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64 Soil Science

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FOREWORD

This RECORD addresses some of the problems of classification and identification of soils for engineering purposes. It will be useful to those engineers involved in early planning and route location as well as to soils engineers in general.

Economy of time and effort will be brought about by utilization of all available information on soils and geology. Johnson describes a well-organized and efficient system for Ohio, which brings about 80 percent of ground truth to light with a minimum of field checking and explorations.

Crawford, Thomas, and Stout developed a computerized system to correlate engineering soils data, representing 20 years of highway soil testing, with pedological soil series units. The correlated data are useful in predicting soil engineering characteristics for proposed routes, aiding in route location and rights-of-way appraisal, and reducing the expenditures for drilling and sampling.

Collapsible soils are difficult to distinguish from ordinary silts until they give way. Thus an important contribution has been made by Arman and Thornton in their development of series of tests that serve to identify collapsible soils. These tests are simple; when the soil meets two of the four stated conditions, it may be considered collapsible and appropriate design and construction techniques applied.

Arulanandan, Basu, and Scharlin present studies to show that the value of the magnitude of dielectric dispersion can be used to characterize clays without destroying or separating the soil mass into different sizes.

A device for measuring subsieve sizes in the field is described by Long and Briggs. It has particular application to nonplastic soils and gives results comparable with those of the standard ASTM hydrometer technique.

The last two papers are companion papers and should be viewed together: They attempt to present to the soils engineer the new Soil Taxonomy, the pedological soil classification system. The helpful and indicative portions of the nomenclature and description can be utilized by the engineer to enhance his knowledge and broaden his basis for understanding this very complex subject, soil. Philipson, Sangrey, and Arnold have made a commendable contribution to translating between the pedologists' and the engineers' interests.

COMPILING PRELIMINARY FOUNDATION DATA FROM EXISTING INFORMATION ON SOILS AND GEOLOGY

Gene O. Johnson, Ohio Department of Highways

The production of foundation data simultaneously with topographic control for highway location and design is created by researching, processing, and presenting the geologic and soils information along a proposed highway location at the same time photogrammetric maps are being plotted. The foundation data are researched from existing field surveys on geology, soils, and hydrology. Photo interpretation is used to detect foundation problems such as landslides, collapse of mine voids, peat bogs, and wet zones. A field check verifies the remote-sensing and foundation data and provides additional first-hand information in critical areas. A written geologic evaluation of the proposed location, with accompanying maps, covers the foundation and slope problems by explaining the geology, soils, and hydrologic controls in the terrain. The cost of this program ranges from 50 to 100 man-hours per mile of proposed highway.

•HIGHWAY foundation problems, such as peat bogs, landslides, wet zones, soft subgrades, and coal mine collapses, are becoming more catastrophic and expensive to solve as modern design and construction practices expand highway involvement in natural and man-made terrain features. Many foundation problems are discovered too late in a highway's development to be able to economically avoid the problem areas. This necessitates the introduction of design changes or expensive corrective measures during the final design or construction.

A few examples of engineering problems that confront current highway programs are the rearrangement of design geometrics due to the discovery of a deep peat bog under a proposed centerline, the delay of the opening date for a new highway because of a landslide triggered by construction, and a pavement collapse into an abandoned coal mine.

Published and resource data on foundation information applicable to the early location and design of highways are available in Ohio from several earth-oriented disciplines. These data have the potential of producing preliminary foundation information throughout Ohio, with as much as 70 to 80 percent ground truth that can be used to make critical location decisions while the highway design is still in the formative stages. Soils, bedrock, hydrology, geomorphology, and mineral industry history are some of the composite data sources that can produce a preliminary stability evaluation along a proposed highway route.

The presentation of the evaluated data is most effectively produced simultaneously with the topographic mapping for highway location and design. This is the first stage of highway development in which the relation of the proposed route is tied to the landform with relative certainty. Through this topographic control, evaluations can be made with a minimum of extraneous effort. Foundation data can be collected, reviewed, and interpreted during the photogrammetric compilation of topographic mapping of highway sites; a report with geologic profiles, cross sections, and stability evaluations can be produced to define problem areas and to suggest engineering advantages such as local aggregate sources or disadvantages of the natural and man-made features.

