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Leachates: Terrain Analysis

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Contents

Part 1: Leachates from Excavations and Fills

EVALUATION OF POTENTIAL WATER QUALITY PROBLEMS ASSOCIATED WITH HIGHWAY EXCAVATION AND FILL
G. Fred Lee and R. Anne Jones 2

QUALITY OF SEEPAGE AND LEACHATE FROM MINE AND MILL WASTES AND CONTROL OF ITS EFFECTS
Dirk van Zyl, Thomas A. Shepherd, and Adrian C.S. Smith 8

INDUCED POLARIZATION SURVEY OF SULFIDE-BEARING ROCKS IN EASTERN TENNESSEE AND WESTERN NORTH CAROLINA
Don H. Jones, Bruce S. Bell, and Jack H. Hansen 13

SURVEY OF TECHNIQUES USED FOR PREDICTING LEACHATE QUALITY
John C. Wright, Jr., and Sampath S. Iyengar 20

IDENTIFICATION OF SOURCE MATERIALS FOR ACID LEACHATES IN MARYLAND COASTAL PLAIN
D.P. Wagner, D.S. Fanning, and J.E. Foss 25

LEACHATES FROM EXCAVATIONS AND FILLS: SUMMATION
Joakim G. Laguros and Larry W. Canter 28

Part 2: Terrain Analysis for Transportation Systems

TERRAIN EVALUATION FOR HIGHWAY PLANNING AND DESIGN
P.J. Beaven and C.J. Lawrance 36

TERRAIN ANALYSIS FOR TRANSPORTATION SYSTEMS IN BRITISH COLUMBIA
Terje Vold 46

SYSTEMATIC WATERSHED ANALYSIS PROCEDURE FOR CLEARWATER NATIONAL FOREST
Dale Wilson, Rick Patten, and Walter F. Megahan 50

PEDOTECHNICAL ASPECTS OF TERRAIN ANALYSIS
Gilbert Wilson, David E. Moon, and Donald E. McCormack 57

QUANTITATIVE APPROACH TO ASSESSING LANDSLIDE HAZARD TO TRANSPORTATION CORRIDORS ON A NATIONAL FOREST
Jerome V. DeGraff 64

GENESIS-LITHOLOGY-QUALIFIER SYSTEM OF ENGINEERING GEOLOGY MAPPING SYMBOLS: APPLICATIONS TO TERRAIN ANALYSIS FOR TRANSPORTATION SYSTEMS
Jeffrey R. Keaton 69

DEVELOPMENT AND OPERATION OF REMOTE-SENSING LABORATORY FOR A TRANSPORTATION DEPARTMENT
Don H. Jones and Jack H. Hansen 75

Authors of the Papers in This Record

Beaven, P.J., Transport and Road Research Laboratory, Department of the Environment, Department of Transport, Crowthorne, Berkshire, England RG11 6AU
Bell, Bruce S., Phoenix Geophysics Limited, 4690 Ironton Street, Denver, CO 80239
Canter, Larry W., School of Civil Engineering and Environmental Science, University of Oklahoma, Norman, OK 73019
DeGraff, Jerome V., Forest Service, U.S. Department of Agriculture, Sierra National Forest, 1130 "O" Street, Fresno, CA 93721
Fanning, D.S., Department of Agronomy, University of Maryland, College Park, MD 20742
Foss, J.E., Department of Agronomy, University of Maryland, College Park, MD 20742
Hansen, Jack H., Space Institute, University of Tennessee, Tullahoma, TN 37388
Iyengar, Sampath S., D'Appolonia Consulting Engineers, Inc., 10 Duff Road, Pittsburgh, PA 15235
Jones, Don H., Transportation Center, University of Tennessee, Knoxville, TN 37916
Jones, R. Anne, Department of Civil Engineering, Texas Tech University, Lubbock, TX 79409; formerly with Colorado State University
Keaton, Jeffrey R., Dames & Moore, 250 East Broadway, Suite 200, Salt Lake City, UT 84111
Laguros, Joakim G., School of Civil Engineering and Environmental Science, University of Oklahoma, Norman, OK 73019
Lawrance, C.J. Transport and Road Research Laboratory, Department of the Environment, Department of Transport, Crowthorne, Berkshire, England RG11 6AU
Lee, G. Fred, Department of Civil Engineering, Texas Tech University, Lubbock, TX 79409; formerly with Colorado State University
McCormack, Donald E., Soil Conservation Service, U.S. Department of Agriculture, P.O. Box 2890, Washington, DC 20015
Megahan, Walter F., Forest Service, U.S. Department of Agriculture, Intermountain Forest and Range Experiment Station, Forestry Sciences Laboratory, 316 East Myrtle Street, Boise, ID 83702
Moon, David E., Agriculture Canada, Land Resource Research Institute, Central Experimental Farm, Ottawa, Ontario, Canada K1A OC6
Patten, Rick, Forest Service, U.S. Department of Agriculture, Clearwater National Forest, Route 4, Orofino, ID 83544
Shepherd, Thomas A., Shepherd and Associates, Inc., University Square, 1311 S. College Avenue, Fort Collins, CO 80524
Smith, Adrian C.S., Steffen, Robertson and Kirsten, Inc., Vancouver, British Columbia, Canada
van Zyl, Dirk, Steffen, Robertson and Kirsten Inc., Suite A 101, 6420 E. Broadway, Tucson, AZ 85710
Vold, Terje, Terrestrial Studies Branch, Assessment and Planning Division, B.C. Ministery of Environment, 777 Boughton Avenue, Victoria, British Columbia, Canada V8V 1X4
Wagner, D.P. Department of Agronomy, University of Maryland, College Park, MD 20742
Wilson, Dale, Forest Service, U.S. Department of Agriculture, Clearwater National Forest, Route 4, Orofino, ID 83544
Wilson, Gilbert, Agriculture Canada, Land Resource Research Institute, Central Experimental Farm, Ottawa, Ontario, Canada K1A OC6
Wright John C., Jr., D'Appolonia Consulting Engineers, Inc., 10 Duff Road, Pittsburgh, PA 15235

Part 1:
Leachates from Excavations and Fills

Evaluation of Potential Water Quality Problems Associated with Highway Excavation and Fill

G. FRED LEE AND R. ANNE JONES

The excavation and disposal of materials and the use of fill materials in highway construction are potential threats to water quality. Although most highway construction does not result in substantial water quality deterioration, there are some situations in which significant problems can develop, especially when excavation and/or filling occurs within or near watercourses. To provide guidance for the detection of potential problems from this source, the U.S. Environmental Protection Agency (EPA) published its Guidelines for Specification of Disposal Sites for Dredged and Fill Material in the Federal Register (December 24, 1980). They specify that a water leachate test be used for evaluating the potential impact of contaminants associated with fill material on water quality at or near the filling site. No information is provided, however, on the characteristics of this test. Current guidelines also specify that applicable state water quality standards be used to interpret the results of the leaching test, without any mixing zone allowance. The recommended approach of EPA has several technical deficiencies. This paper discusses the approaches that have been recommended for use in evaluating fill material for environmental impact and also the approaches that should be followed for making such evaluations. Outlined is a water quality hazard assessment approach for evaluating the potential significance of contaminants associated with fill material derived from highway excavation and filling, which will promote technically valid, cost-effective, yet environmentally protective evaluation and control of excavation and fill materials associated with highway construction.

The excavation and fill activities associated with highway development have the potential to impair beneficial uses of waters receiving area drainage. Although federal regulations for dredge and fill operations (P.L. 92-500, Section 404) have existed since the early 1970s, it appears that the portions dealing with fill materials have been largely ignored by the regulatory agencies. Interest in this area was prompted several years ago, however, when highway construction in the eastern Tennessee-western North Carolina Smokey Mountain region resulted in large-scale fish die-offs in area waters. It appears that sulfide minerals in the fill material used in that project were oxidized to sulfate on contact with air. Hydrogen ions were released, leading to the formation of sulfuric acid, which is alleged to have caused the fish kills in streams that received drainage from the highway area.

On December 24, 1980, the U.S. Environmental Protection Agency (EPA) published its proposed revised guidelines for implementing Section 404 of P.L. 92-500 (1). There are, however, a number of potentially significant technical problems with the approaches advocated in the guidelines for fill material proposed by EPA. If implemented into public policy, these guidelines could readily result in the taxpayers' spending large amounts of additional money for highway construction with little, if any, improvement in environmental quality. There remains a need for technically valid, cost-effective testing procedures that can detect potential environmental problems associated with highway construction, such as the generation of sulfuric acid from sulfide-bearing fill materials, without placing an unnecessary economic burden on the public for highway construction, most of which, in general, would not have a significant detrimental impact on the water quality of the surface and groundwaters of the region.

It is important to point out that, in both the classical and legal senses, "water quality" must be viewed and evaluated in terms of the desired beneficial uses of waters potentially affected, which are designated by the public. While possible desired beneficial uses for a particular water are often many, those generally considered are recreation-aesthetics, sports fisheries, and water supply. An activity that alters a physical, chemical, or biological characteristic of a water does not necessarily alter water quality unless the change adversely impacts a desired beneficial use of the water.

This paper reviews EPA's proposed regulations governing fill materials associated with highway construction, discusses potential problems with the implementation of the regulations into public policy, and recommends approaches that should be used to develop regulations that are more technically valid, cost-effective, yet at least equally and in some cases more environmentally protective than those proposed by EPA in December 1980.

REVIEW OF POTENTIAL SIGNIFICANCE OF HIGHWAY FILL MATERIAL ON WATER QUALITY

There are principally two areas of potential water quality concern associated with highway filling operations. One is the physical impact of solid material transported to watercourses from highway construction sites; the other is the impact of chemical contaminants in the fill material.

Potential Physical Impacts

During highway construction, there may be sufficient amounts of suspended particles transported from the area in runoff to cause waters of the region receiving the runoff to become highly turbid. In waters with low background turbidity, the suspended solids derived from highway construction and/or erosion could be judged to be adverse to water quality based on their impact on the aesthetic quality of the water. In general, the public does not like to see "muddy"-turbid water, especially if the waters were normally clear. If erosion were particularly severe, then several other potential problems would have to be considered. Large amounts of suspended solids can have direct effects on aquatic organisms by burying them or clogging their gills. Altered erosion can also have indirect impacts; it could cause changes in substrate particle size, which could have a significant adverse effect on aquatic organism habitat. While expected to be a rare occurrence, it is possible that sufficient erosion could take place to alter normal flow patterns of the waterbody, which in turn could have a significant impact on the aquatic environment. Normally, however, the placement of a highway in a region will have such a dramatic impact on the runoff pattern of the area that any erosional materials added because of erosion of the fill material after highway construction has been completed would be inconsequential as far as affecting aquatic habitat. Further, in general, except for very sloppy construction and/or poor design, it would be rare that the physical aspects of erosional materials derived from highway construction would have any impact other than temporarily causing the water to be somewhat cloudy. Eventually, even this would be mitigated as the fill material became stabilized with terrestrial vegetation.

Potential Chemical Impacts

The area of greatest potential concern with respect to fill materials is the potential release of contaminants from the fill material either while in place or during and after being transported to a watercourse with runoff-erosion. All fill materials contain contaminants that are potentially hazardous to aquatic life. Fortunately, most of the contaminants are sufficiently firmly attached to the soil particles so that they are not available to affect water quality.

The EPA in the Federal Register (December 24, 1980) (1) attempted to address the problem of contaminant release from fill material in several ways. First, it proposed that if the fill material were "clean," i.e., if there were no"... contaminants in the fill material above background levels ...", the filling may take place without further testing. There are several significant technical deficiencies in this approach. First, simply because all contaminants are present at background levels or less does not ensure that no adverse impact on water quality will occur. An example of this is the instance previously mentioned in which the area material used for highway fill contained sufficient sulfides to ultimately result in a fish kill in waters receiving area drainage.

Second, while we support EPA's approach of preliminary screening for fill material, its foundation on contaminant levels in the background and fill materials is technically invalid. It is well-known that the concentration of a contaminant in solid materials, such as soils or sediments, is not a reliable index to the potential for release of the contaminant to water or its potential impact on beneficial uses of the receiving waters. This has been repeatedly demonstrated by us in studies of contaminant release from dredged sediment, as discussed in a subsequent section. The fact that two sediments contain equal amounts of a contaminant does not indicate that both will release the same amounts. The basic issue that must be addressed is not the concentrations of the contaminants in the fill material but rather the potential mobility of these contaminants under the conditions that will exist at the filling site, and en route to and in the waters of concern. Mobility is governed by a variety of factors, the most important of which are the chemical forms of the contaminants in the system of interest.

Another significant problem with the use of background concentrations as a screen for potential water quality problems is in the definition of the background concentration for the region. Usually, considerable expense would be associated with properly establishing the normal background concentrations for the wide variety of contaminants for which EPA has developed water quality criteria. It is important to avoid the recurrence of problems encountered several years ago in the Great Lakes region when an EPA Region V staff member somewhat arbitrarily established "background levels" for certain contaminants in Great Lakes' sediments. Examination of these levels showed that for some contaminants, the "background" concentrations were less than the normal crustal abundance for these elements. Further, it is important that the highway construction field not adopt the mechanical approach that is being used in many areas of the water pollution control field today, of automatically requiring the analysis of the composition of the material, in this case fill, just to have numeric values to put in a report or impact statement. Substantial amounts of public funds are being wasted by using this approach. In order to properly implement this screening portion of EPA's proposed regulations, a large number of chemical analyses would be required to establish the background contaminant levels for a region and the character of the fill material. Since this would provide little if any insight into potential environmental problems and would only tend to confuse the technical issues, it would seem more appropriate for regulatory agencies to screen for potential water quality-related problems associated with the use of fill material based on the origin of and activities within the region from which the fill material was derived. Most importantly, this approach will save the taxpayers substantial amounts of money in useless testing and provide an approach that is at least as reliable, if not more reliable, than the one that is currently advocated by EPA. Under no circumstances should a regulatory agency establish a concentration of a contaminant in fill material to act as a signal to conduct further testing or to alter construction practice.

The EPA also specifies that there is no need for further testing of contaminated fill material if this material can be "... adequately contained to prevent leaching and/or erosion" (1). Ordinarily, while emphasis is given to contamination of surface waters by fill material, it is possibly more important to consider the potential for groundwater contamination from contaminated fill material. It is possible that certain types of contaminants in fill material that would be adequately contained with respect to surface water contamination could result in groundwater contamination. As a result of the implementation of the Resource Conservation and Recovery Act (RCRA), it is unlikely that highly hazardous industrial waste would be used for highway construction, but it is possible that certain types of mining wastes might be used. Before these types of wastes or other highly contaminated solid wastes or materials are used for this purpose, they should be reviewed in the same manner as they would be under the provisions of RCRA.

Water Leachate Test

The EPA has specified that when a material does not pass the screening test, a water leachate test shall be used to evaluate the potential release of contaminants from fill material. No information was provided, however, in the Federal Register, or by reference therein, to the nature of this test. It appears that neither EPA nor the U.S. Army Corps of Engineers have formulated the details of this test; it does not appear that this test is even under development at this time. Based on our discussions with staff members of the agencies responsible, the agencies seem to be inclined to recommend some type of column leaching test in which water would be percolated through the fill material for the purpose of attempting to simulate what might happen when the fill is in place. While this type of test might be suitable for certain types of filling operations and for more advanced-level tiers of testing if groundwater contamination is of concern, it is not recommended as a screening test. These types of tests are generally expensive and time-consuming, and their results are not interpretable in terms of contaminant release in runoff. When such tests are used for groundwater contamination evaluation, their designs must in general be site-specific; even for this application, their results are often difficult to interpret.

The elutriate test, a sediment leaching procedure developed by the Corps of Engineers and EPA for assessing potential contaminant release from hydraulically dredged sediments during open water disposal, provides a better starting point for the development of a screening test for highway fill material. It is simple, less expensive and time-consuming, and has been demonstrated to predict contaminant release potential for somewhat similar applications. Lee and others (2) and Jones and Lee (3) present a detailed discussion of the development and laboratory and field evaluation of the elutriate test for dredged sediment. Basically this test involves mixing one volume of sediment with four volumes of water for 30 min under oxic conditions. The mixture is allowed to settle for 1 h. The supernatent is filtered and the "soluble" contaminants of interest are measured. Jones and Lee (3) found that this test in general provided a fairly reliable estimate of the direction and amount of contaminant release that occurs during open water disposal of hydraulically dredged sediment. A test of this type would be appropriate for fill material that would become slurried in the water column, or as discussed below, as a screening test for the release of contaminants from fill material. A situation in which this type of elutriate testing would be most directly applicable to fill material would be a filling operation in water, such as construction of a causeway. Under these conditions appreciable amounts of solids could be suspended in the water column.

In the use of a leaching test similar to the dredged sediment elutriate test for fill material screening, some of the test specifications that can impact contaminant release should be altered to take into account the differences in the systems. For example, one of the factors that can significantly influence the results of elutriate tests is the liquid to solid ratio. It would be rare that the erosion from highway fill would result in a liquid-solid ratio of 4:1 in the runoff; usually the fraction of solid would be much less. It is suggested, however, that the 4:1 liquid:solid ratio be used in the screening test to represent a "worst case." If potentially excessive concentrations of contaminants are found to be released, then a series of additional elutriate tests should be run incorporating 20:1 and 100:1 liquid:solid volume ratios to determine the dependence of the amount of contaminant release per volume solid on the liquid:solid ratio.

Another factor that should be considered is the sediment/water contact time used in the leaching test. The dredged sediment elutriate test employs an approximately 1.5-h contact time. This was specified because it approximates the typical contact time found in many hydraulic dredging-open water disposal operations. Further, for most aquatic sediments most of the contaminant release occurs within an hour or so of contact. For fill material, however, since one cannot be certain that similar contaminant release patterns would be found, it is suggested that both 1.5-h and 24-h contact periods be used for the leaching test. If significant differences are found in the two test results, then an additional leaching period of one week should be used. It should be noted that certain potential problems such as sulfuric acid production from pyritic ores may not be detected even with several weeks of incubation. The formation of sulfuric acid under these conditions is similar to the formation of acid in acid mine drainage; the reaction appears to be catalyzed by bacteria that may take a number of weeks to become sufficiently active to be readily detectable. While this type of reaction is of importance where it occurs, it is doubtful, in our opinion, that it is worthwhile to try to screen for it through a leaching test unless the fill material is shown to have high concentrations of sulfides.

The waters used in the screening fill material leaching tests should be typical of the region in which the filling will take place. If the only water that will be in contact with the fill is slightly contaminated rainwater, then a distilled-water leaching test should be used. Ordinarily, however, almost instantaneously on contact, the distilled water or rainwater would assume a character dominated by the fill material as a result of the release of more readily soluble, dominant cations and anions such as Na^+, Ca^{++}, Mg^{++}, Cl^-, $SO_4^=$, and HCO_3^-. Obviously, if the water in contact with the fill is marine or estuarine, then waters of the same pH and salinity should be used.

As discussed by Jones and Lee (3), care must be taken in interpreting the results of sediment leaching tests. The results should not be mechanically compared with water quality criteria or standards for the purpose of judging potential water quality impact. Rather, a tiered hazard assessment approach, such as that described by Lee and Jones (3-5) and subsequently in this paper, should be used in which factors such as the rate and amount of contaminant release and the characteristics of the receiving waters are considered in determining and evaluating the potential impact of the contaminants released on water quality. For further details on the hazard assessment general approach, consult Lee and Jones (4,6) and Lee and others (7).

APPLICATION OF WATER QUALITY CRITERIA AND WATER QUALITY STANDARDS TO FILL OPERATIONS

The EPA states, "... the permitting authority shall determine whether the concentration of each contaminant identified during the 230.61 evaluation [leaching test] is substantially greater than the appropriate existing federal or state water quality standard" (1). This section of the proposed regulations is the one that would cause the greatest problem in implementing fill material environmental regulations in such a way so as to ensure that funds spent for contaminant control are used in a technically valid, cost-effective and environmentally protective manner. First of all, it should be noted that contrary to the Federal Register wording, there are no federal water quality standards; EPA has developed water quality criteria (8,9) that, while having no regulatory authority, are, according to P.L. 92-500, to serve as a basis for state standards that do have a regulatory function. The basic technical problem with this section is that as they exist today, the federal criteria and state water quality standards against which the concentrations of contaminants released in the water leachate test are proposed to be judged are in general inappropriate for this application.

The first set of EPA water quality criteria (Red Book criteria) was released in July 1976 (8); a second set of criteria for 64 of the 65 "Consent Decree" "toxic chemicals" was released in November 1980 (9). The parameters included in the November 1980 criteria, many of which are "exotic" chemicals, were established out of a lawsuit [Natural Resources Defense Fund *et al.* v. Train (EPA)] and did not receive appropriate peer review. Some of the chemicals on this list have not been found to be significant water pollutants. A number of the parameters in the July 1976 criteria were revised in the November 1980 criteria. Many of the remaining July 1976 criteria will be revised in December-January of 1981-1982. The EPA criteria are essentially equivalent to chronic exposure safe concentrations of the available forms of the chemicals, designed to protect essentially all forms of aquatic life. They assume that the organisms in contact with the contaminants will receive a chronic, usually life-time, exposure. Further, they assume that all forms of the contaminants in contact with the organisms are 100 percent available to the organisms. They are primarily directed toward regulating contaminants derived from municipal and industrial wastes. This per se is not a problem; however, EPA administration policy, until recently, has been that if a state adopts a numeric water quality standard, it must be at least as stringent as the EPA criterion for that parameter, or acceptable justification for a more lenient standard must be provided. Further, these state standards have in general been applied to the total concentrations of contaminants rather than the available forms of the contaminants.

In the late 1960s and early 1970s, it was decided that numeric water quality criteria and standards represented the most politically expedient and bureaucratically simple approach for developing water pollution control regulations in the United States. The basic premise of this approach was that if a single value, numeric standard can be established for a contaminant, all that the pollution control agency personnel would have to do would be to take a sample outside of the mixing zone or from the contaminant source. If the concentrations of contaminants in the sample were to exceed the numeric standard, then there would be a violation of the state water quality regulations that would require some type of corrective action. At the time that this approach was first adopted, little was known about how contaminants impair beneficial uses of water and, in particular, those promoting this approach did not have a very good understanding of the great importance of the aqueous environmental chemistry of many contaminants in affecting how a contaminant impairs beneficial uses of water.

It would be very rare that all of the contaminants associated with highway fill material would be in available forms; a substantial part of such contaminants would be associated with particulate matter, most of which would not likely become available to affect water quality. Therefore, if the water leachate test included the measurement of particulate contaminant forms, it could grossly overestimate the amounts of contaminants potentially available to affect water quality. Even if the contaminants in the leachate were soluble, and therefore likely to be available at the point of leaving the filled area, there would likely be sufficient amounts of suspended solids from erosion in the area runoff to convert many soluble contaminants to particulate forms within fairly short distances from the fill area, and thereby mitigate and sometimes completely eliminate, any water quality problem associated with contaminant release from the fill material.

Another significant deficiency with trying to use EPA water quality criteria, or state standards numerically equal to them, directly for judging the potential environmental significance of contaminants associated with fill material is the fact that, typically, fill material contaminants would leave the area of filling during relatively short periods of time associated with rainfall-precipitation-runoff events. If contaminants derived from these areas were to reach a watercourse, they would enter in pulses; the duration of elevated concentrations in the waterbody would be expected to be short compared with the chronic--life-time duration that was used to establish the criteria--standards. It would indeed be very rare that EPA criteria of the type released in July 1976 or November 1980 would be directly appropriate to judge the potential environmental impact of contaminants released from fill material in a water leachate test.

The Federal Register announcement of toxic contaminant criteria (9) contains two important new provisions that could significantly change the approach used to judge the significance of contaminants associated with fill material. Until this date, if a state adopted a numeric water quality standard, it had to be as stringent as the EPA criterion for that contaminant. As of that date, EPA dropped its "presumptive applicability" policy for its criteria and began to allow states to adopt site-specific standards. While Lee (10) pointed out many years ago that there were significant differences between the chemical environments of the bioassay test used to develop the criteria and real-world waters, it is only now that EPA is beginning to focus on providing guidance on the development of site-specific standards, adapting criteria to natural waters. With the significant cutbacks in federal funding, however, it is doubtful that funds will be available to address the development of site-specific numeric standards that would be applicable to the typical situation associated with contaminants derived from highway fill material in a meaningful way. It is recommended that no attempt be made to develop single value, numeric standards to be applied to all situations. This approach, while politically expedient and bureaucratically simple, will be unnecessarily strict in some instances and too lenient for environmental protection in others. Instead, the hazard assessment approach of the type described subsequently and by Lee and others (4-7) should be used to evaluate the potential impact of fill material-associated contaminants on a site-specific basis.

The Federal Register (9) contains another important provision that could significantly affect the evaluation of the significance of contaminants derived from fill material. While EPA has rescinded its presumptive applicability policy, it has required that states adopt water quality standards for all parameters for which it has developed criteria. Until this announcement, if a state did not want to adopt the EPA criterion value for a particular parameter, it could do so simply by not adopting any standard for that parameter. If fully implemented, this new policy will mean that the water leachate from the fill material testing will have to be analyzed for many more parameters (many of which are likely to be irrelevant) than have been required in the past. It is doubtful at this time, however, even if EPA should attempt to enforce this requirement, that this approach will be followed for any significant period of time. As discussed above, there are several of the criteria released by EPA in November 1980 for which states should not, in our opinion, develop standards.

For most discharges, water quality standards are to be applied to waters outside of a zone of mixing of the discharge with a receiving water. The EPA (1), however, specified that no mixing zone shall be used to interpret the potential significance of contaminants released in the fill material water leaching test. No rationale is given for this approach, nor do we see any logic to it. A mixing zone or "limited use zone" might be a way of allowing development of site-specific standards without having to designate specific numeric values. Lee and Jones (11) have recently discussed the use of the hazard assessment approach for the development of mixing zones for point source discharges of contaminants. This discussion should be consulted for additional information on this topic. It is hoped that EPA will not carry through on its proposed regulations on mixing zones as they apply to fill material. Rather than arbitrarily ruling out any mixing zones, EPA should allow the development of site-specific, appropriately sized mixing zones that would protect the publicly designated beneficial uses of the receiving waters, i.e., the swimmable-fishable character. This is in the best interest of the public in terms of highway development, other aspects of filling operations, and environmental protection.

APPLICATION OF DREDGED MATERIAL RESEARCH PROGRAM RESULTS TO FILL MATERIAL

A lack of validity of using bulk sediment criteria as a basis for judging the potential environmental significance of contaminants associated with dredged sediment resulted in the Congress' establishing a $30 million, five-year Dredged Material Research Program (DMRP) through the U.S Army Corps of Engineers and devoted to various environmental aspects of dredged sediment disposal. While the program was supposed to cover both dredged and fill material, those responsible for administration of this program within the Corps of Engineers gave only limited attention to the environmental aspects of fill material compared with that devoted to dredged sediment disposal. This was understandable from several points of view. First and foremost, the Corps has been given substantial Congressional authority to maintain U.S. waterways by dredging. They have limited activity and authority in the area of fill material. Second, it was the potential problems of contaminants in dredged sediment that stimulated the funding. Actually, to our knowledge, except for the situation mentioned above of sulfuric acid formation from pyrite-containing fill material, there has not been a single documented case within the United States of an open water-dredged material disposal or a filling operation's having caused a detrimental impact on water quality because of solids-associated contaminants.

A series of intensive studies was conducted by the Corps of Engineers as part of the DMRP, which was designed to detect potential, significant environmental quality problems. No problems were detected at any of the intensive site studies or at any of the other sites investigated that would justify using alternate, more expensive methods of dredged sediment disposal.

Another reason why the DMRP did not focus on fill material is that filling operations are a highly heterogeneous group of operations that cover a very wide variety of activities, each with its own somewhat peculiar characteristics. On the other hand, dredging and dredged-material disposal activities fall into a limited number of categories, many of which are readily amenable to study in a generalized way.

Although the Corps' DMRP did not specifically address fill material impacts to any significant extent, it did provide considerable information that can be used to guide investigations of the environmental quality aspects of a particular filling operation. First, it is clear that every filling operation must be treated on an individual basis. Attempts to generalize will either be under- or over-protective of the public's interest. It also clearly established, reinforcing what was already known, that bulk contaminant concentrations in solids cannot be used to estimate potential water quality problems.

One of the most significant results of the Corps of Engineers' DMRP that is pertinent to some, if not most, filling operations is the clear demonstration that the concentration of available forms-duration of exposure relationships that are found during open water dredged sediment disposal are such that EPA's water quality criteria (and hence standards equivalent to them) have limited direct applicability for judging the potential impact that a particular disposal operation may have on water quality. Further, out of the DMRP came the development of bioassay procedures and leaching tests that can be used to indicate if a particular sediment may release potentially significant amounts of contaminants that could cause water quality problems if disposed of in a particular location. The EPA and the Corps of Engineers developed a rather elaborate set of bioassay procedures designed to detect potential water quality problems that may be caused by contaminants in dredged sediment. Unfortunately, these procedures are not being widely used primarily because of their complexity and cost, as pointed out by Jones and Lee (3) and Lee and others (12). Essentially the same amount of useful information for management decisionmaking purposes can be gained from a single simple bioassay procedure as from the multiplicity of tests developed by EPA and the Corps of Engineers. For further information on dredged sediment bioassays, consult Jones and Lee (3) and Lee and others (12).

HAZARD ASSESSMENT APPROACH FOR FILL OPERATIONS

While it appears that the excavation and fill associated with highway construction would rarely have significant adverse impacts on aquatic systems beyond those that would occur because of the placement of the highway in the area, it is important to screen fill material used in highway construction for potential adverse impacts. This screening should be done in a tiered hazard assessment such as is discussed by Lee and others (7) and Lee and Jones (5). The EPA has recently proposed a similar approach for use in connection with the permitting of hazardous waste disposal sites (13). Basically, this approach involves an assessment of what may migrate from the deposition area to the surrounding area. Depending on results of screening tests, estimates would be made of the rate of migration, expected rate of dilution, and any attenuation or transformation that might occur between the site of placement of the solids and a point of concern for surface and groundwater quality.

In the first tier of testing, the source and general character of the proposed fill material should be reviewed as well as the probability for substantial amounts of erosion occurring. The sediments should also be evaluated for sulfides. If there are questions regarding the potential for contaminant release or leaching to groundwaters, or if there is likelihood of potentially significant amounts of solids being transported from the fill area, tier 2 testing should be undertaken.

Tier 2 testing should include worst-case screening tests for contaminant leaching similar to the elutriate test described previously. It is important to emphasize that the results of such tests should only be used in the context of the hazard assessment and not as a direct indicator that the fill material is unsuitable, etc. Consideration should be given to the mode and amount of potential transport to a watercourse of importance and to the environmental chemistry-fate of the contaminants in question. Where it appears that contaminant leaching may be significant to the quality-beneficial uses of the surface and/or groundwaters receiving runoff from the fill area based on interpretation guidance provided by Jones and Lee (3), tier 3 testing should be undertaken.

In tier 3, a series of chemical leaching tests should be conducted that bracket the conditions expected at a particular filling site with respect to water contact with the fill. Interpretation of the results of these tests should involve consideration of how the leachate from the fill containing the contaminants of concern would interact with the aquatic organisms of concern in the waters of the region. For these tests, EPA water quality criteria will likely be useful to flag those contaminants and fill materials that may have an adverse impact on water quality. If concentrations in tests designed to imitate real-world conditions are in excess of the chronic safe concentrations, tier 4 testing should be conducted.

Tier 4 tests should be designed to determine whether or not the "excessive" concentrations would cause a potentially significant impairment of the beneficial uses of the water of the area and justify alternate methods of construction and maintenance. These tests involve consideration, on a site-specific basis, of the amount and forms of contaminants that would be released from the fill material that would reach the watercourse of concern and the concentration of available forms-duration of exposure relationships that would exist in the waters of concern. In the Federal Register (1) EPA indicates that additional testing may be used if there are questions about the potential significance of contaminants released from fill material in impairing beneficial uses of the waters of the region. It is likely that tier 4 testing may include aquatic organism bioassays such as those developed by Lee and others (2,12). It is very important that this tier 4 assessment be based on the potential for actual impairment of beneficial uses. If the results of the tier 4 hazard assessment show that there is a significant potential hazard associated with the use of a particular fill, then, and only then, should alternate, more expensive sources of fill or fill containment be sought and evaluated as described herein.

Where groundwater contamination may be of concern, we recommend that EPA's announcement in the Federal Register (February 5, 1981) (13) as well as Lee and Jones (14) be used as a guide for examining the potential for groundwater contamination associated with filling operations. This is especially true for situations in which an attempt is made to "contain" hazardous fill material as mentioned in the Federal Register (1).

There are several significant advantages of using a sequential, tiered evaluation process such as outlined above. First, it provides rational, technically valid guidance for collecting information pertinent to the problem at hand, rather than having random pieces of information collected with the hope of being able to evaluate potential impacts. At the same time, because of the sequence proceeding from simple, inexpensive, but gross testing to sophisticated, more refined but more expensive testing, the hazard assessment scheme is highly cost-effective. Testing may be stopped at any tier once the reliability of the potential impact has been determined with sufficient reliability for the particular situation.

It is recommended that EPA modify its December 24, 1980, proposed methods for assessment of the environmental significance of contaminants in fill material to permit the use of a hazard assessment approach of the type described in this paper. The adoption of this approach ensures that funds spent for alternate, more expensive methods of highway construction and maintenance will result in a cost-effective expenditure of funds for environmental quality control.

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Quality of Seepage and Leachate from Mine and Mill Wastes and Control of Its Effects

DIRK van ZYL, THOMAS A. SHEPHERD, AND ADRIAN C.S. SMITH

Mine and mill wastes, such as waste rock and tailings, are possible sources of road construction material. However, although such materials may be suitable from geotechnical considerations, they may prove to be problematic as they may produce contaminated seepage and leachate. A classification is presented of the types of mine and mill waste. Three important considerations in the use of these mine wastes are (a) the origin and characteristics of the waste rock; (b) the influence of mineral extraction process on leachate quality from tailings (typical problems associated with the various waste types are highlighted); and (c) changes in soil structure due to leachate, e.g., the Na ion, which can accelerate weathering or lead to changes due to ion exchange. Leachate from mine waste can have detrimental effects on the environment due to effluent quality. It can also influence the integrity of engineering structures through chemical attack in many forms. The detrimental effects of leachate from mine waste can be controlled by treatment before placement, treatment during placement, treatment of effluent, and other methods, e.g., the use of detergents to inhibit bacterial activity in the formation of acid drainage.

Mine and mill wastes, such as waste rock and tailings, are possible sources of road construction material. Such materials are available often in abundance and usually exhibit excellent geotechnical characteristics. Furthermore, because these materials are waste products, they are usually economically attractive. However, it is important that the potential chemical problems associated with mine wastes be investigated prior to their use as road building materials. Such problems can usually be solved in time, if they are recognized.

Although many chemical leachate problems can be associated with mine and mill waste, as will be discussed later, acid drainage is by far the most common and potentially serious. Acid drainage is the result of the oxidation of sulfur-rich minerals, most commonly pyrite. Bacteria act as important catalysts in the oxidation process and the development of acid drainage problems.

The purpose of this paper is to present an overview of seepage and leachate problems associated with mine waste and possible ways of limiting their impact. The information is based on our experience and some of the latest literature sources.

EVALUATING MINE WASTE

Classification of Mine Waste

Mine waste is defined here as all solid wastes associated with mining activities and smelters as well as the chemical industries where a mineral is used in the manufacturing of chemicals, such as the fertilizer industry.

Mine waste will be classified for this discussion as follows:

1. Overburden material resulting from stripping operations for strip or open pit mining;
2. Waste rock, including rock that contains subeconomic ore grades as well as "country rock" or rock that is not ore-bearing;
3. Tailings, the fine material remaining after crushing, milling, and processing of an ore;
4. Slag, the waste from smelting operations and usually disposed of as a high-temperature-melted material (the resulting waste is therefore very hard and massive unless recrushed); and
5. Other materials, such as calcine from pyrite roasting for the production of sulfuric acid (1) and gypsum tailings resulting from the production of phosphoric acid (2), fall in this category.

Although it is useful to classify mine waste, as done above, it must be emphasized that no unique leachate problems are associated with any type, e.g., all the types of mine waste can produce acid drainage. The usefulness in the classification is to identify the sources of waste and disposal methods, as each type of waste is usually disposed of separately during mining operations, e.g., overburden and waste rock dumps are separated from tailings impoundments and slagheaps.

Leachate-Producing Capacity of Wastes

There are two major considerations in evaluating the capacity of mine and mill waste to generate contaminated leachates: (a) the origin and characteristics of the waste rock, and (b) the influence of mineral extraction processes, especially the influence of chemicals added.

Origin and Characteristics of Waste Rock

The origin and characteristics of ore or waste rock determine the sulfide and carbonate contents of the waste and its potential for acid generation; hazardous chemical and radiochemical constituents present in the waste, such as heavy metals; and the potential for mobilization and release of these hazardous materials by way of expected interaction with the environment that will be developed by the use of the waste.

Caruccio and others (3) state: "In terms of a sample's potential to produce acidity (all other parameters being equal) the samples with a predominance of fine grained (framboidal) pyrite generate orders of magnitude more acid than samples having coarse grained pyrite".

An important consideration in the acid-producing capacity of a material is the relative percentage of both sulfide and calcareous minerals present. Consideration of only sulfur content may give a wrong impression of the potential acid production of a material. The calcareous minerals present may act to neutralize the acid formation. However, the exact physical state and the low solubility of specific carbonate minerals in water may inhibit alkaline production (3).

Caruccio and others (3) conclude: "In general, samples with neutralizing potential (NP) values of more than 15 mg of $CaCO_3$ equiv. per 1g and sulfur contents less than 0.5% can be expected to produce alkaline leachates, whereas samples with NP values of less than 2 mg of $CaCO_3$ equiv. per 1g and sulfur contents greater than 1.5% can be expected to produce acidic leachates."

Heavy metals, e.g., copper, lead, and zinc, present a problem if they are both chemically available and chemically mobile. Physiochemical reactions--adsorption, precipitation, etc.--inhibit mobility at normal pH (±7) conditions and metals tend to be mobile only at low pH values; i.e., pH<5.3. Ideal conditions for such mobilities are the intimate association of sulfides and metals, such as disseminated sulfide type of wall rocks adjacent to ore bodies. When there are sulfide oxides in this type of waste rock, the heavy metals are available for ready mobilization. In most cases the potential to produce acid leachates will also be indicative of a waste's potential to liberate contained hazardous materials to the leachate. This is especially true for heavy metals and radioactive elements such as radium, thorium, and uranium. The solubility of the elements, and therefore their mobility, increase dramatically in acid environments 4,5).

Influence of Mineral Extraction Processes

There are very few mineral extraction processes that do not involve the addition of one or more chemicals to the crushed ore. In hydrometallurgical processes dependent on leaching, some kind of leach solution is applied, e.g., cyanide (usually NaCN) for gold and silver, sulfuric acid or sodium carbonate and bicarbonate for uranium, and sulfuric acid for copper. Most minerals are extracted best in an acid solution, but some are extracted in an alkaline environment.

It is important that the particular metallurgical process, as well as the possible leachates that can be expected from such waste, be considered in evaluating the suitability of mine waste for use in construction.

Extraction efficiency is improved in many instances by grinding the ore very finely. In some cases, material is produced that is 80 percent finer than the no. 400 sieve (0.038 mm). In addition to chemical concerns of such materials, the goetechnical characteristics of such fine material are questionable also with respect to their use in earth structures.

Radioactive minerals such as uranium, thorium, and radium are liberated not only through grinding, but also are concentrated during the extraction process. Uranium mill tailings have good geotechnical characteristics (6); however, the radiation hazards associated with such tailings make them unacceptable for use in construction. In Grand Junction, Colorado, uranium tailings were used as backfill around residences and public buildings. This practice led to unacceptable increases of radon gas concentrations within the structures and resulted in a costly remedial action program (7). However, for nonconfined conditions, radon gas buildup would not likely be a health concern. Physical separation from radioactive constituents must be assured in any construction use.

Heap leaching of low-grade ores is becoming common practice (8,9). In such cases, the ore is stacked in a heap (crushed or uncrushed) and leached with a concentrated extractant solution. At the end of the leach cycle, the heaps are usually flushed with water to secure maximum recovery of the extracted product. Mine waste resulting from heap leach operations may produce, therefore, "acceptable" leachates. However, more than surface sampling of such materials is necessary to evaluate them. Some leaching operations may lead also to accelerated weathering and degradation of the rock leached, which influences the geotechnical characteristics of the material.

PROBLEMS ASSOCIATED WITH LEACHATES FROM MINE WASTE

Two major implications of the quality of leachates from mine wastes are the (a) impact on the natural environment and (b) impact on engineering structures through chemical attack. These implications are important when mine waste is considered as a possible construction material. However, they become of paramount importance when construction is planned in the vicinity of existing (or future) mine-waste-disposal facilities. Leachates from such facilities can attack not only concrete and steel structures but also can influence the integrity of earth structures, e.g., through the more rapid weathering caused by acid leachates.

This section will consider some of the chemical processes involved in producing these impacts. Such an understanding is important when control techniques for leachates are evaluated.

Impact of Leachate on Natural Environment

Acid Generation

Acid drainage from sulfide-rich rocks has long been recognized as a problem, and the basic technology and philosophy of acid mine drainage control have not changed in more than 30 years (10). It has been known for about the same period that the bacterium Thiobacillus ferrooxidans influences acid formation. There are other bacteria that influence acid formation; however, T. ferrooxidans is by far the most important (3,10). This bacterium is unimportant in saturated environments, but it increases acid formation near the land surface where oxygen is readily available. It is intermittently significant; furthermore, in the intermediate zone of aeration where it increases acid production for three to four days from infiltration after each rainfall, after which the rate of such formation diminishes (10).

The major reactions responsible for pyrite oxidation and subsequent acid formation are given in Figure 1 (10). In general terms, these types of reactions apply also to other sulfide minerals, e.g., chalcopyrite, galena, etc., to varying degrees. This additional problem with heavy metal sulfides is the increased availability of the heavy metal itself for transport on acidification. Kleinmann and others (10) give a detailed description of the three stages in this process. The following are important considerations when control techniques are evaluated:

1. It is possible to forestall acidification during stage 1 by adding alkalinity to the reaction system; if alkalinity exceeds acidity, the major downstream effect is an increase in sulfate concentration.
2. Once acidity significantly exceeds alkalinity, it becomes much more difficult to return an acid-producing system to stage 1.
3. Stage 2 is initiated as abiotic oxidation of

Figure 1. Reactions in acid generation from pyrite.

1. $FeS_2 + \frac{7}{2} O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$

2. $Fe^{2+} + \frac{5}{2} H_2O + \frac{1}{4} O_2 \rightarrow Fe(OH)_3(s) + 2H^+$

3. $Fe^{2+} + \frac{1}{2} O_2 + H^+ \rightarrow Fe^{3+} + \frac{1}{2} H_2O$

4. $FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$

Stage 1

Mechanism	Reaction 1:	proceeds both abiotically and by direct bacterial oxidation
	Reaction 2:	proceeds abiotically, slows down as pH falls
Chemistry	pH above approximately 4.5; high sulfate; low iron; little or no acidity	

Stage 2

Mechanism	Reaction 1:	proceeds abiotically and by direct bacterial oxidation
	Reaction 2:	proceeds at rate determined primarily by activity of T. ferrooxidans
Chemistry	approximate pH range of 2.5-4.5; high sulfate; acidity, and total iron increasing; low Fe^{3+}/Fe^{2+} ratio	

Stage 3

Mechanism	Reaction 3:	proceeds at rate totally determined by activity of T. ferrooxidans
	Reaction 4:	proceeds at rate primarily determined by rate of reaction 3
Chemistry	pH below approximately 2.5; high sulfate, acidity, total iron and Fe^{3+}/Fe^{2+} ratio	

Fe^{2+} slows and T. ferrooxidans takes on its primary role of oxidizing Fe^{2+}, thereby allowing reaction 2 to continue producing acidity and ferric hydroxide.

4. It is possible to stabilize pH during stage 2 if the soil permeability is low and when a small amount of pyrite surface area is exposed. Otherwise, the pH decline continues to the third stage, where acid production is most rapid.

5. Stage 2 includes the oxidation of both framboidal and coarse-grained pyrite.

6. Once stage 3 is reached, acid production can be reduced only by slowing reaction 3 (see Figure 1). It is done traditionally by limiting the available oxygen, but the more direct route of inhibiting T. ferrooxidans is also possible.

The principal impacts on water/leachate quality from such oxidation will be elevated levels of iron, sulfate, totally dissolved solids, and a lower pH value. Unless the environment in which the leachate is being generated has an inherently high neutralization capacity, iron levels will exceed water quality standards in the majority of cases, as drinking water standards are low (0.3 mg/L). In terms of construction and structures, the higher sulfate levels and low pH value give cause for concern, as both are known to degrade concrete.

Impacts themselves may not be apparent immediately but can be serious over an extended period. For example, oxidation can occur despite apparent neutralization in wastes giving a delayed impact. A recent investigation by one of the authors in New South Wales, Australia, showed that tailings water from a base metal mine, which was neutralized to pH = 10 with lime at the thickener stage of the process, produced a liquid in the return water reservoir with a pH of ±3.5.

Acid Leachate as a Result of Extraction Process

As mentioned above, acids are often used as leach solutions in extraction processes. For example, copper is leached from heaps by using a solution with pH = 0.5, while the effluent has a pH of about 3.5. Uranium ore is typically leached at a pH of 1.2 to 1.5. From the discussion of acid generation, it is clear that if any acid-generating minerals are present, the acid drainage problem will be worsened considerably in this case.

When no acid-generating minerals are present, as is usually the case in the production of uranium through acid leaching of sandstone-related ore, the presence of a neutralizing source, such as calcium carbonate ($CaCO_3$) as a neutralizing agent, is the most important consideration in controlling the quality of leachate (4).

