 20418.

This report presents the results of a comprehensive review and assessment of the current practices of state highway and transportation agencies in the acquisition and use of geotechnical information in route selection, design, and construction of transportation facilities. Information is presented on such matters as planning, conducting, and presenting information from geotechnical investigations, the equipment, procedures, and selection of sampling locations for geotechnical investigations, and the structuring and positioning within the agency framework of the organization that must acquire and use geotechnical information.

Reference 15
HIGHWAY-MATERIALS SURVEYS

Highway Research Board. Washington, DC; 1952. 113 p. (Bulletin 62).

Order from: University Microfilms International, 300 North Zeeb Road, Ann Arbor, Michigan 48106.

Four papers are presented which cover the modern (1952) aspects of materials surveys. The paper on the use of airphotos and maps for material surveys, describes how to classify engineering materials in an area using aerial photographs, agricultural soil maps, topographic maps, and geological maps. Several types of materials are mapped and the materials and

the methods to identify them are detailed. A procedure for conducting a material survey using air photos is proposed. The paper, "Geologic Considerations in Relation to a Materials Survey", emphasizes the recognition of the need for information on surface conditions as an aid to engineering and allied sciences. In response to this need, a new system of mapping is cited and illustrated. The paper, "Geophysical Methods of Subsurface Exploration Applied to Materials Surveys", describes the refraction seismic test and its applications, as well as the theory and procedure of the earth-resistivity tests. Typical applications of the latter test in the location of construction materials are also described. The limitation and relative merits of seismic and resistivity tests are noted. The last paper, "Material Inventories", discusses methods employed in establishing an inventory record together with current practices in making such information available to prospective bidders.

Reference 16
MATERIALS INVENTORIES

Highway Research Board. Washington, D.C.; 1963. 65 p. (Highway Research Record 1).

Order from: University Microfilms International, 300 North Zeeb Road, Ann Arbor, Michigan 48106.

Seven papers are presented which describe specific inventory procedures and results reported by six states as well as a discussion of subgrade saturation in India. The paper, "Inventory of Construction Aggregate Sources in Michigan", presents a method used for compiling information pertaining to test data on existing construction aggregate sources. It also describes the geological origin of the natural gravel deposits found in Michigan and its effect on the aggregate quality. "Surveys for Potential Sources of Aggregates" describes the procedure, field work, reports, map preparation and departmental activities associated with the surveys. "Highway Materials Survey in Tennessee" describes an aggregate survey which helped geologists and engineers become familiar with the construction characteristics of the various formations quarried throughout Tennessee. "Vermont Highway Materials Inventory" details the investigations associated with inventorying highway construction materials. "Methodology of the Oklahoma Materials Inventory Research Project" describes the method used to locate new sources of materials and to determine the quantity of materials available from previously known sources and from potential sources. "Arizona Materials Inventory Reports" details the form and content of the reports which include a pit and quarry map, a photogeologic map, and a data sheet. "Countrywide Survey of Maximum Highway Subgrade Saturation in India" describes a survey to determine the degree of subgrade saturation (mostly under flexible pavement) at the time of recession of the monsoon when moisture conditions are worst. The survey indicated that the degree of saturation varies considerably and does not justify the design of pavement at 100 percent saturation of the subgrade at all places in India.

Index

The following index is an alphabetical list of subject terms, names of people, and names of organizations that appear in one or another of the previous parts of this compendium, i.e., in the Overview, Selected Texts, or Bibliography. The subject terms listed are those that are most basic to the understanding of the topic of the compendium.

Subject terms that are not proper nouns are shown in lower case. Personal names that are listed generally represent the authors of selected texts and other references given in the bibliography, but they may also represent people who are otherwise identified with the compendium subjects. Personal names are listed as surname followed by initials. Organizations listed are those that have produced information on the topic of the compendium and that continue to be a source of information on the topic. For this reason, postal addresses are given for each organization listed.