Sponsored by Committee on Exploration and Classification of Earth Materials.

The geological engineering unit of the aerial engineering section has been producing evaluations of highway foundation stability simultaneously with the compilation of photogrammetric maps for highway corridor studies, location, and design. The system of landform evaluation is organized into three modes of development: (a) review of all resources for available foundation information, (b) compilation and interpretation of the data, and (c) production of the written report describing the engineering features of the landform. This paper is a compendium of the system of producing preliminary foundation data from existing information on soils and geology for the Ohio Department of Highways and is designed to disseminate the sources, techniques, and results of that system.

COMPILATION OF FOUNDATION DATA

The research of previously composed data available along the highway location has a tenfold return on the time invested. An example of the time element and manpower savings is the measured rock section performed by a field geologist. A detailed measured section in the field may take up to 6 hours to complete with sufficient integrity to allow interpretation for highway locations. However, several times this amount of data can be compiled in less than an hour from the files and literature of the Ohio Geological Survey along with interpretations of the past engineering performance of individual rock members. The example demonstrates the time savings available in all seven of the research areas explored by the geological engineering unit.

The seven primary sources of information utilized are Ohio and U.S. Geological Surveys, Ohio Division of Oil and Gas, Ohio Division of Groundwater Resources, Ohio Division of Lands and Soils, United States Department of Agriculture Soil Conservation Service, Ohio Division of Mines, and photo interpretation and field checks. The agencies noted are the major depositories of foundation data within the state of Ohio, and similar agencies exist in many other states. Photo interpretation and field checks verify the validity of the other information and aid in collecting new and specifically oriented data pertaining to the interrelation of the rock, soil, and water constituents of the landform.

The Ohio Geological Survey has produced several reference works to facilitate the rapid location of applicable reference information. These include the list of publications of the Survey's literature and the Bibliography of Ohio Geology. From these two sources the published and unpublished data including these and in-house reports applicable to the project area are located and then gleaned for points of information relating to the foundation. The survey also has on file maps and measured sections with specific rock units delineated and defined as to type, color, thickness, composition, and relative strength.

The oil and gas division is the state depository of oil and gas well locations and logs. The files and maps of this division have information on wells dating back to the 1900s. The well locations are organized by political coordinates and are surveyed at the time of drilling. The well logs contain pertinent information relative to the completion or abandonment of the individual wells. Data available on the completion logs include location, initial oil or gas production, subsurface stratigraphy, and aquifers encountered in the well. The abandoned well logs record the location, subsurface stratigraphy, aquifers, and the plugging record of the well. By Ohio law, abandoned wells must be plugged between formations to prohibit interformational leakage and also plugged at the surface to avoid collapse or artesian water leakage. If these plugs are improperly set or if wooden plugs are used and rot out, the abandoned well may become a sinkhole for subsiding soil or a source of contaminated artesian water. These data give the highway engineer the knowledge from which he can plan construction practices to avoid destruction of the surface plugs and release of subterranean water, oil, or gas.

The groundwater resources division has on file the records of all the residential and industrial water wells drilled in the state since the 1950s. The water well data are recorded by the individual operators at the time of drilling and sent to the division. The water well's location, owner's name, depth to rock, total depth of the well, and pumping test water-level drawdown are some of the well data recorded on the logs. These data define the location and quantity of the aquifers along the highway corridors and contain information that is another source of stratigraphic control supplementing the measured rock sections from the Ohio Geological Survey. The diverse background of the well drillers makes quality control a problem in this data source. As a result, much of the information must be interpreted as to the real geologic significance. Nevertheless, this is a valuable source for obtaining the main control for the definition of the hydrologic setting in the project area including water flow, direction, and quantity. The definition of this natural phenomenon allows the highway geologic engineer to predict the sources and influences of lubricating groundwater in the proposed back slopes and fill areas. Other data available from this division include published reports and maps of county-wide hydrology, water quality, and top of bedrock.