Cyanide

Cyanide (NaCN) is commonly used for the extraction of precious metals as well as in some flotation processes to suppress the influence of pyrite. The wastes contain usually low levels of cyanide in the latter case; however, this is not always true in the former. Although some washing is accomplished after cyanide leaching, the cyanide level in the waste usually exceeds drinking water standards (0.06

Table 1. Various cyanide complexes and their relative stability.

Term	Examples Present in Solutions for Extracting Gold
Free cyanide	CN^-, HCN
Simple compounds	
Readily soluble	NaCN, KCN, $Ca(CN)_2$, $Hg(CN)_2$
Relatively insoluble	$Zn(CN)_2$, $Cd(CN)_2$, CuCN, $Ni(CN)_2$, AgCN
Weak complexes	$Zn(CN)_4^{2-}$, $Cd(CN)_3^-$, $Cd(CN)_4^{2-}$
Moderately strong complexes	$Cu(CN)_2^-$, $Cu(CN)_3^{2-}$, $Ni(CN)_4^{2-}$, $Ag(CN)_2^-$
Strong complexes	$Fe(CN)_6^{4-}$, $Co(CN)_6^{4-}$

mg/L). Furthermore, cyanide has been classified as a hazardous waste under the Resource Conservation and Recovery Act (RCRA) of 1976.

Cyanide can be present as free cyanide or in metal composition that has various degrees of stability. These are shown in Table 1 (7).

Free cyanide means the two species, cyanide ion (CN^-) and hydrocyanic acid (HCN), also known as hydrogen cyanide. The latter is of particular environmental concern, since it is the form of cyanide most toxic to aquatic life, capable of killing fish at concentrations as low as 0.05 mg/L (11). It should be remembered that cyanide is not a cumulative poison for people such as some heavy metals are. Therefore, the toxicity of a system must be determined on total concentration and not prolonged exposure.

The toxicity of the metal-cyanide complexes generally results from their dissociation to produce hydrogen cyanide and not from the stable complexes per se. However, copper and silver cyanide complexes, as such, have been shown to be acutely toxic to fish (11).

Free cyanide concentrations in aqueous systems will be lowered by several natural degradation processes. Cyanide will oxidize in the presence of natural oxygen to cyanate complexes that will then hydrolize to NH_3 and CO_2. Cyanide is also given off from the aqueous system by volitalization. Both processes result in a lowering of cyanide concentrations and therefore the toxic properties of a system.

Impact of Leachate on Engineering Structures

Acid drainage is a leachate with a major impact on engineering structures. This impact is caused by the low pH of the leachate leading to corrosion of metals and attack on concrete and by high sulfate concentration that also degrades concrete. This process is well understood and will not be discussed further.

Another result of acid formation is where deposits resulting from the bacterial action build up in subsurface drains and finally clog them (12). Typical deposits in drains can consist of iron, manganese, or calcium carbonate. Iron deposits in drains are often called ochre (12). Ochre can be described as a sticky, gelatinous, yellow to reddish mass of ferric hydroxide plus organic material that can clog subsurface drains. Clogging of subsurface drains through ochre is a common occurrence in agricultural drains but can also be a problem in other applications (12).

TECHNIQUES TO CONTROL LEACHATE QUALITY FROM MINE WASTE

A useful classification of control techniques for acid drainage problems was proposed by Wewerka and others (13). This classification will be followed here, but in an extended form.

Techniques to control leachate quality from mine waste can be classified as follows: (a) treatment before placement, (b) treatment at and after placement, and (c) treatment of effluent. The techniques involve physical and chemical treatment procedures. Physical treatment may be the simplest in most cases and usually leads to better long-term control of leachates. Both physical and chemical procedures will be discussed here.

Treatment Before Placement

The physical preparation of mine waste will influence its acid-generating potential. Pyrite-rich overburden and waste rock should be blasted into large fragments to expose the smallest practicable surface areas. Calcareous material, on the other hand, should be blasted into smaller fragments to increase the area of its reactive surface (14). Such preparation is especially important where these materials will be used together.

Cyanide-rich mine waste can be spread out to allow oxidation and volitalization of the cyanide, as discussed above. Such wastes can also be washed with water to reduce the cyanide content. These two methods must be used with care to prevent acid generation when the waste is pyrite-rich.

Wewerka and others (9) propose the use of calcining as a pretreatment of acid-generating waste. Although they had considerable success with this method, incomplete calcining can lead to a false sense of security.

Calcining consists of oxidation of the sulfur at high temperatures to produce an inert slag. This is the same process used in the production of sulfuric acid from sulfide-rich ores. Smith and Middleton (1) describe environmental problems associated with such waste. The "inert" slag is indeed a good geotechnical material but causes acid generation if incomplete calcining takes place. Calcines are known to have residual pyrite contents of up to 5 percent sulfur. Similar problems can therefore be experienced after calcining.

Treatment At and After Placement

One treatment that is meeting with success is the co-placement of acid-generating waste with alkaline agents (13,14). Either natural alkaline agents such as calcareous rock materials can be used, or specially produced materials such as powdered lime can be mixed in with the acid-producing material. One uncertainty in such co-disposal is the long-term effectiveness to reduce acid generation.

Acid generation is dependent on the availability of water and oxygen, as shown above. Both these factors can be controlled through proper design of the proposed earth structure. Acid-generating mine waste can be encapsulated, therefore, in inert soil or rock materials (1,14). Such cover material should have low permeability to limit the infiltration of water. The cover must be shaped such that no ponding of water is allowed, but the run-off rate must be controlled to reduce erosion potential. Erosion resistance of the cover is important to ensure long-term protection.

Acid-generating materials should not be used as fill at levels much higher than the natural ground level in areas where the groundwater level is high or where ponding can take place. In such cases, wetting and drying can occur that would lead to acid generation.

Groundwater flow should be cut off with subsurface drainage if it becomes a problem in acid generation.

Anionic detergents can be used to inhibit the bacterium T. ferrooxidans economically. Such detergents are readily available in biodegradable forms and are environmentally safe at low concentrations. Concentrations above 10 parts per million (ppm) slow acid production while concentrations of at least 25 ppm reduce acidity levels completely by killing the bacteria. Rubber formulations are used with the detergent to obtain controlled release of it for extended periods of time (5).

Thus far, anionic detergents have been used with rubber formulations as sprays for acid-generating waste dumps. An extension of this method is obviously to inject such detergents into an acid-generating mass, almost as a grout. It would be most economical if the level of application can be selected such that T. ferrooxidans is killed and then to follow it up with lime injection to prevent further acid generation.

Treatment of Effluent

Treatment of acid drainage effluent can be done economically by alkaline neutralization (13). It is necessary to have a catchment basin for such effluent in order to ensure proper treatment and retention time prior to discharge.

Cyanide leachate can be treated by intercepting it in a catchment basin and then to allow oxidation of the cyanide. A positive cutoff should be provided between the cyanide leachate and the groundwater table. A clay liner will result in retardation of the cyanide in leachates, as discussed above. Such a liner is preferred, therefore, to a synthetic liner, which will not provide retardation capacity.

It must be emphasized that treatment of effluent is not to be considered as a long-term solution. Such treatment is usually labor intensive and therefore uneconomical. The source of the leachate must be eliminated. The methods discussed above under treatment at and after placement must therefore be considered.

SUMMARY AND CONCLUSIONS

The geotechnical characteristics of mine waste material are usually such that these materials can be used for road construction. However, the chemical characteristics of such wastes should be understood before they are used in construction. The problem of acid leachate is by far the most important problem; however, chemicals resulting from process considerations must also be considered. These include cyanide and heavy metals.

Leachates can have an influence on the natural environmental quality, but they can also influence the integrity of engineering structures through corrosion, chemical attack of concrete, and clogging of drains.

Leachate quality can be controlled through treatment before placement, treatment at and after placement, and treatment of the effluent. The first two are the most effective ways of controlling the problem.

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Induced Polarization Survey of Sulfide-Bearing Rocks in Eastern Tennessee and Western North Carolina

DON H. JONES, BRUCE S. BELL, AND JACK H. HANSEN

Iron pyrite in minute crystal form occurs extensively in the Anakeesta Shale formations in the Appalachian Mountains and can cause serious environmental problems when exposed in highway cuts and embankments. Many remote sensing techniques were evaluated in an effort to find a means of economically, accurately, and expeditiously locating these low-grade sulfide mineral deposits and to establish their vertical and longitudinal boundaries along a proposed highway corridor. Other benefits also are discussed. Good results were achieved by using induced polarization techniques along a route in the Tellico Mountains of eastern Tennessee and western North Carolina.

Low concentrations of sulfide minerals are a serious cause for concern when they occur in the path of proposed highway construction. The Appalachian Mountains of eastern Tennessee and western North Carolina are noted for deposits of both rich and low-grade ores of iron pyrite. The Anakeesta shale formation, which occurs extensively in the Tellico Mountains between Tellico Plains, Tennessee, and Robbinsville, North Carolina, contains low-grade deposits of iron pyrite or iron sulfide (FeS_2) with crystals often too small to detect with the unaided eye. When exposed to the elements and permitted to weather, the minute crystals oxidize quickly to form a weak solution of sulfuric acid (H_2SO_4) and probably iron oxide (Fe_3O_4), both of which are damaging to aquatic life. In an area experiencing occurrences of acid rain and the natural production of tannic acid through the decomposition of certain organic materials, the addition of even a weak solution of sulfuric acid can severely upset the balance. Many natural trout streams occur in the rather scenic area, which attracts many avid trout fishermen and protectors of the environment. Acid runoff strong enough to corrode asphalt-coated corrugated metal pipe is a cause of concern to environmentalists, judges sympathetic to environmental concerns, governmental officials, and professional highway engineers.

Acid drainage and its adverse environmental impact are very familiar to residents and researchers of Appalachia from Maine to Georgia, especially to those from the coal-mining regions and the mining operations of the Copper Basin, which is in the vicinity of this project. The environmental problem resulting from the construction of the highway project discussed in this paper may have occurred on many projects but could have gone unnoticed or ignored because of the need for highways. Many of the problems that did occur with acid leaching have stabilized over many years or are overshadowed by mining or other such disturbances. The seriousness of the problem was highlighted recently when acid drainage occurred during construction of a proposed highway connecting Tellico Plains, Tennessee, to Robbinsville, North Carolina.

Once sulfide minerals are disturbed by highway construction and leaching begins, remedial measures can be very expensive compared with incorporating appropriate protective measures during the design stage. Detection of the deposits and the use of design procedures incorporating a combination of measures to avoid the deposits and remedial measures may be the most economical and expedient approach.

Detection or location of the sulfide mineral deposits prior to the final design and before disturbance during construction is crucial to the adequate protection of the environment. To be effective and acceptable, detection must be both accurate and economical. Any detection method used in the Appalachian region also must be adaptable to rough mountainous terrain characterized by fairly complicated geology and dense forest vegetation. Under these difficulties the induced polarization and resistivity detection method was tested for the first time in highway work in a successful effort to find low-grade iron pyrite deposits located along a proposed continuation of a route where previous highway construction had caused pollution problems.

ENVIRONMENTAL PROBLEMS ASSOCIATED WITH SULFIDE MINERALS

Acid mine drainage and acid rain are problems familiar to many, but acid drainage from highways has not been considered a widespread problem, although problems have been experienced at some locations, especially in the Appalachian Mountain range. The most common source of acid drainage is the leaching of compounds containing sulfur of which iron pyrite is the main contributor in the Appalachian Mountains. The problems occur generally when widely disseminated, minute crystals of iron pyrite contained in somewhat porous rock are disturbed and left exposed to weathering. Highway cuts and embankments, if not protected by blankets of impermeable materials, create such exposure to weathering and resultant leaching. The telltale signatures of the presence of iron pyrite are rust-colored stains on cut slopes and on exposed broken rocks in fills, the deterioration of pipe culvert inverts, the deposition of iron oxide in streams or ditches, the dying of aquatic plants and animals, and the appearance of certain algaes. In some locations such as the Copper Basin, galvanizing on steel guard rails has a life span of only two to five years as a result of acid rain and splashing of acid drainage generated through the processing of sulfide minerals.

The need to locate and deal with sulfide minerals effectively is certainly a matter of concern for highway planners and designers. Although environmental problems have only recently been considered important by many, they now must be handled effectively. The expertise of geologists is essential not only to the corridor and route selection process but also in the construction and operational phases. Geologists should conduct preliminary investigations during the conceptual stage. If pyrite deposits are obvious, they can be avoided. The obscured disseminated deposits can cause problems, but they can be located during the preliminary design stages immediately after preliminary center lines and profiles have been developed. If communications are good among planners, environmental sections, location sections, and geologists, suspect areas can be delineated in the early stages and can receive proper attention as the proposed route is developed more fully.

Once iron-pyrite-bearing formations have been exposed in highway cut sections and in embankments, the process that breaks down the pyrite into the environmentally damaging iron oxide and sulfuric acid is difficult and expensive to control. Usually a combination of remedial measures is necessary. The increased acidity of streams must be lowered to ambient levels. For best trout survival and reproduction, particularly in a natural habitat, the pH level must be kept between about 6.5 and 8.5. A pH level of 5 can be tolerated to some extent by the trout of the Appalachian range where streams tend to be acidic. At intolerable pH ranges, expensive treatment facilities and monitoring stations may be required for lowering the acid levels. Sodium hydroxide (NaOH) or lime, quick lime (CaCO), or hydrated lime [$Ca(OH)_2$] may be used as the neutralizing agent (1). When these compounds are dissolved in water, heat is generated. Thus temperature monitoring may be required also, especially in trout streams of marginal quality. For trout reproduction, stream temperatures must range from 40°F to 50°F (4.44°C to 10°C) for a few months, and for continued healthy survival, stream temperatures must not exceed about 70°F (21.11°C). The same chemical compounds used to neutralize the generated sulfuric acid will cause the precipitation of iron oxide as the pH level rises. In order to control appearance and to remove the solids at the point of neutralization as required by the U.S. Environmental Protection Agency, the water may have to be passed through a retention pond capable of maintaining a detention time of about 30 min. The location of such a treatment facility is critical, especially if a retention pond is necessary. Aeration may also be necessary to provide free oxygen in the outfall, to provide for mixing, and to provide for complete oxidation. Such facilities do not blend well aesthetically.

Massive doses of lime applied to the cut and fill slopes will provide some short-term neutralization. If the cut slopes are near vertical, little else can be done except to direct the drainage to the treatment facilities. Fill slopes may cause the most serious leaching problems if the fills are constructed with pyritic rock without choking the voids and sealing the slopes with an impervious material. An embankment of large rock containing large voids will allow rain water to run freely through the fill, dissolving the pyrite in massive quantities. A fair remedial measure may be to work in as much limestone dust as possible and envelope the embankment section in a thick, impervious layer of clay.

The deterioration of pipe inverts caused by acid drainage is very difficult to remedy. About the only solution is to reline the deteriorating pipe culverts with vitrified clay or plastic pipe. This effectively reduces the original pipe size, which, in turn, may cause ponding at the inlet end. The resulting overflow around the culvert and through the fill will dissolve iron pyrite in the embankment material and further defeat efforts to limit acid water generation. If ponding occurs, protection must be provided against seepage through the fill. Inlet structures must be constructed carefully to direct all drainage into the vitrified or plastic liner. The outlet end may require an anchoring device and a paved ditch if it emerges up in the side of the fill

Remedial measures always seem to leave something to be desired, usually are expensive, and usually require constant maintenance and monitoring. A better approach is to try to avoid the pyrite deposits that can cause problems or to incorporate protective measures into the original design. In many cases, troublesome deposits if adequately located, can be avoided by slight line shifts or by changes in the profile grade line to avoid cutting into the deposit. It may not always be feasible or practical to avoid the deposits. Then economics and design problems may necessitate other considerations such as designing the cut slopes so they will support a thick blanket of impervious clay at least over the pyrite zone. Rock containing the pyrite may have to be disposed of either in embankments or waste areas where the materials can be enveloped on the top, bottom, ends, and sides with an impervious clay layer. Usually if handled in the design phase, treatment facilities can be avoided, and the cost will be considerably less.

TECHNOLOGY TRANSFER OF INDUCED POLARIZATION TO THE HIGHWAY FIELD

The problems with water quality encountered when highway cuts penetrated rock strata that contain widely disseminated minute crystals of iron pyrite were causes for serious concern. With many miles of highways still needed in the Appalachian region and with some highways nearing the final design stage, an accurate, economical, and expedient means of locating the worrisome, low-grade sulfide mineral deposits was very much in demand. The use of core drilling rigs in the area is very expensive, is disruptive to a sensitive environment, and might cause public concern.

Many miles (kilometers) of the Tellico-Robbinsville project were virtually inaccessible to drill rigs. At accessible points, the drill rigs would have had to be moved in on skids with tracked vehicles or cables or set with helicopters. Tracked vehicles would have had to haul in water for the drills or water would have had to be pumped for about two miles up 45- to 60-degree slopes. Skidding in the equipment would have required a great deal of clearing, and some clearing would have been required even if drills were set by helicopter. Every possible cut section would have had to be cored, and even then some deposits could have been missed. Recognizing these problems, some type of remote sensing methods seemed to be needed. Consideration was given to the various types available.

The photographic and nonphotographic imaging techniques of remote sensing can be used in mineral exploration and detection, but these methods are keyed entirely to interpretive methods that rely on surface indicators. These techniques also must be coordinated with seasons due to the dense foliage, although vegetation types are sometimes indicators of soil condition and minerals present. Some types of remote imaging techniques are good for determining soil types and plotting geologic formations. However, anything that lies below the surface does not lend itself very well to detection by these methods.

Electrical and magnetic geophysical exploration and prospecting methods were considered next. Almost all of these techniques can be used in either a movable surface mode or in aircraft. These methods are used extensively in the search for oil and minerals, and the electromagnetic techniques are known to be very good for locating iron pyrite. Consideration was given to the possible use of aircraft to search for the scattered, low-grade iron pyrite deposits plaguing the completion of the forest road across the Tellico Mountains just south of the Great Smokey Mountains. The method employs either airplanes or helicopters usually towing a bird trailing about 200-500 ft (60-150 m) below and behind the aircraft containing all or part of the signal transmitting and receiving equipment. The aircraft must also fly from 200 to 400 ft (60 to 120 m) above the ground. The terrain, weather conditions, and forest types common to this area present problems in the use of such airborne systems. Because of the rough, steep terrain, associated severe air currents, rapidly occurring thunderstorms, and tall, dense vegetation, the movable surface surveying mode was considered most practical.

The remaining practical choices of conducting a surface mineral survey seemed to be either electromagnetic or induced polarization methods. Both methods are good for finding sulfide mineral deposits and for defining geologic features. However, electromagnetic methods are mostly limited to locating massive sulfide deposits of about 15 percent by volume or above. The induced polarization technique is sensitive enough to locate deposits of approximately 1 percent concentration. Although the induced polarization technique has a number of favorable attributes, it became apparent, after helping carry the equipment over 17 miles (27 km) of rough mountainous terrain between 3000 and 5000 ft (900 and 1500 m) in elevation, that the method involved considerable effort. The favorable final results, however, made the effort worthwhile.

Although no reference could be found to the use of induced polarization in the highway field prior to this undertaking, the method seemed appropriate for the need. Induced polarization methods are widely recognized in geophysical exploration and are known to be capable of delineating anomalies indicative of low-grade iron pyrite deposits. To test the applicability of the method for the sulfide concentrations occurring along the proposed highway route, a small demonstration project was set up along a 2-mile (3.22-km) section of the centerline. Core samples had been taken, and geological maps and profiles had been prepared for this area by capable geologists. A reconnaissance line was run using an electrode configuration with 200-ft (60.96-m) spacing and dipole-dipole array (see Figure 1). At locations where anomalies indicative of iron pyrite were detected, a detailed survey was made using a 25-ft (7.62-m) spacing and dipole-dipole array at 25-ft intervals along the centerline. Both the lateral and vertical limits of a sulfide deposit can be defined by a detailed survey.

Detailing is the most expensive and time-consuming part of the survey, but the need for such detailing is greatly reduced by the reconnaissance survey. The exact location and horizontal limits of the areas needing detail work will be defined by the reconnaissance survey. In addition, if a preliminary profile of the proposed line is available, then any deposits falling entirely within embankment sections can be eliminated from the full detailed survey and possibly skipped in the reconnaissance survey.

Absolutely essential to the use of induced polarization techniques is the use of qualified personnel. The interpreter or geophysicist must be knowledgeable by education and experience in the areas of geophysical exploration and geology, must be capable of comprehending the area being surveyed, and must have a complete understanding of the induced polarization equipment being used. The survey team must be chosen on the basis of proven experience and ability.

INDUCED POLARIZATION EQUIPMENT AND METHOD OF USE

Polarization refers to the phenomenon that occurs when current that is applied to moist soil just below the ground surface is blocked at the interface of a metallic surface by an opposing current (see Figure 2). The mode of conduction of the current applied to the moist soil is ionic in nature. This applied current flows through the solutions in the pore spaces of rocks. When this current reaches the face of the pyritic mineral, the ionic current is converted to electronic current or is blocked until it builds up sufficiently to give up or receive the electrons contained in the crystal lattice of the metallic particles in the pyrite bearing formation. The blocking action, or the resistance to the flow of current, increases with the time that the induced direct current is allowed to flow through the conducting medium. This results in the build up of ions at the metallic interface. Eventually, an excess of ions builds up at the interface, which appreciably reduces the amount of current flow through the metallic particles. The electromotive (coulomb) forces between the charged ions at the polarization zone force the ions to return to their normal position when the induced flow of direct current is cut off. This reversal of charge or

Figure 2. Diagrammatic sketch of induced polarization process.

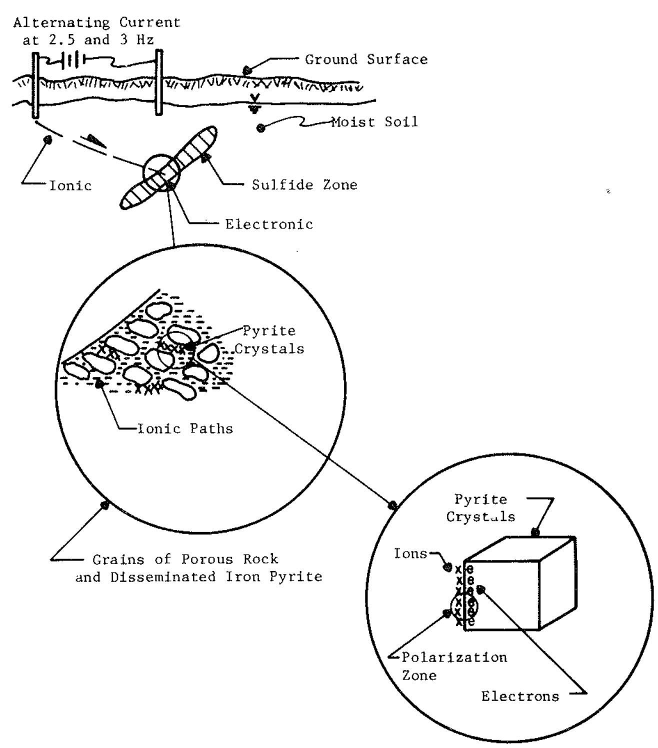
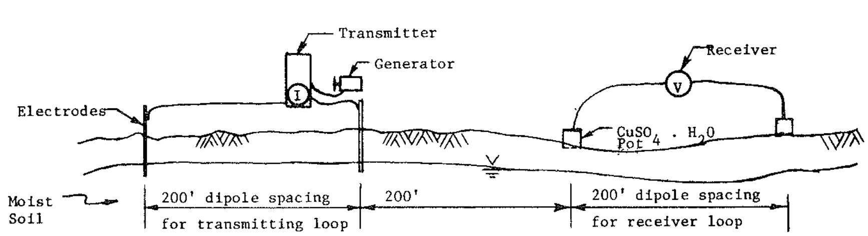


Figure 1. Electrode configuration with dipole-dipole array; constant spacing of 200 ft was used on reconnaissance survey.



transient flow of charged particles creates a small current flow that can be measured as a voltage at the ground surface as a decaying potential difference. This "pulse transient" induction method of detecting polarization can be achieved either by applying the current for a period of time and measuring the decay after cut off or by averaging several decays by applying the current in alternate directions in a series of pulses. These measurements are taken in the "time domain." The geophysicists look for areas where current flow is maintained for a short time after the applied current is terminated. By reversing or alternating the flow of current repeatedly at frequencies of from direct current to a few cycles per second before the polarization occurs, the effective resistivity of the system will change as the frequency of the switching occurs, thus permitting measurements to be made in the "frequency domain." The apparent resistivity value is measured as the frequency of the applied current is altered. The presence of metallic minerals is indicated by changes in the apparent resistivity. A correlation can be developed between the type of material present below the ground surface and the recorded data, which include measured resistivities, frequencies, and applied voltage (2-5).

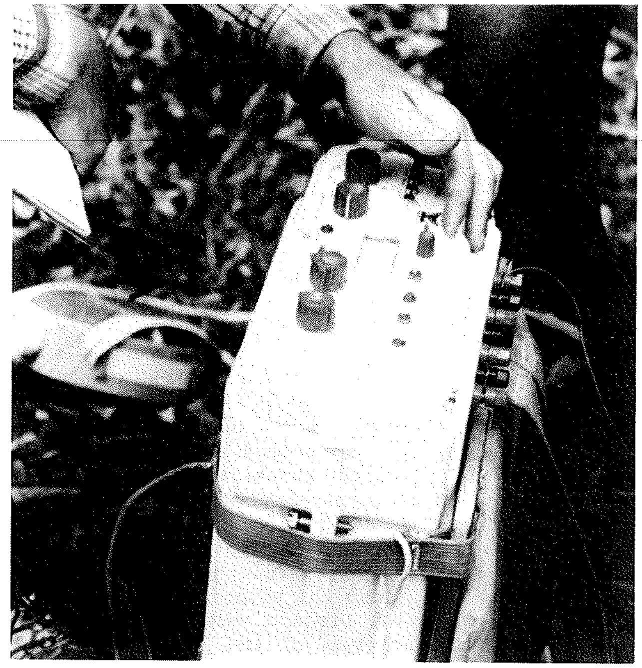
The resistivity of the material encountered or its ability to conduct electrical current is the key to the interpretative process. Since graphite, for example, is an excellent conductor, this property allows easy detection of graphitic shales into which the current seems to disappear. Some graphitic shale was encountered on the project and provided a good demonstration of this characteristic. Decreased or low resistivity and increased polarization are indicative of contact with a pyrite deposit.

The induced polarization technique functions in accordance with Ohm's Law, i.e., voltage equals current times resistance ($V = IR$). Current is passed into the ground by the transmitter at specific preset frequencies, and the receiver measures the output voltage. Since the earth is not really a true resistor, inductance and capacitance are present, and impedance is referred to as the apparent resistivity. Capacitance and inductance are frequency dependent. Voltage measurements are actually taken at the higher frequency; then the frequency is lowered to obtain a frequency effect measurement that is related to the polarization of the subsurfaces.

Figure 1 illustrates the configuration of the equipment and the spacing of the dipole-dipole array used in the reconnaissance survey made along the center line of the proposed highway. The equipment used to conduct the survey was divided into two categories--one for the transmitting electrodes and one for the receiving electrodes. A number of hollow, steel stakes about 30 in (75 cm) long to provide for maximum contact were used as the electrodes and were equipped with quick-connection alligator clips. The electrode conductors were heavy-gauge, insulated copper wire. Additional items used consisted of a small sledge hammer, an axe, a small supply of water for occasionally wetting the soil around the electrodes, an extra supply of wire, a tool kit for adjusting the equipment, and walkie-talkies.

There are two distinct circuits in the system--the transmitting circuit and the receiving circuit. In the transmitting circuit, the transmitter (see Figure 3) is equipped for varying the frequency of the applied current while maintaining a constant voltage through the electrode to the moist soil. The transmitter was very sensitive to moisture and condensation caused by frequent showers, high humidity, and condensation caused by extreme changes in

Figure 3. Induced polarization transmitter with frequency control and alternating input current regulator.



temperature. (This problem was solved by the use of a desiccant.) The transmitter, weighing about 40 lb (18 kg), could not be left in the field overnight because of the moisture problem and possible damage by the wild hogs in the area. The geology of the area, rough terrain, soil conditions, soil moisture, and high currents required by the high resistance to current flow in the area prevented the use of a battery-pack-powered transmitter, thus necessitating the use of a gasoline-operated generator weighing about 50 lb (23 kg). About 2 gal (7.5 L) of gasoline had to be carried in for about a 10-h operating period.

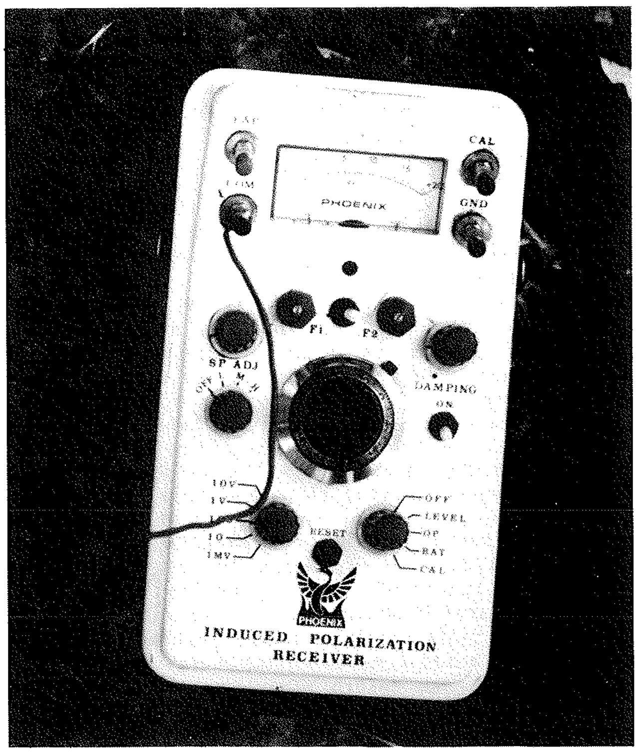
The receiving circuit consisted of the receiver (see Figure 4) for measuring the voltage, two copper sulfate pots that acted as the receiver dipole electrodes, and the connecting wire. Water was added to the soil beneath the copper sulfate pots to provide the necessary moisture, and the copper sulfate level was checked daily.

A four-person crew was probably optimum with everyone taking turns carrying the equipment. However, a larger crew seemed desirable at the end of a 10-h day when the vehicle was more than 5 miles away, over a ridge, and about 1000 ft (300 m) higher or lower in elevation. The day always began with a rough ride, usually a long hike into the line, and a careful calibration of the receiver to the transmitter while the first station setup was under way.

INTERPRETATION OF DATA

The reconnaissance survey procedure used is described as a surface mode, moving set-up, induced polarization and resistivity survey that uses the frequency domain. The transmitting and receiving dipoles were spaced 200 ft (60.96 m) apart to obtain only the N = 1 induced polarization and resistivity measurements (see Figure 5). Both sets of dipoles were moved continually along the survey line at 200-ft (60.96-m) intervals that provided a measurement of resistivity and polarizability within a half sphere with a radius of 100 ft (30.48 m) or to a depth of 100 ft. When areas of decreased resistivity and increased polarizability were located, detail work was recommended or conducted to more accurately determine the boundaries and depth to the anomalous source. The detail survey employed 25-ft (7.62-m) or 50-ft (15.24-m) dipole settings for determining the width and depth of the sulfide mineral deposits. As the data were interpreted, profile maps were developed showing the location of definite, probable, and possible induced polarization anomalies. The occurrence of anomalies is indicated by bars as illustrated in the lower part of Figure 6. The bars represent the surface projection of the anomalous zones as interpreted from the location of the transmitter and receiver electrodes when the anomalous values were measured.

Figure 4. Induced polarization receiver for measuring output voltage for calculating resistivities ranging from 20 ohm meters to greater than 80 000 ohm meters at frequencies of 2.5 and 3 Hz.



Since the induced polarization measurement is essentially an averaging process, as are all potential methods, it is frequently difficult to pinpoint the source of an anomaly. No anomaly can be located with more accuracy than the electrode interval length. Using 200-ft (60.96-m) electrode intervals, the position of a narrow sulfide body can be determined only to lie between two stations 200 ft apart and 100 ft deep. In order to locate sources at some depth, longer electrode intervals must be used, with a corresponding increase in the uncertainties of location. Therefore, while the center of the indicated anomaly probably corresponds fairly well with the location of the source, the length of the indicated anomaly along the line should not be taken to represent the exact edges of the anomalous material since the exact edges will lie somewhere between the dipole spacing used and the set-ups that incorporate the first and last readings indicating an anomaly.

Metal factor (MF) anomalies, percent frequency effect (PFE), and resistivity are shown on detail data plots, but only resistivity and PFE anomalies are shown on reconnaissance plots. The PFE results indicate polarizable areas without taking into account the resistivity of the areas. The MF or "metallic conduction factor" is obtained by combining the PFE and the resistivity data.

The PFE is a ratio of the apparent resistivity (ρ) at the low frequency (f_1) or switching cycle

Figure 5. Electrode configuration with 200-ft dipole array; X = 200 ft and N = 1 for reconnaissance work; X = 25 ft or 50 ft and N = 1, 2, 3, and 4 for detail work.

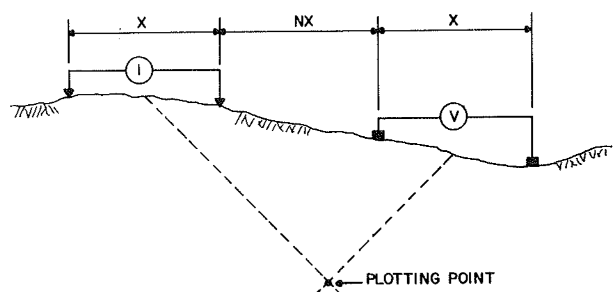
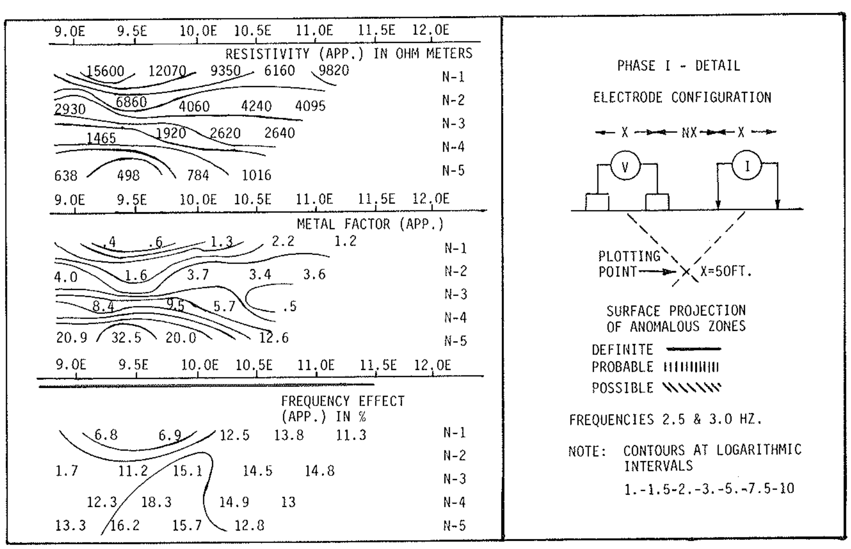


Figure 6. Typical output plot of induced polarization data showing resistivity plot, percent frequency effect, and metal factor plot, with symbols for indicating location of pyrite deposits.



and the apparent resistivity at the higher frequency (f_2) (5).

Apparent resistivity at low frequency at station a = $[\rho(f_1)/2\pi]$ a (1)

Apparent resistivity at high frequency at station a = $[\rho(f_2)/2\pi]$ a (2)

Apparent frequency effect = $(fe)_a = \{[\rho_a(f_1)/\rho_a(f_2)] - 1\}a$ (3)

The MF is obtained by combining the PFE and the resistivity.

$$MF = (fe \times 100)/[\rho(f_1)/2\pi] \times 1000 = \{[\rho_a(f_1)/\rho_a(f_2)] - 1\} \times 100 \div [\rho_a(f_1)/2\pi] \times 1000 = \{[1/\rho_a(f_2)] - [1/\rho_a(f_1)]\} \times 2\pi \times 10^5 \quad (4)$$

A good conductor (low resistivity) that is strongly polarizable (high PFE) will give a well-defined or "definite" MF anomaly. Less-well-defined MF anomalies are designated as probable or possible. The PFE and MF parameters are complementary. The relative importance of each type of information depends on the particular geophysical environment encountered and the type of target expected. For example, a mineralized silicified zone will give a "definite" MF anomaly. Alternatively, an oxidized ore zone may only give a "weak" PFE anomaly but a "definite" MF anomaly.

The plot of the reconnaissance data usually shows only the apparent resistivity and PFE. The variation in resistivity is related to the variation in rock units. Low resistivity indicates conductive material and/or highly permeable rock, such as carbonaceous slates or phyllites. High resistivity indicates tightly compacted rocks such as quartzite or sandstones. A high PFE response of 10 or above suggests a very high concentration of sulfides or polarizable material; conversely, a low PFE response indicates low or nonexistent sulfide content. A combination of low resistivity and high PFE can be assumed to represent areas where sulfide mineralization would readily dissolve if exposed in a road cut or fill.

RESULTS OF STUDY

On this project, a section of low resistivities was encountered in the first 2000 ft (610 m), but the PFE response was not continuous, indicating some points of high sulfide content. The PFE response dropped dramatically at some locations, and the resistivity remained low, which led to the conclusion that the rock units in these areas were very permeable but contained very little sulfide mineralization. At several other locations, the apparent resistivity was moderately high, approximately 5000 ohm meters, and the PFE was anomalous. These areas probably contained several narrow massive sulfide veins or disseminated sulfide mineralization zones across most of the 200-ft (60.96-m) intervals. Only a detailed survey of these locations would validate the interpretation. The detailed survey or shorter interval profiling conducted in the demonstration phase proved the importance of conducting detail work at locations where the reconnaissance survey indicated high sulfide content or anomalous response.

High PFE readings were received along the entire line but at varying depths, with some areas exhibiting highly polarizable material at or near the surface. Near the central portion of the line, a high PFE response was recorded at depths greater than 50 ft (15 m). Road cuts in the areas of shallow response would undoubtedly expose the pyritic material, but probably no significant amount of pyrite would be encountered in the central portion.

There was a wide variation in apparent resistivity for the entire proposed highway center line, ranging from 20 ohm meters to greater than 80 000 ohm meters. The areas of low resistivity and high PFE were symbolized on the data plots by solid bars above and below the line respectively (see Figure 6). Where these bars coincide, sulfide mineralization occurs in conductive and/or extremely permeable rock and most likely would present problems if disturbed by cutting or if the material were used unprotected in embankments. The depth and width of these areas could not be determined with any precision by use of the reconnaissance data alone. Detailed surveys in these areas would be required if they appeared to fall within cut sections where the profile grade would penetrate the pyrite deposit. Several areas were located that exhibited a high sulfide content as symbolized by a solid bar below the line and indicated by moderate to high resistivity readings. The high resistivity indicates a less permeable, more dense rock unit that, if exposed to weathering, may not be subject to serious leaching or release of sulfides into solution. Additional insight is provided elsewhere (9,10) into the physics involved in the induced polarization process and discusses applications through a case study.

OTHER POSSIBLE BENEFITS

The benefits derived from the use of induced polarization and resistivity surveys for locating troublesome deposits of sulfide minerals as applied to route location have been demonstrated. Other benefits that may be of use in highway construction include the potential for locating areas of very sound rock, which is structurally and environmentally acceptable for use in roadway work for rock blankets, riprap, fills, or aggregates. Very dense, compact rock with good structural characteristics are indicated by apparent resistivity measurements above 10 000 ohm meters and a PFE response of less than 2 percent occurring through several continuous dipole intervals. The induced polarization and resistivity technique will give readings to depths of about 600 ft (180 m), which is well within the penetration range of most quarrying operations. Faults and large fractures are detectable by using the induced polarization survey method, as are cavities and voids containing moisture. Faults may be indicated by no return signal or by no readings at the receiver if all the equipment is operating properly. Under certain conditions negative readings can be obtained, indicating that the circuit may be broken between the transmitter and the receiver. This might be indicative of faulting, fracturing, or some strong discontinuity. A force field in the underlying strata strong enough to overcome the applied current and to reverse the flow may be indicative of some geologic phenomenon.

It was realized early in the project that good geologists who are fully knowledgeable of the induced polarization equipment and its capabilities could determine a great deal about the geologic formations occurring below the surface and could determine approximate depths of formations fairly well. This knowledge would be very useful in preliminary design work and should be considered if the induced polarization equipment is used for locating iron pyrite deposits in the early stages of design considerations. Another potential use is for locating natural sand-gravel deposits in areas where they may be present.

SUMMARY AND CONCLUSIONS

Sulfide minerals, even in low concentrations, particularly iron pyrite, can cause some serious problems when deposits of minute mineral crystals contained in rather porous rock are disturbed in highway construction and subjected to weathering (11). Remedial measures, after the weathering and breakdown of iron sulfide begins, can be expensive and difficult to accomplish. Locating the troublesome deposits and avoiding them or incorporating methods of dealing with them into the design seems to be the most logical, economical, and practical means of avoiding later problems.

The feasibility of locating troublesome iron pyrite deposits using induced polarization and resistivity surveys was well-demonstrated on the proposed forest highway connecting Tellico Plains, Tennessee, and Robbinsville, North Carolina. This was the first time that induced polarization techniques had been applied to highway work, although the technology for such use had been proven and in existence for mining surveys since the early 1950s. Excellent results were obtained in this demonstration, and induced polarization surveys have been conducted for other highway projects since. Other benefits of induced polarization surveys in highway work were also demonstrated to be feasible. However, some research into interpretative techniques and correlations between data generated and geologic formations indicated should be conducted before actual field applications are made.

The data obtained from an induced polarization and resistivity survey must be interpreted. Although one can determine with almost absolute certainty that a potentially troublesome iron pyrite deposit exists, one cannot determine directly that the formation in which the deposit occurs will or will not neutralize the sulfuric acid formed by the dissolving pyrite. Just as qualified geologists must carefully examine core samples and personally visit the site where core samples are taken, so must they review the data obtained from induced polarization and resistivity surveys and conduct their own personal field investigation. Nor can geologists and soils engineers make absolute determinations about subsurface conditions without additional information gained by core drilling, petrographic analysis, and induced polarization. Good usable results are obtained by diligent qualified personnel by using appropriate methods and procedures while recognizing limitations. Used appropriately, an induced polarization and resistivity survey can produce information that will help locate points strategically for core sampling resulting in possible substantial savings of many thousands of dollars and considerable time.

Induced polarization surveys may be conducted most profitably after good preliminary center lines and profile grade lines have been developed but before lines and grades are committed to such a stage that only costly shifts and adjustments can be made. If some preliminary geological studies have been conducted, including some on-site reconnaissance, the survey time required may be kept to a minimum and having to recall the induced polarization survey team may be avoided--an important factor when using private firms located in distant states. In this concept, the induced polarization process shows good promise as a planning, location, and design tool in the highway field. As with any technique, the capability of the process must not be exceeded, and the value of a qualified geologist operator and interpreter must not be minimized. Induced polarization is no genie, although it will find gold.

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Survey of Techniques Used for Predicting Leachate Quality

JOHN C. WRIGHT, JR., AND SAMPATH S. IYENGAR

Prediction of waste or fill leachate quality is often an important consideration, as it can be used in determining material placement, drainage designs, leachate containment (clay liner), or surrounding material interaction evaluations and identifying potential impacts to hydrologic regimes, ecological systems, or treatment requirements. In addition, leachate characteristics are often used to classify materials (e.g., hazardous wastes or acid-producing overburden or fill). There are several leachate evaluation test methods, which range from predicting the potential presence of selected characteristics within possible leachates to actual leachate quality determinations of representative materials by using representative leachate fluids. Because cost and time requirements vary with each leachate prediction test, the test method chosen to evaluate a material's potential leachate quality should be based on information requirements of the investigation. Several nonleaching, batch, and column leaching tests were examined as to information that can be obtained from these leachate prediction techniques. Several of these leachate quality prediction techniques, which included reaction pH, total sulfur, acid-base accounting, American Society of Testing and Materials 1:4 shake extraction of solid waste with water, U.S. Environmental Protection Agency extraction procedure toxicity test, and periodic column leaching tests, were then applied to several waste materials. The resulting test data were then compared. The application and usefulness of the various testing procedures in predicting leachate quality of inorganic parameters are discussed.

This paper examines the most commonly used techniques for predicting the potential leachate quality of wastes and other materials. In addition, the techniques are assessed as to information that can be obtained and to their most appropriate application.

The potential presence of selected characteristics in a leachate from a waste can be assessed by employing several nonleaching methods, such as those given in Table 1. These methods have been widely used to predict the potential environmental impact from geologic and waste materials (e.g., acid mine drainage) (1). Nonleaching test methods can be used to predict leachate characteristics because poor-quality leachates are most often associated with materials that are acidic or significantly soluble in water. Even though nonleaching methods have been used with considerable success, they are only qualitative and do not provide any quantitative information about specific pollutants that may contaminate the environment.

The representative leaching fluids from a waste or fill material have traditionally been obtained by using some form of laboratory leach test. Existing leach test methods fall into two broad categories: batch (shake) and column tests. In batch tests, the material to be leached is placed in a container with a known volume of eluant and agitated for desired parameters. Several batch tests have been proposed, and the basic differences among them lie in the nature of eluant used, solid-to-liquid ratio, material particle size, elution time, number of elutions, and type of agitation. Examples of the most commonly used batch tests include American Society of Testing and Materials (ASTM) shake extraction and U.S. Environmental Protection Agency (EPA) extraction procedure (EP) toxicity tests, among many others.