Numbers that follow a subject term, personal name, or organization name are the page numbers of this compendium on which the term or name ap-

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Indice

El siguiente índice es una lista alfabética del vocablo del tema, nombres de personas, y nombres de organizaciones que aparecen en una u otra de las partes previas de este compendio, es decir, en el Vista General, Textos Seleccionados, o Bibliografía. Los vocablos del tema que se listean son aquellos básicos necesarios para el entendimiento de la materia del compendio.

Los vocablos del tema que no son nombres propios aparecen en letras minúsculas. Los nombres personales que aparecen representan los autores de los textos seleccionados y otras referencias dadas en la bibliografía, pero también pueden representar a personas que de otra manera están conectadas a los temas del compendio. Los nombres personales están listeados como apellido seguido por las iniciales. Las organizaciones nombradas son las que han producido información sobre la materia del compendio y que siguen siendo una fuente de información sobre alguna parte o el alcance total del compendio. Por esta razón se dan las direcciones postales para cada organización listeada.

Los números que siguen a un vocablo del tema, nombre personal, o nombre de organización son los números de página del com-

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Index

Cet index se compose d'une liste alphabétique de mots-clés, noms d'auteurs, et noms d'organisations qui paraissent dans une section ou une autre de ce recueil, c'est à dire dans l'Exposé, les Textes Choisis, ou la Bibliographie. Les mots-clés cités sont ceux qui sont le plus élémentaires à la compréhension de ce recueil.

Les mots-clés qui ne sont pas des noms propres sont imprimés en minuscules. Les noms propres cités sont les noms des auteurs des textes choisis ou de textes de référence cités dans la bibliographie, ou alors les noms de personnes identifiées avec les sujets de ce recueil. Le nom de famille est suivi des initiales des prénoms. Les organisations citées sont celles qui ont écrit sur le sujet de ce recueil et qui continueront d'être une source de documentation. Les adresses de toutes ces organisations sont incluses.

Le numéro qui suit chaque mot-clé, nom d'auteur, ou nom d'organisation est le numéro de la page où ce nom ou mot-clé parait. Les numéros écrits en chiffres romains se rapporpears. Roman numerals refer to pages in the Overview, Arabic numerals refer to pages in the Selected Texts, and reference numbers (e.g., Ref. 5) refer to references in the Bibliography.

Some subject terms and organization names are followed by the word ***see.*** In such cases, the compendium page numbers should be sought under the alternative term or name that follows the word ***see***. Some subject terms and organization names are followed by the words ***see also***. In such cases, relevant references should be sought among the page numbers listed under the terms that follow the words ***see also***.

The foregoing explanation is illustrated below.

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pendio donde el vocablo o nombre aparecen. Los números romanos se refieren a las páginas en la Vista General, los números arábigos se refieren a páginas en los Textos Seleccionados, y los números de referencia (por ejemplo, Ref. 5) indican referencias en la Bibliografía.

Algunos vocablos del tema y nombres de organizaciones están seguidos por la palabra *see.* En tales casos los números de página del compendio se encontrarán bajo el término o nombre alternativo que sigue a la palabra *see.* Algunos vocablos del tema y nombres de organizaciones están seguidos por las palabras *see also.* En tales casos las referencias pertinentes se encontrarán entre los números de página indicadas bajo los términos que siguen a las palabras *see also.*

La explicación anterior esta subsiguientemente ilustrada.

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tent aux pages de l'Exposé et les numéros écrits en chiffres arabes se rapportent aux pages des Textes Choisis. Les numéros de référence (par exemple Ref. 5) indiquent les numéros des références de la Bibliographie.

Certains mots-clés et noms d'organisations sont suivis du terme *see.* Dans ces cas, le numéro des pages du recueil se trouvera après le mot-clé ou le nom d'organisation qui suit le terme *see.* D'autres mots-clés ou noms d'organisations sont suivis des mots *see also.* Dans ce cas, les références qui les touchent se trouveront citées après les mots-clés qui suivent la notation *see also.*

Ces explications sont illustrées ci-dessous.

Illustration (from Comp. 1) **Ilustración** (del Comp. 1) **Illustration** (du Recueil 1)