The lands and soils division and the soil conservation service have been mapping the soils of Ohio in detail since the 1930s. At present, approximately 70 percent of the state is covered by county soils survey reports. Numerous spot maps of individual farm plots are available in the counties where whole county coverage has not been completed. These maps are produced by an experienced soil scientist who determines the type of soil of every lot and landform. By definition of a prescribed set of rules, each soil must fall within a set of characteristic limitations. The soils mapping of Ohio and other states includes the soil series, topographic slope, and erosion factors (how much topsoil has been lost). Also, the tables in the text of the report include the average qualitative and quantitative engineering characteristics of each soil series to a depth of 5 ft or more. The qualitative characteristics include engineering soil type (AASHO, Ohio, or Unified), engineering recommendations for embankment stability-bearing value-subgrade rating, drainage and seasonal high water table, shrink-swell, corrosivity, depth to bedrock plus location, origin, general agricultural use, and other pertinent miscellaneous information. The quantitative characteristics include the physical and mechanical analysis of the individual horizons in the average type of soil. These characteristics include soil texture, engineering classification, group index, liquid limit, plastic index, optimum moisture, maximum dry density, soil pH, and mechanical sieve analysis with silt and clay percentages. From these data, an accurate, representative engineering picture of the individual soils along the highway project can be developed and used to estimate the effect of the proposed highway on the landform's soils and vice versa.

The mines division has on file many of the mine maps of abandoned mines in Ohio and is a data source when a proposed highway is to enter the coal-bearing regions of eastern Ohio. The maps are drawn to a scale of 1 in. equals either 100 or 200 ft, and some date from as far back as the turn of the century. The mine maps show the entries, manways, and pillars of the mine, elevations of the mine floors, and the relation of the mine to section corners on the surface. These maps are integrated with the photogrammetric maps and indicate the relations of mine voids, groundwater from the mines, and remaining mineral resources in the terrain to the proposed highway location.

Aerial photo interpretation is one of the best methods of obtaining information for the foundation evaluation of highway locations when used in conjunction with stereoplotted topographic mapping. Wet zones, peat bogs, potential sites of soft foundation, mine void collapse, and active and potential slide areas are only a few of the foundation problems revealed by this technique. Areas of foundation advantage, such as good fill material sites and zones of definite foundation stability, can also be delineated by photo interpretation. The spatial relation of the individual foundation features are described on the highway location map via the mapping model in the stereoplotter. This topographic control enables the correlation of the foundation problems to the geologic and soils factors causing the instability. With this knowledge of the problem areas in the terrain, the potential foundation problems and associated extra costs can be evaluated.

The field check is performed after most of the data have been collected from the sources. It is used to check and evaluate the information and to gather additional data. The photo interpretation of the area is checked for the ground truth and any additional developments in those features since the flight date of the photography. The previously measured sections are reviewed to associate the exposures with the office data. Additional rock sections can be measured and used to expand the data bank of geologic information. A soil tube is used to analyze the soil profile and investigate the slides, wet zones, and other pertinent foundation features along the corridor. Geophysical investigations, such as seismic or resistivity surveys, can be used to define top of rock elevations and depth to specific materials at critical points. The field check usually requires only 1 day on the project location for a representative 2- to 4-mile job.

PROCESSING INFORMATION

The procedure for processing the foundation information includes correlating stratigraphic terms to the exposed rocks, extending the stratigraphy through the area along the highway corridor by using water wells and photo interpretation, cross-referencing the soil's parent material to the terrain, and correlating foundation problems with specific units. The photogrammetric map usually serves as the best base for this procedure and ultimately provides the compiler with a three-dimensional plan of the topography and geology from which he can produce diagrams and demonstrations for the report.

Bedrock is the basement of all landforms and is the prime factor controlling terrain evolution and stability. With a detailed understanding of the bedrock, all the other superimposed materials, such as soils, alluvium, and colluvium, are easily defined and evaluated. The bedrock correlation throughout the project areas is developed with the geologic discipline by compiling the measured sections with other geologic data on profiles or maps and then correlating the stratigraphic terms to the rock unit. The stratigraphic names of formations and members used in geology have been assigned by geologists in order to facilitate definition and communication. By keying these names to the types of rock in the highway corridor, the discussion in the text of the report is easily organized and interpreted. After the major geologic units have been established by definition and location in the project area, the water well logs are used to extend the outcrop control into the subsurface and to define the hydrologic setting in the area. Photo interpretation is used to extend the surface control by studying the photo pattern at a known rock unit outcrop and observing the lateral extent of that pattern in the landform. Photo interpretation is also used to extend the control on the hydrologic setting by spotting local wet zones and springs.