There are several advantages and disadvantages in using batch tests. These are noted below:

1. Advantages: (a) experimental variables can be more easily controlled, (b) several environmental factors that affect leaching potential of material can be simulated, (c) most reproducible, and (d) simple, quick, and inexpensive.
2. Disadvantages: (a) equilibrium conditions are hard to achieve; (b) data concerning long-term reaction kinetics are difficult to obtain; (c) conditions chosen may be difficult to relate to actual in situ conditions; (d) test results are dependent on duration of test, solid-to-liquid ratio, particle size of waste, and eluant; and (f) often much more aggressive than natural leaching environment.

Although the batch tests have several disadvantages, the ease of operation of batch tests and, more importantly, the long time requirements and high cost of column tests have convinced researchers to accept batch tests as the only feasible alternative for generating leachate from a waste or fill material on a routine basis.

Column tests are usually performed by placing the materials to be leached in a glass or plastic column of known dimension and then allowing a desired eluant to flow through the materials in the column. The primary advantages of column tests are that the time variability in potential leachate quality can be evaluated and in situ conditions can be more accurately simulated, including sample permeability and solid-to-liquid ratio. Eluant is added to the column either continuously (continuous column leaching test) or periodically (periodic column flushing test) at set intervals, usually with oxygenation between leachings by the passing of water-saturated

Table 1. Summary of nonleaching test methods for predicting potential leachate quality.

Test	Measurement and Test Use
Reaction pH	Equilibrium pH at 25°C of a distilled water and test material mixture that is used to assess acid or alkaline reaction of material
Buffer pH and exchangeable acidity	Equilibrium pH at 25°C of a test material, distilled water, and buffer mixture used to assess exchangeable acidity (acidity that will be immediately available to be leached by percolating waters) or lime requirement of material
Total sulfur	Total level of all sulfur forms present; includes sulfates, sulfides, and organic sulfur; used to determine maximum potential acidity
Pyritic sulfur	Total level of all metal sulfides present; may be used to calculate potential acidity
Maximum potential acidity and potential acidity	Indicates "latent" acidity of a material; this type of activity usually results from oxidation (of sulfide minerals for most geological materials) and may be released over a long period (months or years); maximum potential acidity is calculated from total sulfur content; may be determined by oxidation and base titration or calculated from pyritic sulfur for geologic materials
Neutralization potential	Characterizes total capability of a material to neutralize acidity
Acid-base accounting	Accounting of overall acid-producing or neutralizing potential of a material that is used to assess its long-term potential to produce acid or alkaline leachates; difference between potential acidity and neutralization potential
Specific conductance and filterable residue	Measure of level of immediately soluble constituents of a material, usually in a 1:1 or saturated paste mixture

air through the sample. The column test effluent is monitored for desired parameters. The rate of flow through the sample is proportional to the gradient across the column sample and the permeability of the material. The primary advantages and disadvantages of column tests are noted below:

1. Advantages: (a) can more accurately simulate in situ environmental conditions, (b) better simulation of material and liquid contact under in situ conditions, (c) can determine potential time variability in leachate quality, (d) more accurate simulation of kinetic factors that affect environmental systems, (e) can provide accelerated natural oxidation of tested materials (periodic leaching test), and (f) can provide data on permeability and long-term changes in permeability of tested materials by using representative (natural) eluants as a permeant (continuous column test).
2. Disadvantages: (a) difficulty in obtaining reproducible results, (b) problems arising from channeling and nonuniform packing, (c) potential unnatural clogging, (d) possible unnatural biological effects, (e) edge effects, (f) long-term and often difficult test, and (g) expensive.

PREVIOUS BATCH LEACHING RESEARCH

An extensive background study was conducted by Ham and others (2) on existing leach test methods to formulate a single leach test method that could be used to generate leachates from various waste or fill materials. They concluded that column tests are too time consuming and difficult to perform for a routine leaching test and recommended shake or batch tests for determining the leaching potential of fill materials. They also proposed a leach test called the standard leaching test (SLT) for generating leachates from waste or fill materials on a routine basis. In this test, the waste is shaken (slow tumbling) with either synthetic leachate (composed mainly of acetic acid and sodium acetate and adjusted to pH 4.5) or distilled water in 1:10 or varied solid-to-solution ratios for 24 h at room temperature. The procedure is repeated three or more times, and the resulting composite leachate is analyzed for desired parameters.

Löwenbach (3) compared and evaluated the SLT (also called the Wisconsin test) with more than 30 other widely used batch or shake tests for their ability to generate data in a reproducible manner, ability to provide rapid assessment of the generation of aqueous toxic contaminants from the disposal of solid wastes in a landfill, ability to model natural leachate generation, their consideration of environmental factors that control leaching in actual landfills, and their ability to serve the legislative and regulatory needs of EPA. After an in-depth study, three tests were recommended for further evaluation: the SLT, the Minnesota test, and the IU Conversion Systems test (IUCS). The Minnesota test consists of shaking the waste material for 24 h either with an acetate buffer (pH 4.5) or with distilled water in a 1:40 solid-to-solution ratio at room temperature (4). In the IUCS tests (5), the waste is agitated with distilled water in a 1:4 solid-to-solution ratio for 48 h at room temperature. The procedure is repeated four times and the combined extract is analyzed for desired parameters. These three leach test methods were compared and evaluated (6) by extracting 14 different industrial wastes supplied by EPA. This study revealed that the SLT was the only test able to representatively leach each of the 14 different industrial wastes and was also the procedure with the most aggressive conditions.

In 1977, ASTM recognized the need for a method to assess the leaching potential of solid materials and proposed two shake extraction methods: ASTM distilled water and ASTM acid methods. The distilled water extraction method consists of shaking (slow tumbling preferred) the test material and distilled water at a 1:4 ratio for 48 h, filtering through a 0.45 μm filter, and analyzing the filtrate for desired parameters (similar to the IUCS test). The acid extraction method is similar to the ASTM distilled waste method except an acetic acid buffer solution (pH 4.5) is used as the eluant instead of distilled water. In 1980, ASTM decided to drop the acid extraction method and proposed only the distilled water extraction method as a standard leachate characterization method (7).

EPA (8) adopted a standard leaching procedure called the EP toxicity test to determine the hazardous nature of waste materials. In this procedure, which is similar to the SLT procedure, the material sample to be tested is mixed with distilled water at a ratio of 1:20 (total), the pH of the mixture adjusted to pH 5.0 with acetic acid (if the mixture pH was initially above 5.0), and the mixture agitated for 24 h; the pH is then monitored and adjusted for the first 6 h of agitation. The resulting extract is filtrated, and the filtrate is analyzed for the EPA National Interim Primary Drinking Water Standards for metals and organics. If the concentration of any of these parameters exceeds the drinking water standards by 100 times or more, then the waste is considered hazardous.

The validity of EPA's EP toxicity test procedure, however, has been questioned by several industrialists and researchers. Some of the major objections to the EP procedure include the following:

1. Too strict and costly,
2. Uses one set of conditions for all situations (9),
3. Does not take into account site-specific conditions (i.e., properties of disposal site, solid-contaminant interactions, etc.) (9),
4. Concentration limits are unreasonable (9),
5. Often poor reproducibility (10,11), and
6. Acidic, aqueous eluant does not satisfactorily extract nonpolar organic compounds in the waste (12).

The ASTM distilled water test has also been criticized for its inadequacy and drawbacks. Lee and Jones (9) contend that this procedure has essentially the same fundamental deficiencies as the EPA EP toxicity test procedure and that the method cannot yield results that can be related to in situ conditions.

Several comparative studies have been conducted to assess the efficacy and reproducibility of the ASTM distilled water and the EPA EP leachate techniques by extracting the same type of waste by these two techniques. Boegly (13) extracted waste ash from the coal gasification process with these two techniques and also with the ASTM acetic acid technique, 0.1 N HNO_3, and 0.1 N NH_4OH and found that the concentrations of Resource Conservation and Recovery Act (RCRA) parameters [arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), selenium (Se), silver (Ag), and zinc (Zn)] in the leachates from the ASTM distilled water and EPA EP toxicity tests were almost identical. The ASTM acetic acid technique, however, extracted slightly more Ba, Cr, Ni, and Zn. The 0.1 N HNO_3 extracted the highest amounts of trace metals from the waste. They also compared the EPA EP toxicity test with a column leaching technique and found that the concentrations of sulfates and other secondary drinking water standard parameters in the leachates from the column technique far exceeded the amounts found in the leachates from the EPA EP toxicity test.

Another study (14) compared the reproducibility of three procedures--ASTM distilled water, ASTM acetic acid, and EPA EP toxicity test--by extracting reference fly ash with these techniques. This study found that the concentrations of heavy metals leached under the three extraction procedures could not, in general, be shown as statistically different. The study also found no consistent difference in precision between the three extraction procedures.

Another investigation (10) into the reproducibility and source of variation in ASTM distilled water and EPA EP leaching techniques was conducted by statistically analyzing the leachate quality results of reference fly ash from 13 different laboratories. This study found that, when the sample heterogeneity was controlled, the principal source of variation in these two methods was the variability in the leaching process. The study also found that the EPA EP method has slightly better precision than the ASTM method, but the differences between the two methods are not significant at the 5 percent probability level. The EPA EP method yielded better precision on pH (as it was buffered) and marginally better precision on trace metals than the ASTM distilled water method.

EXPERIMENTS

Three coal-related waste types were used to demonstrate some of the variances in different leachate prediction methods. These included a slag material and a power station bottom ash and fly ash. Nonleaching potential leachate quality predictive methods (1) included reaction pH, total sulfur, and acid-base accounting. Leachates were generated by using two batch techniques: ASTM 1:4 shake extraction of solid wastes with distilled water (7) and the EPA EP toxicity test (8). Leachate from the slag material was also generated by using a periodic column leaching method modified after Caruccio and others (15). This method, which is similar to the recently proposed ASTM method (16) for column leaching, consisted of placing the slag in a glass column and flushing it continuously with water-saturated air to simulate natural but accelerated oxidation of the slag. The slag was then periodically (approximately biweekly) leached with known volumes of distilled water by allowing the eluant to remain in contact with the slag for 1-h periods. Leachates were chemically monitored for selected parameters and composited for later analysis. The test was concluded at four weeks, after both acidity and specific conductance of the leachates had reached peak values. All leachates were filtered through a 0.45-μm filter and analyzed in accordance with EPA procedures (17).

RESULTS AND DISCUSSION

The nonleaching characteristics of the waste materials selected for study are given in Table 2. The reaction pH of waste materials indicates that the slag and fly ash are moderately acidic in nature, whereas the bottom ash is near neutral in nature. However, none of the tested materials showed any exchangeable or immediately available acidity. The total sulfur content points out that the slag material, which contains almost 0.8 percent sulfur, has a higher potential to be acid producing than the two ash materials. This is substantiated by the acid-base accounting values. The slag material has an acid-base accounting of -2 t of $CaCO_3$ equivalent per 1000 t, which indicates that this material has a slight potential to produce acidic (and therefore toxic) leachates if exposed to an oxidizing environment in the presence of water. The two ash samples have an acid-base accounting of +8 and +5 t of $CaCO_3$ equivalent per 1000 t of material, which indicates that potential leachates from these two materials would probably not be acidic or, hence, toxic in nature.

Table 2. Nonleaching characteristics of test materials.

Parameter	Unit	Waste Type		
		Slag	Bottom Ash	Fly Ash
Reaction pH	pH	5.50	7.10	4.95
Buffer pH	pH	7.60	ND[a]	7.00
Exchangeable acidity	meq H^+/100 g	0	0	0
Total sulfur	Percentage of S	0.78	0.14	0.19
Potential acidity	Percentage of $CaCO_3$ equivalent	1.6	0.4	0.6
Neutralization potential	Percentage of $CaCO_3$ equivalent	1.4	1.2	1.1
Acid-base accounting	Percentage of $CaCO_3$ equivalent	-0.2	+0.8	+0.5

[a]ND = not determined, or irrelevant, if reaction pH is 7.0 or above.

The nonleaching characteristics of these materials point out that only the slag has a potential to produce acidic leachates and, hence, should be treated (neutralized) or disposed of with proper precaution. These characteristics, however, provide only a qualitative indication, but no quantitative information, about the magnitude of pollutant concentrations that may be released from the materials. This information is often necessary to assess the extent of possible contamination or to design necessary leachate treatment facilities.

The characteristics of leachates from all three materials that were generated by using the ASTM 1:4 and the EPA EP extraction methods are given in Table 3. Also included in this table are the characteristics of the leachate from the slag generated by using a periodic column leaching technique. The column leachate values represent solute concentrations in composited effluents from eight different leachings.

The ASTM 1:4 leachates given in Table 3 generally are of poorer quality than those leachates generated by the EPA EP toxicity test method for all three waste materials. Typically, higher filterable residues, anions, and metal levels are observable in the ASTM leachates. In contrast, the ASTM leachates for the two ash materials also had pH's that were higher than those of the EPA EP method. This would appear to be a contradiction, as one would expect these wastes to be more soluble in leachates with lower pH's (most metals are mobilized in acidic environments). However, closer examination of the leaching techniques shows that the waste materials were more soluble in the lower pH 5.0 EPA EP leachates. The ASTM method uses a 1:4 extraction ratio while the EPA EP toxicity test uses a 1:16 extraction ratio (1:20 final dilution). Therefore, on a mass soluble per unit mass of waste material, the EPA EP method was the most aggressive leaching technique for all three waste materials. [To convert the EPA EP leachate analyses values from mass per volume of leachate (mg/L) to mass soluble per unit mass of waste material or micrograms soluble per gram of waste (μg/g), multiply the reported mg/L value in Table 3 by 20. The same conversion for the ASTM

Table 3. Leachate characteristics of test materials.

Parameter	Unit	Slag: Periodic Column Test	Slag: ASTM 1:4 Extraction	Slag: EPA EP Toxicity Test	Bottom Ash: ASTM 1:4 Extraction	Bottom Ash: EPA EP Toxicity Test	Fly Ash: ASTM 1:4 Extraction	Fly Ash: EPA EP Toxicity Test
pH	pH	5.00	4.45	4.90	8.15	5.45	7.40	5.30
Acidity	mg/L $CaCO_3$	378	98	ND[a]	<2	ND[a]	<2	ND[a]
Alkalinity	mg/L $CaCO_3$	10	0	ND[a]	64	ND[a]	38	ND[a]
Filterable residue	mg/L	595	278	156	250	501	2320	659
Chloride	mg/L	52	22	11	9	2.4	20	2.4
Sulfate	mg/L	380	180	88	83	4	1200	204
Dissolved metals								
Aluminum	mg/L	14	2.5	2.6	<0.1	0.2	0.1	2.4
Arsenic	mg/L	0.015	0.006	0.005	0.005	<0.001	0.015	0.008
Barium	mg/L	<0.1	<0.1	<0.1	0.13	0.76	0.18	0.11
Cadmium	mg/L	0.08	0.03	<0.01	<0.001	<0.001	0.01	<0.001
Calcium	mg/L	88	45	12	65	74	420	80
Chromium	mg/L	0.13	0.03	0.08	0.008	<0.001	<0.01	0.017
Copper	mg/L	0.05	0.03	0.02	<0.01	<0.01	0.2	0.21
Iron	mg/L	7.5	1.6	51	<0.01	5.5	9.5	<0.1
Lead	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Magnesium	mg/L	14	7.0	2.0	3.8	3.0	39	8.0
Manganese	mg/L	1.2	0.6	0.6	<0.01	0.61	0.50	0.41
Mercury	mg/L	<0.0005	<0.0005	<0.0005	0.001	<0.0005	<0.0005	<0.0005
Potassium	mg/L	20	10	3.9	11	1.5	160	25
Selenium	mg/L	0.043	0.029	0.0034	1.15	0.23	0.0025	<0.001
Silver	mg/L	<0.01	<0.01	<0.01	<0.001	<0.001	<0.0025	<0.001
Sodium	mg/L	17	8.5	2.8	7.3	3.0	81	11
Zinc	mg/L	9.9	3.9	0.8	0.02	0.02	1.2	0.22

[a]ND = not determined due to addition of acetic acid to leachates.

method is performed by using a multiplier of 4.] However, due to the solid-to-liquid ratios of the two methods, the EPA EP method allows greater dilution in the final leachate that, for these waste materials, resulted in better-quality leachates than those generated by the ASTM method. Note that, in some instances, higher metal levels, especially for iron, were found in the final leachates of the EPA EP method but that these leachates have an overall lower solute concentration than those of the ASTM method.

The leachate quality results of the ASTM and EPA batch leaching techniques showed variations in the materials tested but could have easily shown more significant differences if the wastes were more alkaline or acidic. This is because there is no pH adjustment in the ASTM method and the leachates of the EPA EP method are buffered at pH 5.0 or lower and diluted five times more than the ASTM method. The more alkaline a material, the more aggressive the EPA EP toxicity test should be as metals generally are more soluble in acidic environments. (The EPA EP toxicity test does limit the amount of acetic acid that can be added to a sample such that extremely alkaline materials should remain alkaline.) Conversely, for slightly to very acidic wastes, the EPA and ASTM methods should yield about similar leachate qualities or the EPA EP toxicity test may even show a slightly better quality due to its dilution ratio, as shown for the tested materials in Table 3.

Comparison of the leachate quality obtained with the periodic column test to those of the two batch techniques (Table 3) shows the column test leachate to be of generally poorer quality than those of either batch protocol. This is attributed to two factors:

1. The pH values of the leachates from the three leaching techniques were approximately the same at pH 5.0, and
2. Enhanced natural oxidation of the slag material occurred in the column test, which caused the slag to continually produce more acid and hence be more soluble.

Therefore, for the tested slag material, simulation of natural oxidation and percolating water through the slag resulted in a poorer-quality leachate than those yielded by the ASTM or EPA batch methods. (This column leaching method did not, nor was it intended to, simulate an in situ solid-to-liquid ratio or compacted slag permeability.)

The results of the nonleaching test (Table 2) indicated that the slag showed the largest potential to produce acidic and high solute concentration leachates. The leaching tests performed confirmed the predictions of the nonleaching tests, although the metal levels of the ash materials were only slightly lower than those of the slag. If the acid-base accounting of the slag had been lower than 0.2 percent $CaCO_3$ equivalent (which is only slightly negative or acidic), more substantial differences in the leachate qualities of the slag and ash materials should have been observable.

SUMMARY

A summary of the most commonly used techniques available for predicting leachate quality is given in Table 4. Reaction pH, buffer pH, total sulfur, and acid-base potential are qualitative techniques and provide minimal quantitative information that can be used to gage the extent of contamination. They are useful indicators of suitability of a material for vegetative growth or of the potential for generation of acidic leachates from a material.

The leaching test methods, on the other hand, are quantitative in nature and provide information as to the nature, type, and amount of contaminants in any waste material. The batch tests (ASTM and EPA methods) are rapid and useful for assessing the leachate quality of wastes on a routine basis. The column tests are time consuming but provide information on the long-term or time-variable quality of waste leachates and can be designed to better simulate in situ conditions. The periodic column tests are useful to study the quality of leachate from a material under a natural but accelerated oxidizing environment. The continuous column method provides time-

Table 4. Application of most commonly used leachate quality prediction techniques.

Method	Application	Test Material	Leachate Predictive Information	Approximate Test Duration	Approximate Cost[a] ($)
Reaction pH	Index test to determine acid or alkaline reaction	All types	Qualitative: assesses acidic or basic nature of material	0.5 h	5-7
Buffer pH	Index test to determine presence of exchangeable acidity	All types	Qualitative: assesses immediate lime requirement to neutralize exchangeable acidity	0.5 h	5-8
Total sulfur or other sulfur forms	Index test to determine presence of latent acidity that results from oxidation	Geologic materials, especially coal related	Qualitative: assesses potential for acidity release on oxidation	0.5 h to 1 day	7-30
Acid-base accounting	Index test to determine differential between potential to produce or neutralize acid	All types	Qualitative: assesses long-term potential to produce acidic leachates	1 day	25-30
ASTM 1:4 shake extraction of solid waste with water	To predict potential leachate quality	All types	Quantitative: yields leachate quality under conditions of the test, simulates natural pH	3 days	30+
EPA EP toxicity test	To predict potential leachate quality and assess possible hazardous nature of materials	All types, especially potentially hazardous wastes that may be regulated by EPA	Quantitative: yields leachate quality under conditions of test, simulates acidic environment	2 days	75+
Periodic column leaching test	To predict potential leachate quality, or time-variable leachate quality under natural oxidizing conditions by using synthetic or representative leaching fluid	All types, especially geologic materials that produce acid on oxidation	Quantitative: yields leachate quality, especially its variability with time and in oxidizing conditions	4-8 weeks	200+
Continuous column leaching test	To predict potential leachate quality, or time-variable leachate quality and permeability of a material by using synthetic or representative leaching fluid	All types, especially those materials where emplaced permeability is important and in situ leaching fluid is very aggressive	Quantitative: yields leachate quality, especially its variability with time	6-12 weeks	350+

[a]Approximate cost per test, excluding leachate analyses.

variable information on the quality of waste leachate and, if properly compacted, permeability of an emplaced material.

Because cost and time requirements vary with each leachate prediction technique, the test method chosen to evaluate a material's potential leachate quality should be based on information requirements, time constraints, and the ultimate goal of each specific investigation. Often, a combination of less-expensive nonleaching tests as indexers can be used with a limited number of leaching tests to provide a maximum of information on material variability and potential leachate characteristics at reasonable costs. However, a material's actual leachate quality will be environment dependent; therefore, the best predicting technique of leachate quality will be the test method that best simulates the field conditions of each material under study.

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Identification of Source Materials for Acid Leachates in Maryland Coastal Plain

D.P. WAGNER, D.S. FANNING, AND J.E. FOSS

Acid leachates are produced in the oxidation of naturally occurring, sulfide-bearing sediments distributed throughout much of the Maryland Coastal Plain. Geologic ages for the sediments span from Lower Cretaceous through Tertiary. When these sediments are exposed to the atmosphere, sulfuric acid is produced in quantities sufficient to prohibit plant growth, dissolve concrete, and corrode metal. Initial pH values of near neutral or above may drop to as low as 2 after the sulfidic sediments undergo oxidation. In addition to pH, characteristics useful in identifying sulfide-bearing Coastal Plain sediments include sulfur content, sediment morphology, presence of sulfide or sulfate minerals, and morphology of surface soils formed from the sediments. Unoxidized sulfidic sediments are mostly dark colored. Typical colors include black (5Y 2.5/1), gray (10YR 5/1), or dark gray (5Y 4/1). Pyrite has been identified as the principal sulfide mineral present in the sediments. Pyrite morphology ranges from large megascopic crystals associated with Lower Cretaceous lignitic deposits to microscopic framboids common in Upper Cretaceous and Tertiary formations. Sulfate minerals formed from pyrite oxidation are useful field indicators of acid-generating sediments. Sulfate minerals that have been identified in acidic sediments include rozenite, szomolnokite, ferrohexahydrite, copiapite, gypsum, and jarosite. Jarosite is a highly persistent mineral and has often been observed in naturally weathered soil profiles formed from sulfide-bearing sediments. The identification of jarosite in near-surface soil horizons thus may serve as an indication of underlying sediments with acid-generating potential.

The generation of excessive amounts of sulfuric acid often becomes a severe problem when excavation activities cause the exposure of sulfide-bearing rocks and sediments to the oxidizing environment of the earth's surface. One of the most common examples of this phenomenon is the well-known problem of acid mine drainage associated with coal mining excavations. Interception of sulfide-bearing strata by earth-moving operations is, however, not a hazard unique only to coal or other mining activities. Numerous reports (1-8) have described the occurrences of sulfidic strata across a wide spectrum of geologic settings.

Soil materials that have undergone sulfide oxidation and have excessively low pH values are commonly referred to as acid sulfate soils or cat clays. In the past, these terms have been used principally for identifying acid-generating soils in tidal areas of the world. Recently, investigators have also found it appropriate to apply these terms to upland Coastal Plain soils that display features derived from sulfide oxidation processes. With studies of acid sulfate features in upland Coastal Plain soils (9-11) has come the recognition of the widespread nature of sulfides in many subsurface Coastal Plain strata. Because of the hazards these sediments pose to building materials and ecosystems when exposed to the atmosphere by excavation, identification of sulfidic strata is an important first step in the course of construction activities to avoid or control acid sulfate problems.

MATERIALS AND METHODS

Study sites were selected on the basis of morphological properties observed in the field. Sites were located by reconnaissance of areas where outcropping geologic formations were suspected of containing sulfides. Soil and sediment samples were retrieved from road cuts, hand-dug pits, and hand borings.

Samples were air-dried and passed through a 10-mesh (2-mm) sieve. Soil pH was measured by using a 1:1 ratio of soil to water. Identification of sulfur minerals was accomplished by either scanning electron microscopy with energy-dispersive X-ray microanalysis or X-ray diffraction. X-ray diffraction analyses were performed by using a Phillips diffractometer with a 2-theta compensating slit and graphite crystal monochrometer. Concentrations of sulfur and free iron were determined by the X-ray spectroscopic procedures of Snow (12) and Fanning and others (13), respectively.

RESULTS AND DISCUSSION

Properties of Sulfidic Strata

At least seven geologic formations in the Maryland Coastal Plain were found to contain subsurface sulfide-bearing strata that, when exposed to the atmosphere, were capable of producing high amounts of sulfuric acid. These sediments were found throughout much of the western and central portions of the Maryland Coastal Plain. The general properties of the sulfidic strata are given in Table 1.

As is apparent from Table 1, a common property shared by each of the sediment types was dark coloration. Dark colors for these materials probably result from the presence of organic compounds associated with reduced sulfidic strata as well as darkness of metallic sulfides (mostly pyrite) themselves. In applying Munsell soil color notation for describing chroma and value, sulfide-rich materials generally have chromas of 1 or less and values of 4 or less.

Beyond color, however, few other similarities existed for the sulfide-rich strata. Textures ranged from loamy sand to clay, and geologic ages for the materials span from Lower Cretaceous through Miocene. In addition, it must be emphasized that the formations listed in Table 1 are generally not

Table 1. General characteristics of sulfidic strata in Maryland Coastal Plain formations.

Formation	Geologic Age	Typical Color (moist) Munsell	Common Name	Textural Class[a]	Other Feature
Potomac Group	Lower Cretaceous	10YR 2.5/1 10YR 5/1	Black Gray	Silty clay loam to clay	Lignitic
Magothy	Upper Cretaceous	5Y 2.5/1	Black	Sandy loam	Glauconitic
Matawan	Upper Cretaceous	5Y 2.5/1	Black	Sandy loam to loam	Glauconitic
Monmouth	Upper Cretaceous	5Y 2.5/1	Black	Fine sandy loam to sandy clay loam	Glauconitic
Aquia	Paleocene	5Y 4/1	Dark gray	Fine sandy loam to loamy sand	Glauconitic
Nanjemoy	Eocene	5Y 4/1 5Y 3/1	Dark gray Very dark gray	Fine sandy loam	Glauconitic
Calvert	Miocene	5GY 4/1	Dark greenish gray	Silt loam	

[a]U.S. Department of Agriculture classification.

Table 2. Chemical properties and color with depth in an oxidizing sulfidic sediment.

Depth (cm)	pH	Percentage of S	Fe_D[a]	Color Munsell	Common Name
Oxidized					
0-6	2.7	0.22	1.72	10YR 4/4	Dark yellowish brown
6-20	2.7	0.58	1.11	5Y 3/2	Dark olive gray
20-30	3.2	0.60	0.92	5Y 3/2	Dark olive gray
Mostly Unoxidized					
30-35	4.1	1.60	0.91	5Y 2.5/1	Black
35-46	7.7	1.59	0.87	5Y 2.5/1	Black
46-56	8.1	1.47	0.55	5Y 2.5/1	Black
56-66	8.3	1.54	0.58	5Y 2.5/1	Black
66-82	8.3	1.58	0.45	5Y 2.5/1	Black
82-97	8.4	1.63	0.27	5Y 2.5/1	Black

[a]Dithionite extractable Fe.

characterized by high concentrations of sulfides throughout. In many instances, sulfide-bearing strata may be thin and laterally discontinuous. Such characteristics are particularly true for sulfide-rich beds within the Potomac Group of sediments. Glauconitic sediments were found to be the most uniformly sulfidic in unoxidized zones.

Measurement of pH of fresh sulfidic samples is of little use in identifying materials with harmful acid-generating potentials. Freshly obtained, unoxidized samples of sulfidic sediments were found to have pH values that ranged from 5 to more than 8. When oxidized, the same sediments had pH values of less than 3.

Similarly, routine chemical analyses for soil fertility performed by most soil testing laboratories would fail to demonstrate the potentially harmful nature of unoxidized sediments. Concentrations of extractable nutrients are often high in these materials. Thus, without measurement of the sulfide content, sulfidic sediments may be incorrectly assessed as fertile media for plant growth.

Pyrite (FeS_2) was identified as the principal sulfide mineral occurring in the sediments. Sulfidic Potomac Group deposits of Lower Cretaceous age typically contained large secondary pyrite crystals that are easily discernable to the unaided eye. The pyrite was usually associated with fragments of lignite in these sediments. In sulfidic deposits of Upper Cretaceous and Tertiary ages, pyrite crystals were not discernable without extreme magnification. The dominant form of pyrite in these sediments is likely that of microscopic (less than 25μm) clusters of pyrite crystals known as framboids. Pyrite framboids were identified by scanning electron microscopy in a sample of the Monmouth Formation of Upper Cretaceous age. Framboidal pyrite, perhaps because of its smaller size and greater surface area, is considered to be more reactive than megascopic pyrite (14).

Properties of Oxidized Strata

Properties so far discussed have been for unoxidized strata only, and sulfidic strata exposed to oxidizing conditions undergo considerable morphological and chemical alterations. This is true for both naturally weathered sediments as well as those that have undergone artificially induced oxidation due to excavation or drainage.

In terms of general appearance, oxidized sediments are distinguished from originally sulfidic materials by usually more reddish hues, lighter color values, higher chromas, and mottling or staining by iron oxides and sulfates. Chemically, differences are dependent on the original chemical composition of the sulfide-rich sediment, especially sulfur content, and on the degree to which oxidation has progressed. Although other factors such as sulfide form or natural acid neutralizing capacity of the sediment can be important, it is generally true that the higher the original concentration of sulfides in the sediment, the greater will be the amount of free acid generated. As long as conditions are sufficiently aerobic, sulfuric acid generation will continue until the supply of oxidizable sulfides is exhausted.

Table 2 gives the characteristics of a soil profile in which both oxidized and unoxidized materials are present. The soil profile is formed from sulfidic sediments of the Monmouth Formation and is situated within a highway cloverleaf. At the time of highway construction, the site appears to have been scalped to a depth of approximately 2-3 m, which exposed unoxidized sediments. The conditions shown in Table 2 have formed within 15 years of the construction work.

As indicated by very low pH values, the most oxidized portion of the profile extends to a depth of about 30 cm. In this zone, pyrite oxidation has resulted in both chemical and morphological changes. In addition to the low pH values typical of acid sulfate soils, the upper oxidized horizons have lower concentrations of sulfur, higher concentrations of free iron oxides, and slightly higher color values than the underlying sulfidic horizon. Lower sulfur values in the most acidic part of the profile have probably resulted from sulfur losses due to leaching of soluble sulfates. Sulfur losses

Table 3. Sulfate minerals identified in oxidized, originally sulfidic Coastal Plain sediments.

Mineral	Approximate Formula	Appearance	ASTM Card File No.
Rozenite	$FeSO_4 \cdot 4H_2O$	White; powdery	16-699
Szomolnokite	$FeSO_4 \cdot H_2O$	White; powdery	21-925
Ferrohexahydrite	$FeSO_4 \cdot 6H_2O$	White; powdery	15-393
Copiapite	$(Mg,Al)(Fe,Al)_4(SO_4)_6(OH)_2 \cdot 2OH_2O$	Lemon yellow; powdery	20-659
Gypsum	$CaSO_4 \cdot 2H_2O$	White to colorless; small needle-like clusters	6-46
Jarosite	$KFe_3(SO_4)_2(OH)_6$	Straw yellow; mottles and pore fillings	22-827

by volatilization during oxidation may also be a factor.

In contrast to the near-surface oxidized zone, the mostly unoxidized sulfidic sediment below 30 cm has been little altered from its original state. Sediment color is black, and concentration of total sulfur is uniformly high with depth. Values for soil pH are also high and appear to be regulated by calcium carbonate from fossil shell fragments present in the sediment. Concentrations of free iron oxides decrease progressively with depth; however, higher values in the upper portion of the dark-colored zone may indicate an initial stage of pyrite oxidation in which iron sulfates are released. Thus, while sharp differences exist between the oxidized and mostly unoxidized zones, downward migration of the acid-sulfate zone appears to be an ongoing process. It should also be noted that some of the free iron extracted from lower increments of the profile may have formed as a result of pyrite oxidation during air drying of the samples in the laboratory.

The conversion of pyritic sulfur to sulfate sulfur is fundamental in the transformation of reduced sulfidic sediment to oxidized acid sulfate soils. Simplistically, the overall reaction that shows oxidative decomposition of pyrite may be expressed as follows (15):

$$FeS_2 + 7/2O_2 + H_2O \rightarrow Fe^{2+}, Fe^{3+} + 2SO_4^{2-} + 2H^+$$

In nature, the reactions that produce sulfates, ferric iron, and acid are rarely so direct or as complete, and numerous reactions that produce an assortment of sulfate and iron compounds are usually involved. Detailed discussions of many of these reactions have been given by van Breemen (16,17), and an effort to recount them will not be expanded here.

Basically, the kinds of sulfates present on a site are dependent on the chemical composition of the original sulfidic sediment and on the nature of the environment to which the sediments have been exposed. Sulfates can begin to form within weeks or even days of the exposure of sulfidic sediments to an oxidizing environment. For this reason, identification of sulfate minerals in the absence of prior investigations for sulfide occurrence can be important in the early recognition of acid-producing materials. Table 3 lists sulfate minerals that have been identified by X-ray diffraction of samples from Coastal Plain sediments and soils.

The most soluble sulfate minerals in Table 3 are the first four given. These soluble sulfates are also among the first to form in freshlv excavated sulfide-rich sediments. They appear as white or yellow powdery efflorescences on the soil surface and often are bitter or astringent to taste. Gypsum is a slightly less-soluble mineral and forms in oxidizing sulfidic sediments that have a high calcium content, such as those containing fossil shells. This mineral has been observed as small (1- to 2-mm) clusters of needlelike crystals in recently disturbed sulfidic sediments. Jarosite is the least soluble of the sulfate minerals identified, and it is one of the most commonly encountered. This conspicuous straw-yellow (5Y 7/6) mineral has been identified in mottles or pore fillings in materials ranging from freshly exposed sulfidic sediments to naturally weathered soil profiles of great age (10).

The identification of jarosite in naturally weathered soil-geologic columns has utility in predicting potential occurrences of sulfide-bearing strata. Because of its low solubility, jarosite may persist well after the processes of sulfide oxidation that formed it have ceased. Thus, jarosite can be found in soils and geologic strata in which sulfides have long since been oxidized and natural buffering systems have restored pH levels to more than 4. In such weathering columns, jarosite was observed in the upper oxidized zone, marking strata that have in the past gone through extremely acid conditions. Given the relative uniformity of the original geologic material with depth, zones that are below the level of natural oxidation may still be sulfidic. As an indication of the former presence of sulfides, jarosite frequently serves as a warning of more deeply lying sulfidic strata. In the weathering profiles studied, the natural depth to sulfides was found to be in the range of about 2-10 m, whereas jarosite was usually present within 1-2 m of the land surface.

CONCLUSIONS

Many of the geologic formations comprising the Maryland Coastal Plain contain sulfide-rich strata. These strata are all darkly colored but have other properties that vary with the geologic formation. Several of the formations that contain sulfides are also glauconitic. Pyrite is the main sulfide mineral in the sediments studied.

Sulfidic sediments undergo considerable morphological and chemical changes when oxidized. Color becomes lighter, and mottles of iron oxides and jarosite form. The conversion from a sulfide-rich material to a sulfate-rich material is marked by extreme lowering of pH, loss of sulfur, increase in iron oxide content, and the formation of sulfate minerals. One of the most common sulfate minerals that forms under the extremely acid conditions produced by the oxidation of pyrite is jarosite. Jarosite is a highly persistent mineral and often occurs in the upper, naturally oxidized zones of soil-geologic columns. As a remnant of extremely acid conditions in the past, jarosite mottling near the surface may indicate the presence of more deeply lying sulfidic strata. Natural weathering depths to sulfidic strata range from approximately 2 to 10 m according to the sites examined in the Coastal Plain in Maryland.

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Leachates from Excavations and Fills: Summation

JOAKIM G. LAGUROS AND LARRY W. CANTER

There are extensive data available on leachate quality and quantity, but the environmental effects and leachate control methods have not been investigated as thoroughly as might be expected. Test methods are primarily centered in the laboratory; there is a need to establish field evalaution methods.

The purpose of this paper is to summarize the five papers presented at the Symposium on Leachates from Highway Fills and Cuts organized by the Committee on Physicochemical Phenomena in Soils (A2L03). It describes the state of the art by identifying areas where information on the role of leachates is available as well as topics that require study or further investigation.

Among the various environmental concerns that have surfaced during the past decade or so, the problem of leachates from fills and excavations has been rather sporadically studied. On the one hand, pollutants and their sources have been rather well identified; on the other hand, field and laboratory testing, which enable the determination of leachate quality and quantity, has not reached the point of established meaningful criteria. It appears, then, that the problem has not been approached with a well-designed overall research plan and balanced emphasis.

GROUPING OF REPORTS

The five papers reviewed herein, as given in Table 1, differ in scope and methodology. Another possible way to categorize these papers is to group them according to the following dimensions of leachates:

1. Source characterization,

Table 1. Classification of reports based on scope and methodology.

Author	Title	Scope	Methodology
Wright and Iyengar	Survey of Techniques Used for Predicting Leachate Quality	To compare and evaluate techniques for predicting potential leachate quality	Assessment of test methods Important parameters in each test Advantages and disadvantages of tests Experiments with slag and ash by using American Society of Testing and Materials (ASTM) 1:4 extraction and U.S. Environmental Protection Agency (EPA) toxicity tests. Some tests are qualitative, but leach tests are quantitative and predict contaminants Batch tests rapid; column tests more dependable but time consuming
Wagner, Fanning, and Foss	Identification of Source Materials for Acid Leachates in Maryland Coastal Plain	To identify sulfidic strata in soils subject to highway construction activities	Seven soils characterized Minerals with high potential in pollution identified in nonoxidized and oxidized form The worst source for pollution is in jarosite, which results from the oxidation of pyrite in acidic environments
Van Zyl, Shepherd, and Smith	Quality of Seepage and Leachate from Mine and Mill Wastes and Control of its Effects	To classify these wastes and identify problems and methods for control purposes	Classification of mine waste Potential to produce acid waste Extraction (metallurgical processes) Problems of impact Acid-generation reactions Time lag in observing pollution impact Extraction Cyanide Low pH; bacterial action Treatment before, during, and after placement; detergents
Jones, Bell, and Hansen	Induced Polarization Survey of Sulfide-Bearing Rocks in Eastern Tennessee and Western North Carolina	To discuss the induced polarization process to detect sulfide deposits and identify environmental problems in disturbing such deposits	Acid drainage from low concentrate sulfide (pyrite) Damages observed Techniques and equipment in induced polarization process, and reconnaissance survey
Lee and Jones	Evaluation of Potential Water Quality Problems in Highway Excavation and Fill	To review EPA regulations on fill materials and evaluate them	Physical and chemical impacts on water quality Water leachate test Deficiency of water quality standards Dredged materials Four-tiered hazard assessment Proposal to modify EPA methods

Table 2. Grouping of reports based on leachate parameters.

Author	Source Characterization	Leachate Testing	Environmental Effects	Evaluation of Environmental Effects	Control
Wright and Iyengar		X			
Wagner, Fanning, and Foss	X				
Van Zyl, Shepherd, and Smith	X		X		X
Jones, Bell, and Hansen	X		X		X
Lee and Jones	X	X	X	X	

2. Leachate testing both in quality and in quantity and rate-determining factors,
3. Environmental transport,
4. Environmental effects and evaluation thereof, and
5. Control and abatement of leachates.

Table 2 presents the results of this grouping method.

SYNOPSIS OF REPORTS

The main theme in Wright and Iyengar's paper is the prediction tests of leachate quality. They present very useful tables on the advantages and disadvantages of various tests. The data relate to slag, bottom ash, and fly ash. They advance the thesis that criteria such as reaction pH, buffer pH, and total sulfur provide minimal information, and between the leach test method and the batch method the latter is preferable because it is rapid. Also, they point out that column tests, while time consuming, are more dependable in studying long-term effects.

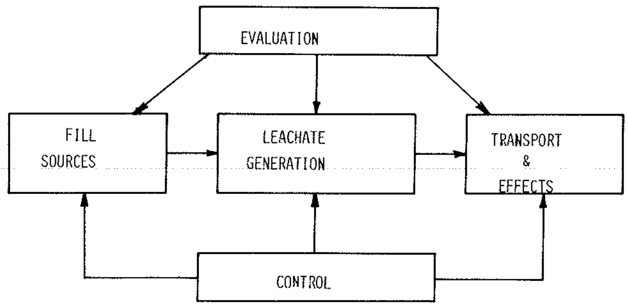
Wagner, Fanning, and Foss deal with the identification of sulfidic strata and describe how pyrite converts from a sulfide to a sulfate form, namely jarosite. The source of the deleterious effects of acid-producing materials is reported to be created when the sulfidic sediments are exposed to an oxidizing environment. This condition follows from excavation activities or from using such sediments as borrow materials for fills.

Van Zyl, Shepherd, and Smith report on leachates from mine and mill wastes. They classify these wastes as "unacceptable" and "acceptable" based on the degree of pollution produced or the extent of curtailing (reducing) the performance of engineering structures such as drains. A very interesting feature of this paper is the treatment on the techniques to control leachate quality. They classify these techniques as (a) treatment before placement, (b) treatment at or after placement, and (c) treatment of the effluent. Needless to say, they prefer the first two approaches as being more effective. For treatments washing, calcining, encapsulation, injection of detergents, and lime are suggested.

The paper by Jones, Bell, and Hansen discusses in detail the technique of the induced polarization survey used in detecting sulfide mineral deposits. Thus, again the problem associated with pyrite comes to the forefront. This technique appears to be very promising as a tool in the planning, location, and design of a highway.

Finally, Lee and Jones review the current evaluation methods used on fill material insofar as its environmental impact is concerned, and they recom-

Figure 1. Component phases of leachates.



mend a four-tiered hazard-assessment approach for contaminants associated with fill materials. The report raises the very legitimate question of the definition of quality in water.

These papers provide a wealth of references that constitute a very impressive codification of the topic on leachates.

CONCEPTUAL FRAMEWORK FOR ANALYSIS

Figure 1 provides a basis for additional discussion of the five papers presented as well as a framework for relating their substantive aspects. It is important to identify the sources of fill material, the potential for leachates being generated from the materials, and the environmental transport and resultant effects from the generated leachate. Evaluation of fill material sources, leachate generation, and transport and effects includes both in situ analysis as well as laboratory evaluation and interpretation. Control measures to minimize the undesirable consequences of leachates from highway fills and cuts include material selection as well as approaches to minimize leachate generation and control environmental transport. The purpose of this section of the paper is to discuss the state of the art of information related to each of the five components within Figure 1.

Fill Sources

Fill sources include natural materials such as soil, rock, and sand as well as man-altered waste materials such as municipal solid waste, incinerator residue, coal ash, and mine tailings. Extensive work has been done on the water pollution characteristics of both natural and waste materials (1). Bhutani and others (2) described some of the general water pollution problems related to the use of natural materials for highway fills and other types of projects. Table 3 summarizes two pertinent types of pollutants and the associated concerns.

Municipal solid wastes may be used as a highway fill material. The impacts of this fill material are difficult to characterize due to the nonhomogeneity of municipal solid waste. Both the physical and chemical composition depend on factors such as geographic location, economic standards of the generating community, and seasonal variations. Numerous studies have been conducted on the characteristics of leachate waters; most focus on chemical constituents (1). Incinerator residue has also been used as a highway fill material. Schoenberger and Fungaroli (3) investigated an incinerator residue disposal site. Their work included an analysis of the chemical composition of solid waste from the City of Philadelphia, the incinerator residue prior to landfilling, and the incinerator residue two years after landfilling. The nutrient content of the leachate was rather high, with the total nitrogen content being about 125 mg/L. The total dissolved solids content was almost 8000 mg/L, and the chemical oxygen demand (COD) was about 1300 mg/L. The biological oxygen demand (BOD) was much lower than the COD, primarily because of the large concentration of heavy metals in the leachate. The principle metals were iron (Fe), zinc (Zn), lead (Pb), copper (Cu), and chromium (Cr).

Coal ash residue consists of bottom ash collected from utility boilers and fly ash collected by air pollution control equipment. Fly ash consists of many small (0.01-100 micron diameter), amorphous, glasslike particles of a generally spherical character. Coal ash has been primarily used as a mineral filler material for concrete highways and other construction projects. A considerable amount of information exists on the composition of coal ash material (4,5). Theis and others (6) pointed out that, while it is important to know the total metal content of fly ash materials, it is perhaps even more important to determine the fraction of these metals actually available to the environment. The potential chemical and biological impacts from the use of coal ash as fill material are related to depletion of dissolved oxygen, changes in pH, and release of trace metals. Depletion of oxygen would have an adverse effect on fish and zooplankton in general and on the species composition of bacteria and other microorganisms in particular; the population of anaerobic microorganisms would probably be enhanced. The pH changes could cause elimination of certain species of fish, with some effects on the species composition of macroinvertebrates, phytoplankton, vascular plants, and benthic organisms. The release of several trace metals, including cadmium (Cd), Cr, cobalt (Co), Cu, Fe, Pb, nickel (Ni), Zn, and perhaps mercury (Hg), may occur. Any or all of these may be toxic to certain species in the environment and could undergo bioaccumulation and biomagnification in the ecosystem.

The papers in this symposium that relate to fill sources include the one by Wagner, Fanning, and Foss on the identification of potential acid leaching from sulfide-bearing sediments, and the one by Jones, Bell, and Hansen on a polarization technique for identification of the location of sulfide-bearing sediments. In summary, relative to fill sources, there is extensive information on the water pollution characteristics of various types of materials used for highway fills (1) and a growing amount of information relating to the potential leachates from highway cut areas, particularly as related to sulfide-bearing sediments.

Leachate Generation

Although both natural as well as waste materials used for highway fill areas may contain constituents that represent potential water pollutants, generation or release of these constituents from the fill area and their transport to the water environment represent the key issues that relate to leachate effects. Extensive work has been done within the past decade on leachate generation from various types of materials, including municipal solid waste and dredged materials (1). In this symposium, the paper by Wright and Iyengar provides a good summary of a variety of laboratory techniques for estimating leachate quality and, depending on the test and the procedures used, information that can be used for estimation of leachate quantity. In addition, the paper by Lee and Jones describes the advantages and limitations of certain leachate testing methods.

The confusing issue that relates to leachate testing is associated with the myriad of potential

Table 3. Water pollution from construction activities—cause and effect matrix.

Class	Pollutant Material	Source Activity/ Occurrence	Effect	
			Beneficial	Adverse
Physical: Sediment	Inert and organic particles; colloids; microorganisms (note, during transport, the sediment load comprises the suspended load plus the bed load)	Land-disturbing operations: surface clearing, grading, excavating, trenching, and stockpiling (note, subsoils often have different erodibility characteristics than surface soils)	May provide material to maintain a receptor stream channel in equilibrium, i.e., provide adequate suspended sediment to prohibit erosive degradation of a fluvial channel, in-stream sediment required in formation of silt-laden farmlands along flood plains and near river mouths; fine-grain sediment helps in removal of ions that adhere to and are transported by particulates, which settle to the bottom; dredged material disposal may also create new land areas (for building sites, beach restoration, waterfowl habitats) and decrease vectors in marshfilling	May exceed equilibrium suspended load of receptor stream, thereby altering many physical and biological characteristics of the channel; these include channel aggredation, silting of reservoirs, undesirable effects on marine life such as blanketing and smothering of benthic flora and fauna, altering the flora and fauna as a result of changes in light transmission and abrasion, destroying or altering the species of fish due to changes in light transmission and abrasion, destroying or altering the species of fish due to changes in flora and fauna on which fish depend, or obstruction of their gill function; also a need may arise for excessive treatment (sedimentation, clarification) prior to consumptive use for municipal, industrial, or irrigation purposes; channel siltation can adversely affect its capacity to carry floor flows or support navigation and recreation; dredged material disposal may destroy land areas (salt marshes, wildlife refuse, vegeted coverage), block flow circulation, or increase vectors in the disposal area
Chemical: Nutrients	Ammonia, orthophosphates, polyphosphates, organic N, organic P	Fertilization of reestablished vegetal cover	Stimulates growth of plants and grasses on areas denuded by construction (especially on slopes), thereby reducing soil loss in rain storms	Nutrients, especially from excessive application of soluble fertilizers, will be transported from new growth surfaces at construction sites in the runoff of precipitation; by then stimulating growth of algae and marine plants, nutrients can have adverse effects on chemical exchange processes, which lead to eutrophication and lowered oxygen levels; in addition to the biostimulation impacts, a large concentration of unoxidized nitrogen (organic nitrogen and ammonia) could represent a significant oxygen demand in the receiving waters.

fill materials as well as numerous test conditions, each of which can yield different results in terms of leachate quality and quantity. Test procedures that focus on worst-case conditions would be desirable in terms of evaluation of potential leachates from various fill materials. Despite extensive work relating to leachate testing, very little systematic study has been made of the rate-determining factors in leachate generation, particularly as related to the environmental conditions within which the fill material will be used. Leachate test procedures typically focus on the qualitative identification of the water pollution constituents in the leachate. Additional testing and/or calculations are needed to enable the highway engineer to effectively estimate both quality and quantity of leachate materials over time. Essentially no information is available on the time variation of the pollution characteristics of fill material leachates.

An additional area of need in conjunction with leachate generation is associated with field verification of laboratory test procedures. As noted in the paper by Wright and Iyengar, the results of leachate testing vary depending on the test procedure used. The relation between these laboratory-based results and what would actually be anticipated under field conditions needs to be established. Accordingly, field studies in selected areas would be desirable to determine quantity and quality of leachates, and then compare those results with laboratory results. Leachate testing is typically conducted on materials prior to their placement and compaction within the fill area. Work is also needed to determine the influence of compaction procedures on leachate quality and quantity.

Transport and Effects

Critical environmental concerns that relate to leachates from highway fills and cuts are associated with the transport of leachates into either the surface or subsurface environment and the resultant undesirable effects that might occur on water quantity and quality as well as the aquatic ecosystem. In addition, effects on engineering structures could occur as a result of their exposure to leachate waters. There is an extensive body of literature associated with quantitative aspects of drainage from highway fill and cut areas (7). This type of information, when coupled with information on leachate quality, could be used to estimate leachate impacts on the receiving water environment.

A growing area of concern within the United States is associated with groundwater quality and the pollutional effects of a variety of man-made sources. It is estimated that more than one-half the population of the United States is dependent on groundwater in meeting their water supply needs. The subsurface transport of leachate materials into underlying aquifers, and the potential contamination of these aquifers or associated interconnected surface streams, are areas that need additional research. Minimal information is available on the subsurface movement of leachates from highway fill areas.

There has been extensive work done on the effects of various leachate constituents found in both surface water and groundwater as well as the aquatic ecosystem. In other words, if metals are anticipated from the potential fill material, then a review of the literature would reveal extensive information available on the water quality and biotic effects of metals (1). The paper by Lee and Jones summarizes some of the types of water quality concerns, while the paper by van Zyl, Shepherd, and Smith describes some of the biotic effects of leachates from mine and mill wastes.

An issue related to the effects of leachates from highway fills and cuts that has not received much attention is associated with potential impacts on engineering structures. The paper by van Zyl, Shepherd, and Smith addresses the potential impacts of acid drainage on engineering structures; the primary areas of concern relate to low pH and resultant corrosion of metals, high sulfate concentrations, and degradation of concrete.

In general, relative to transport and effects, greater attention needs to be given to subsurface movement of leachate materials as well as the potential effects associated with exposure of engineering structures to leachates.

Evaluation

Evaluation encompasses source characterization of the fill material as well as testing for leachates and resultant environmental effects. Several of the papers presented in this symposium relate to evaluation. Source characterization is presented in the papers by Wagner, Fanning, and Foss; van Zyl, Shepherd, and Smith; Jones, Bell, and Hansen; and Lee and Jones. Leachate testing is addressed in the papers by Wright and Iyengar, and Lee and Jones. Environmental effects are addressed by van Zyl, Shepherd and Smith; Jones, Bell, and Hansen; and Lee and Jones. The specific research needs within each of the areas have been discussed in conjunction with fill sources, leachate generation, and transport and effects.

Control

As additional information becomes available on the effects of leachates from highway fills and cuts, more systematic approaches can be taken to control or abate the undesirable effects. Control measures may include selection of fill material characterized by minimal leachate quantity and constituents that cause undesirable water pollution effects, the application of measures to minimize leachate generation or transport, and actual treatment of the environment to clean up resultant undesirable effects. The paper by Jones, Bell, and Hansen relates to the use of induced polarization for identification of sulfide-bearing sediments in a given geographical location. Application of this technique would enable the selection of fill materials that would have a minimized potential for leachate generation. In addition, general knowledge about the water pollution constituents that might be present in leachates from a variety of materials could be used in fill material selection.

The paper by van Zyl, Shepherd, and Smith provides examples of control measures for minimizing leachate generation and environmental transport, as well as approaches that can be used for treatment of undesirable environmental conditions. Extensive literature is available on abatement or control measures for certain types of fill materials and the resultant types of leachates that would be generated. Specifically, an extensive amount of research has been done on the subject of acid mine drainage and control (8).

The general area of need is for systematic, engineering-oriented studies to identify and evaluate potential control measures for minimizing the undesirable effects of leachates from highway fills and cuts. Currently available information is generally oriented to certain types of materials but without extensive field application and evaluation. Although extensive research has been conducted on the control of acid mine drainage, the applicability of these research results to highway fills and cuts is somewhat questionable.

RESEARCH NEEDS

In summary, and based on the discussion associated with Figure 1, several general areas of needed research in this substantive field can be identified. These are as follows:

1. Fill characterization: Although extensive information is available on the water pollution constituents that might be found in certain types of potential fill materials, the development of systematic laboratory procedures for the evaluation of leachate quality and quantity, as well as the rate-determining factors, have not been achieved. In addition, research is needed to verify the results of laboratory testing in the actual field conditions in which fill material is used.
2. Leachate control: The emphasis given in this symposium to source characterization as well as identification of undesirable effects of leachates is indicative of the general minimal emphasis given to leachate control. Only two out of five papers provide information on control, and neither treats the issue in a comprehensive fashion. Research is needed on field-oriented methods that can be used to minimize leachate generation and transport. This type of research can be best accomplished by using an interdisciplinary approach that involves both chemical experimentation as well as engineering and geological inputs.
3. Subsurface movement: The majority of attention given to leachates from highway fill materials is associated with potential undesirable effects on surface watercourses. Leachates can also move through the subsurface environment and reach underlying aquifers. Information is needed on the rate-determining factors in subsurface movement as well as measures to minimize or control leachate penetration to underlying groundwater resources.
4. Groundwater effects: There is minimal information available on the groundwater quality effects that result from leachates from highway fills and cuts. No discussion of this subject was provided in any of the five papers presented in the symposium. Leachates could be anticipated to cause effects on physical, chemical, and biological characteristics of groundwater. In addition, informa-

tion is needed on the removal mechanisms that might occur in both the unsaturated and saturated zones of the subsurface environment.

CONCLUSIONS

This paper attempts to summarize the most significant conclusions presented by the authors of the five papers. The pertinent points made by the authors may be summarized as follows:

1. The preponderance of available data indicates that leachate quality and quantity is a problem of great concern.
2. Although the undesirable effects of leachates on surface watercourses have been studied adequately, the data on groundwater quality are minimal.
3. Sources of leachates have been well identified and there is continuing, if not increasing, interest in this area. However, leachate control data lag very much behind source data. Field-oriented studies on a broad scale should be initiated to identify leachate control methods.
4. In general, the studies on rate-determining factors for nearly all phases of leachate effects appear to have not reached a level that offer dependable design values.

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Part 2:
Terrain Analysis for Transportation Systems

Terrain Evaluation for Highway Planning and Design

P.J. BEAVEN AND C.J. LAWRANCE

Studies of the terrain to select route locations and sites for detailed geotechnical investigations are essential preliminaries to highway survey and design. The process of using all sources of information, including remote sensing, to derive an understanding of the engineering characteristics of an area is known as terrain evaluation. The basis of terrain evaluation is a terrain classification, whose purpose is to act as a geographical indexing system into which all terrain-related data, collected throughout the duration of a project, may be fitted. A terrain classification can be based on land form patterns, which are related to the underlying geology, soils, and water conditions. A land form classification has the advantage of being readily mapped from aerial photographs or remote-sensing images. It can be used to predict changes in soil conditions and to relate data from individual sampling sites to areas of terrain. The two most useful forms of remote-sensing imagery are aerial photographs for detailed work and Landsat imagery for regional studies. Panchromatic photography is available in many parts of the world, and there is increasing experience of its use in the tropics. If more detailed photography using special films is required, the use of a light aircraft that carries small-format cameras can provide high-quality photography at low cost. Landsat imagery has proved useful for preliminary surveys. Photographic prints of imagery are inexpensive and easy to produce. Detailed analysis by using digital images can be carried out with a computer, normally in conjunction with an interactive processor, and the use made of these systems will probably increase as their cost decreases. The principal aspects of terrain evaluation for highway surveys are illustrated by examples of work carried out in Africa and Asia.

The objective of highway planning and design is to construct a road at the appropriate standard to satisfy an expressed need for transportation. Consideration of the terrain is an integral part of the planning process and contributes much to the success of the design. The design stage itself is controlled by codes of practice and manuals that set out specifications and procedures to be followed. In contrast with this, the early stages of a project, notably the location of initial tentative alignments and the choice of sites for investigation in the field, are poorly supported by guides to practice. The reason is that the appraisal of terrain requires an assessment of many related natural factors, sometimes over very large areas, for which the writing of a simple manual is impracticable.

It is important that decisions taken during the early stages of a project be based on some reasonably accurate and comprehensive assessment of terrain conditions. The object of this paper is to show how aerial photographs and remote-sensing techniques can be used to gain an appreciation of the important engineering characteristics of the terrain and to devise a representative sampling and site-investigation procedure along routes that are considered to be feasible. The process of using all sources of information, integrated within a single scheme that can be applied throughout the duration of the project, is known as terrain evaluation. Terrain evaluation techniques are of most immediate value in areas where information is limited or not available, although they can equally well be applied in parts of the world where terrain information is available but not coordinated.

The examples given of work carried out in Africa and Asia each illustrate a particular stage or aspect of the projects they describe, rather than the project as a whole. At the end of the paper, the various techniques are brought together in a table that shows which technique is considered to be most relevant to each individual stage of the survey.

PRINCIPLES AND TECHNIQUES OF TERRAIN EVALUATION

Terrain evaluation is the appraisal of the capabilities and limitations of an area of ground in relation to a particular kind of land use. The word "terrain" refers not merely to the shape of the land surface but to all the factors that act in combination to mold the land itself, namely the relief, geology, soils, and water conditions. The advantages of using a terrain evaluation approach to engineering surveys are as follows:

1. By studying a problem within its region, it is possible to see all available options for routes.
2. A terrain evaluation will indicate points where the terrain changes from one type to another. It is possible to devise a sampling program to cover sites that are typical of large areas and thus to extrapolate information from known to unknown ground with some degree of confidence. A regional approach to mapping also helps to draw attention to particularly important individual sites that may influence the design.
3. The study of sites in relation to the terrain emphasizes the fact that data should not be treated as a series of isolated points but as being representative of a continuous medium that varies in ways that can be defined.
4. By relating information to a classification of terrain units, it is possible to use the same units from the early phases of planning through to the final stage, so that data can be carried forward and amplified as necessary in each succeeding stage.

For the highway engineer, the terrain evaluation process should aid such diverse activities as determining the alignment of a highway, identifying deposits of gravel or rock for use in construction, or arranging a soil sampling program. A terrain evaluation is able to do this effectively when based on a terrain classification, or map of terrain types, where each type has its own engineering characteristics to which survey work can be related. The process of terrain evaluation takes place in two stages, of which the production of a terrain classification map represents the first stage. The evaluation stage is completed when engineering characteristics are related to each of the terrain units in the classification, which are gathered from information collected during the field survey stages.

Certain techniques have proved themselves to be particularly suitable for terrain evaluation, especially those that provide information to establish an appropriate form of terrain classification. These mainly involve the use of imaging remote-sensing systems, which convey a large amount of information about the terrain, especially when supported by basic thematic mapping such as geology or soils maps.

Aerial photographs are the oldest form of remote-sensing imagery, and they are still the most important form for highway engineers. New forms of imagery have appeared in the past two decades, which create images that yield new types of information, but which can still be interpreted in the traditional way provided due allowance is made for their individual characteristics. One of the first systems to be available was infrared line scan, and this has had some limited application. Airborne multispectral scanners have also been used, but by far the greatest use is that made of small-scale multispectral data from the Landsat satellites.

A potential source of imagery is radar, which is currently available as an airborne system, although in the future satellites will carry versions capable of a 20-m ground resolution. The great advantage of radar is its independence of weather and time of day, which indicates that it will become of increasing importance in areas where persistent cloud cover prevails. Airborne radar surveys have been carried out in parts of Central and South America, West Africa, and Southeast Asia, but for commercial or strategic reasons the imagery is often difficult to obtain.

Aerial photography and Landsat imagery have found the widest acceptance of all remote-sensing systems by virtue of their versatility, wide coverage, and relatively low cost. It is the interpretation of the imagery from these systems that has provided the basis of most terrain evaluation studies that have been made.

TERRAIN CLASSIFICATION

The basis of a formal terrain evaluation is the recognition of land surface patterns that can be grouped together into a terrain classification. Most engineers recognize the repetitive nature of terrain in areas that they know well, and they can see the association between landforms, with their typical soils, drainage conditions, and vegetation, and the underlying rocks on which they occur. Terrain classification sets out to define these relations in a systematic way. There are many different systems of terrain classification in existence, as illustrated by the range of published thematic maps such as geology, geomorphology, or soils maps. These classifications may be used as the basis of a terrain evaluation for highway engineering where they exist. For an engineer, it would be advantageous to combine several types of mapping (e.g., geology, topography, and soils mapping) to produce a classification that consists of composite units that reflect the engineer's interest in a variety of aspects of the terrain.

In developing countries, detailed thematic mapping is often not available, but a form of mapping that offers a convenient compromise is landform mapping. Preliminary resource surveys often contain maps of this type, and many parts of the world have been mapped in this way (1,2). Landform mapping has the advantage in that it consists of units that represent a combination of geological, soils, and hydrological factors, and that they are relatively easy to map. Landform classification can be used where no other form of survey exists, although such a classification is considerably improved if it is augmented by information from existing thematic maps. A landform classification can be extracted from topographical maps, but it is much more effectively compiled from remote-sensing images.

Landform Mapping: Land Systems and Land Facets

There are strong links between patterns of landform, drainage, and vegetation with the underlying geological formations and hydrological regime. Therefore, a landform map to some extent reflects the properties of the terrain beneath and, in addition, takes account of aspects of the terrain that relate directly to the engineer's sphere of interest, namely relief and slope, bedrock, materials of the subgrade for use in construction, and surface and subsurface water flow. The mapping units are relatively easy to map from the air and space, and large areas can be covered in a short time.

A version of landform mapping, which incorporates aspects of geology, geomorphology, and soil distribution, has been formalized in England after a period of research and comparison with similar work carried out in South Africa and Australia (3). This is similar to the use of physiographic units in the United States (4) but extends the classification to include smaller areas of ground. It was recognized that landscapes fall naturally into hierarchical associations, in which groups of small terrain units combine to form larger ones. The two most important units are the land system and its constituent land facets (see Figure 1). A land system is a large area of characteristic landform, drainage pattern, and associations of materials developed on a single geological unit or sequence. It is typified by a distinctive scenery and is generally mappable at about a 1:250 000 to 1:1 000 000 scale. The component parts of a land system, called land facets, are defined in a similar way, but they are smaller and less variable, such that an engineer would normally expect a single design to be appropriate for sections of road built on each facet. The number of land facets in a land system is generally few, and they always occur in the same relation; the land system is made up of land facet associations repeated over a wide area. Figure 1 also shows how land facets may be subdivided into land elements--the smallest features of the terrain. These would only be mapped where they are of particular importance (e.g., an outcrop of gravel), but their presence would be included in the description of the land facet.

At the other end of the scale, land systems may be grouped into larger units called land regions, comprising land systems that have similar geology and topography. At this level of detail, a land region inevitably contains a considerable variety of landforms and a lower degree of homogeneity than would be expected of smaller units. Nevertheless, general engineering characteristics, such as the range of soil types, depth to bedrock, subgrade moisture conditions, and recurrent problems, often remain consistent over these large areas. Land region classification is useful during the earliest reconnaissance stages of an investigation to identify the principal characteristics of an area. It is equivalent to the "section" in the American classification (4).

Examples of Terrain Classification in Highway Engineering

Reconnaissance Survey: Trans-African Highway

The Trans-African Highway project is part of the African international network of roads, the first stage of which is to provide an all-weather road between Lagos and Mombasa. To identify the agreed route, a prefeasibility study of the whole area was commissioned to inventory existing roads and identify sections that needed improving. To assist in this work, the Transport and Road Research Laboratory (TRRL) prepared a land region map of the area (Figure 2), which covers all of the routes that were likely to be considered. Where possible, this map was prepared from existing land system mapping but, where this was not available, the best topographic and geological maps were used, assisted by air photograph mosaics in a few places.

The map defines regions with distinct topographic and foundation conditions, within which it can be assumed that the costs of road building are reasonably consistent. A map prepared in this way, without the assistance of field work to check it, is likely to require some revision before a final land region map can be published. However, the proposed boundaries provided workable survey units for collecting and classifying engineering and other land

Figure 1. Relation among land system, land facet, and land element.

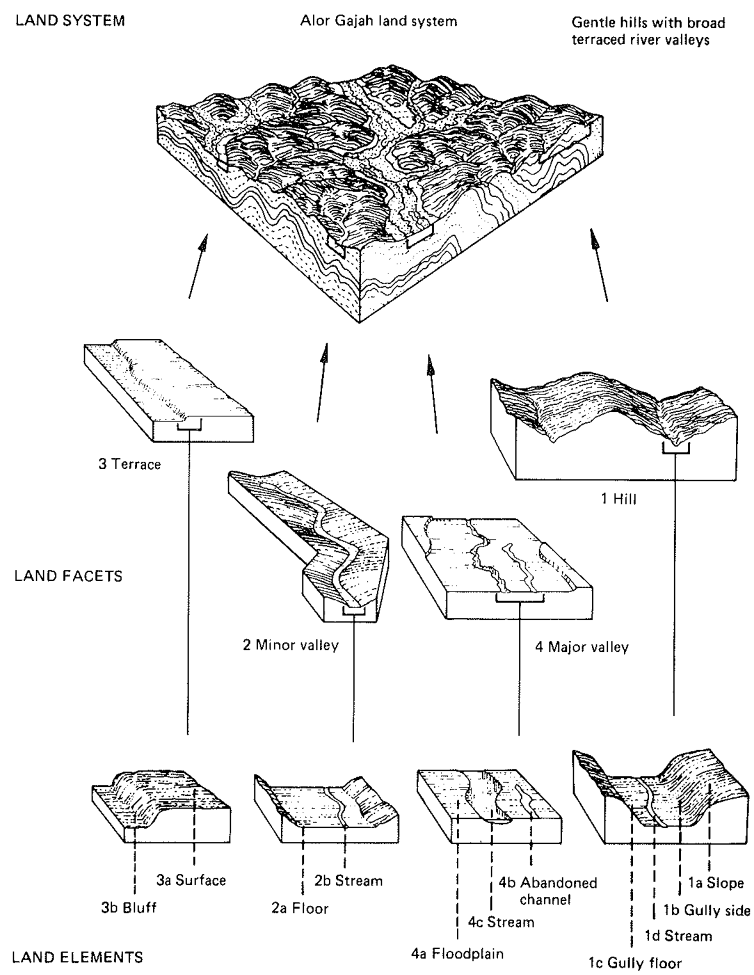
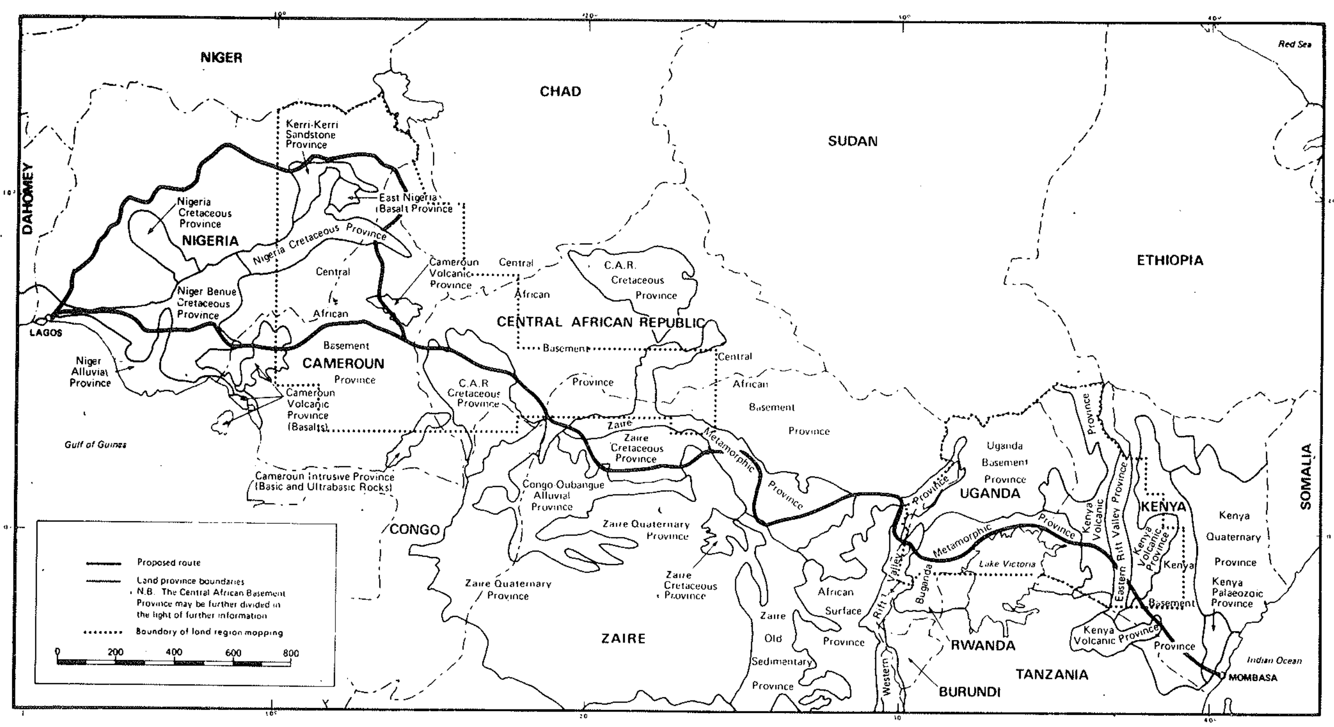


Figure 2. Land provinces of Trans-African Highway.



use data for a prefeasibilty survey. Soil changes noted during the ground reconnaissance were related to boundaries drawn on the map, and from this background it was possible to forecast conditions on routes that were put forward as alternatives after the completion of field work.

Feasibility Survey: Rumpi-Chiweta Road, Malawi

For the next stage of work--a feasibility study of a selected section--more detailed mapping would be needed over a narrower corridor. Land systems mapping is suitable for this, provided air photograph cover can be obtained, although in some areas Landsat cover might provide an alternative source of imagery for this purpose, so long as changes in topography are sufficiently pronounced.

An example of terrain evaluation used in more detailed surveys is a materials survey undertaken for a road project in Malawi. The consulting engineers responsible for the design of this project wished to use the information collected during field work carried out for the feasibility study to prepare tender documents without further field investigations. The project involved two alternative alignments that totaled 130 km (Figure 3). Although the two routes run quite near to each other, the topographic and geological conditions are quite distinct on each. The materials survey commenced before the final choice of alignment; therefore, it was necessary to devise a sampling and testing program of the soils in such a way that a pavement design could be prepared for a road located in any part of the whole area.

Two possible routes were identified. Before field work commenced, the area that contained the two routes was studied to establish the pattern of land systems, facets, and elements. Having identified all the terrain units, the field survey was arranged to collect at least one major soil sample from all units that would be crossed by either of the alternative routes. Where the soil or moisture conditions of any land facet appeared to be variable, extra samples were collected for testing in the laboratory.

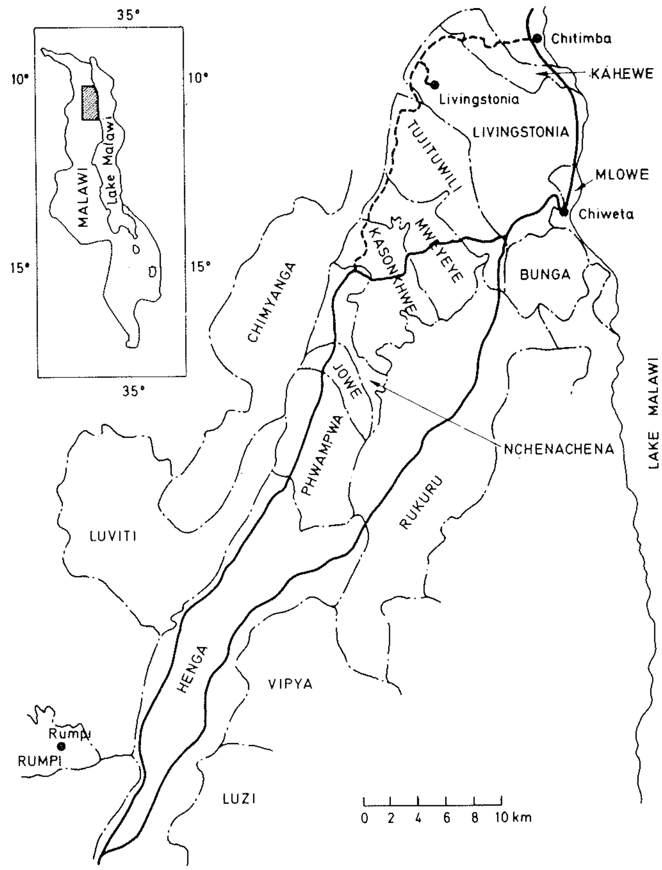
The laboratory testing program was arranged to determine the strength of the soils for all likely conditions of subgrade density and moisture content. From the test data, together with measurements of actual moisture content, a pavement design was prepared for every land facet traversed by the road, including a provisional estimate of the quantities of materials needed for construction.

AIR PHOTOGRAPH INTERPRETATION

Aerial photographs contain a complete record of the land surface and can be interpreted to predict subsurface conditions and provide information on many features important in engineering design. Although some knowledge of the natural sciences is helpful in interpreting aerial photographs, an engineer need not be deterred from attempting to use them due to lack of experience or knowledge of geology. It is possible to carry out useful work with air photographs after only a basic tuition, and expertise in interpretation rapidly comes with practice. Air photographs should always be viewed under a stereoscope to achieve the significant benefits offered by the three-dimensional linage.

There are many standard textbooks (5) and reports (6) that describe the practice of air photograph interpretation, which draw on North American and European examples. The technique for organizing an air photograph study does not differ significantly when applied in the tropics, although tropical terrains

Figure 3. Rumpi-Chiweta transportation corridor land systems.

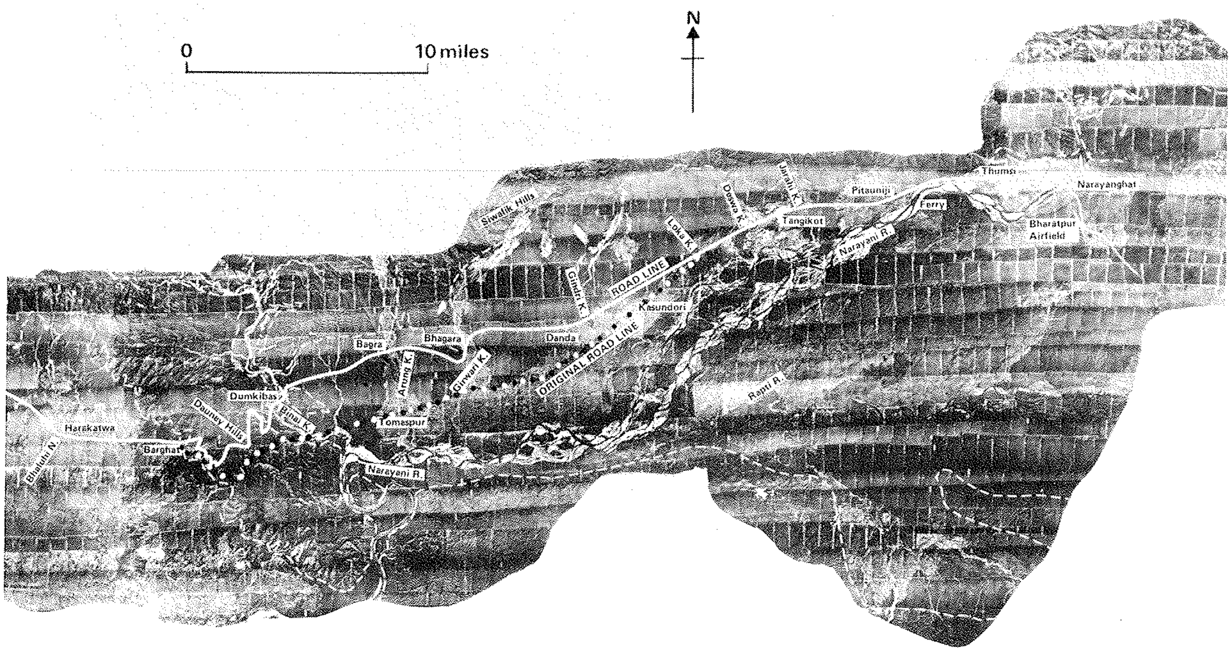


themselves are generally very different from those in temperate zones. Interpretation is often based on photography taken for photogrammetric purposes, typically 9-in panchromatic film in large cameras at a scale of between 1:20 000 and 1:50 000. Where more specialized photographs are needed, a simpler camera system can be used in a light aircraft to obtain high-quality nonmetric photographs at the required scale, using color film if necessary (7). The use of conventional and specialist photography is illustrated by two separate road schemes in Nepal.

The Butwal-Narayanghat section of the East-West Highway in Nepal, which was funded by the British government, provides an example of the use of air photograph interpretation to align a road and organize the search for materials on a rational basis based on a terrain evaluation. The eastern section of the road (Figure 4) runs roughly east-west for 56 km; it is constrained on the north by the foothills of the Himalayas and on the south by the Narayani River. Between the lower slopes of the mountains and the floodplain of the river lies a complex arrangement of terraces with a well-defined piedmont-fan system that extends southward from the foot of the mountains.

An original alignment, lying to the south near the Narayani River, traversed low-lying terraces and floodplains of fine-grained plastic soils used for wet paddy cultivation, and it involved the crossing of wide ill-defined watercourses. It became clear that a relocation of the road 1-3 km to the north of the original route would place the road within the zone of gravel terraces, where materials are plentiful and the river courses are better defined. Existing black-and-white air photographs of the area at a scale of 1:12 000 were examined to identify the main

Figure 4. Part of Butwal to Narayanghat Road, Nepal.



terrain types, potential sources of gravel, old stream channels, and areas liable to inundation. Particular attention was paid to identifying the best crossing points of three large and several smaller rivers in this section of the route at points where the floodplains are narrowest and most stable. In order to compare the relative merits of the two routes in this section, rough quantities were taken off by scaling from the photographs. Arbitrary unit rates were applied to these quantities, which showed a gross cost reduction of the order of 30 percent in favor of the northerly route. Although this figure was only a crude estimate of the potential cost difference between the two routes, it was felt that there was ample justification from the purely engineering point of view to direct subsequent survey and design effort on the northerly alignment. The road was opened to traffic on this line in 1975.

A second road project in Nepal, for which specialized aerial photography was flown, lies in the east of the country. The road runs from Dharan, on the plains, to Dhankuta, situated in the foothills of the Himalayas. The road is 51 km long and involves a cumulative ascent and descent of some 3000 m.

The geotechnical problems encountered in this area are severe; they involved widespread instability and the location of a large bridge site across a major river that is known to scour its banks and bed (Figure 5). There are no roads and few major footpaths in the area; movement across the country is made slow by dense vegetation and intensive terrace cultivation, and the slopes are extremely steep and often dangerous. Under these circumstances, an engineering survey cannot adequately be carried out by field work alone. Air photograph interpretation proved vital in evaluating features (especially unstable ground) that were either inaccessible or too large or too diffuse to be recognized at ground level.

Black-and-white aerial photography at 1:25 000 scale was available, but for some sites, particularly the major bridge site, the scale was too small to identify all the salient features of the locality. To have the area reflown at a larger scale would have been difficult, owing to the isolated nature of the area and the very variable weather conditions that prevail. However, at a time when possible routes were being considered by the consultants responsible for the design of the project, TRRL was developing a range of camera systems to provide a package that can be taken overseas easily and fitted simply to a light aircraft. A lightweight bracket allows the cameras to be mounted in a housing fixed to the side of the aircraft (Figure 6). This camera system was used to acquire large-scale multispectral photographs of the area through which the proposed road would run. In Nepal, a Pilatus Porter aircraft was available that had an internal mount for cameras, thus simplifying the mounting and operation of the cameras. It was possible to use two camera sets at one time, so a comparison was made of photographs taken with an intermediate format camera that used 125-mm film and a cluster of four 70-mm format Hasselblad cameras. The larger size of camera covered a

Figure 5. Detail of bridge site to be located on rock bar, Nepal.

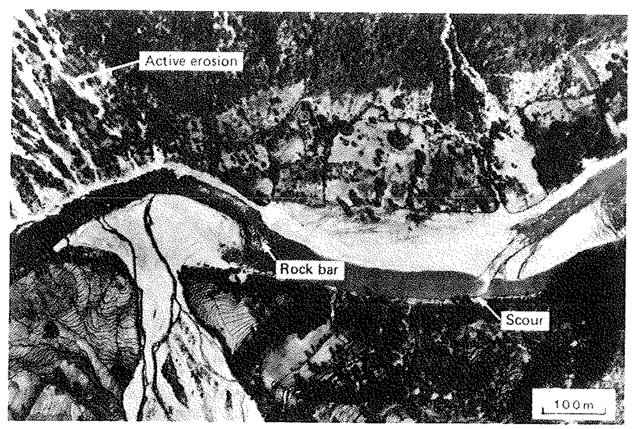
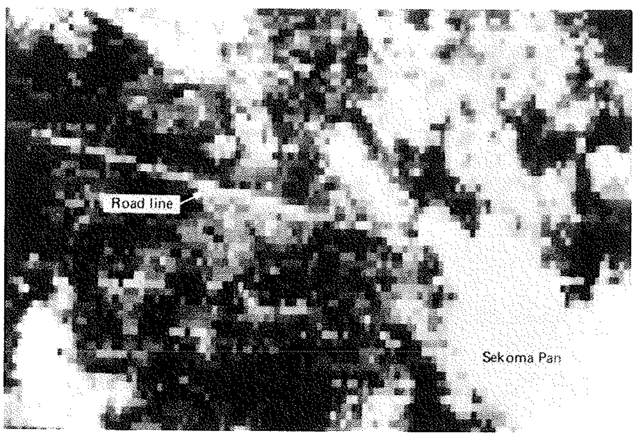


Figure 6. Pod to carry up to four 70-mm cameras fitted to Cessna 172 aircraft.

Figure 7. Digital Landsat image of Sekoma Pan area, Botswana, which shows part of pan and trace of road.



greater area of ground for a given scale, but only negative film was available for this camera size. It was thus very suitable for producing large prints. The range of film types for 70-mm cameras is very extensive, and processing is more widely available. A range of 70-mm films was tested, including high-resolution films suitable for small-scale photography, natural and false color films, and panchromatic films with filters. Three of the panchromatic images can be combined by using a color additive viewer to recreate a normal or false color image. For general-purpose investigations, the natural color films proved most useful. False color films do show up minor variations in vegetation that are very hard to see in natural color, but in Nepal the hills cast strong shadows that are accentuated by the high contrast of infrared film. The added complexity of manipulating the multiband panchromatic photography has not been justified by the extra information obtained from the interpretation.

Small-format aerial photography offers advantages beyond the low cost of the survey. A light aircraft can usually be hired locally and should therefore be relatively easy to obtain. Many light planes, which operate from unsurfaced airstrips, can fly in areas that would be too dangerous for larger aircraft. Moreover, they can be more easily held on standby, ready to operate at short notice between spells of bad weather or on occasions when it is necessary to photograph the terrain at specific times.

LANDSAT SATELLITE IMAGERY

Since the launch of the Landsat program in 1972, three successive satellites have returned more than 1 million images of the earth's surface to receiving stations in the United States, Argentina, Australia, Brazil, Canada, India, Italy, Japan, South Africa, and Sweden. The orbit of the satellites is so arranged that they pass in a north-south direction over the same piece of ground every 18 days, and on command they can transmit an image to one of these receiving stations. Most of the information has been collected by the multispectral scanner (MSS), which builds up an 185x178-km image of the ground by recording successive west-east scan lines as the satellite moves south. The images are issued to customers either as a computer-compatible tape (CCT) or as photographs at a scale of 1:1 million.

Within each scan line, reflectance is measured at four separate wavelengths equivalent to green and red light and two bands of infrared. The scan line is sampled at a frequency that is equivalent to a movement of 57 m along the ground, and the data are reproduced conventionally as picture elements (pixels) 79x57 m in size. Within a pixel, small features such as buildings or roads cannot be resolved individually, but they contribute to the total reflectance of that pixel and may bias it. Thus, the road in Figure 7, although less than 10 m wide, alters the reflectance of the pixels that cover it so that they stand out from the background. The line of the road can be seen, but there is no way of determining its width from Landsat data alone. (Note in Figure 7 that the individual elements are visible. The original scale on a television screen was 1:22 000.)

A higher resolution is achieved with the return-beam vidicon (RBV) camera on Landsat 3. This system uses two cameras, each covering one-quarter of the area of the MSS scene, and has a resolution of 30-40 m. Currently, the data are usually made available in photographic form at a scale of 1:250 000, but CCTs are now being produced. The high resolution of this system generates such a large amount of data that it has been necessary to restrict it to one channel; thus, it is not possible to produce an RBV color image. However, experiments have been made to add the MSS data to the higher-resolution RBV data in order to obtain the benefits of both systems. The thematic mapper (TM) on Landsat D, due for launch in 1982, will combine the advantages of false color representation and 40-m resolution.

INTERPRETATION OF LANDSAT IMAGES

The interpretation of Landsat data consists of two phases: data preparation and extraction of information. The preparation of an image in a form suitable for interpretation (as a false color composite, for example) is a necessary first step to facilitate the interpretation process. An interpretation, carried out at its simplest level, can be made in a similar way to the interpretation of small-scale air photograph mosaics.

Landsat Photographic Techniques

The basic Landsat data are held on four photographic negatives that can be usefully enlarged to a scale of about 1:250 000. Larger prints may be useful to correlate with maps but give no extra information. These images may be interpreted individually but, to take full advantage of the system, it is necessary to combine data from more than one band. The normal way to study three different images is to use a color composite, and the simplest method is to purchase a standard product, either a transparency at 1:1 000 000 scale or an enlarged print. The process of making a master color negative is relatively simple but requires experience to obtain good color balance. An alternative method of producing a color composite is to use a color additive viewer, where the three images are projected through color filters and accurately superimposed on the screen. The effect of changes in color filters is seen immediately and the image can be interpreted as projected, but it is usual to make a color photograph that can be studied more conveniently.

Images may also be combined in pairs, if desired. A simple technique is to view two different spectral bands, or images taken at different dates, under a stereoscope. No stereoscopic view is obtained, but the effect is to reduce disturbances caused by scan lines and image "grain", thereby leaving unchanging terrain features to stand out more clearly. Pairs of images may be combined photographically as ratio images, in which a positive transparency of one spectral band is superimposed on a negative transparency of another. If the two images are identical, they cancel each other and leave a neutral tone. Any differences between the bands will show as either darker or lighter areas to give a simple form of ratio image. More complex ratios are produced by digital processing in a computer.

Use of Landsat for Materials Investigations in Sudan

Individual Landsat scenes at scales between 1:500 000 and 1:1 000 000 were used in a study of the terrain of the Wad Medani-Kosti area of Sudan to locate materials for road construction in two projects in the area (see Figure 8; scale is 1:1 300 000). The projects involved the construction of the Wad Medani-Sennar-Kosti road and the extension of the road network east of Sennar in connection with new irrigation works. In both areas there was difficulty in locating sufficient quantities of gravel for road construction. Some field work had been carried out, but the known deposits were inadequate for the needs of the project. Topographic mapping was old and of poor quality, and air photograph cover was limited to very small areas. Under these circumstances, satellite imagery afforded the only comprehensive view of the land surface that was available. Basic topographic details such as towns, major roads, and river systems were readily identified on the imagery, which incidentally also provided an up-to-date picture of the extent of irrigation development.

The area consists of two contrasting terrain types: the predominant and very extensive black clay plains through which protrude occasional outcrops of granitic rock, and the valleys of the White and Blue Nile, which cut across the plains in a wide tract of alluvium. Several types of natural gravel occur in the area, indications of some of which can be discerned in the images, for which confirmation in the field was obtained. One of the most positive indicators of natural gravel is the aureole of light-toned (sandy) soils that surround even very low outcrops of rock in the plains. These materials contain pockets of weathered rock that can provide a usable gravel. The outcrops themselves consist of hard rock that can be used for quarrying. The black clay plains contain a variety of coarser soils that form contrasting tones in the images. At the western end of the road, sandy ridges associated with the White Nile provide firmer foundations but yield no gravels. Lateritic gravels are present in this area, which have a high and distinctive reflectance in the red and infrared bands. But their outcrop of up to 300 m² is generally too small to allow a positive identification to be made from Landsat. To the east, on each side of the Blue Nile valley, extensive areas of red quartzitic clayey sand occur within the clay plains. The sands contain deposits of gravel, but it is not possible to separate the sands from the gravels in the images. Sands and gravels also occur along the banks of the river itself, and they are easily identifiable by their distinctive shape and position and high contrast with their surroundings. But, as before, it is not possible to separate the sands from the gravels by interpretation alone.

Figure 8. Landsat satellite image of Wad Medani area, Sudan, which shows (A) valley of Blue Nile, (B) black clay plains, (C) areas of red quartzitic clayey gravel, and (D) rock outcrop.