The soils information, including the physical parameters of the parent material, are used to process the terrain by cross-referencing the substratum data. This extends the surface control, as defined by the soil type, into the subsurface control with the use of data from water wells and measured sections. The soils information also reveals the detailed engineering characteristics of the most important upper 5 ft of the terrain. An engineering soils map is compiled from existing soils mapping on a copy of the photogrammetric base map. This facilitates orientation and interpretation of the data and produces one of the most easily explained demonstrations of foundation potential for the report. The soils data are composed on engineering soils sheets to be used in the report appendix. The final product of the soils processing is a reasonably accurate estimate of the soil engineering capability and a detailed map of the geographic limits of those estimates.

The correlation of the foundation problems is produced most effectively while the photogrammetric map is being compiled in the stereoplotters. This enables the exact limits of the foundation problem to be defined and delineated on the highway corridor map. This map then becomes the base for the geology and soils maps. This provides a three-dimensional aspect to the problem areas for subsequent analysis and documentation and facilitates the correlation of the various foundation problems with the specific geologic and soils units causing the instability.

GEOLOGIC REPORT

The geologic evaluation is the written total of all the pertinent information revealed by the compiler during the research and processing of the foundation data. This report presents in an explanatory sequence all the influential factors that define the engineering characteristics of the landform components and foundation problems. The detailed topics of the reports are reviewed in the following general outline used by the personnel of the geological engineering unit.

Abstract

The abstract includes the location and topography of the project area with engineering soils, general geologic reasons, and controls of the foundation problems. The abstract also includes an explanation of the economic mineral resources of the area and the major types of foundation problems including the specific controls for the definite and probable foundation problems.

Geology

Introduction—The geologic introduction includes the physiographic province, geologic formations, general structural features, general lithologies, and potential mineral resources along the proposed highway.

The second paragraph of the introduction contains the geologic history of the area including the depositional history of the bedrock, the erosional and weathering development, and the post-erosion depositional history of the area if any.

Bedrock—The bedrock text includes a description of the individual lithologic characteristics of each rock unit in chronological order. The characteristics include the most useful information, such as thickness, type of rock, color, texture, mineral composition, facies, structural features, and the engineering potential of each unit. Special emphasis is placed on the lithologic units causing the foundation problems and the processes involved.

Nonbedrock—The data on nonbedrock materials (glacial, alluvial, colluvial, and man-made land) are each described in a paragraph including the type, location, source, and composition of each unit. Special attention is paid to nonbedrock material involved in foundation problems along the route.

Economic Geology—The valuable mineral deposits are defined and described with references to information sources. Both potential and real economic minerals are evaluated. Other potential functions involved with mineral development, such as increased resource transport traffic, can be discussed.

Summary—The summary includes a brief review of the significant geologic points applicable to the foundation problems. The rocks with useful engineering characteristics and/or significant economic mineral resources within the right-of-way lines are also noted.

Soils

Introduction—The soils introduction includes sources of information, climate, precipitation, and general parent materials of the area plus the engineering evaluation of the soil associations along the proposed highway. A brief reference is made to the soils appendix.

Residual, Glacial, and Alluvial Soils—The information on residual, glacial, and alluvial soils groups includes the origins, thickness, occurrence, and engineering characteristics of the problem soils. The colluvial soils are included in the residual section. The engineering characteristics of the soil groups contain the engineering classification, foundation potential, agricultural value, and the probable groundwater influence (e.g., shrink-swell).

Special Materials—The special soils are the man-made soils and debris, i.e., dumps mine waste, fills, and so forth. The data on these materials contain the origin, thickness, composition, occurrence, age, and engineering characteristics. The specific engineering characteristics that are included are the engineering classification, foundation potentials, agricultural value, and probable groundwater influence.