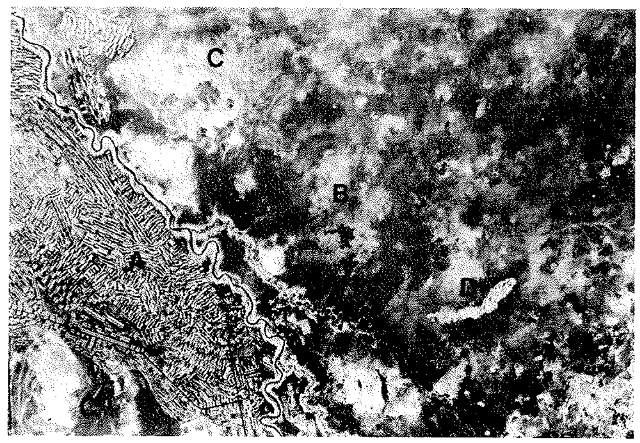
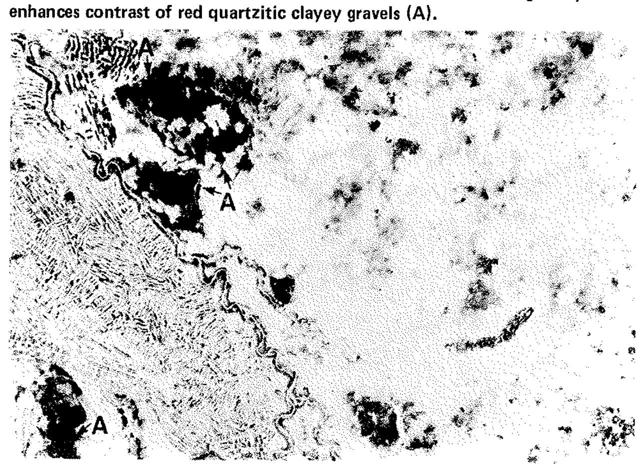


Figure 9. Photographic density slice of part of same area as in Figure 8, which enhances contrast of red quartzitic clayey gravels (A).



The interpretation of the satellite images was assisted by the use of color composites as well as black-and-white pictures and by a density-slicing technique that was used to enhance the appearance of the red quartzitic gravels and make them stand out more clearly. The color composites were made in an additive viewer. The density-slicing technique was carried out photographically. The scene was photographed onto high-contrast film to bring out all areas of a specified grey tone at the expense of contrast in the remainder (see Figure 9). Three spectral bands of the scene were treated in this way and combined into a color composite. This technique can be very effective for areas of uniform tone that contrast well with their surroundings, as in this case. However, in complex images it is difficult to avoid including areas in the density slice that have a similar brightness value (color) on the ground but that are not, in fact, related. Methodical field work is required at the right time of year to check that surface characteristics of the terrain (soil, color, vegetation, etc.) are both diagnostic of the features of interest and consistent over a wide area before attempting to use density slicing to identify features in the terrain.

Processing of Landsat Data: Digital Methods

The original Landsat data are recorded on a tape that contains four bands of reflectance data for the 8 million pixels that make up a scene, which total more than 30 million reflectance values in all. These data may be mathematically analyzed in a computer, for example, to count the percentage of pixels of a certain value for correlation with some known ground feature. Alternatively, the pixels from three bands can be displayed on a color television screen to generate a full-color image that may be interpreted in the normal way. However, the data can also be manipulated mathematically before output to the screen, thereby enhancing the picture for interpretation and analysis. Television viewing systems, when connected to a computer to enable the effect of data transformations to be seen immediately, are known as interactive processors.

The use of an interactive processor for the study of Landsat data offers two major advantages over photographic techniques. First, the range of data transformations available in the processor is much greater than those achievable by photographic processing, and the results are available almost instantaneously. There is thus a greater opportunity to find an enhancement best suited to the user's needs. Second, the intensity range of the data can be stretched over the full range of the display system, which allows very subtle color variations to be observed. A computer-generated image, therefore, is a very high-quality product that makes the most appropriate display of the data in terms of the user's requirements.

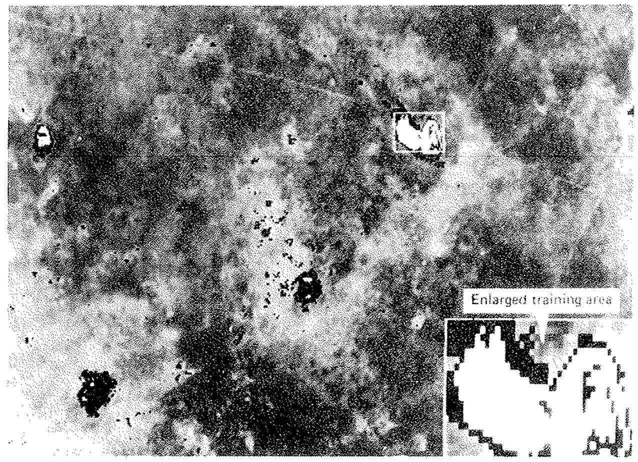
There are, however, certain aspects of digital-image processing that have discouraged its use in the past in favor of simpler photographic techniques. These are

1. Higher costs in terms of both original data on tape and either the capital costs of a processor or hire of a computer (the cost of computer time may be considerable if many options are explored before arriving at a suitable image), and
2. The need to produce a hard-copy picture, either by an expensive color writing process or by photographing the television screen directly, with consequent loss of image quality.

Despite these disadvantages, the use of interactive viewers is becoming more common, and this trend will undoubtedly increase as they become adapted to minicomputers and microcomputers at correspondingly lower cost.

The U.K. Remote Sensing Centre at the U.K. Royal Aircraft Establishment operates a typical large interactive processor, which is linked to a mainframe computer for bulk processing of data. The processing facilities are of two types: geometric, in which the size or shape of the whole image is modified, and spectral processing, in which the reflectance values of the pixels are enhanced.

Figure 10. Classification of calcrete areas in vicinity of Sekoma Pan, Botswana.



1. Geometric transformation of data: Simple processing can skew the original rectangular array of pixels into an image that takes account of earth rotation and that is geometrically fairly accurate, even at a scale of 1:250 000. More elaborate processing, in conjunction with control points, can be used to resample the pixel array so that it conforms with a map projection. Experiments have been made to combine topographic maps and Landsat data to produce an image that has height information superimposed onto a detailed topographic base.
2. Spectral processing of data: Spectral processing involves changing the original pixel intensity values to a new set by mathematical transformation. The range of processes available is therefore very wide to serve a number of purposes. Often some form of preprocessing is applied to correct atmospheric and radiometric distortions in the data in preparation for interpretation. At the interpretation stage, most images require some color enhancement or "stretching", in which the original pixel values, crowded into a narrow part of the brightness range as they normally are, are redistributed over the whole range to improve the brillance and separation of the colors.

In the process known as density slicing, data between certain levels of a single band are displayed to the exclusion of the remainder. The automatic classifier uses a form of density slicing to select pixels that have a range of intensity defined for all bands and hence have similar reflectance characteristics on the ground (Figure 10). Ratio images, generated by dividing the pixel values of one spectral band with those of another, emphasize the differences between bands. Ratio images may be combined with normal bands to produce new images or used in classifications to refine groups of pixels into tightly defined color populations. More elaborate processing can be used to enhance the edges of features where strong tonal contrasts are present and thereby to heighten the edge of sharp features (e.g., fault scarps) that have a linear trend on the ground.

A more general transformation is to calculate the principal components of the data; this is a mathematical technique that takes any number of data sets and calculates an equivalent number of components with the more significant information contained in the first few sets. Thus, the four bands of Landsat data yield four principal components, of which most of the relevant information is contained in the first three. The fourth component almost completely consists of noise. The three components can be displayed on the monitor as a color image and interpreted in the normal way. For images in which the reflectance data are highly correlated between the four bands, principal component displays present the interpreter with well-defined color groupings that are easy to discriminate.

Digital Processing in Search for Construction Materials in Botswana

TRRL has used the image processor in a study to assist the Ministry of Works and Communications, Botswana, to assess reserves of calcrete for road construction within a route corridor between Jwaneng and Takatswaane in central Botswana. The corridor is about 400 km long and 40 km wide, and it provides access to a large part of western Botswana with possible extensions into Namibia. Calcrete is a calcareous material that forms within the Kalahari sands. It accumulates abundantly in large bare depressions (pans) but also in smaller quantities beneath the sand itself in areas where no pans occur. Calcrete is the only form of natural gravel in the area, and this study to determine the distribution of deposits has been undertaken to decide whether relocation of the existing sand track through areas that contain more calcrete would be justified.

Over most of the corridor, the Kalahari sands, which cover central Botswana to a considerable depth, form an almost imperceptibly undulating plain with scattered pans. Some of these pans are very large (up to 5 km across) and are abundant sources of calcrete. The smallest are less than 50 m across and are much less reliable sources of the material. Large parts of the corridor contain no pans at all, but calcretes can still be found beneath the Kalahari sand, where the only clue to the existence of the material is a change in the color of the sand from its normal reddish or brownish hue to a neutral grey.

The pan features are visible in Landsat digital imagery down to about 100 m in diameter, provided good contrast exists between the pan surface and the surrounding sand plain. Black-and-white aerial photographs were used successfully to map even the smallest calcrete-bearing features, but they were quite unable to map the grey sands because the change in sand color from red to grey is not depicted. In contrast, it was found that the Landsat scanner is extremely sensitive to this color change, the principal component display being particularly effective in the discrimination of this subtle feature. Owing to the small size of many of the grey sand areas, they are poorly visible and barely mappable in photographic Landsat products. But the increased resolution of the computer-generated image, enhanced by the principal component transform and contrast stretching, enables the interpreter to map grey sand areas as small as 100-300 m across (Figure 11). (Note: For Figure 11, the aerial photograph, although able to resolve tiny details on the land surface, does not distinguish areas of grey sand where calcrete occurs from the surrounding reddish-brown sands. The computer image has been enhanced to maximize the difference between sand colors and shows them clearly in dark tones. Numbers 1-6 indicate corresponding features in each image.) An image was produced that depicts the grey sand areas to the exclusion of all other features from which a photographic negative was made by an optical film writer. This image has formed the basis of a map of the grey sand areas between Jwaneng and Takatswaane. The computer images have shown that the existing route passes few deposits of calcrete, but that it could be relocated through areas where many potential sources of the material exist.

CONCLUSIONS

The application of geotechnical survey techniques to highway engineering covers a great diversity of operations and involves many environments, but the development of sophisticated remote-sensing systems has improved our ability to evaluate ground conditions in all types of terrain. The foregoing examples illustrate some of the ways in which remote-sensing and terrain classification methods can be incorporated into engineering surveys, although the precise ways in which they are employed depend on the circumstances of the survey and the types of imagery available. It is important to use a scale of imagery appropriate to the level of detail of a

Figure 11. Comparison between black-and-white aerial photograph (left) and computer-generated Landsat image at some scale of area near Sekoma, Botswana.

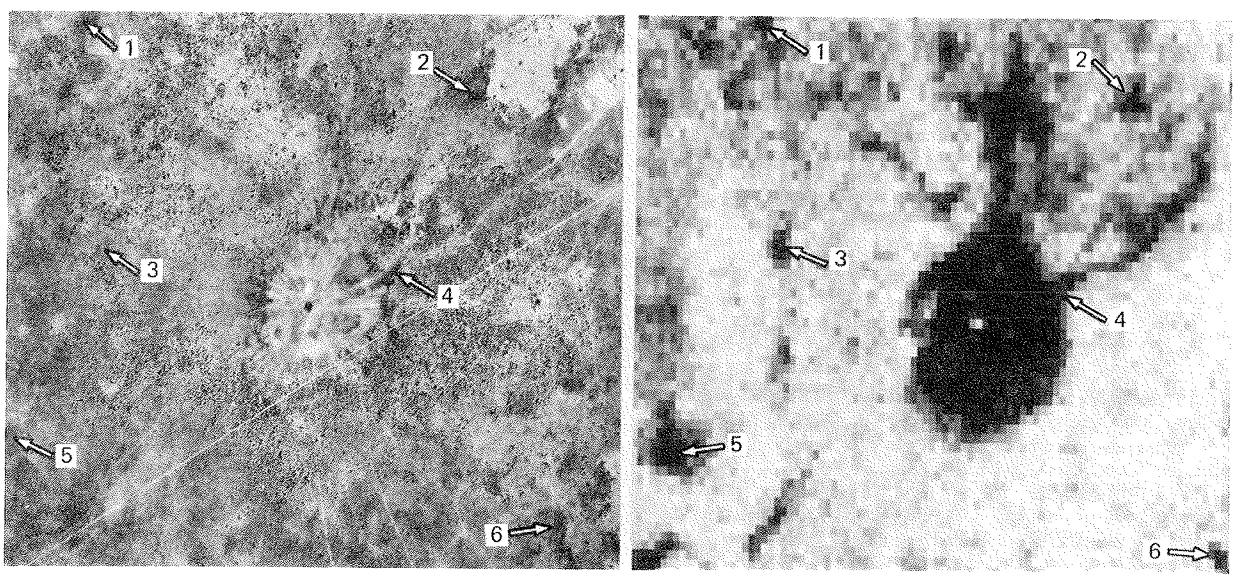


Table 1. Summary of road alignment survey activities typically augmented by widely available remote-sensing techniques.

			Remote-Sensing Techniques		
Project Stage	Aim	Activity	Landsat MSS and RBV	Existing Black-and-White Air Photography	Specialized Remote-Sensing Techniques
Preproject phase	To identify main sources of information and to put project into context with respect to terrain	Collect together all relevant published material relating to project to assess requirements for mapping and interpretation during survey stages	Purchase Landsat MSS imagery in a form suitable for requirements of project; select images from several dates or seasons if necessary; make false color composite images at 1:500 000-1:250 000; purchase Landsat RBV imagery if available, 1:250 000-1:100 000	Make inquiries in Europe or of host government to purchase air photography and air photograph mosaics	Find out if specialized air photography or other form of remote-sensing coverage has been made for some previous project in area
Reconnaissance	To identify possible alternative routes and define strategy for construction program	Define project in terms of size, political and physical constraints, and geotechnical complexity; examine possible routes on maps and satellite images and air photograph mosaics if available; undertake broad terrain classification for collation of regional information; visit site to check interpretations; report on findings and plan next stage	Examine MSS photograph products in conjunction with maps; scale as above; interpret influence of major features on road alignment, e.g., changing course of major rivers; catchment area of major river systems; extent of flooding of low-lying areas; possible sources of water for construction; possible sources of construction materials (e.g., alluvial terraces and fans); pattern of regional instability; extent of erosion; spread of deforestation; assessment of land acquisition or site clearance problems.	Air photograph mosaics at approximately 1:100 000 used in conjunction with Landsat material	
Feasibility	To appraise route corridors and select best route	Make detailed interpretation of conditions on all routes and, if necessary, make a more detailed terrain classification of area; interpret foundation conditions, earthworks (borrow and spoil areas), drainage, materials sources (gravels), major bridge sites, and hazard zones; carry out site investigation of alternative routes, noting key physical and geotechnical features; cost comparisons; selected laboratory and field testing; recommend best route and prepare report	Use MSS and RBV as base map if no more detailed mapping is available; supplement air photograph interpretation with color information from MSS	Use air photographs for all detailed interpretations and terrain-classification study; scale 1:20 000-1:60 000, as available: (a) foundation condition survey; (b) calculate catchment areas and location of culverts; (c) identify spoil areas, also possible borrow areas; minimize erosion risk; (d) identify possible sources of construction material; (e) location of all possible bridge sites, and (f) identify major hazard areas (poorly drained soils, spring lines, unstable areas, erosion in river courses)	Commission specialized air photography (possibly small format) at a scale appropriate to size of task and degree of ground complexity (approximately 1:10 000-1:30 000); examine Landsat computer-compatible tapes in interactive processor (scales 1:20 000-1:100 000)
Design	Detailed study of selected route to engineering design standards	Comprehensive site investigation of selected route with full sampling and testing program; prepare final design documents		Use air photography to support all field survey activities	
Construction and post-construction maintenance period	Build road and carry out repairs prior to handing over	Road construction activities		Use aerial photography to locate access roads for construction traffic in difficult terrain	Large-scale air photography may be used to monitor changes taking place at important sites as construction proceeds; may also be used to record damage done by landsliding, erosion, or flooding in preparation for design of rehabilitation measures

survey, beginning with small scales to cover large areas in a general way and moving to larger scales as the investigation proceeds toward the selection of a final alignment. To emphasize the sequential nature of terrain evaluation procedures and how they are matched to survey requirements, the main engineering activities and appropriate terrain evaluation techniques are summarized in Table 1.

Aerial photographs taken for mapping purposes remain the most important form of remote-sensing imagery for both general terrain studies and investigations of specific sites. The use of aerial photographs to map land systems and land facets--terrain units based primarily on land form--is seen as an effective way of organizing a field survey to sample all relevant parts of a corridor under study. The use of a terrain classification saves time in the field by relating the data collected at individual sites to larger areas. Low-cost nonmetric cameras can provide high-quality photographs for interpretation, and the film type, scale, and timing of the survey can be adapted to the subject under study.

Aerial photography is now supplemented by Landsat satellite imagery as a small-scale mapping tool. The information from Landsat may be presented either in photographic or digital form. Photographic images are inexpensive to produce and require little specialized equipment beyond the facilities of a photographic color laboratory for their reproduction, although an additive viewer extends their scope. The time delay in obtaining original material is usually quite small, and this position is likely to improve with the setting up of regional centers that hold stocks of Landsat negatives. For these reasons, photographic processing is likely to remain of great importance for surveys in developing countries.

Despite the high quality of Landsat photographic images, Landsat data can only be fully used when images are generated from the digital data held on computer tapes. The resolution of these images is limited to the 80-m pixel size of the scanner, but they convey a large amount of spectral (color) information about the terrain. Developments are taking place in interactive viewing systems away from the concept of large, sophisticated machines toward smaller, simpler systems, which often consist of assemblies of standard components linked to a microcomputer that can perform functions similar to those of a large machine but concede some limitations of speed and flexibility.

With greater international interest being shown in the development of Third World countries, the role of remote sensing to highway engineering, as with all natural resource studies of terrain, will increase in importance. Refinements in sensing systems will enhance our ability to detect subtle changes in terrain conditions, and improvements in data handling will permit more sensitive interpretations to be made.

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Terrain Analysis for Transportation Systems in British Columbia

TERJE VOLD

A terrain classification system was developed in British Columbia and accepted nationally in Canada. The mapping system emphasizes features that can be interpreted from aerial photographs and readily verified by field checking. Genetic materials classified according to their mode of deposition form the substance of the terrain map unit. The material's texture, surface expression, and the presence of any geologic processes of modification are additional components of the system. This system also provides the framework for much of the soil mapping in the province, since soils have inherited many properties from these parent materials. A manual on terrain interpretations for roads and linear developments that involve shallow excavations has been prepared. The manual is designed for planners and indicates how terrain information may be used to assess capability for these transportation-related uses. Physical land constraints and natural hazards that affect transportation systems are explained. Interpretive maps that show the distribution of natural hazards and physical land constraints for development can be prepared from base terrain and soil maps. These maps can be of use to planners in assessing alternative transportation corridors and in anticipating potential trouble spots before construction has commenced.

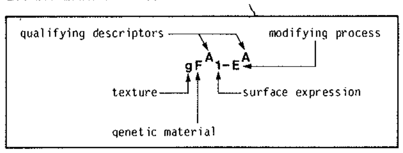
Terrain analysis refers to the inventory and assessment of the physical conditions of land. This is a general term that includes both geological and pedological (soil) evaluations. There are three distinct, although somewhat interrelated, groups of scientists who study the physical nature of land: geologists, soil scientists (pedologists), and soil engineers (geotechnical engineers). Each of these professions focus their work on a slightly different aspect of the earth's surface.

A terrain classification system was developed in British Columbia (1) in 1976 and accepted nationally in Canada in 1978 by soil surveyors (2); it is also widely used by most consultants in British Columbia (3). The system encourages a common approach to terrain inventory and provides standard nomenclature that has improved communications between earth scientists (4). This system also provides the framework for much of the soil mapping in the province and elsewhere in Canada, since soils have inherited many properties from their parent materials.

The terrain classification system was developed for reconnaissance mapping surveys (scales of 1:50 000 to 1:100 000) by government (5,6) but has also been applied for detailed surveys (scales of 1:20 000) by consultants (3). The system emphasizes features that can be interpreted from aerial photographs and readily verified by field checking, thereby enabling coverage of approximately 2590 km^2/mapper/year at a scale of 1:50 000. Genetic materials classified according to their mode of deposition form the basis of the terrain map unit.

Figure 1. Terrain map symbols.

B.1 EXPLANATION OF LETTER NOTATION



B.2 GENETIC MATERIALS

LETTER SYMBOL	NAME (PROCESS STATUS[1])
A	anthropogenic (A)
C	colluvial (A)
E	eolian (A)
F	fluvial (I)
F^G	fluvioglacial (I)
I	ice (A)
L	lacustrine (I)
L^G	glaciolacustrine (I)
M	morainal (I)
O	organic
O^B	organic (bog) (A)
O^F	organic (fen) (A)
O^S	organic (swamp) (A)
R	bedrock (I)
U	undifferentiated (I)

B.3 TEXTURE

LETTER SYMBOL	NAME
b	bouldery
g	gravelly
s	sandy
$	silty
c	clayey
d	diamicton
r	rubbly
a	blocky

B.4 SURFACE EXPRESSION

LETTER SYMBOL	NAME
a	apron
b	blanket
f	fan
h	hummocky
l	level
m	rolling
r	ridged
s	steep
t	terraced
u	undulating

B.5 MODIFYING PROCESSES

LETTER SYMBOL	NAME (PROCESS STATUS[1])
A	avalanched (A)
C	cryoturbated (A)
D	deflated (A)
E	channelled (I)
E^G	channelled by glacial meltwater(I)
F	failing (A)
G	frost shattered (A)
H	kettled (I)
K	karst (A)
N	nivated (A)
P	piping (A)
S	solifluction (A)

B.6 QUALIFYING DESCRIPTORS

LETTER SYMBOL	NAME
G	glacial
B,F,S	bog, fen, swamp
A, I	active, inactive (process status descriptors)

B.7 COMPOSITE UNITS

	.	the components on either side of this symbol are approximately equal.
	/	the component in front of the symbol is more extensive than the one that follows.
	//	the component in front of the symbol is considerably more extensive than the one that follows.
e.g.	Mb//R	Mb is considerably more extensive than R.
	Mb//R.Cv	Mb is considerably more extensive than R; R and Cv are of roughly equal extent.
	Mb/R//Cv	R is less extensive than Mb; Cv is considerably less than R.

B.8 ON-SITE SYMBOLS

- drumlin, drumlinoid ridge
- escarpment
- cirque
- kettle

[1] See Qualifying Descriptors for definition of Process Status.

Figure 2. Terrain map.

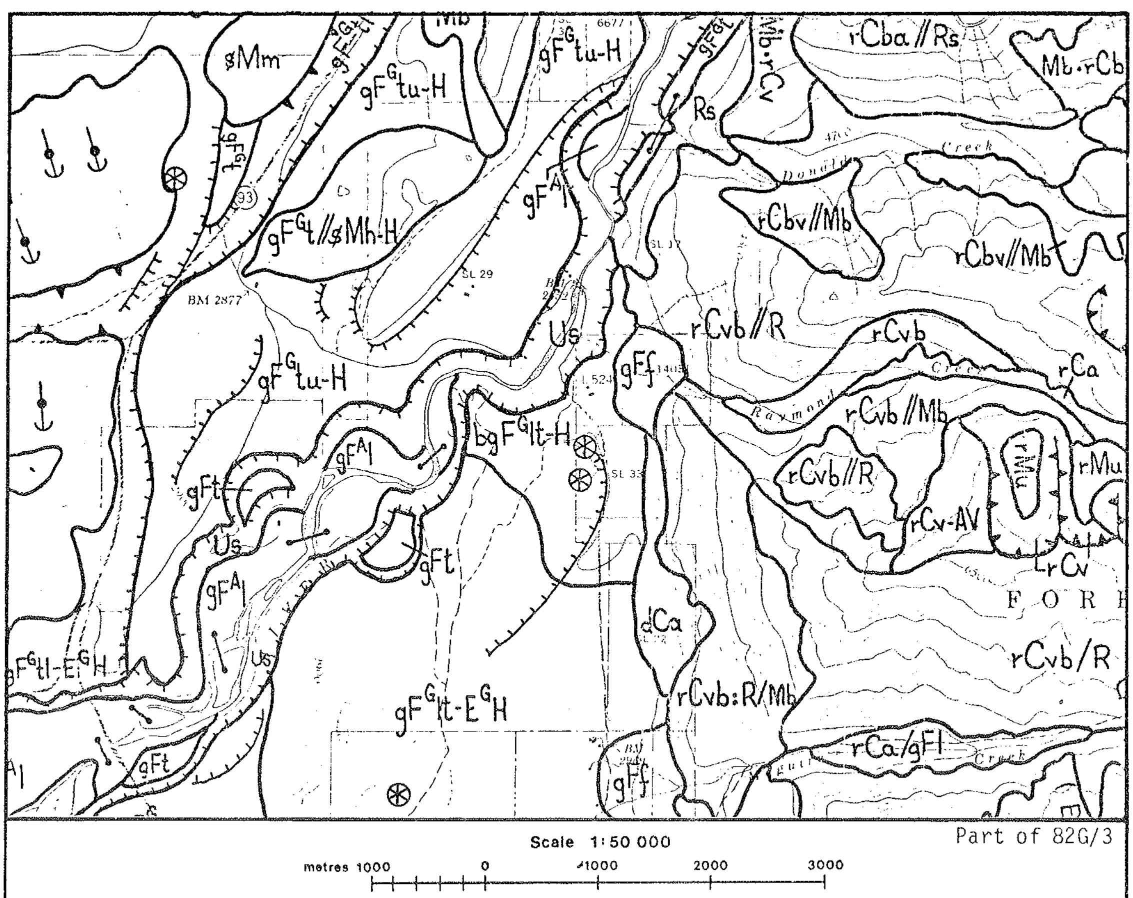


Table 1. Physical requirements and limitations that determine ease of excavation.

Optimal Conditions	Potentially Troublesome Conditions
Depth to water table and impervious layer more than 3 m	Imperfect to very poorly drained soils; water table or impervious layer within 3 m of surface
Bedrock more than 3 m below the ground surface	Bedrock within 3 m of the surface
Slopes less than 10 percent	Depending on the size of excavation, slopes in excess of 20-25 percent; undulating topography; depressional areas
Cohesive or cemented materials that have good sidewall stability; moderately coarse to fine-grained sands with a binding matrix	Plastic silts and clays (CH, MH[a]); gravels (GW, GP), and coarse sand (SW, SP) with no cohesive binder; organic sediments (OL, OH, Pt); highly indurated materials (e.g., basal till or cemented gravels); large proportion of boulders or a few very large boulders
No restrictive conditions within 3 m of surface	Bedrock, water table, or impervious horizon within 3 m of surface; a confined aquifer below an impermeable surface material
	Permafrost; periglacial processes

[a]CH, MH, and other alphanumeric symbols represent unified soil groups.

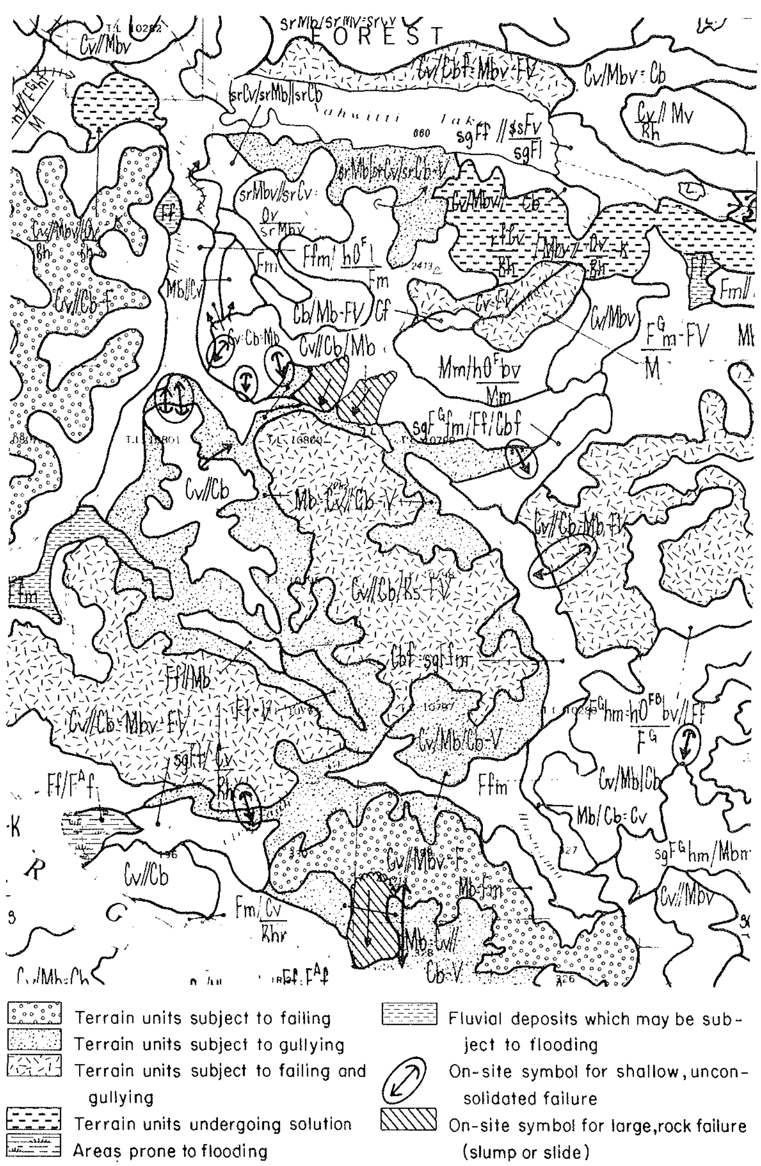
The material's texture, surface expression, and the processes of modification are additional components of the system (see Figure 1). A portion of a terrain map is shown in Figure 2 (6).

The symbols on a terrain map are descriptive, and they are located so that a lower-case textural symbol comes first, followed by an upper-case symbol that denotes material type. Common genetic materials in glaciated environments include moraine, colluvium, fluvial, lacustrine, and organic deposits. Following the material symbol is a lower-case symbol that denotes its surface expression; for example, whether the terrain is fan-shaped, hummocky, level, ridged, steep, or terraced. Blanket is an expression used for deposits thicker than 1 m, and veneer is used for those less than 1 m when materials conform to the topography of the underlying deposit (e.g., bedrock).

Any modifying processes that are affecting a terrain unit are represented by an upper-case symbol that follows a dash. For example, areas that are subject to snow avalanching, failing (landslides), frost churning, channeling, and gullying are shown.

Terrain and related soil inventory data at a reconnaissance scale of 1:50 000 exist for most of

Figure 3. Geological hazards map.



British Columbia. New transportation systems are being planned for remote areas; for example, an infrastructure of new highways, railways, and town sites is being examined by government in order to support the development of coal-bearing regions of the province (7).

In order to bridge the gap between the inventory terrain and soil maps and their utility for transportation planning, a manual on terrain interpretations for roads, sources of sand and gravel, linear developments that involve shallow excavations, and related concerns has been developed (8). The manual is designed to indicate to planners how terrain information may be used to assess capability for these transportation-related uses.

Natural hazards and physical land constraints that affect transportation systems are explained in the manual. At a reconnaissance scale, hazards such as flooding, snow avalanching, and the presence of active failures can be derived from the terrain maps.

Physical characteristics that commonly affect the ease and cost of land development include characteristics and behavior of surficial materials, hydrologic conditions, stratigraphic conditions, topography, and bedrock conditions. The manual indicates which terrain conditions are optimal and potentially troublesome for development. As an example, Table 1 (8) summarizes physical requirements and limitations that determine ease of excavation.

Interviews with land use planners and engineers in British Columbia were recently conducted to determine their preferences in interpreting engineering uses of soil and related terrain information (9). Land use planners generally want terrain scientists to provide interpretive ratings based on physical constraints to development. Engineers, on the other hand, were most interested in the base maps and data alone and many would not use the interpretations. The interviews indicated that planners and engineers are two distinct users of terrain information.

Planners do not generally have expertise in earth sciences and thus want terrain scientists to summarize their knowledge about particular terrain or soil units by indicating the degree of constraints to use in terms like slight, moderate, or severe. Most engineers felt that interpretations would be misconstrued as recommendations and incorrectly used for making on-site decisions and thus should not be provided. A few engineers perceived the use of interpretations for small-scale planning purposes, which could alert the designer to future site problems or direct engineers to areas that require more detailed investigation.

Interpretive maps that show natural hazards [see Figure 3 (5)] and physical land constraints for development can be derived from terrain and soil maps (10). These maps are useful to planners in assessing alternative transportation corridors, in determining general benefit/cost ratios of particular route locations, and in anticipating potential trouble spots before construction has commenced. Terrain or soil maps, of course, are available for those engineers who do not need interpretive maps.

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Systematic Watershed Analysis Procedure for Clearwater National Forest

DALE WILSON, RICK PATTEN, AND WALTER F. MEGAHAN

Natural and man-caused disturbances, including roads, may cause accelerated on-site erosion, increased downstream sedimentation, and changes in channel conditions. A procedure has been developed to estimate the magnitude of these effects on the Clearwater National Forest based on a land systems inventory that uses the "landtype", which is defined as a unit of land that has similar landform, geologic, soil, and vegetative characteristics. The dominant erosion hazards, which include surface erosion and rotational and debris landslides, are evaluated for each landtype in a watershed. The efficiency of a landtype to deliver eroded material into the channel system as sediment is also evaluated for each landtype. Erosion and sedimentation data collected locally or extrapolated from nearby areas with similar characteristics are used to estimate the erosion and sedimentation responses of road construction, timber harvest, and forest fire. Predictions can be made for undisturbed conditions and also to determine the effects of past or proposed management alternatives. Predictions are sensitive to changes in erosion over time. A relation based on analyses of 65 watersheds makes it possible to define allowable increases in sediment production based on channel equilibrium conditions. The procedure is useful to transportation planners because it provides a means to evaluate the effects of alternative road locations and road design features and allows scheduling construction over time to minimize unwanted effects.

There has been considerable interest in recent years in the effect of alternative cultural practices on water quality. On forest lands, the pollutant of primary concern is sediment, and the primary cultural practice that causes accelerated sediment is road construction (1). This is particularly true in the western United States, where accelerated sedimentation following road construction commonly results from both surface and mass erosion processes (2).

Various procedures have been developed to estimate the effects of alternative soil-disturbing practices on erosion. Most of these were developed on agricultural lands (3,4) and have subsequently been adapted to other types of soil disturbances, including construction sites and roads (5,6). Unfortunately, these methods have limited application for evaluating road erosion in much of the mountainous West because they are not adapted to snowmelt conditions, they do not consider gulley and mass erosion, and they make no provision for subsurface flow intercepted by roadcuts.

We have developed a procedure for predicting the effects of alternative watershed disturbances, which include road construction, timber harvest, and forest fire. The procedure uses a systems approach based on the landforms found in the basin, empirical data to estimate the effects of disturbance on annual surface and mass erosion, and the resulting response in both annual sediment yields and channel equilibrium conditions. By using the Clearwater National Forest procedures, responses are measured in terms of changes in annual sediment yields and channel equilibrium conditions and are usually evaluated over a period of less than 20 years.

ROLE OF LANDTYPE

The "landtype" is one stratum of the hierarchical land systems inventory described by Wertz and Arnold (7). The higher-level strata, which include physiographic provinces, sections, and subsections, are all delineated on the basis of climatic and geologic differences and are roughly classified by size as greater than 1000 $mile^2$, 100-1000 $mile^2$, and 25-100 $mile^2$ for each level, respectively. Further stratification requires the evaluation of additional factors, including landform, soils, and vegetation. The landtype association reflects a common genesis for a group of lands and can range in size from 10 to 25 $mile^2$. The basic land unit used for the watershed analysis procedure is the landtype itself, and it is defined as an area of land with similar landform, parent material, soil, and vegetation characteristics. Landtypes range from 40 to several hundred acres in size and average about 150 acres. Guidelines and additional background information on the delineation of landtypes are available elsewhere (8-11).

Landtypes and Slope Hydrology

Landtypes are used as the basic component for describing the watershed system because factors used to delineate landtypes are the same factors that influence the hydrologic function of slopes. Characteristics that describe slope hydrology, or how a slope handles water, include (a) slope shape, (b) slope length, (c) slope gradient, and (d) surface drainage characteristics (12).

When analyzing slope hydrology, it is helpful to consider how a slope disposes of water and how the above-mentioned factors influence runoff timing, as follows:

1. Slope shape: Slope shape influences whether water is dispersed or concentrated. Slope shape classes mapped include the following: (a) class 1--slopes that are convex horizontally disperse water movement in all directions; this tends to discourage concentration and decreases contributing area to streams that originate on the slope; (b) class 2--straight slopes accumulate water in straight flow paths down the slope; and (c) class 3--horizontally concave slopes concentrate water movement to common points; this increases the contributing area of streams that originate on the slope.
2. Slope length: Longer slopes tend to accumulate more water on the lower portions of the slopes.
3. Slope gradient: Steeper slopes decrease the time of concentration of slope water movement and increase flow velocities.
4. Surface drainage characteristics: Slope dissection, stream density, stream length, and entrenchment all affect time of concentration and contributing area of slope water movement.

Soil and parent material characteristics used to delineate landtypes include soil mantle depth, soil texture, soil structure, soil consistency, bedrock type, bedrock weathering, and bedrock jointing and fracturing. Each factor modifies mantle drainage and, subsequently, the subsurface water movement on slopes. Soil and bedrock characteristics can vary within a landtype but occur in a predictable pattern; thus, differences are reflected in the overall slope hydrology.

The last basic criterion that describes the landtype is vegetative habitat type (13). This also indicates basic slope hydrology by expressing relative soil moisture regimes over the slope throughout the year. Vegetative habitat types are used to define soil mantle stability through correlation with vegetative cover and vegetative recovery potential.

Delineation and Description of Landtypes

The actual landtype delineation process requires, first, delineation by landform, which is a morphological descriptor. Landform is described by slope shapes, slope length, slope gradient, etc., and landtypes are classified and mapped by aerial photograph interpretation. Field traverses that cross representative areas of each mapping unit are then taken to provide detailed site information. Patterns of landform, soils and vegetative habitat types, and general parent material characteristics are described and extrapolated over the mapped areas. The mapping units are then transferred from the aerial photographs to 1:24 000 scale topographic maps. A final, detailed landtype description is developed for each unique mapped unit and includes a general description and setting, physical landform characteristics, slope hydrologic properties, parent material, soil, and vegetation characteristics.

Landtype Erosion Hazards

Interpretations of the hazards for various kinds of erosion, including rotational mass wasting, debris avalanche, and overland flow erosion, are made for each landtype in order to define the relative sediment production potential for each area of land. Ratings for each attribute are classified relatively from very low (class 1) to very high (class 5).

Rotational Mass Wasting Hazard

Rotational mass wasting is defined as movement that occurs along internal slip surfaces (usually concave and upward) with backward tilting common. Movement is usually deep seated in response to increased subsurface water concentrations in the vicinity of the slide plane (14). Hard bedrock surfaces do not constitute the slippage plane. Criteria used in evaluating the hazard are incidence of subsurface water concentration, mantle depth, soil and bedrock characteristics, and evidence of past rotational failures. These factors are interrelated, but they are discussed individually.

Slope hydrologic characteristics describe an incidence of subsurface water concentration. Factors considered are slope shape, slope gradient, drainage density, lower-order stream characteristics, and mantle drainage characteristics. Areas with a high incidence of subsurface water concentration include stream headlands with convex-shaped slopes that change to concave shapes where large numbers of first-order streams originate. Also, subsurface water concentrates in deep-mantled, weakly dissected, over-steepened slopes (streambreaks) where almost all slope drainage is subsurface, which causes water concentrations in middle and lower slopes. An example of an area with a low incidence of subsurface water concentration would be low relief lands with a well-developed, high-density, dendritic drainage pattern.

Soil cohesive strength of the mantle also affects rotational mass wasting potential. This is evaluated by using pertinent soil and geologic characteristics such as type of bedrock and soil textural properties. For example, sandy soils developed from quartzites with large percentages of coarse fragments have much lower cohesion strength than silt loam and silty clay loam soils developed from micaceous shists.

Debris Avalanche Hazard

Debris avalanches are defined as rapid and usually sudden sliding of usually cohesionless mixtures of soil and rock material that range in depth from several inches to 4-5 ft (14). Criteria used to assess the hazard are slope gradient, slope shape, aspect, surface soil creep hazard class, and evidence of past debris avalanches such as slide scars, talus slopes, and colluvial cones or fans at the toe of the slopes.

Debris avalanches are most common on steep, concave slopes with soils susceptible to surface creep. On the Clearwater National Forest, most debris avalanches occur when the heads of draws are overloaded with sediment eroded from adjoining slopes through dry surface creep. The occurrence of a large, high-intensity hydrologic event (often rain on snow) triggers the debris avalanche.

Surface creep is the gravitational movement of solid particles dislodged by various processes such as raindrop splash, wind, frost action, and animal movement. Criteria used to assess surface creep are slope gradient, aspect, soil cohesion and coefficient of friction, soil particle size, and vegetative cover potential. Surface creep is a gravity process; therefore, slope gradient is a dominant factor. Aspect influences the frequency of freeze-thaw cycles that occur during the spring. Soil cohesion and particle size refer to surface soil properties. Loose, noncohesive soils with large particle sizes are much more susceptible to gravity movement than fine-grained cohesive soils. Vegetative cover greatly reduces surface creep by reducing surface temperature fluctuations and protecting the soil surface from particle movement.

Overland Flow Erosion Hazard

Overland flow erosion refers to erosion caused by tractive forces developed by water running over undisturbed natural surfaces bared of vegetation. This erosion occurs as sheet erosion and rilling. Factors used to rate surface erosion hazard are based on the detachability of soil particles and the potential for occurrence of overland flow and are very similar to those used for rotational mass wasting: slope shape and slope gradient, mantle depth, and soil particle detachability. Raindrop splash or overland flow is required to detach and move particles. Slopes that concentrate water have the greatest potential for overland flow (for example, steep concave slopes that concentrate runoff from a larger area into a smaller area). Landforms that exhibit this property include breaklands, stream headlands, and glacial cirque basins. Broad convex ridges have a lower potential for overland flow because runoff is dispersed over the slope.

Thin soil mantles are more likely to have overland flow than thick soil mantles that occur on similar slopes because of more limited water storage capacity. Soil particle detachability is a function of the apparent cohesion of individual soil particles within the soil matrix. For example, coarse-textured, single-grain soils are more susceptible to particle detachment than cohesive soils with strong structures.

Slope Delivery Efficiency

On-site erosion is only manifest at downstream locations as sediment if the eroded material is delivered to the stream. Thus, the ability of a given landscape to deliver sediment downslope (termed slope delivery efficiency) is an important concern. Specifically, slope delivery efficiency describes rates at which water and sediment are transported from different slopes to the water system, including ephemeral draws. Slope delivery efficiency defines the role the landtype plays in sediment production in a watershed and refers to the ratio of sediment delivered into the water system over a 5- to 10-year period.

Slope delivery efficiency for mass erosion is based on data that quantify downslope delivery of landslide material collected on more than 600 landslides on the Clearwater National Forest (15). Slope characteristics used to interpret slope delivery for each landtype are slope gradient, slope shape, slope dissection density, and internal relief. Ratings for slope delivery efficiency are made similar to erosion hazard ratings that range from very low (class 1) to very high (class 5).

SEDIMENT PREDICTION FROM FOREST MANAGEMENT PRACTICES

The hazard ratings derived for each landtype provide the basis for quantification of sediment yields from watersheds in both the undisturbed state and following alternative kinds of land use practices. The simulation technique generates probable sediment rates caused by accelerated mass erosion on each landtype from roading, logging, or fire. It also generates sediment caused by induced surface erosion from road prisms, logging, or fire. A natural sediment rate is generated to interpret the magnitude of effects with respect to a specific watershed system and its water resource values.

Basic assumptions involved in the sediment prediction process include the following:

1. Sediment yields can be simulated and used as expected annual volumes per unit area of the system routed to the mouth of the system.
2. Natural sediment yields are generated by in-channel erosion of banks and stored sediment in beds. This material is supplied principally by long-term mass movement (slumps and slides; debris avalanches, flows, and torrents; and creep) and, to a lesser degree, by natural surface erosion that is a function of catastrophic wildfires.
3. Mass erosion and surface erosion can be treated as separate processes, although in fact they are often interactive and interelated. Essentially, mass erosion is assumed to be accelerated by management activities, while surface erosion from wildfires, roads, and logging is induced or created by activities. The erosion products are delivered to the channel system by distinctly different processes: mass erosion is a colluvial or gravity process while surface erosion is moved principally by flowing water. Many of the same landtype properties are used to determine delivery efficiency for the two types of erosion processes, but the influence of those properties is different.

Natural Sediment Rate

The natural sediment rates, expressed as tons per square mile of watershed area per year, are derived from a composite on-site erosion hazard based on a weighted average of the individual on-site erosion hazards developed for each landtype. The composite on-site erosion hazard is calculated as follows:

$$\text{Composite on-site erosion hazard} = (0.4 \times \text{rotational mass wasting hazard}) + (0.4 \times \text{debris avalanche hazard}) + (0.2 \times \text{overland flow erosion hazard}) \quad (1)$$

The weighting factors are based on the fact that most natural sediment production on the Clearwater National Forest is caused by mass erosion that feeds material directly to stream channels. However, some overland flow erosion occurs following natural wildfires. Megahan and Molitor (16) found a total of 700 tons/mile^2 of soil loss from surface erosion after a wildfire on landscapes similar to those on the Clearwater National Forest. Soil losses were highest immediately after the burn and decreased to zero within five years in response to vegetative regrowth. The average wildfire frequency for vegetative types on the Clearwater National Forest is estimated to be about 140 years (17). Based on a wildfire erosion rate of 700 tons/mile^2 in 5 years and a fire frequency of 140 years, the average overland flow erosion from natural wildfire over a fire cycle is 5 tons/mile^2/year. Megahan (18) reported an average annual sediment yield of 25 tons/mile^2/year for undisturbed drainages similar to those on the Clearwater National Forest. About 5 tons/mile^2/year or 20 percent of this is caused by long-term surface erosion from fire on the Clearwater National Forest. The remaining 80 percent is divided about equally between rotational mass wasting and debris avalanche, hence the weighting factors of 0.4 for rotational mass wasting and debris avalanche and 0.2 for surface erosion.