Summary—The soils summary includes a review of the significant soil quality such as clay content and type/ shrink-swell, slide potential, frost action, and any other characteristics that may be involved in the foundation problems. An evaluation of the potential engineering use of the soils along the right-of-way is included.

Foundation Problems

Introduction—The introduction begins with a general overview of the specific problems and the major causes of these problems. It also contains an explanation of the field observations and photo interpretation techniques used as methods of detection and the sources of geologic and soils information.

The definition of the system for the foundation stability potential is presented as the classes of definite problems, probable problems, and possible problems. The definite foundation problems are defined as active hazards within the right-of-way. The probable foundation problems are defined as the inactive hazards in the right-of-way plus the active hazards threatening the right-of-way. The possible foundation problems are defined as areas within the right-of-way that could develop into hazards.

Individual Foundation Problems—Each of the three classes is presented as individual foundation problems located by reference to centerline stationing. This sequence is taken from the photogrammetric map and can be demonstrated by single-page maps of each area plus a typical geologic profile of the area.

Summary—The summary includes a grouping of the associated foundation problems and a general explanation of their causes.

Conclusions

Introduction—The introduction to the conclusions includes the proposed location of the highway centerline, important geology of the area, and soil associations with engineering classifications.

Foundation Problems—The definite and probable foundation problems are presented in numerical sequence as plotted on the map with a concise review of the individual problems. This review includes the type, location, cause, and favorable engineering capabilities of each foundation problem. The total number of possible problems is included.

Evaluation—The conclusions will also include an evaluation of the project's overall foundation stability.

CONCLUSIONS

The compilation of preliminary foundation data from existing information on soils and geology is effectively created by researching the various sources of data available, processing the information through the geologic discipline, and producing a report with diagrams and text describing the foundation of the highway location. With this system of research, approximately 70 to 80 percent ground truth is produced during photogrammetric compilation of topographic maps to be used for highway corridor studies or location and design. The distribution of the report reaches the design and construction agencies in the Ohio Department of Highways almost simultaneously with their receipt of the highway plan map. At this stage of the highway plan development, critical location and design decisions can be made to solve the foundation problems along the proposed route. The cost of this program ranges from 50 to 100 man-hours per mile of proposed highway.

COMPUTERIZED SOIL TEST DATA FOR HIGHWAY DESIGN

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Sample sites of 22,404 highway engineering soil test samples, representing more than 20 years of highway soil testing throughout South Dakota, were precisely located on soil maps of the National Cooperative Soil Survey, and the test data for each sample site were identified by soil series name. Mapping was sufficiently accurate and most soil series were sufficiently unique to encompass a relatively narrow range of values for any engineering characteristic. The engineering test data include gradation, liquid limit, plasticity index, maximum density, and optimum moisture. The data were placed on computer tape, and a statistical program was written to compute minimum, maximum, mean, and standard deviation of test data, Unified Soil Classification System, old and new AASHO Soil Classification Systems, and mean and maximum California bearing ratio for each horizon of each soil series. Both the unprocessed and the statistical data have been sorted and printed out in several forms for maximum usefulness. The correlated data enable engineers to use pedological soil survey maps to accurately predict the engineering characteristics of soils along proposed highway routes, assist engineers in planning a much abbreviated and economical yet more effective drilling and testing program, indicate specific locations of possible sources of granular and select borrow materials, make possible the compilation of large-scale engineering soil maps or profiles based on any engineering characteristic, aid in route selection, right-of-way appraisal, and location of selected soil series, and give soil scientists and engineers reliable characterizations of soil series based on statistically significant sample size.

•DURING the course of designing and constructing highways, the South Dakota Department of Highways has obtained thousands of soil samples along highway routes during the past quarter century. These samples have all been tested to determine their engineering characteristics. This vast collection of soil information was of very little use after design and construction of the projects on which the samples were taken because the data could not be extended beyond the immediate area of sampling due to a lack of any type of engineering soil mapping.