Watersheds with landtypes similar to those on the Clearwater National Forest have been shown to yield average annual sediment volumes that range from about 10 to 100 tons/mile^2/year (18,19). Values within this range were assigned to each landtype identified on the forest based on the landtype's relative composite on-site erosion hazard. Each landtype's contribution is summed and weighted by area to account for potential sediment from all the lands in the watershed system.

This value provides an estimate of the total potential sediment for basins of similar size to the basins where the original data were collected. These study basins ranged from 0.15 to 2.5 mile^2 in size and averaged about 1.0 mile^2 (18). In order to estimate sediment yields for larger basins, it is necessary to correct for losses caused by channel storage. This is done by multiplying by a channel routing coefficient. The coefficient (C) is obtained from a relation developed by Roehl (20) by using a water shed area (A) in square miles. Roehl's original relation is adjusted to provide a coefficient of 1.0 at 1 mile^2 as follows:

$$C = A^{-0.18} \quad (2)$$

The procedure to estimate natural sediment yields from composite erosion hazard used on the Clearwater National Forest is adapted from a general procedure in use by the Forest Service, U.S. Department of Agriculture, in the northern Rocky Mountains (21).

Sediment from Accelerated Mass Erosion

The basic premise for quantifying sediment from mass erosion processes is that management activities accelerate natural mass erosion potential. The amount of increase is based on the landtype mass erosion hazard rating developed by using the rotational mass hazard, the debris avalanche hazard, and the slope delivery efficiency determined for a landtype, as follows:

$$\text{Landtype mass erosion hazard} = (\text{rotational mass wasting hazard}) + (\text{debris avalanche hazard}) \times (\text{slope delivery efficiency}) \quad (3)$$

Acceleration factors derived from studies in the Idaho Batholith (15) and modified by work on the Clearwater National Forest (22) are used to predict the increased risk of mass erosion due to roading, logging, or fire as a function of parent material and time after disturbance. The sediment from accelerated mass erosion is simply the landtype mass erosion hazard multiplied by the applicable acceleration factor, the area of the disturbance, and a coefficient to account for mitigation measures for roads and logging or fire intensity. The following illustrates the relation used for roads; similar relations are used for fire and logging:

Increased sediment = 20 x (landtype mass erosion hazard) x (road acceleration factor) x (area disturbed by road) x (mitigation) - 20 (4)

Sediment from Surface Erosion

Sediment derived from surface erosion is similated as an independent process with respect to mass erosion. The basic premise here is that roads, logging, and fire create, rather than accelerate, surface erosion. The methodology was developed by the Forest Service interregional task force and is documented in their report (21).

Surface erosion rates are assigned for each type of land disturbance activity, including road construction, logging, and wildfire. Assigned erosion rates are defined for each kind of disturbance and modified as needed if the disturbance is not in keeping with the definition. For example, the erosion rate for roads is based on the "basic road", which assumes a road with a 16-ft subgrade width, no surfacing, balanced construction, and no ditch.

Erosion rates are modified as the road deviates from this standard. Likewise, erosion rates are modified to account for differences in logging practices and wildfire intensity. Erosion rates also vary by landtype, elapsed time since disturbance (in years), and mitigation measures designed to reduce road erosion. Data for this effort come primarily from research conducted in Idaho (15,16, 18,23,24) supplemented by data from the West Coast (25-27). Erosion rates are in terms of tons per unit area of disturbance; therefore, the rates are multiplied by disturbed area to get total erosion for each landtype.

As with mass erosion, all soil losses caused by surface erosion are not delivered to streams because of enroute storage. A modification of a procedure developed by the Forest Service (21) is used to estimate delivery of surface-eroded material. Three variables are used to determine delivery:

1. Slope shape determines the ability to produce water for movement of sediment in the channel efficiently,
2. Slope gradient defines energy availability, and
3. Stream density represents slope length and proximity of the erosion source to the water system.

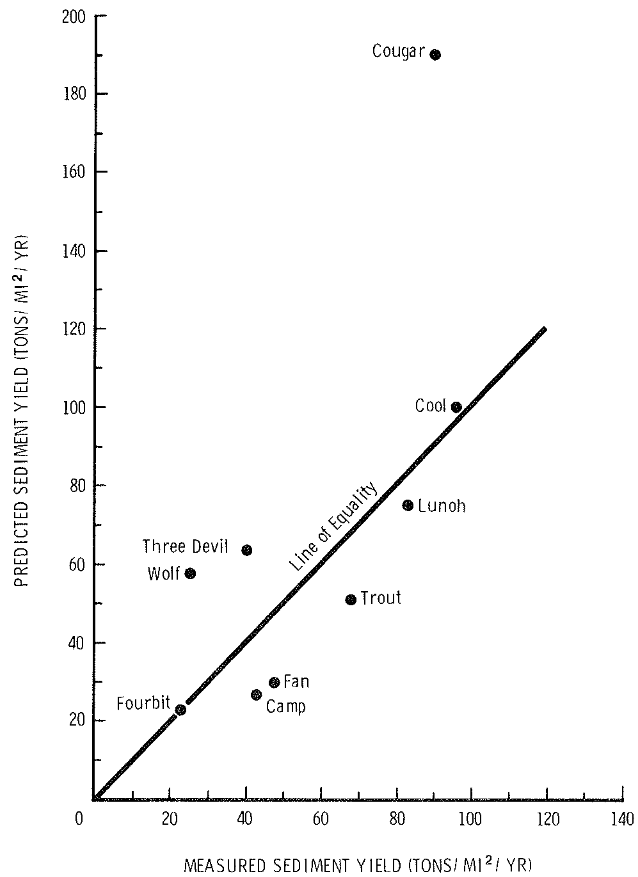
The relation used to predict surface erosion from roads is shown below; similar relations are used for fire and logging:

Increased sediment from road prism = (road base rate) x (mitigation) x (parent material erosion hazard) x (area disturbed by road) x (landtype slope delivery efficiency) (5)

PREDICTED VERSUS ACTUAL SEDIMENT YIELDS

The sediment yield prediction procedure is designed to provide average annual sediment for both natural and disturbed watersheds. This level of precision is analogous to the average annual sheet and rill erosion predictions for agricultural lands provided by the universal soil loss equation (4). In both cases, predictions for a specific year can be considerably different than actual, simply because of deviations in climatic conditions from the average.

Figure 1. Predicted versus measured average annual sediment yield.



Comparisons between actual and predicted values must be made for the average of a number of years of data to be valid.

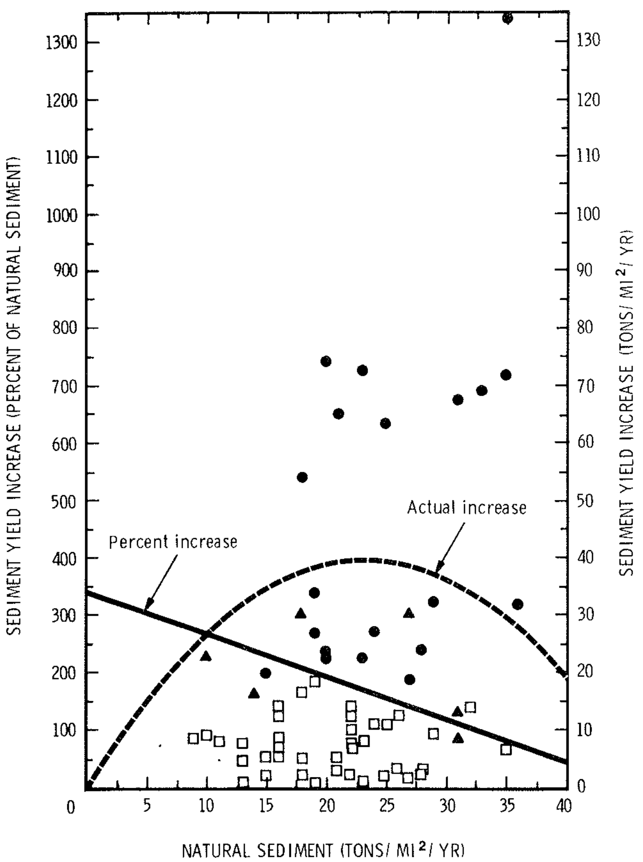
We do have relatively long-term sediment yield data for nine watersheds on the Clearwater National Forest that can be used for comparison purposes. Data consist of suspended and bed-load samples collected at irregular intervals during the year. Each annual data set ranged from about 10 to 16 samples. Individual sediment samples were prorated by time between samples to estimate annual sediment yields. A total of from six or seven years of sediment yield data are available for each watershed.

The actual versus predicted average annual sediment yields are shown in Figure 1. Most streams show relatively close agreement with little bias except Cougar Creek, where predicted values exceed actual by about 100 tons/mile²/year. The Cougar Creek drainage contains many old roads that did not exhibit as much mass erosion as was predicted. On-the-ground inspection indicated that mitigation measures had been applied at a number of high erosion hazard situations but had not been accounted for in the prediction process. Although this comparison hardly provides a validation of the sediment estimation procedures, it does suggest that the estimates are reasonable in most cases.

CHANNEL EQUILIBRIUM

Predictions of annual sediment yields provide a convenient means for comparing watersheds and for comparing the effects of alternative land management practices over time. However, predicted sediment yields do not, in themselves, provide a means to

Figure 2. Sediment yield increase versus natural undisturbed sediment yield.



evaluate changes in channel conditions. Most streams in mountain lands in the western United States are supply limited (28). This means that more energy is available for sediment transport than there is sediment. Consequently, streams are characterized by coarse-textured beds commonly with rubble and boulder-sized materials dominating. There is limited bar development in such streams and bed forms consist primarily of nondescript accumulations of gravel and rubble materials that form the riffle and run areas found in such streams. Stream channels tend to maintain this characteristic appearance with increasing sediment loads for as long as the system is supply limited. However, eventually, sediment yields are accelerated to the point that sediment supply begins to approach transport capability. When this happens, finer bed materials begin to accumulate, as evidenced by accumulated sand particles between the coarser bed materials, development of bars, and other bed forms. Continued acceleration of sediment yields aggrades the bed further and may induce increased bank cutting, altered flow patterns, and major changes in bed forms such as formation of sand dunes, etc. Change in channel conditions are no doubt reflected in the health of the aquatic ecosystem as well.

Analyses of annual sediment yields have been made for a total of 65 watersheds on the Clearwater National Forest for both natural (undisturbed) and disturbed watershed conditions. Predictions for disturbed conditions were made by using the kinds and timing of disturbances that actually occur on each watershed. Values for the predicted maximum increase in annual sediment yield (expressed as a percentage of natural) were then plotted against the natural sediment yield (Figure 2). Channels at the mouth of each watershed were then subjectively evaluated for evidence of loss of equilibrium. Criteria used included accelerated deposition of bed materials (e.g., sand bars, dune bed forms, sand terraces along banks), loss of channel capacity (e.g., bank cutting, channel braiding), and change in substrate particle-size distribution (e.g., sand accumulations that surround gravel, rubble, and boulder material).

Each watershed represented by a point in Figure 2 was classified according to whether it was definitely out of equilibrium (solid circles), at or near equilibrium (solid triangles), or within equilibrium (open squares). An obvious grouping of data is apparent in this figure. The line shown represents the approximate envelope curve for channel equilibrium: Sediment supply exceeds available energy for watersheds above the line, whereas available energy exceeds sediment supply for watersheds below the line.

This curve provides a geomorphic basis for defining response levels of sediment increases in watersheds. Interestingly, the line is not horizontal but rather indicates that larger percentage increases in sediment can occur for watersheds with low natural sediment yields as compared with high sediment yield watersheds. This relation is clarified when the percentage changes in sediment are expressed in absolute units of tons per square mile per year (dashed curve on Figure 2). On this basis, maximum increases in sediment production can occur on watersheds where natural sediment yields equal about 20-25 tons/mile²/year. Apparently, watersheds with natural sediment yields greater than this can stand progressively less sediment increases because they are progressively nearer to equilibrium in the natural state. In contrast, watersheds with natural sediment yields less than 20-25 tons/mile²/year can stand progressively less increases in sediment because they are less capable of cleaning themselves due to limited transport energy.

PROCEDURE APPLICATIONS

These procedures make it possible to test the results of alternative land use practices on erosion, sediment yield, and channel equilibrium conditions. Erosion and sediment yield estimates are an important concern because they provide an index of potential effects on both on-site vegetation productivity and damage to downstream developments, respectively. Likewise, estimates of changes in channel equilibrium are useful because they provide an index of change to the aquatic ecosystem. By varying the kinds of practices, the time sequence of application of practices, and the various kinds of mitigation measures, we can define a mix of activities that optimizes land use benefits without causing large environmental alterations. The primary application is for project-level planning of forest management practices in a watershed system. It is an excellent tool for developing and comparing alternatives, identifying trends and recovery, scheduling activities, and recognizing potentially damaging situations.

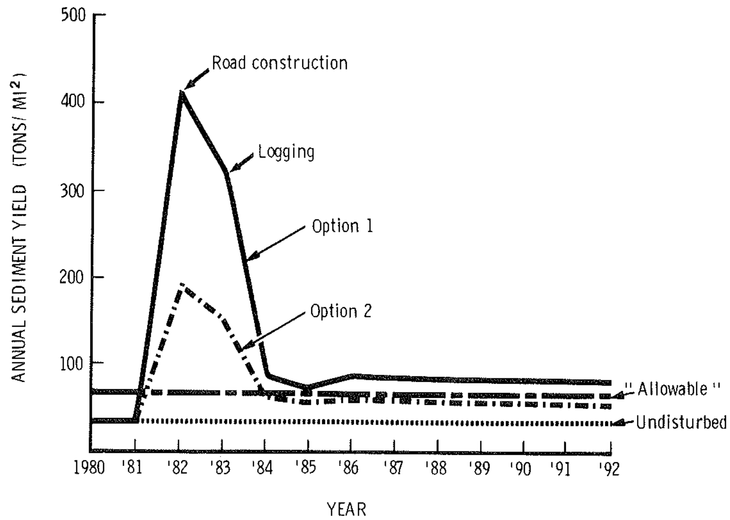
Example of Model Application

A simplified example of the application of the analysis procedures has been developed by using a representative watershed situation and landtypes found on the Clearwater National Forest. The 1000-acre watershed was developed on an old erosion surface by downcutting of the major drainage system in the area. Elevations range from 4000 to 4900 ft, and the bedrock on the watershed is granitic. Five

Table 1. Nature and amount of disturbance by landtypes for alternative timber harvest access routes.

Option	Road Length (miles)	Road Subgrade Width (ft)	Side Slope (%)	Calculated Area Disturbed by Road or Cutting Unit Area (acres)	Landtype	Type of Road Prism
1	1.0	15	25	2.4	22-G03	Balanced
	1.0	15	25	2.4	22-G03	Balanced
	0.5	15	70	1.4	61-G08	Full bench
	1.0	15	50	4.1	60-G11	Balanced
				100	22-G03	
				125	22-G03	
2	1.5	15	25	3.7	22-G03	Balanced
	1.0	15	25	2.4	22-G03	Balanced
	1.0	15	40	3.2	32-G02	Balanced
				100	22-G03	
				125	22-G03	

Figure 3. Percentage change in sediment yields for alternative road and logging practices.



different landtypes are found on the watershed.

Two options are considered in this example. Both required 3.5 miles of road construction in 1982 and logging of 225 acres of timber by using clearcutting and tractor skidding in 1983. Option 1 requires accessing the area from the bottom of the watershed and crossing the steep, high erosion hazard breaklands. Option 2 provides access from the top of the watershed and crosses the lower erosion hazard terrain. The amount and type of disturbances by landtypes are given in Table 1.

The example data were analyzed for a 10-year period following disturbance (Figure 3). The time dependence of the sediment responses is apparent. Sediment yields increase in 1981 in response to road construction. Rates decrease in 1982; however, the rate of decrease is reduced somewhat because of the logging activities. Additional decreases in sediment yield occur over time but not back to predisturbance levels because of long-term accelerated erosion on roadcuts.

According to Figure 3, increases in annual sediment yields up to about 90 percent over natural will not cause apparent channel deposition. Option 2 is clearly preferred to option 1 in terms of total increase in sediment production and duration of effects. However, other considerations may be important, depending on the nature of the uses elsewhere, the value of the water resource, and the juxtaposition of the example watershed over time and space with other watersheds in the area.

Application Elsewhere

This procedure is empirical and, as such, has limited application elsewhere. However, we feel that the principles involved can be extrapolated anywhere. An analysis procedure of this type can be designed in areas with minimal local erosion and sedimentation data by using basic principles to define relative erosion hazard ratings. These evaluations can then be used to design erosion and sediment monitoring programs that serve to update the prediction procedure. Basic requirements for implementing the watershed analysis system are as follows:

1. The dominant landforming and erosional processes of an area must be recognized,
2. The relative role of processes must be understood,
3. Landtypes or land stratification units must be designed to rate the dominant erosion processes,
4. Landtypes or land stratification units must be designed by using criteria essential to making slope delivery efficiency interpretations, and
5. The watershed system must be supply limited in the natural state.

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Pedotechnical Aspects of Terrain Analysis

GILBERT WILSON, DAVID E. MOON, AND DONALD E. McCORMACK

Terrain analysis is defined as part of the process through which terrain is evaluated for specific land uses. The example used in this paper concerns the environmental impacts of constructing low-volume roads on steep slopes in forest areas. The basic source of data for the terrain-mapping system described is the standard soil survey, which is already well established in most countries of the world. The paper describes interrelations between principles of pedological mapping and geotechnical analysis of slope stability. A soil survey map and its application to man-created slope failures (shallow translational and rotational failures) in British Columbia is used for illustration of the techniques involved. By analyses carried out in the field, the process of terrain analysis is used to extend and better communicate soil survey data to engineering problems.

Terrain analysis is generally defined as part of the process through which the terrain is evaluated for specific land uses or for solution of specific terrain problems. Because the process is analytical, the particular land use or terrain problem must be defined specifically enough so that the kind and detail of the data needed may be determined. Because the problems usually concern very large areas rather than specific sites, the information base is typically generalized and not site specific. The mapping system used may be any orderly, relevant terrain-mapping system. The mapping may vary from reconnaissance to detailed, depending on the nature of the problem to be solved. The results of the terrain mapping and the terrain analysis may be used along with other data to solve the land use problem.

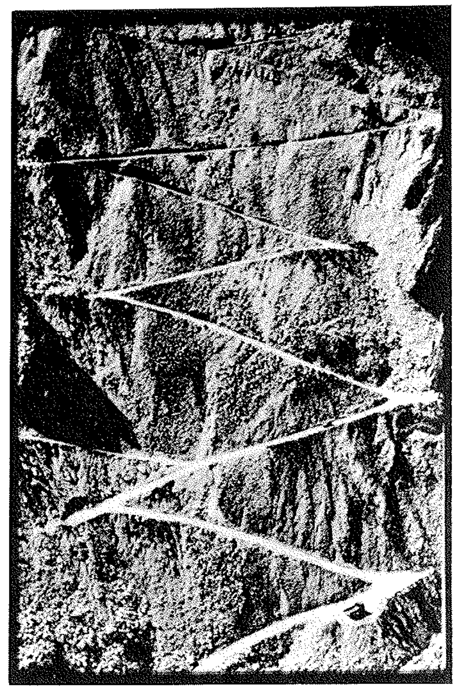
SPECIFIC TERRAIN PROBLEM

The specific terrain problem used here as an example concerns slope stability associated with low-volume roads in mountainous territory. Such roads may include forest or mining-industry access roads that are not necessarily part of any provincial or national system. For this type of road, funds are commonly insufficient for detailed geotechnical investigations, especially considering the complex nature of the problems. The immensity of some of the slope stability problems is illustrated in Figure 1. Many of these roads are not accessible to the general public. The casual visitor may wonder how roads could ever be built on such steep slopes, but engineers have been building them quite successfully for many years. The problem today, however, is that the engineer can no longer assure success by providing an adequate roadbed. The ecological impacts of siltation in mountain streams and other water bodies as a consequence of road construction are well documented (1,2). It is now standard practice to submit environmental impact statements before road construction proceeds.

In many instances, however, ecological disasters due to slope failure precipitated by road construction still occur, despite comprehensive and well-written impact statements. Thus, communication problems must exist. Perhaps their existence is understandable, since quite different interests and different disciplines are involved. In environmental assessment there commonly are engineers, ecologists, the general public, and perhaps even politicians involved.

The viewpoints of two of these groups can be compared by using the analogy of the pendulum. Ecologists, as a group, seem to consider the stability of steep slopes as an inverted pendulum (unstable equilibrium): Any imposed stress may precipitate a catastrophic collapse. The term "inherently unstable" is often used (3). Planning and design engineers in offices remote from the field of activity may be led to think of a very brittle type of stability when they read some ecological reports. In contrast, field engineers actually working at these slopes may use the simple pendulum analogy: Imposed stresses less than the ultimate strength of the soil can be taken up by nature, the result being simply a deflection of which the magnitude and direction are proportional to the imposed stress.

Figure 1. Access roads in mountainous terrain.



Conceptual differences are not only between disciplines, but they are also within disciplines. The term "slope misbehavior" is used by engineers (4,5) who suggest that the engineering technology of slopes has grown exponentially in recent times, but unfortunately the proper use of this knowledge has only grown linearly, if at all. The technology is often available, but the majority of problems result from failure to recognize the need for it or apply it properly.

The objective of the particular type of terrain analysis described in this paper is to provide a framework by which soil surveys can be better and more effectively used--in this particular case, to reduce the ecological impact of access road construction in mountainous areas. It is not to be used to provide a framework for designing the actual control or mitigation of environmental problems but rather to supplement the existing information base (6). It is not to further develop the geotechnics of slopes but rather to better communicate the evidence revealed by completed soil surveys as to whether ecological impacts are likely, where they might occur, what type they might be, and what might be done to reduce them.

TERRAIN-MAPPING SYSTEM

The soil surveys used are based on pedological concepts. The basic concepts of pedology, which originated in the late 1800s in Russia, centered on the notion that it is possible to understand, classify, and map the complex interactions in nature by studying the soil. The soil was viewed as the logical result of natural processes acting on the parent rock over a period of time (7). A basis was established not only for understanding past events that have shaped the land as we see it today but also for speculating about future events, including consequences of human intervention.

Details of soil surveying have evolved over the years to meet current needs; the basic concepts have not been changed. The preparation of soil surveys requires extensive field study to develop a model that depicts the soils on the landscape. The model is a projection or forecast of the nature of the soil, and attendant natural processes, in each part of the landscape. Field observations are made to verify or revise these forecasts and to document the performance of soils. The resulting soil survey is, in effect, a summary of such observations, verifications, and revisions. Detailed soil surveys, mostly at scales of 1:15 840 to 1:24 000, have been completed for only 1 percent of the land in Canada compared with 70 percent of the land in the United States.

The frequency of field observations and the confidence levels or reliability of the information presented should be understood by users of soil surveys (8). Although dominant soils are indicated for all areas, the scale of mapping dictates the minimum size of delineations, and small areas of different or contrasting soils may be included. The occurrence of small bodies of a contrasting soil too small to be delineated may be accurately forecast by recognizing contrasting landforms, vegetation, or other factors. Special spot symbols are sometimes used to show the location of these included soils. The descriptions of soil map units indicate the nature and extent of such inclusions and any unique features, such as landscape positions or vegetation, that would help locate them.

The soil surveys used in the example given are part of a national inventory program and are not necessarily done on behalf of either the forestry or mining industry or exclusively for any of the regulatory bodies. However, their use by these bodies is quite valid, provided that they are supplemented by a minimum amount of additional information. The additional information needed is the terrain analysis information.

TERRAIN ANALYSIS

Pedotechnical Approach

In quantitative pedology, Jenny (7) has indicated that any pedological soil property (s) can be shown to be a function of the soil-forming factors, such as climate (C), organisms (O), relief or topographic position (R), and time (T), which have acted on the parent material (P) to produce that soil; i.e.,

$$s = f(C + O + R + T + P) \tag{1}$$

By quantitatively analyzing each of these factors in turn, a theoretical solution to a soil problem may be identified. Alternatively, by comparing the soil properties of the problem soil with known soils, on which specific soil stability measurements have been documented, an empirical solution may be obtained. The pedological map shows the distribution of these known soils, and the agriculturalist or the engineer has in this map a useful tool. In the pedological concept, whereas the classification scheme embraces collectively all the five soil-forming factors, identical soils may be grouped together and their behavior thus rendered predictable.

The expression given also provides a link with engineering and other earth sciences. In geotechnical engineering, a slope may be analyzed theoretically, assuming homogeneity of materials within a delineated slope or layer by defining theoretical solutions, and then by sampling the soil to determine quantitatively each of the properties and other factors involved in the slope analysis. As the process develops, more and more complex slopes can be analyzed. But when the ground conditions are too complex for analysis, engineers then resort to the empirical method of observation (9). The two disciplines of pedology and engineering can thus be related through the pedological concept and the engineering method of observation. Information provided by the soil survey map can then be interpreted in behavioral engineering terms from observation and the map used to advantage for a variety of purposes.

However, as the purpose changes, so does the relative significance of each of the factors that describe identical soils. From a geotechnical viewpoint, this altered emphasis may be used to define pedotechnique (10). For geotechnical purposes, the consideration and evaluation of soil behavior in soil survey procedures may be far from complete (11). In addition to soil-forming factors, soil behavioral factors should also be considered, and the relation between actual slope failures and unique kinds of soils should be observed and documented. The intent, however, is not to convert pedological maps into geotechnical maps or to revamp established pedological mapping techniques but to show how the information on a pedological map can be used and interpreted. This is quite a different approach from that commonly used in solving engineering problems; the geotechnical approach would probably result in entirely different map units to focus on the central problem. Such a focus is not the intent of the pedotechnical approach at all. The pedotechnical approach aims at full interpretation of information available in the existing pedological map for a multiplicity of potential land uses.

Geotechnical Connection

The first step toward developing a common viewpoint to the question of slopes and their stability (on the basis of strength of soil material) may be to examine the pendulum analogies already stated from the standpoint of the infinite slope concept (12, 13). In this concept, a slope is infinite if the depth to the potential failure plane is very small compared with the length of the slope. Although the soil may be stratified, the slope could be considered infinite if the soil layers or horizons are parallel to the slope and analysis made, assuming that a vertical column of soil is typical of the entire slope.

The infinite slope condition could be assumed to occupy a significant portion of the landscape and, as such, it is mappable in pedologic terms. For the geotechnical approach of starting with a simple model amenable to static analysis, a mine waste dump composed of relatively homogeneous materials could be an ideal starting point. The slopes of the mine waste dump (Figure 2) might resemble those of scree slopes, which are well-known features of mountain landscapes. Some simple questions may be asked with regard to such slopes. As the rock is dumped at the top of the waste pile, what happens? Does the rock run down the slope? Why is it that the slopes are everywhere identical? If a road was constructed across such a slope, what type of ecological consequences could result?

Figure 3 illustrates (in terms of an engineering analysis) that if a structure (A) exerts a stress in the downhill direction, it will begin to cause failure of the slope when the imposed stress (f) plus the active lateral earth stress (a) acting behind the structure equals the passive lateral earth stress (p) acting in front of it. At failure it could be stated that

$$f = p - a \tag{2}$$

or, if the imposed stress was zero, the factor of safety (F) of the slope could be considered to be

$$F = p/a \tag{3}$$

The magnitude of the lateral earth stresses on sloping ground for a retaining wall design can be determined by the Mohr diagram (13). The failure envelope (Figure 4), which is defined by the ultimate friction angle, determines the maximum active (Aa) and passive (Ap) stress circles, which meet at the common point defined by the vertical stress (Av) at the depths (A) considered. For horizontal ground, the common point of the circles (Av) is on the abscissa and, since the maximum passive stresses greatly exceed the maximum active stresses, the factor of safety is high. For sloping ground, however, the common point changes, somewhat increasing active stresses and decreasing passive resistance.

Besides illustrating the ratio of active to passive stresses, the same diagram also gives the direction of the failure plane; this is represented by a line drawn from the maximum stress point to the intersection between the failure envelope and the appropriate circle. The active stress angle is thus steeper than the passive stress angle.

Taylor's original diagram, which was for a retaining wall design, has been extended here to examine slope failure of infinite slopes. At progressively steeper ground-slope angles, an ultimate condition is reached; that is, at a ground slope equal to that of the failure envelope, there is only one lateral stress circle: The active stresses that act downhill are equal to the passive stresses that resist the movement. In addition, the difference in the angles of the failure planes gradually decreases until, at the ultimate condition, the failure planes are all parallel to the ground surface.

The implication of this concept is that, if the factor of safety of the slope is taken as the ratio of the passive to the active stresses, it can never drop below 1 (unity). The ultimate state of the slope, therefore, is one of balance rather than imbalance. The reason why the slope of the mine dump is so regular, despite variations in the size and types of rock on it, and what happens to the load of rock after it is dumped at the top of the slope can also be surmised. The rocks do not tumble down the slope; the whole slope simply readjusts. The slope surface itself is the failure plane, and the angle of the slope is an average inclination of the failure surface for the entire slope--hence its very consistent value.

Because the slope surface is the failure plane, a roadbed built on the surface would not be stable; the standard practice must entail excavation into the slope to obtain a stable roadbed. Failures in the backslope of such excavations would inevitably result. These failures would progress eventually to the top of the slope.

Analyzing Terrain

The rock slope example is for better understanding of certain aspects of the landscape for pedotechnical interpretation purposes. For natural landscapes, the vegetation (O) also contributes to slope

Figure 2. Limiting slopes of rock waste pile.

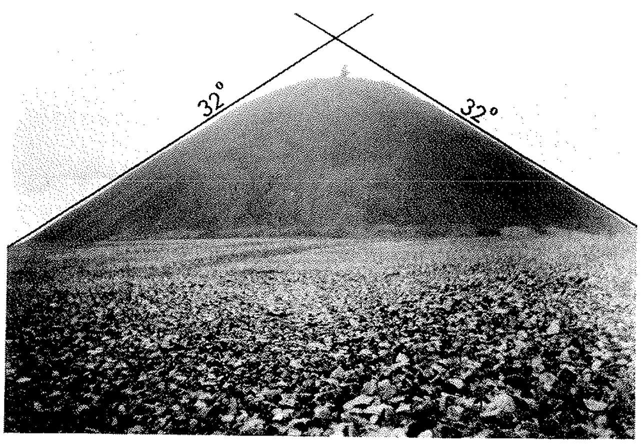


Figure 3. Earth stresses on slopes.

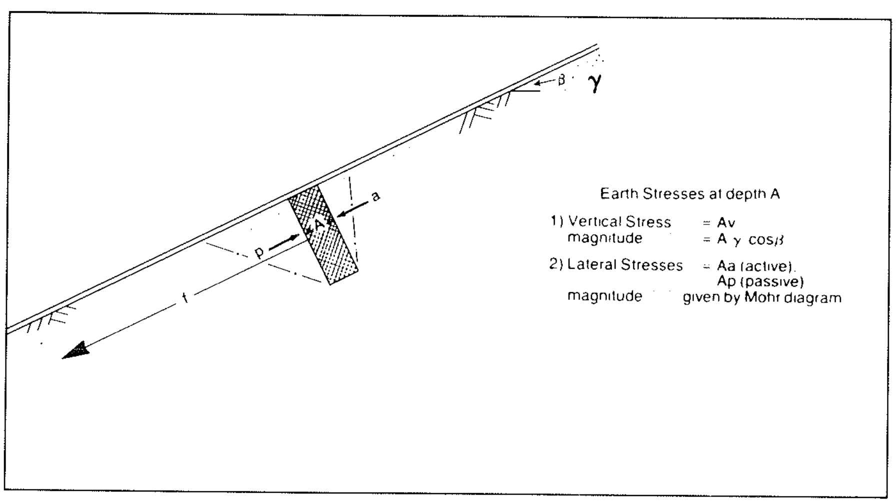
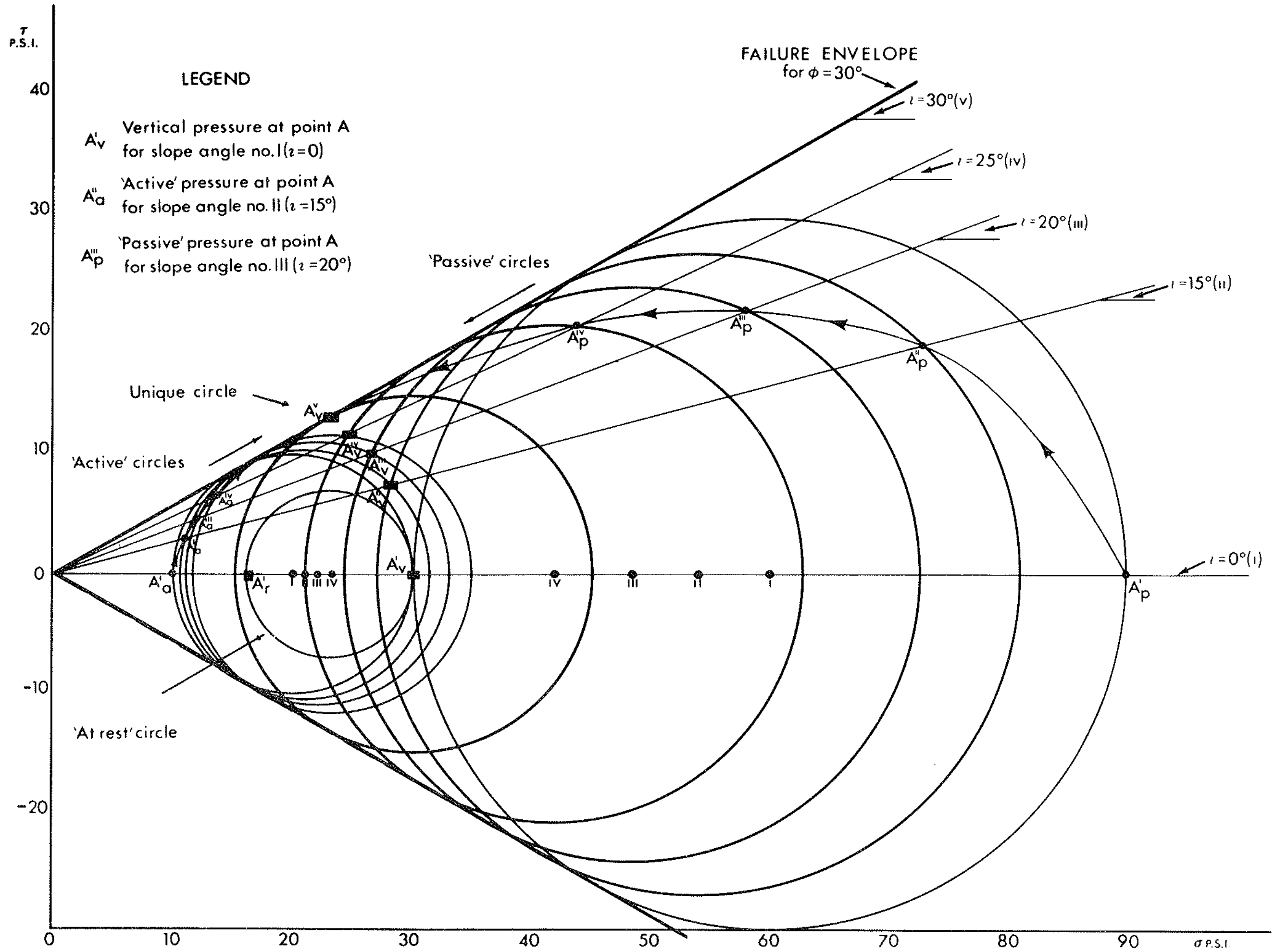


Figure 4. Mohr circles for sloping ground.



development. By combining the pedological concept and the geotechnical method of observation to the development of natural slopes, Equation 1 may be reduced to the following form:

$$LS = f(P + O) \quad (4)$$

where LS refers to the limiting slope of landscapes defined by the soil parent material (P) and the vegetation (O). This would be for given soil age (T), soil climatic conditions (C), and shape of slopes (R).

Geotechnical analyses of the type illustrated indicate that, for nonvegetated slopes like the mine dump or for forested slopes on deep frictional soils where the friction angle increases with depth, Equation 4 reduces to

$$LS = f(P) = f(\phi') \quad (5)$$

where ϕ' represents the average effective shearing resistance of the parent material on infinite slopes and the vegetation is no longer a variable.

Observations of the slopes of the mine dump provide an example of the use of Equation 5. The maximum slopes were found to be 32°, and this is the limiting slope (LS) of a landscape so defined. Road excavations into such slopes would result in progressive failure of the backslope, which would have to be retained to mitigate this type of hazard. This slope angle also provides a practical value of the effective shearing resistance of the rockfill at the site conditions that prevail on the natural slope.

For the natural forested landscapes in this area, two different types of LS were generally observed. For example, the well-drained sandy fluvioglacial terraces had characteristic maximum natural slopes of 35°; but the "side-cast" materials, which result from failure of the backslopes of road excavations, had LSs of 32°. Because of this, these forested slopes had often been termed oversteepened, and the additional strength of the tree roots accounted for the steeper 35° slopes. For certain slopes this may be the case, but not for these deep frictional soils. Equation 5 would indicate that 35° is the effective shearing resistance of the well-drained undisturbed parent material, whereas 32° is the value for the same parent material but in the looser disturbed conditions after side casting. As a consequence, it could instead be concluded that deforestation may not necessarily result in generalized mass movement as the tree roots decay. Such decay is said to occur within five years of clearing (14). Ecological impacts of such road construction might only be localized and could possibly be mitigated by providing minimal backslope retention.

The observational method may be extended for pedotechnical purposes even beyond the concepts of infinite slopes. In soils with both friction and cohesion, rotational failures can occur, and these, by nature, depend on the particular geometry of the site. Pedological mapping units are not site-specific entities and normally are not directly applicable to site-specific problems. However, by including the geometrical factors (including LS) within the soil survey interpretation, the method of observation can also apply to rotational slope failures.

LS defines one geometrical boundary of the road section; its other two geometrical boundaries are the width of the roadway and the height of the backslope. In very steep terrain, the roads have single lanes of standard width excavated into the hillside slope. The normal height of the backslope could thus also be considered, for interpretation purposes, to reach a maximum value at the LS. The observation that, in certain cohesive soils (dense tills), backslopes of single-lane access roads remain stable on very steep slopes without any tendency for shear failure becomes significant. It means that, as long as the road sections are similar, access roads excavated elsewhere in the same soil should, in general, perform likewise (pedological concept); in other words, the average long-term shear strength should, in general, be adequate for vertical back slopes that are approximately the same height as the road width, a fact very difficult to determine with even detailed site investigation techniques.

However, in certain types of cohesive soils, the cohesive strength happens to be decreasing progressively with time due to natural causes. These soils include, for example, highly overconsolidated clays. Slopes in such soils may fail, regardless of road construction. The problem presented by such soils is a separate issue (not considered here) but, by extending the combined theoretical and observational techniques as outlined, useful predictions of the performance of such slopes could also be made.

The method of terrain analysis illustrated is thus, first of all, to observe actual slope failures and determine the limiting natural slopes for the various soil map units. Like large engineering structures, the landscape, as portrayed by these map units, is as stable as its foundations.

The second phase is to tie in the record of any existing construction, and what ecological problems occurred and why. Interdisciplinary cooperation is commonly needed at this phase to identify failures that resulted from avoidable construction mistakes or poor practice; failure could be simply a result of interrupting surface drainage or overloading slopes with side-cast material. Once these spurious failures have been eliminated in the observational process, the actual behavior caused by soil properties of slopes in road construction becomes manifest. Also, these observations may help experienced field engineers determine kinds of mitigation measures to help correct the failure.

Connection with Other Earth Sciences

It has been possible to treat the infinite slope concept and its application to this type of soil survey interpretation only in the briefest way. It is likewise impossible to adequately treat the role of geology, hydrology, geomorphology, or other related disciplines that are required to define all aspects of slopes and their behavior. For this particular application of terrain analysis, only the superficial soils are considered. There is no suggestion of attempts to predict ecological impacts from hydrological or deeper-seated geological causes. A possible exception is the case in which mass movements are already in progress or have occurred in the past. If they are somehow visibly manifest, if their scale is great enough, and if a characteristic soil has developed, such areas are commonly identified on soil surveys. However, for specialists concerned with the total problem of specific slopes in the field, evidence from all of these sources must be considered.

RESULTS AND METHOD OF PRESENTATION

Results

In British Columbia, a field observation program was carried out in an area where a soil survey map existed and where slope stability problems had been associated with access road construction in steep terrain. The objective was to determine whether realistic LS values for the pedological map units could be obtained by applying the terrain analysis reasoning outlined above.

The main problem foreseen was the occurrence of a high percentage of nontypical failures, i.e., failures due to unique local or site-specific variations of the landscape characteristics, and failures due to natural causes such as stream-bank erosion and other types of deep-seated slope failure. Although such failures did occur, they were not found to be dominant, and realistic LS values for the mapping units could be identified. Special attention had to be paid to failures that were due to avoidable construction practices. The most prevalent of these were interruption of the natural drainage and overloading of slopes with side-cast material and other debris. The latter could also be classified as nontypical because the terrain analysis problem is intended to apply to access road construction under modern restrictions and by using the best available practice that is economically feasible. Guidelines that encourage such practices have been prepared (15).

When all such nontypical incidents were eliminated, it was deduced that access roads could be built with minimal impact on slopes much steeper than those usually agreed on by ecologists.

In addition to indicating realistic LS values, the terrain analysis indicated other aspects of the ecological problem in the area. The effects of excavating into long, very steep vegetated slopes have already been mentioned. Even with comprehensive soil mechanics testing, it is often quite difficult to predict the long-term effects of such excavations, especially in deep loam till soils. The difficulties are due to imperfections in sampling; presence of thin, weak layers; and the variability of natural materials. The observational record showed that these soils actually failed by a raveling process in the solum rather than by a shearing in the parent material. Such a record gives useful information otherwise difficult to obtain. With this information, it was possible to discuss with contractors methods by which the raveling process could be controlled before it would become a more serious environmental problem, and the ecologist, engineer, and contractor were thus able to communicate. The results of such a discussion are summarized on the pedotechnical interpretation sheet (Figure 5).

In the whole area covered by the survey, the majority of ecological situations fitted into only four well-defined slope categories. Thus, four interpretation sheets, of which Figure 5 is but one example, could adequately define the ecological problem for this survey.

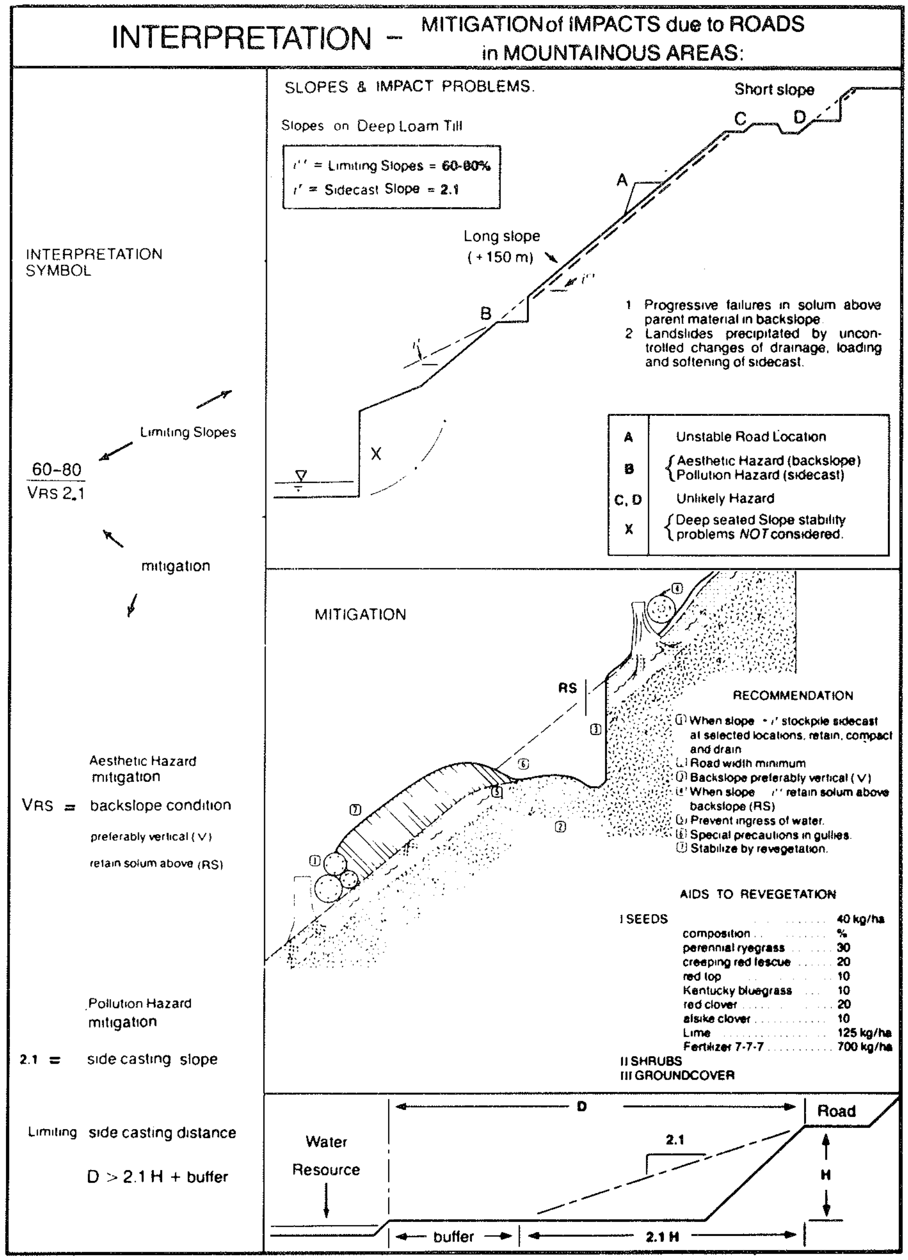


Figure 5. Pedotechnical interpretation sheet.