In some cases, a soil testing program was conducted on new routes that closely parallel old routes even though they were tested originally. Figure 1 shows I-90, which in many places is within ½ mile of the federal-aid routes it replaces over most of its 414-mile length across South Dakota. Soil samples taken along much of the old route could not readily be used in the design of the new route because the areal extent of the various soils was not known. As a result, a new soil exploration and testing program was conducted on much of the new route. It was at this time that the study discussed in this report was started. Its main goal was to find a way of using the large amount of past soil testing experience on new highway locations.

Sponsored by Committee on Exploration and Classification of Earth Materials.

The U.S. Department of Agriculture's Soil Conservation Service (SCS) in South Dakota has, during the normal course of its work, accumulated a sizable store of published and unpublished soil maps and soil classification information. In 1965 it was decided that an attempt would be made to determine the soil series represented by each highway soil sample based on the type of soil mapped at each sample site. If found to be statistically reliable, this would provide a means of extending the engineering soil data over the entire area mapped by the SCS. Preliminary work indicated that mapping was sufficiently accurate, and most soil series were sufficiently unique to encompass a relatively narrow range of values for any given engineering characteristic.

This paper presents a discussion of the method and results of correlating soil series names with 22,404 engineering soil samples and developing a statistical program to present the data in a useful form.

RECORDING SOIL TEST DATA

The first step in correlating engineering soil test data with SCS taxonomic units was the orderly tabulation of the engineering data. A coding sheet was used to record the engineering data and the project and location data for each sample site. These data included project number, stationing, offset, depth, gradation, liquid limit, plasticity index, maximum density, optimum moisture, and color of each soil sample. This information was then placed on computer-punched cards.

To avoid lengthy checking of the soil classification data as recorded on the original soil data sheets, a computer program was written and each soil sample classified in accordance with AASHO, Unified, and highway textural classification systems. The computer was also programmed to detect obvious errors in recording data and keypunch errors, such as checking to see that the liquid limit value for each sample was larger than the plasticity index and that the percentage passing each sieve was greater than or equal to the percentage passing the next smaller sieve size.

Sample location information, engineering characteristics data, and classifications of each sample were then printed out by the computer. With this printout and a map of each highway project, the exact location from which each soil sample was obtained could be determined. With this information in hand, the SCS started a correlation and identification procedure. This procedure usually did not involve field inspection but was carried on in the office using test information, location of samples, and soil survey maps to properly identify the soils concerned. Each soil series was assigned a code number that was placed on the data sheet for each sample. In addition to soil series identification, the horizon designation was also determined. The depth of engineering soil samples often spanned more than one horizon, but the horizon thought to be best represented by the sample depth and test data was selected. Horizon designations were limited to A, B, C, 2C, and R.

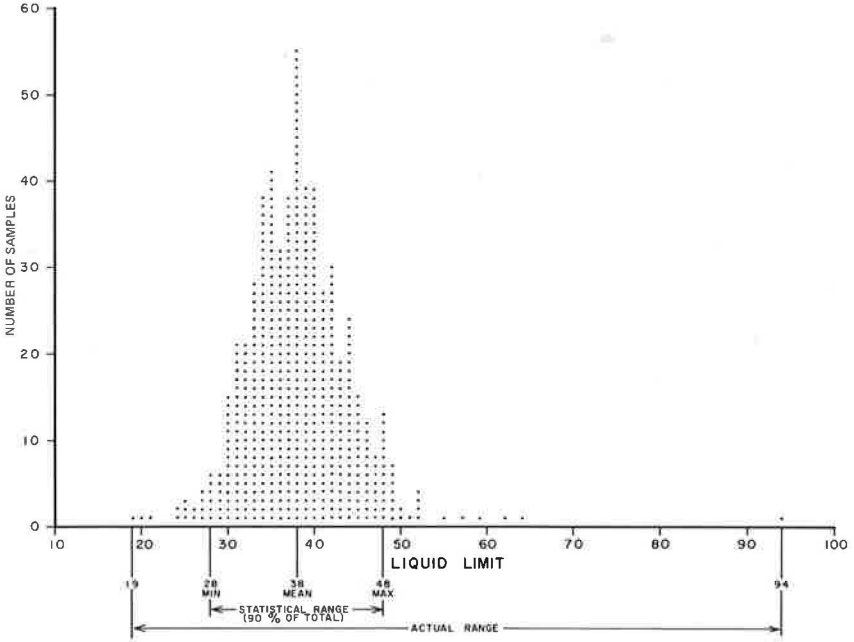
Following the correlation of engineering data with the soil types, the next step was to print out the correlated data.