Method of Presentation

The objective of a soil survey is neither to solve road construction problems such as this one nor to administer slope regulations; instead it attempts to inventory the land resource. It is therefore most important to exhibit the information as clearly and briefly as possible for those concerned with the problems (16).

All the predictive information available from the soil survey relevant to this particular problem is given on a map and an interpretative legend. Some modern soil survey maps contain so much information that they may be cumbersome for specific uses. This problem is solved with a derived map that contains only the information relative to the specific purpose.

Computerized cartographic facilities now exist, and the Canadian Soils Information System (CanSIS) has two main data-storage systems in operation (17). The cartographic facility permits the boundaries of soil map units to be digitized. A turnaround document system permits derived maps to be generated by automated symbol conversion from the original detailed soil map. The turnaround document is generated from the digitizing process and lists every map unit symbol on the original soil map. By use of the pedotechnical interpretation sheet (Figure 5), the original map unit symbol is transposed to an interpretation symbol that relates to the specific terrain analysis application. The turnaround document then generates a new map (see Figure 6). The interpretation sheets become the legend for the new derived map. The derived map thus shows, independent from all the other inventory information, the application of the survey to the particular terrain problem of immediate interest.

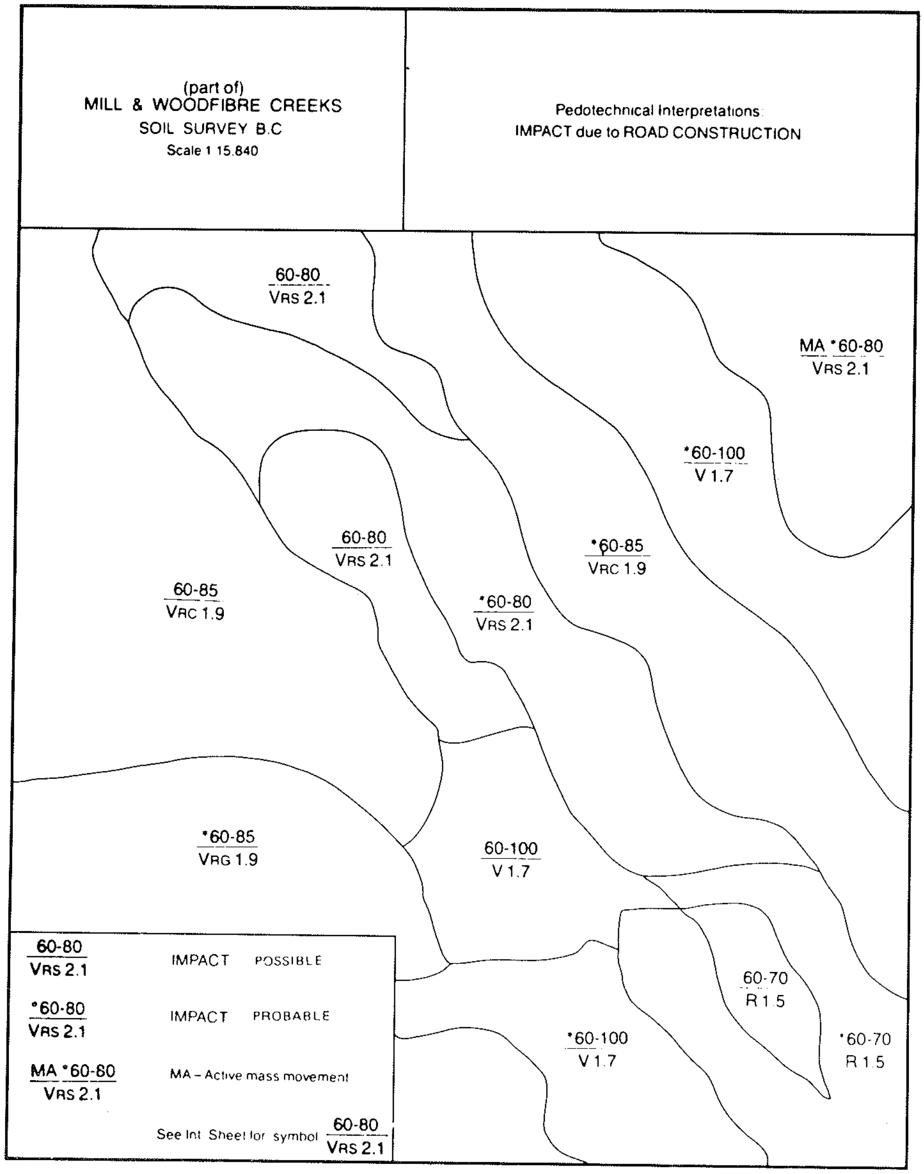


Figure 6. Derived terrain analysis map.

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Quantitative Approach to Assessing Landslide Hazard to Transportation Corridors on a National Forest

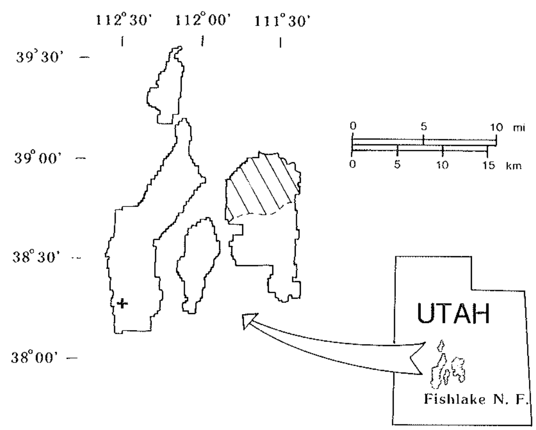
JEROME V. DeGRAFF

The occurrence of damaging landslides along transportation corridors in the mountainous western United States can be expected to rise with the expansion of the regional transportation network. Because national forests typically encompass major mountain ranges throughout the West, assessing landslide hazard is of special concern to forest management. The Fishlake National Forest in central Utah employs quantitative methods to assess this hazard. The matrix-assessment approach forecasts landslide hazard for planning purposes. It seeks to avoid reactivation of existing landslides or creation of new ones. The other method is applied to maintenance concerns. It emphasizes the frequency and areal extent of landsliding over time. Both methods have the following common characteristics: (a) each employs a numerical procedure, (b) each employs measurable terrain characteristics, and (c) procedure results can be assigned to specific geographic locations. The matrix assessment for transportation corridor planning is illustrated by application to the Wasatch Plateau section of the Fishlake National Forest. The method used in maintenance problems is illustrated by application to an 8.2-mile section of UT-153 along Beaver Canyon in the Tushar Mountains.

On February 27, 1981, a landslide developed along a paved county road that crosses the Fishlake National Forest in central Utah. The failure occurred in natural slope materials where the road is cut along a steep valley slope. This rotational landslide destroyed half the width of the outside lane for a distance of 100 ft. This road is the only access to a major coal mine within the forest. All traffic was restricted to a single lane for one month. This included empty incoming and loaded outgoing double-trailer coal trucks, which averaged one truck/10 min. As the party charged with road maintenance, the coal company spent approximately $150 000 stabilizing and restoring the road. Prior to this occurrence, a similar amount was programmed for improvement to the existing mine facilities. Restoration of the access road failure caused a delay in efforts to increase mine productivity. This example clearly illustrates the importance of assessing landslide hazards to transportation corridors.

Shifting population growth and a developing energy industry are creating an increased demand on transportation networks in the West. Corridors capable of satisfying transportation needs are limited by mountainous terrain common to this region. Landslide hazard can be acute along these corridors due to steep slopes, climatic extremes, and landslide-prone bedrock. Assessing landslide hazard potential for expanding or developing corridors is of special concern to national forests. Forest land typically encompasses major mountain ranges throughout the West.

Figure 1. Location map of Fishlake National Forest.



The Fishlake National Forest assesses landslide hazard for both planning and maintaining transportation corridors. Assessment for planning focuses on avoiding reactivation of existing landslides or creation of new ones. For planning purposes, potential landslide hazard is forecast by using the matrix-assessment approach (1). Application to the Wasatch Plateau within the forest provides an example of the method (see Figure 1). (Note: Cross-hatched area delineates the southern Wasatch Plateau section of the national forest, and the cross denotes the location of a landslide-prone road segment in Beaver Canyon.) Assessment for maintenance emphasizes the frequency and areal distribution of landsliding. An approach developed by Ogata (2) defines existing landslide hazard for maintenance situations. Landslide activity along UT-153, which crosses the forest in Beaver Canyon, is used to illustrate this technique (Figure 1).

Both matrix assessment and Ogata's technique are terrain analysis methods that share some common characteristics. First, each method follows a numerical procedure. This minimizes subjective interpretations and quantifies results for comparison. Second, basic data are measurable terrain characteristics. This ties evaluation to basic conditions that contribute to landslide activity. Third, assessment results can be assigned to specific locations. This facilitates comparison of landslide hazard along a corridor or between corridors.

ASSESSMENT FOR PLANNING

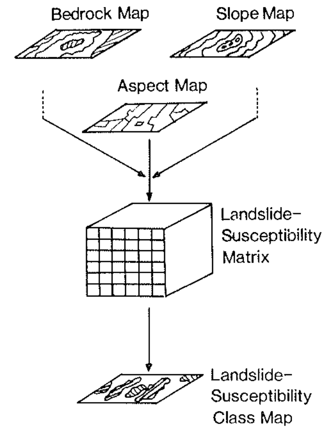
Matrix assessment aids in achieving the planning goal of avoiding reactivation or creation of new landslides along transportation corridors. Matrix assessment is a numerical approach that yields an index of relative landslide risk potential. It employs the key measurable terrain characteristics of bedrock, slope, and aspect. Relative landslide potential for specific locations is defined by discrete combinations of terrain characteristics.

The concept of landslides as threshold phenomena provides the basis for quantitative treatment of landslide potential by using the matrix approach (1). It is possible to numerically define landslide thresholds as the point at which driving forces that promote landslide movement are equal to resisting forces that prevent landslide movement (3). For unfailed slopes, the ratio of driving forces divided by resisting forces is less than the threshold value. The difference between this value and the threshold value is the relative risk of future landslide occurrence. Rather than attempt the difficult task of determining the absolute threshold and the ratio of driving to resisting force values, matrix assessment establishes their relative difference based on past landslide occurrence.

Matrix assessment employs key measurable terrain characteristics. Sharpe (4) categorized basic conditions that favor landsliding as lithologic, stratigraphic, structural, topographic, and organic. Matrix assessment evaluates relative landslide potential in the context of these five condition categories by using bedrock, slope, and aspect as measurable terrain characteristics. Bedrock includes both consolidated and unconsolidated units in an area and is used by formation or mappable member. Differences in physical and chemical factors, including permeability, fractures, and cementation, cause some bedrock units to be more landslide prone than others (4). Landslide potential may be a function of landslide-prone soil derived by weathering of a particular bedrock (5). Slope identifies inclinations of the ground surface susceptible to landsliding (4). It is expressed in percent and grouped in 10 percent classes. Aspect is the compass direction a slope faces, and it is expressed as eight compass direction classes (N, NE, SW, etc.) defined by degrees of azimuth. Aspect is used to include any significant slope orientations that might enhance landsliding by interaction with structural or climatic variables (4,6-10).

Application of matrix assessment begins with an inventory of existing landslides in the area of interest. From this inventory, a matrix of bedrock, slope, and aspect is assembled. The total acres of landslide-disturbed terrain with a given set of bedrock, slope, and aspect characteristics are identified. If all acreage values for every set of bedrock, slope, and aspect are added together, it yields the total acreage of landslides inventoried. A corresponding matrix of all bedrock, slopes, and aspects is developed for the entire study area. The total acreage for all of these combinations equals the total study area acreage. All bedrock, slope, and aspect combinations with no corresponding landslide acreage value define areas with low landslide susceptibility. For all other combinations, the landslide acreage is divided by the corresponding study area acreage to yield the proportion of that combination subject to past landslide disturbance. These proportions are grouped to produce three clusters.

Figure 2. Schematic diagram of landslide-susceptibility mapping.



Grouping is achieved by a nonhierarchical clustering method that begins with an initial partition and attempts iterative improvements (11). The initial partition consists of creating three equal divisions for the range of proportion values. The sum of squared deviations about each group mean, called a W function, is calculated. Values are then moved across the group boundaries and the sum of squared deviations about the group means is recalculated until the minimum value is achieved. The group that contains the lowest range of proportional values defines areas with moderate landslide susceptibility. The group that contains the highest range of proportional values defines areas with extreme landslide susceptibility. The intermediate range of values defines areas with high landslide susceptibility. In each group, the combination of bedrock, slope, and aspect within the defined range of proportional values identifies all unfailed areas that have a particular relative landslide susceptibility. Inventoried landslides identified as inactive are assigned a high landslide-susceptibility rating. Inventoried landslides identified as active are assigned an extreme landslide-susceptibility rating.

The relative landslide-susceptibility values generated by matrix assessment are readily locatable. Each susceptibility rating is defined by one or more discrete sets of terrain characteristics. All map locations with the same set of terrain characteristics will have the same relative landslide-susceptibility rating. Map units are constructed from sets of contiguous points with identical landslide-susceptibility ratings (see Figure 2). (Note: Landslide-susceptibility ratings, defined by the matrix, are assigned to bedrock, slope, and aspect map combinations. Contiguous points with the same rating are grouped into mapping units.)

PLANNING EXAMPLE: WASATCH PLATEAU

Transportation corridors have a major impact on management of the Fishlake National Forest near Salina Canyon on the southern Wasatch Plateau (Figure 3). (Note: The cross-hatched section denotes the location of the area shown in Figure 6.) Interstate 70 between Denver and Los Angeles follows the canyon across the forest. This highway serves as a major conduit for trucks that haul coal from regional mines as well as long-distance traffic. Trucks annually haul 1.8 million tons of coal along an access road to I-70 from a mine on the forest. Two 345-kV powerlines follow a corridor parallel to the southern rim of Salina Canyon. Expansion or development of two access roads to I-70, a 69-kV powerline, and a coal slurry pipeline are all projected additions to the current transportation network near Salina Canyon.

Matrix assessment was initiated with a revised landslide inventory completed in May 1981. The inventory identified, described, and located 72 landslides and 25 landslide zones greater than one acre in size. Individual landslides range in size from 1 to 810 acres. Landslide zones are areas that exhibit complex or multiple movement. Landslide zones range in size from 49 to 1320 acres. Most, but not all, landslide features are currently inactive. A total of 10 625 acres, which amounts to 4 percent of the study area, is subject to landslide disturbance. Data on bedrock, slope, and aspect collected for every landslide feature were assembled into a matrix form (Figure 4). A total of 42 bedrock, slope, and aspect combinations were represented out of a possible 336 combinations within the study area. Computer manipulation of digitized bedrock and topographic data yielded the corresponding acreages for these 42 bedrock, slope, and aspect combinations within the Wasatch Plateau. Proportions generated by dividing corresponding combination acreages range from 0.01 to 1.00 (Table 1). The resultant equal range partition consisted of 0.01 to 0.31, 0.32 to 0.51, and 0.52 to 1.00 with an initial W function of 0.200 676. Final partitioning consisted of 0.01 to 0.15, 0.16 to 0.51, and 0.52 to 1.00 with a final W function of 0.138 630.

Figure 3. Detailed location map of transportation corridors that cross Wasatch Plateau section of Fishlake National Forest.

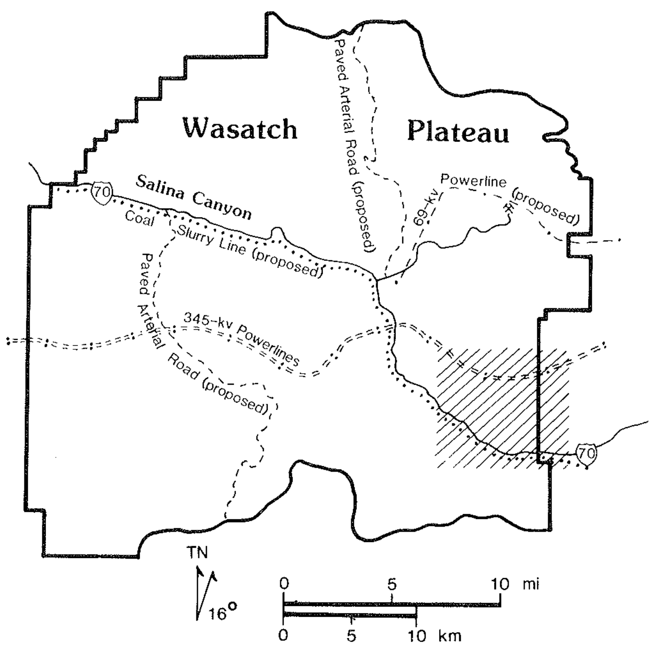


Figure 5 shows a part of the landslide-susceptibility zonation map with I-70, the proposed coal slurry pipeline (heavy dotted line), and the two 345-kV powerlines (dot and dash lines) indicated. [Note: Unshaded areas within the forest boundary (heavy line) have a low susceptibility rating. Light shading shows areas with a moderate susceptibility rating, and heavy shading shows areas with a high susceptibility rating. No areas with an extreme susceptibility rating are present. Accord Lakes 15-min quadrangle is used as the topographic base. Contour level is 250 ft.] Assessment of future route feasibility will include comparing proposed corridors to identify the least landslide-prone corridor and to pinpoint sites that require detailed engineering geology study.

ASSESSMENT FOR MAINTENANCE

A numerical procedure developed by Ogata (2) aids

Figure 4. Sample of matrices that show values for North Horn Formation on Wasatch Plateau.

LANDSLIDE HISTORY MATRIX
MANAGEMENT AREA MATRIX
RATIO

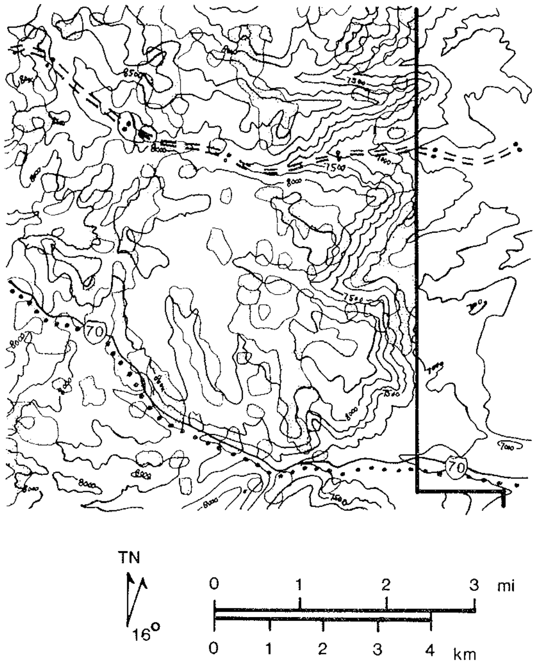
BEDROCK CODED # 5 (North Horn Fm)
(ACRES)

SLOPE	NORTH	N-EAST	EAST	S-EAST	SOUTH	S-WEST	WEST	N-WEST	TOTAL BY SLOPE
					ASPECT				
0-15:	5.0 3718.2 .013	.0 4150.4 .000	238.0 3377.7 .070	.0 4087.9 .000	284.0 2666.9 .106	133.0 2852.4 .047	119.0 2760.1 .043	.0 4037.8 .000	824.0 27651.5
15+-25:	214.0 1431.2 .150	.0 1657.9 .000	214.0 2368.3 .090	134.0 2790.4 .048	1216.0 2574.3 .472	575.0 2275.8 .253	403.0 1936.6 .208	134.0 1720.1 .078	2890.0 16754.7
25+-35:	52.0 761.9 .068	52.0 741.4 .070	111.0 1122.4 .099	143.0 1040.0 .137	10.0 1050.3 .010	96.0 1070.9 .090	137.0 1029.9 .133	48.0 855.1 .056	649.0 7671.9
35+-45:	.0 401.6 .000	38.0 514.8 .074	22.0 638.4 .034	12.0 350.1 .034	12.0 556.0 .022	19.0 638.4 .030	5.0 690.1 .007	12.0 370.8 .032	120.0 4160.2
45+-55:	.0 195.6 .000	.0 298.6 .000	.0 113.3 .000	19.0 205.9 .092	.0 453.0 .000	.0 494.2 .000	4.0 401.8 .010	.0 236.8 .000	23.0 2399.3
55+-65:	.0 103.0 .000	.0 30.9 .000	.0 30.9 .000	.0 92.7 .000	.0 288.3 .000	.0 154.4 .000	.0 61.8 .000	.0 144.2 .000	.0 906.1
65+ :	.0 72.1 .000	.0 10.3 .000	.0 10.3 .000	.0 51.5 .000	.0 61.8 .000	.0 41.2 .000	.0 41.2 .000	.0 20.6 .000	.0 308.9
TOTAL BY ** ASPECT **	316.0 6683.6	90.0 7404.3	585.0 7661.2	308.0 8618.5	1522.0 7650.6	823.0 7527.4	668.0 6921.5	194.0 ** 7385.4 **	43506.0 59852.5

Table 1. Landslide susceptibility partitioning and related W function values that lead to final partition of proportional values.

Partition	Landslide Susceptibility			W Value
	Moderate	High	Extreme	
Initial	0.01 to 0.31	0.31+ to 0.51	0.51+ to 1.00	0.200 676
Left	0.01 to 0.25	0.25+ to 0.51	0.51+ to 1.00	0.168 319
Left	0.01 to 0.21	0.21+ to 0.51	0.51+ to 1.00	0.142 149
Left	0.01 to 0.15	0.15+ to 0.51	0.51+ to 1.00	0.138 630
Left	0.01 to 0.14	0.14+ to 0.51	0.51+ to 1.00	0.159 149
Initial	0.01 to 0.15	0.15+ to 0.51	0.51+ to 1.00	0.138 630
Left	0.01 to 0.15	0.15+ to 0.47	0.47+ to 1.00	0.261 244
Right	0.01 to 0.15	0.15+ to 1.00	1.00+ to 1.00	0.805 297
Final	0.01 to 0.15	0.15+ to 0.51	0.51+ to 1.00	0.138 630

Figure 5. Landslide-susceptibility zonation for part of Wasatch Plateau.



assessment of landslide problems in maintenance situations. Specifically, it applies to landslide activity induced by construction of highways, railways, and powerlines in mountainous terrain. The procedure assumes that initiation of new landslides and natural stabilization of existing landslides on a slope follows a stochastic process. Rather than examine landslide activity in terms of exogenous and endogenous factors or mechanical analysis, Ogata considers change in activity over time to forecast future landslide conditions. Assuming a stochastic process introduces the element of uncertainty into the analysis (12). This incorporates the variability of both basic and initiating conditions that contribute to landslide activity for a given slope (2,4). Ogata's analysis approach is not carried through to a model that yields probabilities. Rather, the approach identifies whether the disturbed slope is tending toward stability or instability over time, the expected number of landslides per unit area, and the projected time for an active landslide to assume a stable configuration. This information is excellent guidance in prioritizing areas that need artificial stabilization and projecting future maintenance work load. Ogata notes that a separate analysis is needed on slopes underlain by different bedrock types. This need is clearly illustrated by examples that apply the analysis approach at two dam and reservoir sites (2).

To apply this procedure, an initial survey locates all landslides within the area of interest. This inventory would likely occur after construction when landslide problems attributable to the project develop. After several years pass, this inventory is repeated. Careful note is made of the number of landslides from the initial survey that are now inactive or stable. This number is divided by the number of years between initial and subsequent inventories. Ogata (2) calls this value the decrement value (K). The number of new landslides that developed since the initial survey is also noted in the subsequent inventory. This number is divided by the number of years between the initial and subsequent inventories. This value is called the increment value (U). If the increment value is divided by the decrement value, i.e., U/K, it yields the equilibrium number. The equilibrium number represents the net change, over time, between occurrence of new landslides and termination of old ones. Comparing U/K with the initial number of landslides present (N_O) indicates whether the slopes are tending toward a more stable or unstable condition: (a) $N_O > U/K$, increasing stability; (b) $N_O < U/K$, increasing instability; and (c) $N_O = U/K$, no change from initial stability conditions.

The equilibrium number (U/K) can be used to provide an index of potential landsliding for a slope. This is accomplished by dividing the equilibrium number by the area being evaluated. The computed value is the potential number of landslides, per unit area, based on the current trend of landslide activity. It is termed "slidability" by Ogata. Slidability enables direct comparison of relative landslide problems between areas of differing size.

Finally, the average life span of a landslide can be computed. This is based on the half-life of existing landslides (2). It uses the decrement value (K) in the following formula:

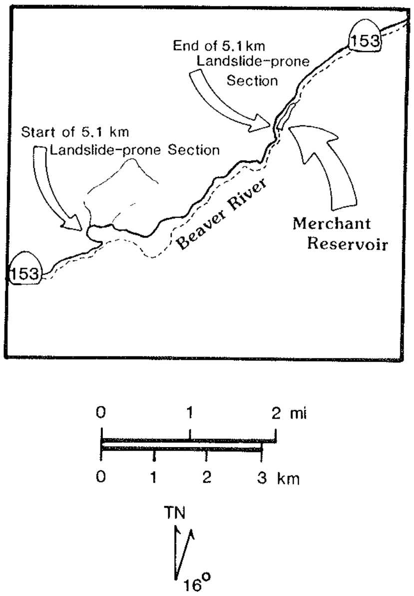
$$\tau = 0.693\,(1/K) \qquad (1)$$

where τ is the average time (in years) that a landslide will be active.

MAINTENANCE EXAMPLE: BEAVER CANYON

A number of roads on the Fishlake National Forest require periodic maintenance due to landslide activity. UT-153, which provides access to the Tushar Mountains via Beaver Canyon, chronically requires maintenance due to landslide activity (Figure 6). (Note: Stipled area is the Big Cove landslide, an old, natural landslide. Beaver Canyon widens significantly above Merchant Reservoir.) The Utah Department of Transportation maintains this highway. However, the national forest is obliged to provide disposal sites to stockpile landslide debris removed from the highway. This limits the amount of sediment that would otherwise enter the Beaver River. Most of the landslide activity occurs along an 8.2-mile section, which was widened and paved in 1962. In this section, the highway was constructed along a natural slope break that corresponds to the contact between basaltic lava flows overlain by ash-flow tuffs (13). An initial survey identified 22 landslides along the road section in 1978. This survey involved ground observation, but an aerial photograph survey may be appropriate in other situations. In 1981, 10 landslides were identified. The basic data on the area and landslides along UT-153 are as follows: observation period, 3 years; road length, 8.2 miles; and number of landslides: $N_O = 22$, inactive = 13, and new = 1. The computed values for

Figure 6. Generalized location map of landslide-prone section of UT-153, which crosses Fishlake National Forest.



landslide activity along UT-153 for the three-year observation period are as follows: increment value (U) = 0.3; decrement value (K) = 4.3; equilibrium number (U/K) = 1; slidability (per mile) = 0.6; and average life span = 1 year.

The following generalizations about landslide activity can be derived from these computed values. The equilibrium number (U/K) of 1 is considerably less than the original landslide total (N_O) of 22. This is an apparent sharp decrease in landslide activity and an increase in slope stability over the past three years. It is unclear if this reflects a long-term trend. Landsliding has occurred for 19 years along this road section. Annual fluctuation in landslide activity has varied greatly: 1978, 22 landslides; 1979, 12 landslides; 1980, 26 landslides, and 1981, 10 landslides. In this particular situation, a three-year observation period is minimal with a five- or seven-year period being preferred. This would ensure the long-term validity of the computed trend. Slidability is calculated as 0.6 landslide/mile. The average life span of a landslide is computed as a year or less. Slidability and life span indicate a reduced need for landslide debris disposal areas. Maintenance needs can be expected to decrease over the next few years. Comparison of these values with other road sections subject to continuing landslide problems would prioritize remedial work to the most troublesome sections.

CONCLUSIONS

As transportation corridors proliferate in the mountainous West, so too will the occurrence of damaging landslides. To avoid the costly impact of landslide activity, more effective assessment of landslide hazard is needed. Quantitative approaches minimize subjective interpretations and quantify results for comparison of alternatives. These approaches are especially effective when based on measurable terrain characteristics related to basic conditions that influence landslide activity. To facilitate comparison of landslide hazard, the approaches must assign results to geographic locations. Assessment of landslide hazard achieves the best results in the planning of transportation corridors. Quantitative assessment of landslide hazard along existing corridors can maximize the return on limited remedial funds.

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Genesis-Lithology-Qualifier System of Engineering Geology Mapping Symbols: Applications to Terrain Analysis For Transportation Systems

JEFFREY R. KEATON

The genesis-lithology-qualifier (GLQ) system of engineering geology mapping symbols provides a convenient and widely applicable means of documenting geologic and soils information in descriptive terms that have direct engineering significance. The purpose of this paper is to broaden the awareness in the engineering community of the existence of this relatively new system, which appears to provide an excellent basis for standardization. Unconsolidated surficial materials are documented by a series of capital and lower-case letters that represent material genesis and lithology. Qualifying information, thickness, and modifying information may be added if understanding of engineering significance will be enhanced. Bedrock materials are documented by conventional geologic shorthand. Stratigraphic sequence can be shown by simply stacking symbols. The GLQ system may be applied to terrain analysis for transportation systems in the areas of (a) planning exploratory programs, (b) predicting foundation conditions, (c) predicting engineering problems, and (d) evaluating construction materials. A conventional geologic map and an engineering geologic (GLQ) map of the same part of the Draper Quadrangle, Utah, are presented to permit engineers and geologists to assess the utility of the GLQ system for their own applications.

The genesis-lithology-qualifier (GLQ) system of engineering geology mapping symbols provides a convenient and widely applicable means for documenting geologic and soils information in a manner readily usable by engineers responsible for the design of transportation systems and other facilities. This relatively new system uses descriptive combinations of capital and lower-case letters to represent geologic materials.

Engineering geology maps traditionally have been produced in two ways. First, conventional time-rock symbols are used in the usual geologic manner (e.g., Tfu for Tertiary-aged Fort Union Formation or Qal for Quaternary-aged alluvium), and a tabulation is provided of selected engineering characteristics. Second, special symbols, which consist of Roman or Arabic numerals, letters, and combinations of numerals and letters, are used to portray the distribution of geologic materials in terms of engineering character. Examples of engineering geology mapping symbols are contained in publications by Varnes (1), the United Nations Educational, Scientific, and Cultural Organization (UNESCO) (2), and Nichols and Campbell (3).

A major deficiency with these two traditional methods is that constant reference to an explanation is needed to understand the engineering significance of the symbol. A symbol such as IIb3 has no significance without reference to its explanation. Furthermore, a different symbol would be assigned to identical material in another region.

The GLQ system consists of symbols that have engineering significance. In addition, the same material in different regions will be represented by the same symbol. It is very desirable to have a system of engineering geology mapping symbols that is standardized; the GLQ system appears to provide an excellent basis for standardization. In most engineering applications, the geologic age of materials is either not important or so important that conventional time-rock mapping is insufficient. Age is not included in the GLQ system; hence, GLQ symbols would not be appropriate for fault evaluation projects.

One notable system of engineering geology mapping was developed by Gardner and described in terms of regional planning by Gardner and Johnson (4). Gardner's system and the GLQ system are very similar in many respects. The most significant difference is that Gardner's system has no term for genesis of surficial materials.

The purpose of this paper is to broaden the awareness in the engineering community of the existence of this relatively new system of descriptive engineering geology mapping symbols. This purpose is accomplished in two ways. First, the elements of the GLQ system are described, and second, applications of the GLQ system to terrain analysis for transportation systems are outlined.

GLQ SYSTEM

The elements of the GLQ system were first described by the originator, Galster, in 1975 (5) and subsequently published in 1977 (6). The name genesis-lithology-qualifier system and the GLQ acronym were proposed in 1980 by Keaton (7) to provide a convenient and descriptive identification of the system.

The GLQ system consists of a set of symbols that are easy to memorize and meaningful at a glance without constant reference to the explanation on a map. The majority of symbols pertains to unconsolidated or surficial materials; bedrock materials are designated by conventional geologic shorthand for rock type.

Surficial Materials

The GLQ name is derived from the principal elements of the symbol for surficial materials. Typical symbols for surficial materials consist of a single capital letter, which identifies the genesis or origin of the material, followed by one or more lower-case letters, which represent the lithology or texture of the material constituents.

Commonly, additional qualifying information that pertains to the topographic expression (geomorphology) of the materials is desirable. Such information may be designated by one or more lower-case letters in parentheses. In some cases, thickness and modifying symbols may be added if they are applicable.

The general formula for symbols that represent surficial materials can be stated as follows:

$$eAb(c)(d) \qquad (1)$$

where

A = genetic symbol; usually a single capital letter;
b = lithologic symbol; one or more lower-case letters;
(c) = qualifier symbol, if desirable; one or more lower-case letters in parentheses;
(d) = thickness, if applicable; Arabic number with feet or meter symbol in parentheses; and
e = modifier symbol, if applicable; one or more lower-case letters.

All symbols for surficial materials must have a genetic symbol and a lithologic symbol. Qualifier, thickness, and modifier symbols may be included if they enhance understanding of engineering significance.

Genetic Symbols

The genetic symbol is the initial symbol because it identifies the process by which the material arrived at its present location. Frequently, a knowledge of material genesis provides insight into engineering properties and material behavior. As Galster (6) states, there is a fundamental engineering and geologic difference between a clayey gravel of residual origin and one deposited as glacial till. In many cases, the process of formation is still active and must be accommodated in the design of engineering works.

Virtually all surficial materials may be classified by one of 10 genetic symbols; these 10 symbols are follows: A = alluvial, C = colluvial, E = eolian, F = fill (man-made), G = glacial, L = lacustrine, M = marine, R = residual, S = slide, and V = volcanic. In some instances, materials of two origins may be interlayered or interbedded, such as alluvial and colluvial deposits or glacial and lacustrine deposits. In these cases, interbedded materials can be designated by the two genetic symbols separated by a slash: A/C or G/L.

Occasionally, some uncertainty of material genesis may exist. Uncertainty of genesis can be designated by the two genetic symbols separated by a hyphen: A-C, G-L, or R-C. Generally, material genesis is sufficiently clear so that only a single symbol is required.

The most significant difference between Gardner's system (4) and the GLQ system is in the genesis of unconsolidated materials. Gardner's symbol for bouldery sand, silt, and clay is SCb, regardless of its origin. The GLQ symbol would have the textural components identified as smcb, which would mean silty and clayey sand (smc) with boulders (b). The GLQ symbol would also identify the origin of the material because the process of deposition influences the engineering behavior. For example, bouldery sand, silt, and clay of glacial (G) origin would have different character than the same materials formed by residual (R) processes: Gsmcb versus Rsmcb.

Lithologic Symbols

The most commonly used lithologic symbols pertain to material texture and are adapted from the Unified Soil Classification System. Additional terms are needed for textural sizes larger than gravel and for materials such as peat and trash. Lithologic symbols consist of the following 12 terms: c = clay, m = silt, s = sand, g = gravel, k = cobbles, b = boulders, r = rock rubble, e = erratic blocks, p = peat, o = organic material, and d = diatomaceous material. The most abundant or significant lithologic constituent symbol should appear adjacent to the genetic symbol. For example, Asm signifies alluvial silty sand.

Interbedded lithologies can be designated by the two symbols separated by a slash: cm/ms signifies interbedded silty clay and sandy silt. Commonly, a number of grain sizes are present in a single deposit. Listing each grain size creates a lengthy symbol, which can be abbreviated with the use of a hyphen: m-b signifies that all textural constituents from silt to boulders are present. Some deposits consist of a principal constituent in a matrix of other textures: rm-g signifies rock rubble in a matrix composed of silt, sand, and gravel.

Qualifier Symbols

Qualifier symbols may be used if noteworthy qualities are present. For example, an alluvial deposit that consists of silt, sand, and gravel will require different design measures if it is a flood plain than if it is an alluvial fan. The GLQ symbol for the first condition is Am-g(fp); the symbol for the second condition is Am-g(f).

Qualifier symbols are generally unique for each genetic classification. The qualifiers proposed below consist of 39 symbols; no two symbols consist of the same combination of letters.

1. Alluvial deposits: (f) = fan morphology, (te) = terrace, (s) = stream deposits, (fp) = present flood plain, (p) = pediment deposits, and (df) = debris flow.
2. Colluvial deposits: (sw) = slope wash, (ra) = rock avalanche, (ta) = talus, and (cr) = creep deposits.
3. Eolian deposits: (d) = dune morphology and (l) = loess.
4. Fill deposits: (u) = uncompacted and (e) = engineered.
5. Glacial deposits: (t) = till, (es) = esker, (ic) = ice contact, (m) = moraine, (k) = kame, and (o) = outwash.
6. Lacustrine and/or marine deposits: (b) = beach, (et) = estuary, (sp) = swamp, (de) = delta, (ma) = marsh, and (ti) = tide lands.
7. Residual deposits: (sa) = saprolite and (wp) = weathering profile.
8. Slide deposits: (ro) = rotational, (ls) = lateral spread, (fa) = fall, (fl) = flow, (tr) = translational, (sl) = slump, and (to) = topple.
9. Volcanic deposits: (a) = ash, (cl) = clinker, (pu) = pumice, and (ci) = cinders.

Thickness

The thickness and stratigraphic sequence of materials can be shown by simply placing the thickness value at the end of the symbol and stacking symbols. For example, if it is known that a certain location has 10 ft or 3 m of eolian silty sand over basalt, the symbols would be written as follows:

$$\frac{\text{Esm(10')}}{\text{BA}} \text{ or } \frac{\text{Esm(3m)}}{\text{BA}}.$$

Modifier Symbols

Occasionally, an extremely important characteristic should be noted in a symbol. Three modifier symbols are proposed for surficial materials: c = cemented, e = expansive, and h = hydrocompactible. As indicated in Equation 1, these symbols precede the genetic symbol. Cemented alluvial sandy and silty gravel would have the symbol cAgsm, expansive residual silty clay would be eRcm, and hydrocompactible alluvial sandy and clayey silt would be hAmsc.

Bedrock Materials

Typical symbols for bedrock materials consist of two capital letters, which represent rock type in conventional geologic shorthand. In some cases, thickness and modifying symbols may be added if they are applicable. The general formula for symbols that represent bedrock materials can be stated as follows:

$$\text{cAA(b)} \quad (2)$$

where

AA = conventional geologic shorthand for bedrock type; usually one set of two capital letters;
(b) = thickness, if applicable; Arabic number with feet or meter symbol in parentheses; and
c = modifier symbol, if applicable; one or more lower-case letters.

All symbols for bedrock materials must have, at a minimum, the two-capital-letter notation for rock type. Thickness and modifier symbols may be added if they enhance understanding.

Rock Symbols

The GLQ symbols for rock materials consist of conventional two-letter abbreviations of rock type. The symbols for sedimentary, igneous, and metamorphic rock types that are given below are modified only slightly from Galster (6).

1. Sedimentary rock types: SS = sandstone, ST = siltstone, CG = conglomerate, CH = chert, DT = diatomite, SH = shale, CS = claystone, DO = dolomite, CK = chalk, and LS = limestone.
2. Igneous rock types: GR = granite (granitic), GA = gabbro, FE = felsite, AN = andesite, VO = volcanic, BA = basalt, SY = syenite, RH = rhyolite, IG = igneous, TU = tuff, and DI = diorite.
3. Metamorphic rock types: QT = quartzite, SC = schist, GN = gneiss, SL = slate, AR = argillite, GS = greenstone, MA = marble, SE = serpentine, PH = phyllite, ME = metamprophic, and HO = hornfels.

Galster (6) also suggested symbols for man-made rock equivalents: CC for portland cement concrete, AC for asphalt concrete, and PA for undifferentiated pavement.

Sedimentary rocks are commonly interbedded to some degree. Interbedded rocks can be designated by the two symbols separated by a slash: SS/SH signifies interbedded sandstone and shale. If the interbeds are sufficiently thick, they should be mapped as separate units.

Occasionally, a rock will require a dual classification similar to some soils. In the Unified Soil Classification System, ML-SM is used to signify that the soil is sandy silt to silty sand. In the GLQ system, SS-ST denotes silty sandstone to sandy siltstone.

Thickness and Modifier Symbols

Thickness and stratigraphic sequence of bedrock materials can be shown in the manner described for surficial materials. Occasionally, an extremely important charactertistic should be noted in a symbol. The modifier symbol "e" for expansive may be used for rock materials as well as soils. Additional characteristics that may be important in denoting rock materials are degree of weathering and degree of fracturing. These symbols are as follows: xw = extremely weathered, hw = highly weathered, mw = moderately weathered, sw = slightly weathered, uw = unweathered, xf = extremely fractured, hf = highly fractured, mf = moderately fractured, sf = slightly fractured, and uf = unfractured. In addition, the use of k for karstic as a modifier for limestone bedrock may be informative in some locations.

Greater use of the GLQ system will likely generate the need for additional symbols, particularly modifier symbols. It is likely that additional symbols will have regional application only.

Explanations and Miscellaneous Symbols

No matter how clear and descriptive a system of symbols is, each map should have an explanation of symbols to be complete. Explanations on GLQ maps can be presented in two ways. If only a few symbols are used (less than about 10), each symbol may be shown and described in detail. Alternatively, if many symbols are required on a single map, then the elements of the GLQ system may be outlined in a manner similar to that presented above. Only those specific symbols used on the map should be included in the explanation. A few representative examples should be included to clearly identify the use of numbers for thickness values and the concept of stacking symbols to portray stratigraphic sequence.

Many conventional geologic symbols are necessary in engineering geology evaluations. These symbols include strikes and dips, contacts and faults, landslides, test pits and borings, and springs and seeps. These symbols are represented on GLQ maps in the same fashion as on conventional geologic maps.

Formation name and age of rock materials can be included in explanatory descriptions of GLQ symbols. In addition, texts that accompany GLQ maps should contain at least a brief discussion of local geology in time-rock terms. The value of the GLQ system is that symbols on a map have direct engineering significance, which reduces the need for reference to an explanation. It must be emphasized that the GLQ system is intended for special-purpose engineering geology mapping. No map can retain readability and contain sufficient information to qualify as a general-purpose engineering geology map.

The GLQ system and the Unified Soil Classification System have only two common combinations of letters. These two are SC, which means schist in the GLQ system and clayey sand in the Unified Soil Classification System, and CH, which means chert and high plasticity clay, respectively. Confusion is not likely to result from this duplication of symbols.

APPLICATIONS TO TERRAIN ANALYSIS FOR TRANSPORTATION SYSTEMS

Engineering geology applications to terrain analysis for transportation systems have been discussed by Bean (8), Krynine and Judd (9, pp. 501-543), Hofmann and Fleckenstein (10), McCauley (11), and Thornburn (12). The engineering geologist can provide assistance in the planning, design, construction, and maintenance phases of highway engineering. Principal opportunities for terrain analysis will occur in the planning and design phases. Early recognition of geologic constraints will permit them to be accommodated in the planning and design of transportation systems; this will tend to minimize emergencies caused by geologic conditions that occur during the construction and maintenance phases.

Route selection appears to be done primarily on the basis of nongeologic considerations. Maximum grades, minimum radius curves, number of bridge structures, and existing land use factors frequently outweigh geologic factors in route alignment decisions. Detailed knowledge of engineering geology conditions along a given right-of-way permits transportation engineers to make more realistic estimates of construction costs. Economic evaluation of alternatives can be more realistic also.

As Thornburn (12) discusses, the engineering geologist can make significant contributions to transportation projects in the areas of (a) planning exploratory programs, (b) predicting foundation conditions for structures, (c) predicting engineering problems, and (d) evaluating construction materials. Some applications of the GLQ system in these areas are presented in the remaining sections of this paper.

Thornburn (12) also states that the engineering geologist can contribute significantly in evaluating slope stability. The GLQ system is not particularly useful in quantitative assessments; however, it may be used conveniently in conjunction with slope stability evaluations.

Exploratory Programs

Knowledge of the areal geology along a given right-of-way can aid greatly in making an exploration program efficient. Because GLQ maps present geologic data in terms of engineering significance, they form a very good basis for minimizing the cost of an exploratory program by differentiating units that can be grouped for preliminary design purposes.

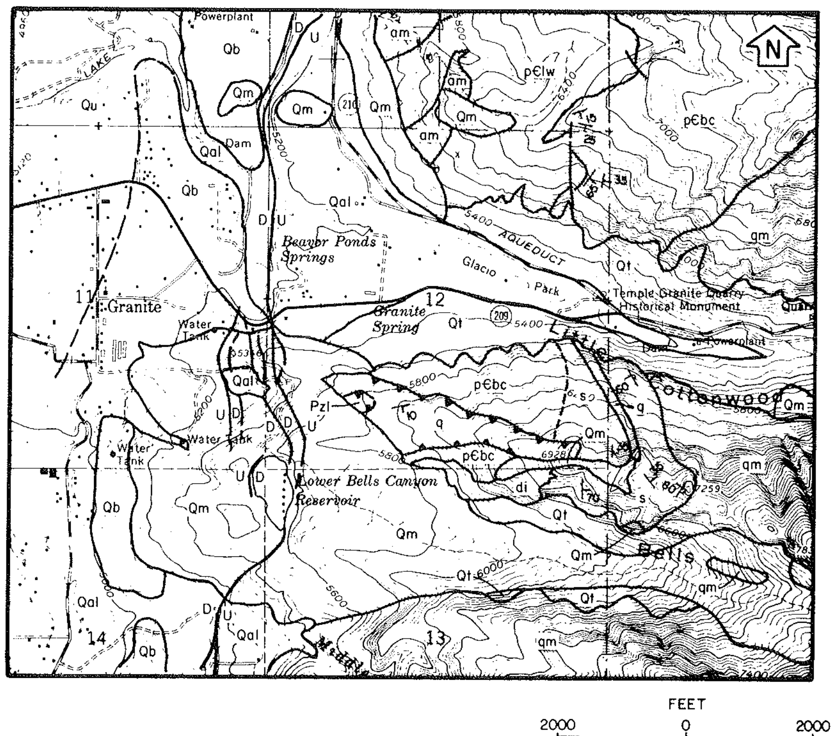
The GLQ system is well suited for documenting veneers of surficial materials over rock. Conventional geologic mapping would portray an area as exposed bedrock even if up to several feet of surficial deposits were present. Most engineers have learned from experience that surficial deposits exist to some extent virtually everywhere. The GLQ system provides a way for the engineer to have some knowledge of the character and thickness of such materials at an early stage in a project. Such knowledge should be of value in planning exploratory programs.

GLQ maps can be constructed to provide a basis for exploratory programs in two ways. They can be produced in the office by relatively straightforward interpretation of conventional geologic mapping. Alternatively, GLQ maps can be produced in the field by direct observation. My experience with the GLQ system is that engineering geologic maps can be produced in the field as quickly as conventional geologic maps. Some laboratory analyses may be used to confirm field interpretations of textural constituents of map units.

Foundation Conditions

Specific foundation conditions can be evaluated adequately only with subsurface exploration and subsequent laboratory testing. For design purposes, engineering geology interpretations must be verified by well-placed (and sufficiently deep) borings. The

Figure 1. Conventional geologic map of part of Draper Quadrangle, Utah.



EXPLANATION

QUATERNARY DEPOSITS

Qal — Stream gravel and valley fill.
Qt — Talus and high-angle alluvial cones.
Qb — Depsits of Lake Bonneville.
Qu — Undifferentiated alluvium.
Qm — Glacial moraine.

CRETACEOUS OR TERTIARY PLUTONIC ROCKS

qm — Quartz monzonite of Little Cottonwood stock.
di — Diorite in Bells Canyon.

PALEOZOIC

Pzl — Gray crinoidal limestone.

PRECAMBRIAN

pЄbc — Big Cottonwood Formation quartzite interbedded with shales and siltstones.
q — Quartzite unit.
s — Shale or siltstone unit.
pЄlw — Little Willow Formation quartz schist interbedded with biotite schist.
am — Lenses of chlorite amphibole schist.

SYMBOLS

Contact, dashed where approximate, dotted where concealed.
U/D Fault, dashed where approximate, dotted where concealed, U, up thrown side.
Thrust fault, sawteeth on upper plate.
35 Strike and Dip of beds, 60 overturned beds.

GLQ system provides a simple means of recording surficial and near-surface engineering geology data in a way that may be able to increase the degree of confidence in projecting anticipated foundation conditions between boring locations.

Engineering Problems

The GLQ system is intended to permit documentation of geologic data with descriptive symbols that have engineering significance. As such, many engineering problems may be anticipated early in a project. Engineering problems usually mean unanticipated geologic conditions.

Examples presented in earlier sections of this paper pertained to documenting conditions of expansive, cemented, and hydrocompactible surficial materials. Each of these three conditions can be accommodated by conventional design measures and/or anticipating additional costs related to construction.

Dynamic processes, such as debris flows and flooding, can be documented by the GLQ system. Am-b(df) in an area where alluvial fans are present would indicate that debris flow activity could be a potential problem to a highway. Amcs(fp) would indicate that the surface is susceptible to flooding.

Peat and organic sediments commonly require special design considerations or expensive construction measures. The GLQ system includes specific lithologic symbols for these materials. Landslide deposits frequently require stabilization measures to reduce the risk of damage to transportation systems. The GLQ system includes a specific genetic symbol for slide materials.

Construction Materials

The location of adequate amounts of suitable construction materials is one of the most important tasks related to the planning and construction of transportation systems. The GLQ system is particularly well suited for documentation of information pertinent to assessment of potential sources of construction materials.

Construction materials of prime importance are

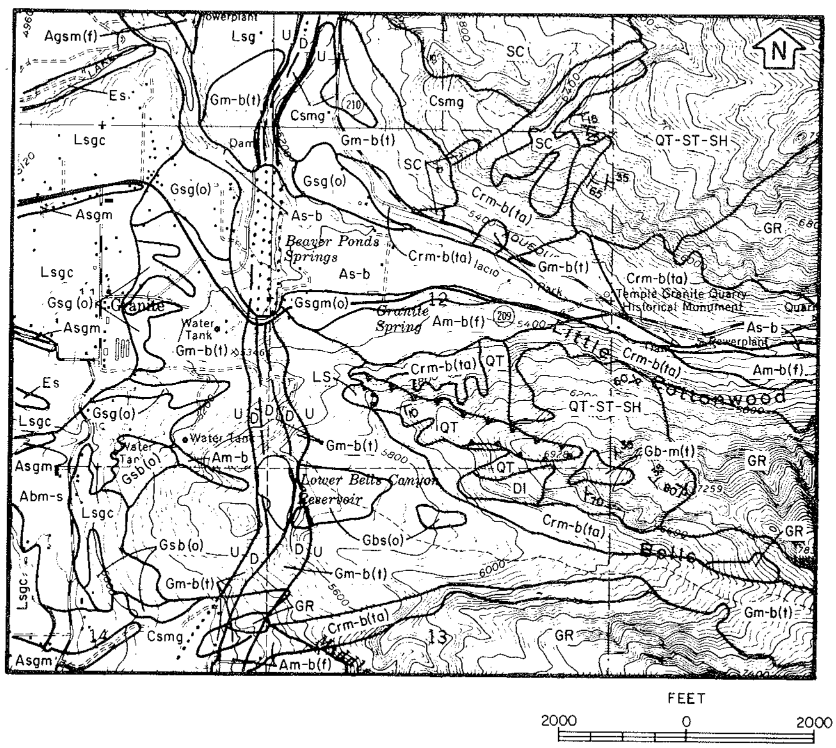


Figure 2. Engineering geologic map of part of Draper Quadrangle, Utah.

EXPLANATION

UNCONSOLIDATED MATERIALS

GENERAL SYMBOL : Ab(c)

A — Genetic symbol.
b — Lithologic symbol.
(c) — Qualifier symbol.

GENETIC SYMBOLS

A — Alluvial. G — Glacial.
C — Colluvial. L — Lacustrine.
E — Eolian.

LITHOLOGIC SYMBOLS

b — Boulders. m — Silt.
c — Clay. r — Rock rubble.
g — Gravel. s — Sand.

QUALIFIER SYMBOLS

(f) — Fan. (t) — Till.
(o) — Outwash. (ta) — Talus.

EXAMPLES

Agsm(f) - Alluvial material composed of gravel, sand, and silt forming an alluvial fan.
Crm-b(ta) - Colluvial deposits composed of rock rubble, in a matrix of silt to boulders forming talus.
Gm-b(t) - Glacial till composed of silt to boulders.

BEDROCK MATERIALS

DI — Diorite. LS — Limestone.
GR — Granitic rock (chiefly quartz monzonite).
QT — Quartzite. SC — Schist.
SH — Shale. QT-ST-SH-Interbedded.
ST — Siltstone.

SYMBOLS

Contact
U/D Fault, dashed where approximate, dotted where concealed, U on up thrown side.
Thrust fault in bedrock, sawteeth on upper plate.
35 Strike and Dip of beds, 60 overturned beds.

granular fill material and aggregate suitable for use in concrete. A significant difference can be seen easily in the following two symbols: As-k(GR) and As-k(SS). The genesis and lithology (texture) of the materials represented by these two symbols are the same, yet most engineers would avoid using sandstone fragments as aggregate in concrete. Either material would be suitable for use as granular borrow material. A similar deposit, which contains predominantly chert fragments [As-k(ČH)], would be unsuitable for use in concrete.

The quality of construction materials at potential sites would have to be evaluated by a thorough laboratory testing program. The GLQ system provides the initial information to assist in the identification of sites where suitable material might be present in adequate amounts.

CONCLUSION

The GLQ system of engineering geology mapping symbols provides a convenient and widely applicable means of documenting geologic information in terms that have direct engineering significance. For comparison purposes, a portion of the Draper Quadrangle, Utah, is presented in Figures 1 and 2. Conventional geologic symbols shown in Figure 1 are taken from a publication by Crittenden (13). The same area is shown in Figure 2, but the GLQ symbols are used in lieu of conventional geologic symbols. The GLQ symbols are derived from publications by Richmond (14) and Morrison (15) in addition to that by Crittenden (13).

The example area contains several types of bedrock materials and several types of surficial materials. The surficial materials are all Quaternary in age and consist of materials deposited in alluvial, colluvial, eolian, glacial, and lacustrine environments. Engineers and geologists who study the two examples of the same area will be able to assess the utility of the GLQ system for their own applications.

The GLQ system appears to provide an excellent basis for standardization of engineering geology mapping symbols. The system has great utility because (a) it is simple and easy to memorize, (b) it is a means of documenting basic geologic data in terms of direct engineering significance, and (c) it is universally applicable.

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Development and Operation of Remote-Sensing Laboratory for a Transportation Department

DON H. JONES AND JACK H. HANSEN

There are many ways to develop and operate a transportation-oriented remote-sensing unit, but almost no written information exists on the subject. The use of remote sensing by state departments of transportation varies all the way from many states that use no remote sensing to at least one state that has an excellent and fully operational unit. An effort was made to examine and analyze many approaches to organizing and operating a remote-sensing unit. Some advantages and disadvantages of the more feasible approaches are discussed. Also included is a discussion of personnel and equipment appropriate for the range or scope of the operations envisioned. The success of any organization is directly related to the management and supervision provided; this matter is also given some attention. Certain other restraints (e.g., funding) are recognized and discussed. One must be aware of the difference between management processes and operating restraints, whether directly imposed (such as defined limits) or indirectly imposed through levels of funding or restriction on the size of the staff. Interactive elements involved in the development and operation of a remote-sensing laboratory are included in the discussion.

Many developments have occurred in remote sensing since the late 1940s. More of these developments will become operational in transportation departments as more attention is given to ascertaining and attaining mission parameters dictated by study needs and available equipment. Perhaps the lingering feeling of mystique in the use of remote sensing makes preparation and proper follow-up seem unnecessary. However, when missions are properly planned, interpretation is adequate, and proper care is used in its application, remote sensing becomes a very useful tool. In this respect, remote sensing can be used to reduce cost and to provide for a more efficient overall operation. The success of a remote-sensing laboratory, as in any other organization, depends on management, operational techniques, equipment availability, and quality of personnel.

Many factors, as illustrated in Figure 1, must be considered in establishing a remote-sensing laboratory in a transportation department. Such a laboratory may be operated in many ways and may serve many purposes. Therefore, the assignment of the laboratory to a particular functioning unit is an important decision. Other factors to be considered include level of service to be provided, quality and quantity of studies produced, level of interaction between other units, type of equipment needed, staffing requirements, and cost of setting up and operating the laboratory. Also important are such considerations as type of imagery to be acquired, purpose of the imagery, and extent of the research to be conducted by the laboratory. Firm decisions that relate to some of these factors do not have to be made until the laboratory is operational, and many such decisions will be based on the economics involved.

Some uses of remote sensing have been skirted (not ignored or overlooked) because of their specialized nature. Some sensing devices, such as radar units that sense vehicular traffic and actuate traffic signals or photo cells that operate lights, require neither analysis nor interpretation. These devices are sensors that receive, translate, and perform. Many sensing devices are available in this category, such as sensors on paving machines, infrared and other sensors that read data cards on box cars and packages, vehicle weighing devices, and speed detectors. A remote-sensing laboratory could have an individual with expertise in this area who would know which devices are available and how they could be used.

Another category of sensors can receive data and transmit the data to satellites that then retransmit the data to stations for analysis and output in various forms. Such instruments have been used to track and monitor the condition of fish and animals. Other instruments have been used to monitor vehicle operator response to such things as flashing messages and railroad crossing warning devices. Transmission is usually in the digital mode, but it may be by videotape. Many types of data can be handled this way, including temperature, stream flow, rainfall, and wind speed.

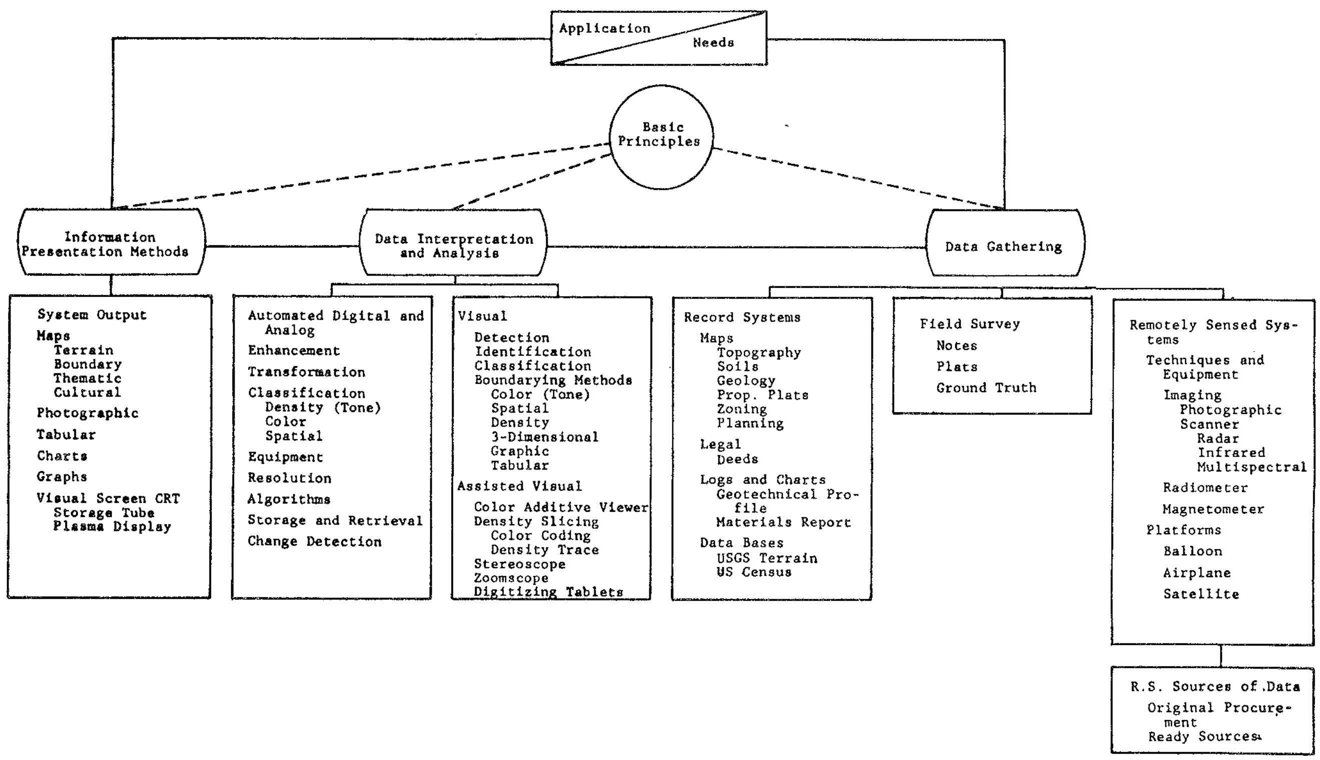
Another category of remote-sensing operations includes video monitoring and photo logging. Video monitoring from remote sites is especially helpful in traffic engineering for monitoring specific sites such as intersections and interchange ramps. Photo logging is used essentially for monitoring pavement conditions and rights-of-way. Still another category of remote-sensing operation involves the use of resistivity, seismic devices, induced polarization, magnetometers, and electromagnetic devices for prospecting and geological exploration. This category also includes nuclear gauges used in soil engineering.

A fully functional remote-sensing laboratory should be prepared to deal with these remote-sensing categories if they are perceived to be of need. They are excluded from further discussion in this paper because of their specific and specialized applications, and they are also excluded from the staffing and equipment costing sections.

In setting up a remote-sensing laboratory or in reevaluating an existing one, a number of factors should be considered. Some of these are enumerated below:

1. What unit or units will most use the services of the remote-sensing laboratory?
2. How will the remote-sensing laboratory administratively relate to other units?
3. What services will the remote-sensing laboratory provide?
4. Will the remote-sensing laboratory provide services for departments other than the transportation department?
5. What level of detail will be provided in data analysis and interpretation?
6. What disciplinary areas (geology, environmental science, archaeology, etc.) will be included?
7. To what extent will ground truthing be carried out?
8. Will the interpreters in each disciplinary area be assigned to the remote-sensing laboratory or to their specific disciplinary units?
9. To what extent will the remote-sensing laboratory be equipped with such instruments as color-additive viewers, density slicers, automated interpretation equipment, zoomscopes, etc.?
10. What will be the laboratory's data acquisition capabilities?
11. Will equipment such as thermal and radar scanners be purchased or rented, or will the imagery be acquired from private companies?

Figure 1. Model for use of remote sensing in transportation information systems.



12. To what extent will high-altitude (U-2 and RB-57) and satellite imagery be acquired, and for what purposes will it be used?

13. To what unit will the remote-sensing laboratory be attached?

HOUSING THE LABORATORY

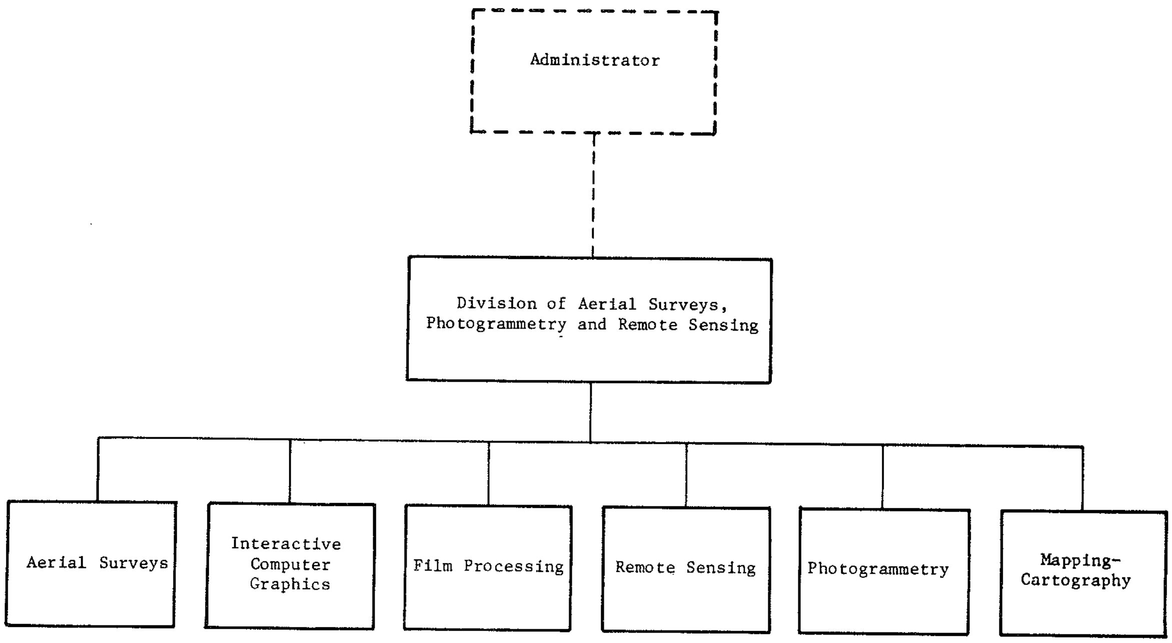
In deciding where to house the remote-sensing laboratory within a transportation department, considerations would include which units, such as geology or environmental science, would benefit most from its service and which units, such as aerial surveys and photogrammetry, would provide the best support activities for the laboratory. One critical factor that affects this decision is whether the laboratory will be limited to providing imagery for other units or if it will provide full services, such as mission planning, interpretative analysis, ground truthing, report preparation, and additional assistance as needed. Where to house the laboratory will gradually evolve as these matters are considered.

The aerial surveys and photogrammetry unit will probably provide the support most needed to sustain the remote-sensing laboratory. This unit will normally have or at least retain some control of the aircraft needed to obtain imagery, the imaging equipment, the processing equipment, the stereoplotters, and the reproduction equipment. Other activities needed to support remote sensing, which are often attached to the aerial surveys and photogrammetric unit, include the mapping, cartographic, and computer-graphics sections. If the aerial surveys and photogrammetry unit does contain all of these sections, then it usually relates well to other units within the transportation department, since it comprises a service unit on which most other units are greatly dependent. When this is the case, the logical place to house the remote-sensing laboratory is with the aerial surveys and photogrammetry unit.

A problem perceived with this setup is that units that specialize in a discipline (such as geology) may not want related personnel (such as geologists) placed separately within the aerial surveys and photogrammetry unit. To overcome possible adversities between units, the remote-sensing laboratory must have the complete respect and cooperation of the other units with which it interfaces. Remote-sensing sections that we observed function best when set up in this manner.

Remote-sensing laboratories can be attached to almost any unit, such as planning, location, or design. Units such as soils and geology may have their own small remote-sensing laboratories that request information from other internal units or hire private agencies to provide the imagery and analysis they need. Some serious problems are inherent with this approach. The interpreters may be able to do a good job with the imagery, but they may have little if any control over mission design and procurement. Such mission control may well be the most important aspect of the whole process. Noncentralized laboratories usually do not promote the use of remote sensing in the rest of the organization. An advantage, however, is that studies are limited to the specific functional unit, thus limiting personnel conflicts. This type of operation usually is not set up to do much research or to sponsor extensive improvements. It also fosters duplication of equipment, operation, and effort. For example, a good remote-sensing laboratory that operates in planning probably will not be fully used by other units, such as location and design, because of distractions caused by factors such as personal ambition, differences in modes of operation, lack of communication and understanding, and refusal or inability to provide the service needed. Although organizational management and supervision are the keys to all operations, the willingness to provide quality service, to cooperate, and to seek out those needing the service are also important factors.

Figure 2. Organizational structure of full-service remote-sensing laboratory within an aerial surveys and photogrammetric unit.



A remote-sensing laboratory can be under the jurisdiction of a specific unit but housed separately. It also can be established as a complete and separate unit. These alternatives also have their advantages and disadvantages. The greatest disadvantage of being housed separately is probably not having access to the peripheral equipment such as computer graphics and plotting equipment. By being a separate unit, acquisition of imagery may not be as expedient as it would be if the laboratory was attached to the aerial surveys unit, since requests to schedule missions may be placed on a waiting list and missions may rarely be combined. Missions designed for night flights and under adverse conditions may be refused. Pilots not trained for precise night flying may balk at such missions. Aerial photographers may also balk at using color infrared film because of the additional care needed in handling and exposing the film. Without a good service group, the addition of special equipment such as thermal scanners, radar, and multispectral scanners would not be effective. Although currently it may be far more economical to obtain this kind of imagery by contracting with private agencies, some equipment is inexpensive and should be housed in the unit.

Another way to handle remote-sensing needs is to rely entirely on private contractors. Problems with this method are difficulties in properly designing missions, in providing necessary controls, and in finding the needed expertise in required fields such as archaeology or pavement analysis. In order to get satisfactory results with this method, the relation between the private company and the transportation department must be very close, and the capability of the private company must not be exceeded. One advantage is that the company is used only when needed. Although the cost for an individual project may be high, the annual cost, as compared with an in-house operation, may be much lower. Some private companies also provide dependable and excellent interpretation services. On the other hand, few private companies have full remote-sensing capabilities, a fact that creates some problems. Even fewer private companies with full capabilities will be located near the study area. Increasing future demands may bring about an influx in the field of more dependable private companies. As this is accomplished, contracting to these companies may offer an attractive alternative to an in-house operation.

Five possibilities were mentioned above for housing a remote-sensing laboratory:

1. As part of the aerial surveys and photogrammetry unit,
2. As part of some unit such as planning or location that has considerable need for the laboratory,
3. In one or more units that have remote-sensing capabilities sufficient to satisfy their own particular needs,
4. In a totally separate unit, and
5. Through private companies by contract.

Based on our observations, the most effective remote-sensing operations appear to be those housed within aerial surveys and photogrammetry units. In addition, the most effective units provided service to many public agencies that reimbursed the laboratory for services rendered. Because the transportation department had responsibility for the laboratory in this case, it also had priority of service. A tentative organizational chart for the first alternative discussed is shown in Figure 2. Charts can be developed easily for the other alternatives. A fully operational remote-sensing laboratory can probably serve the needs of many state agencies in addition to the transportation department, such as surface mining, conservation, water resources, and wildlife resource agencies.

LEVEL OF SERVICE

When the establishment of a remote-sensing laboratory is being considered, some decisions must be made regarding the range and quality of service to be provided. The range and quality of service will depend on the equipment available, staffing and staff expertise, and interaction with all other units. The level-of-service concept is one of many possible approaches and probably can be demonstrated best by discussing some examples.

Full Service

Full service infers that the remote-sensing laboratory must be able to obtain the proper imagery, design the flight missions, provide full interpretive capability in all areas, and produce reports, maps, overlays, photographs, and any other needed graphics. Full service requires an extensive equipment layout, access to computer graphics equipment, printing and reproduction capability, and the ability to acquire the necessary types of imagery, including radar, satellite, and black-and-white photography. The most important element of the full-service approach is the ability to sit down with those who need the service and to take the time to work out all the details necessary for planning the mission: determine the kinds of imagery needed, the exact purpose of the project, and the exact form the output should take; set a time schedule for all efforts; allocate time and costs; and determine the detail to be included in the final report. These are crucial issues that must be worked out prior to initiating the study. Good estimates are needed, especially those that relate to study costs. The professional staff must be well trained, qualified, and respected. They should and must follow through on every project to the extent that they question the adequacy of the data gathered to meet the study's objectives, and they must determine if improvements can be made. This staff must be available for consultation by the users after the reports are completed. This type of operation becomes invaluable to the user.

Medium Level of Service

A medium level of service would probably constitute a resource commitment of equipment and personnel sufficient to provide well thought out and planned missions, good interpretation, a contract specification capability for color infrared photography and thermal infrared imagery, and personnel qualified in some of the disciplines that use remote sensing most. A well-qualified individual with a good general background in the use of remote sensing would be invaluable in training and assisting others in the use, analysis, and interpretation of imagery. At this level, more generalized prepared reports might accompany the package of imagery obtained for the requesting unit. A considerable amount of analysis and interpretation would still be left to the user. Only the key features would be delineated on the imagery and explained in the report. For this level of service, stereoscopes, zoomscopes, and other low-cost items of equipment needed to assist in visual interpretation must be available. Density-slicing equipment with color-coding capability may be helpful; however, due to its expense, it should be acquired only if the need for it can be justified.

Partial Level of Service

The partial-service concept may result in a remote-sensing laboratory being severely limited in the type of imagery it can provide, in the equipment it can acquire, and in the personnel it can employ. The remote-sensing laboratory may be limited, for instance, to obtaining only photographic imagery, i.e., panchromatic black and white, ektachrome color, black and white infrared, and color infrared. These types of imagery can be provided in-house by most standard aerial surveys units, although some aerial surveys units, for various reasons, strongly resist providing anything other than black-and-white aerial photography. Other types of imagery may be obtained through private companies, many of which are capable of meeting most imagery requirements.

Various types of imagery can be obtained from other agencies such as the EROS Data Center and the Tennessee Valley Authority. If the service to be provided includes evaluation and analysis of high-altitude and satellite imagery obtained from federal agencies, then the laboratory must be able to determine what types of imagery are available, the scale, dates of coverage, how much it will cost, and when it can be obtained. Some agencies, such as the EROS Data Center, provide automated interpretative assistance on a cooperative project basis. Other agencies, such as the Tennessee Valley Authority and the U.S. Department of Energy, obtain imagery of various kinds, such as thermal infrared imagery, for specific purposes. Such imagery may also serve the needs of the remote-sensing laboratory. Often a remote-sensing laboratory that provides only partial service can extend its service quantity considerably by taking advantage of the low-cost services provided by various outside agencies. Some private-sector companies, such as Texas Instruments and Mark Hurd Aerial Surveys, Inc., may have various types of imagery that, if satisfactory for the stated purpose, may be acquired at reduced rates. This also may be a way of extending the service level considerably at little extra cost.

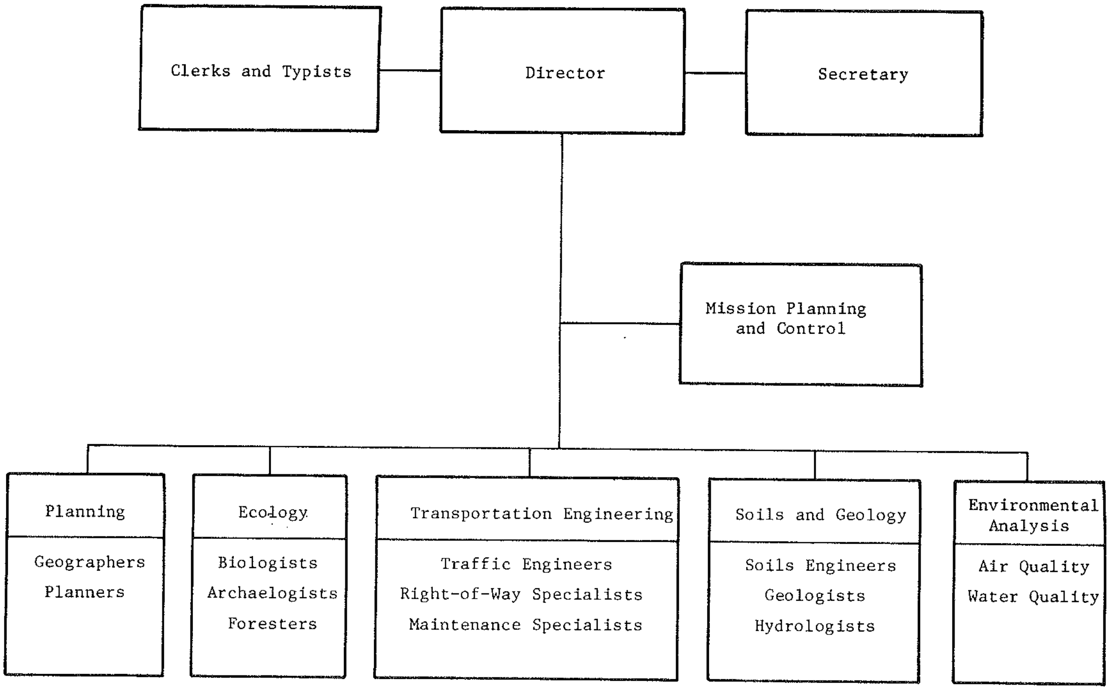
Low Level of Service

The lowest level of service for a remote-sensing laboratory would consist of providing only imagery, probably as a function of the aerial surveys and photogrammetry unit. Sometimes, this may include contracting for certain kinds of imagery, such as thermal infrared and radar. It may also include acquiring available imagery from other agencies and sources. This service level would not include interpretation, analysis, enhancement, or reporting. The lack of expertise for mission planning for the more sophisticated imagery may result in study failure. The flight mission for the purpose of obtaining thermal imagery, for instance, must be carefully timed to coincide with proper surface conditions. Only experts can design such missions. At this level of service, the studies that may be done are limited.

Influence of Personnel

Personnel are the key to the level of service that can be provided. At full service, staff personnel must be qualified in specific areas, such as archaeology, geology, biology, and forestry. These professional employees must be experts in their fields as well as in the use of remote sensing. They must also be able to design the mission, determine the types of imagery needed, use all available equipment in the interpretation process, perform data analyses, and prepare reports that are accurate and comprehendable. From this full-service level, the laboratory may be scaled down to the point that no professional employees are included on the staff in the various disciplinary areas and the laboratory provides only assistance in designing the mission and obtaining imagery. Generally, under the latter setup, the person requesting the imagery must know what type of imagery is needed and the conditions under which the mission should be flown. This setup may not be very effective, and it requires that the unit that uses the remote-sensing imagery have qualified interpreters. When more than one unit needs remote-sensing capabilities, duplication of equipment and manpower results.

Figure 3. Proposed tentative staffing plan for remote-sensing laboratory.



Influence of Equipment

Equipment available to assist the interpreter is rather extensive, and a fully equipped remote-sensing laboratory can cost millions of dollars, even when computer services and computer graphics capabilities are available from other groups. The full-service laboratory will probably contain such equipment as zoomscopes, density slicers, color-additive viewing equipment, an array of photographic equipment, magnification capability, and other automated and assisted visual interpretation equipment. Equipment available for analysis and interpretation affects the level of service that can be provided in a manner similar to the influence of personnel. If equipment is not available at a central location, the user must provide all equipment, even small hand lenses and pocket stereoscopes. Most remote-sensing laboratories will probably provide equipment at some intermediate level. Density-slicing equipment is fairly expensive but quite useful. Such equipment may best be housed at one location and made available to all qualified users. It may be practical to have the operation of analytical equipment assisted by one trained individual and the interpretation conducted by experts from the functional area that the study addresses to ensure accuracy. Usually, the more sophisticated the equipment, the greater the need for highly trained operators.

PERSONNEL REQUIREMENTS

Stringent personnel requirements are necessary for the professional employees, including the director of a remote-sensing laboratory. As illustrated in Figure 3, a full-service laboratory should employ a number of professional employees with good educational backgrounds in specific disciplinary areas. They should be well qualified through education and experience in the use and interpretation of remote-sensing imagery as applied specifically to their disciplinary areas. These positions should include, as a minimum, personnel with expertise in soils, geology, hydrology, geography, planning, ecology, biology, forestry, botany, archaeology, and transportation engineering. These employees should have rather broad backgrounds. For instance, the transportation engineer will be responsible for applying remote-sensing techniques to traffic engineering, maintenance, right-of-way, etc.

Under this setup, usually only one qualified individual, possibly with an assistant, will handle a specific area. In soils and geology, a soils engineer or a geologist may have to handle the entire area. In the ecology area, however, biologists and foresters are so different that both may be necessary. In the transportation-engineering area, a transportation specialist or someone with a broad general education and experience background may suffice, provided that this person works very closely with other units that need the services of the remote-sensing laboratory such as traffic engineering. The development of an effective laboratory is greatly dependent on obtaining a professional staff with good backgrounds in the use of remote sensing and in the interpretation of imagery. The laboratory should be set up so that it will be flexible enough to do studies in many broad areas, but yet restricted sufficiently, for example, to avoid letting biologists conduct traffic-engineering studies. The laboratory should provide a service and should not consider itself as being the final authority in any area. These laboratories should work with, support, and assist the units that have the responsibility for and specialize in a specific functional activity.

The director must be proficient in the management and operation of a remote-sensing laboratory. This individual must know about the various types of available imagery, instruments, and equipment; be familiar with interpretation methods and procedures; be proficient in mission design and control; be knowledgeable about photogrammetry and aerial surveys; have a good knowledge of photography and photographic laboratory procedures; and have good supervisory and managerial skills. It would be beneficial if this person were versed in the application of remote sensing in transportation, but few such individuals are available. The experience base of the director must be broad and must include positions of responsibility for problem solving, preferably in the role of team leader. Such individuals may have gained most of their experience in governmental agencies such as the National Aeronautics and Space Administration or military intelligence, in research at universities, or in private industry at such companies as Jet Propulsion Laboratory, Inc., and McDonnell-Douglas Aircraft Company. Work experience at more than one agency would also be an advantage to consider.

Personnel requirements will be predicated on the type of laboratory needed and by the type and level of operation envisioned. Overstaffing is probably worse than understaffing. Yet, adequate staffing of qualified personnel generates reliability and dependability. Unqualified personnel should not be hired, since the adverse effect on such a unit could be severe. Time and resources should be allocated for personnel training, which includes seminars, short courses, professional activity in the given discipline, and on-the-job training. Professional growth and development and peer recognition are especially important and should be provided. Dead-end positions cause serious problems and discontent and should be avoided if at all possible through the provision of promotional grades and eventually movement out of the remote-sensing laboratory into areas with more advancement potential. A progressive influx of personnel is essential to the generation of new ideas, creativity, and progress.

The management concept should encompass managerial and supervisory techniques necessary to operate a service-type organization and should be especially sensitive to restraints that control the operation. Management by objectives is one example of an effective management process and requires the development of realistic goals and objectives for the laboratory. The overall goals should be broad enough to encompass new methods, approaches, and developments. Goals should be receptive to change and include objectives that are realistic and flexible.

A remote-sensing laboratory must operate within a budget that could be expanded or reduced on an annual basis. This represents a definite restraint that must be recognized if a smooth, orderly operation is to be realized. Restrictions on the number and sometimes quality of personnel are also representative of restraints that can be imposed externally but that should not be permitted to unduly hamper the operation. Some trade-offs will always have to be made, and the goals and objectives should recognize and accept this reality. For instance, decisions often will be whether to acquire a piece of equipment, hire a needed professional, or postpone both for a year or indefinitely.

Table 1 lists the minimal needed staff, general qualifications, and estimated salary ranges. Salary ranges can be adjusted by a department's personnel section.

EQUIPMENT REQUIREMENTS

The equipment listed in Table 2 will be required for a full-service remote-sensing laboratory. For laboratories with less than full-service capabilities, the equipment should be chosen on the basis of expected study needs and on the qualifications of the professional staff. This applies to the more sophisticated equipment such as thermal scanners and density slicers. Most of the equipment listed under the first three categories in Table 2 is considered essential. This list is promulgated on the supposition that a full aerial surveys and photogrammetry unit exists or that this work is contracted for through the private sector and is available to the remote-sensing laboratory. Although a remote-sensing laboratory can function without access to computer terminals and computer-graphics capabilities, the availability of such equipment extends the laboratory's overall capability. Computer equipment is not itemized in Table 2 because, ordinarily, such equipment is on a time-lease basis, is centralized, or primarily serves another purpose. There are, however, circumstances that would necessitate the acquisition of a computer for the remote-sensing laboratory. The goals and objectives of the laboratory should be well established before considering the acquisition of a computer. An up-to-date cost estimate for equipping a remote-sensing laboratory can be accomplished quickly by referring to Table 2 and by consulting suppliers, many of whom advertise in such publications as Photogrammetric Engineering and Remote Sensing (published by the American Society of Photogrammetry, Falls Church, Virginia).

REMOTE SENSING THROUGH THE PRIVATE SECTOR

A number of firms in the private sector are set up to provide partial or full remote-sensing services, including radar and thermal scanning. Some of these firms are truly expert and have excellent interpretive capabilities, yet they do not totally substitute for a full in-house remote-sensing laboratory. For instance, it is difficult for private firms to maintain a full-time staff of individuals with expertise in the many areas addressed by a transportation department. The principal disadvantage of going to private firms is the difficulty in properly planning and designing the mission. The transportation department must prepare a set of rigid specifications, which means that it must have on hand at least one person well versed in remote sensing. Another disadvantage is that, due to contracting policies of most public agencies, consultant capabilities and department needs are difficult to realize fully or use. However, over the long run, contracting through the private sector may be the most economical approach. A fully organized company can provide service immediately, but a newly organized remote-sensing laboratory may not be fully operational for from a few months to a few years after being instituted.

For full effectiveness, a private company chosen to provide remote-sensing services should have full capability, have competent and well-qualified employees, be accessible, have good equipment, be reliable and dependable, and be able to work very closely with employees of the department of transportation. A possible approach may be to select a firm to provide services for a three- to five-year period. Such a company may be chosen on the basis of proposals submitted in response to a formal request that sets out specifications for quality, types of imagery that will be required, etc. Quantities to be delivered may be on demand within a limited schedule. A costing method will have to be devised that contains proper escalating clauses in order to protect the profit incentive of the private company. There seems to be a tendency among some transportation departments to be more stringent and more demanding of private companies than of their own organizations. Such an attitude is self-defeating and in the end will result in a lower quality of service.

RESEARCH CONSIDERATIONS

Research should be an important element of any well-

Table 1. Personnel requirements.

Personnel	Qualification	Estimated Annual Salary Range ($)
Director[a]	Expert in entire area of remote sensing is preferred; almost any disciplinary area is acceptable, but a generalist with a broad range of education and experience is best	30 000–40 000
Transportation specialists[a]	Should be transportation engineers with knowledge of structures, traffic engineering, maintenance, etc.	18 000–25 000
Soils and geology specialist[a]	Either a soils engineer or geologist may be used; individual should have some education and/or training in listed areas not represented by degree area and a knowledge of hydrology	18 000–25 000
Forester[a]	General background is probably best, since most have good educational backgrounds in wildlife, vegetation studies, resource management techniques, and statistics	16 000–25 000
Archaeologist[a]	Education in archaeology, anthropology, and historical documentation is necessary	14 000–20 000
Biologist[a]	General biologist with knowledge of aquatic life, mammals, and birds is needed; fisheries and wildlife majors will fit this description also	14 000–20 000
Geographer-planner[a]	Geographer-type planner may best fit the needs of this position because of more general background, which should include urban, rural, and transportation planning and especially the application of remote sensing	14 000–20 000
Secretary	Qualifications should be general, but individual must be able to adapt to use of technical terminology in many diversified areas; technical reports will be a major duty in addition to standard secretarial work	8 000–12 000
Clerks and typists	Typists should have ability to produce quality technical reports	7 000– 9 000
Editor	A background and education in journalism and/or English are preferred; individual must be able to handle technical writing; this is a valuable and useful position and must be staffed with a competent person	12 000–15 000

Note: The pilot who flies special missions may be assigned to the remote-sensing laboratory. If so, this person should have responsibility for assistance in mission planning and design but not the authority to dictate policy beyond personal safety. The aerial photographer or remote-sensing aerial equipment operator may or may not be assigned to the remote-sensing laboratory. If these persons are assigned to the laboratory, then they should be included in the list above.
[a]Professional.

Table 2. Equipment list and estimated cost.

Item	1981 Estimated Cost ($)
Adequate lighting (nonglare) within room and on images	
Simple general-use instruments to assist visual interpretation and analysis	
Magnifying glasses	
5 x large	15
10 x small	25
Pocket stereoscopes	20
Light tables (with even lighting)	150
Light tables with automatic film advance and retract mechanism	1000
Mirror stereoscope with magnification	1000
Planimeters, plain	250
Planimeters with digital readout	600
Dot grid for calculating areas	5
Overhead viewer (for transparencies)	500
Opaque projector with light curtain	1500
Sophisticated general-use instruments to assist visual interpretation and analysis	
Stereo zoomscope for cut or single frame transparency viewing	9000
Bausch & Lomb 95 zoom stereoscope or equivalent for viewing uncut roll film	5000
Specific-use instruments to obtain and analyze thermal imagery	
Thermal scanner (on-board mounted with magnetic tape) (Daedalus)	300 000
Thermal scanner with on-board analog computer analyzer (Daedalus)	700 000
Portable low resolution thermal scanners (AGA or Inframetrics, Inc.)	85 000
Density slicer with color coder, television camera and stand, analog computer, cursor or pointer control, and cathode ray tube (CRT) (color)	15 000
Polaroid camera and hood for use with density slicer	1000
Direct color hard copier (Dunn Instruments or equal)	12 000
Instruments to density slice and color code black-and-white imagery (same as specific-use instruments listed above)	
Landsat satellite imagery interpretation and analysis	
Interpretation of Landsat imagery, when obtained in the form of photographs, may be accomplished with the types of instruments listed here and under the heading of simple general-use instruments	
Landsat data tape reader with enhancement and data classification capability, output on CRT with hard-copy prints provided by Dunn Instruments or equal	105 000
Color-additive viewer for analysis of Landsat imagery (not recommended for acquisition unless it can be obtained from government surplus and reconditioned for a total cost of less than $1000)	1000
Radar imagery	
In siting dams and bridges and in locating highways, available radar imagery should be ordered; analysis of such imagery only necessitates the use of inexpensive types of equipment as listed under general-use instruments	
When coverage is not available, contracting for radar imagery is advised rather than purchase of radar equipment	
Radar equipment	500 000–1 000 000
Color infrared capability—cost over and above that required to produce black-and-white photography	
Additional film cost	-[a]
Film storage cost assumes refrigeration is currently used	None
Additional processing cost	-[b]
Digital analysis equipment	
Television camera, light table, flood lights, adjustable television camera mount, cursor control and video monitor	20 000
Digital-to-analog and analog-to-digital converter	15 000
Additional addressable memory	15 000
Minicomputer including tape and disk storage	50 000
Software (varies with complexity of analyses desired)	10 000–100 000
Active table, cursor, menu tablet	10 000

[a]Costs about three times that of black-and-white photography.
[b]Costs about two-and-a-half times that of black-and-white photography.

functioning unit. This is especially true for a remote-sensing laboratory because of the continuous advances in automated interpretation, analysis techniques, new films, computer applications, etc. Research in new application areas is essential for a viable laboratory. New ideas, techniques, and methods should be explored and used as soon as a reasonable degree of confidence is obtained. Of course, research should not be permitted to interfere with operations, nor should production reliability be sacrificed. A reasonable range of effort and commitment of resources to research is probably between 10 and 20 percent, with some reasonable degree of flexibility between research and production. Pure or basic research, in most cases, should be relegated to the higher educational institutions, but applied research is appropriate and probably essential. An example would be studies on the use of thermal scanners for detecting moisture under pavements. It is probably not appropriate for such a unit to commit more than 20 percent of its resources to research. Above this commitment, one must ask what benefits accrue to the operational units. Research is, however, necessary for progress, generation of new ideas, and creativity. Occasional new personnel and research are necessary ingredients for change and progress and for helping to prevent stagnation.

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