ANALYSIS OF DATA

Upon completion of the correlation portion of this study 22,404 individual soil samples had been processed. This was still a prodigious volume of soil information that, to be useful, had to be reduced to a concentrated yet meaningful form. Figure 2 shows the distribution of the liquid limit values of the 561 samples of the Houdek series, C-horizon. The actual range of these values was from 19 to 94. This range includes several samples that obviously are not within the concept of the Houdek series, C-horizon. Through statistical analysis it was found that 90 percent of the soil can be expected to fall within the range of 28 to 48, using the standard deviation of 6.2 with a mean of 38. This limited range better portrays the actual variation expected in the C-horizon of areas mapped as the Houdek series. The maximum and minimum values shown in Figure 3 for all engineering characteristics are statistically derived to include 90 percent of the range centered about the mean, with the extreme upper and lower 5 percent excluded. The soils at these extremes are assumed to be inclusions of other soils that would not be called Houdek if they occurred as areas large enough to be

Figure 1. Old and new highway routes across South Dakota.

Figure 2. Sample distribution curve for Houdek series, C-horizon.



mapped separately. This results, for instance, in 95 percent of liquid limits for each soil or horizon falling below the maximum values shown. These data were then calculated for all horizons of all series by use of a computer program. Figure 3 is an example of the computer output from this program. This printout includes some additional information that the computer was programmed to provide. The new AASHO Soil Classification System was added showing the revised group index numbers. Also added were the California bearing ratio (CBR) values as determined from the liquid limit as calculated by the South Dakota Department of Highways. Figure 4 shows the relation of liquid limit values and CBR values as used in highway design procedures in South Dakota.

The soil data have been printed out in the following forms:

1. The results of the statistical program are machine-sorted (a) statewide by series as shown in Figure 3 (this is the primary end product), (b) by counties (in order of series within each county), and (c) by series (sorted by counties in which each series occurs); and
2. The individual sample data are machine-sorted (a) statewide by project and stationing, (b) by county (in order of series and horizons within each county), (c) statewide by soil series and horizon (in order of increasing liquid limit within each series and horizon), and (d) by AASHO Soil Classification System.

Printouts of programs for any of the statistical or individual sample data sorts are available from the South Dakota Department of Highways.

USES OF CORRELATED SOIL DATA BY THE SOUTH DAKOTA DEPARTMENT OF HIGHWAYS

Highway Design

With the correlation of engineering properties of soil with the soil maps produced by the SCS, engineers have a means of extending their knowledge of a soil from the immediate area in which it was sampled to the entire area over which the soil is found. The agriculture industry has been extending its knowledge of soil in this manner for years. In the past, the lack of engineering soil maps and the lack of correlation of engineering soil properties with existing soil maps have prevented engineers from applying their knowledge of soil over broad areas of the state. Where soil maps are published, an engineer must only locate a proposed highway route on the maps, scale the distance to each soil contact boundary, and look up the engineering characteristics of each soil to determine the soil properties along the proposed route. In areas where published maps are not available, an engineer may obtain soil mapping information from the appropriate SCS office. In areas that have not been mapped, SCS can rapidly map a strip of land along and adjacent to a proposed route. Soil maps are thus available or can be obtained for any area within the state with a minimum of effort.

On some projects where time does not permit a detailed field drilling and sampling program, the engineer has found it necessary and expedient to design directly from the computer data using soil survey maps. In South Dakota the standard method of determining the strength of soil requires using the average liquid limit from a group of samples sorted by similar characteristics and test results, determining the CBR from the curve shown in Figure 4, and proceeding with a CBR design method. By using the average liquid limit, 50 percent of the highways constructed on this soil are theoretically underdesigned. However, by using the maximum value as shown in Figure 3, 95 percent of the highways constructed on a given soil series will be properly designed. For most soils this increase will add approximately 1 in. of thickness. The estimated CBR values are computed by using both the mean liquid limit and the maximum liquid limit.

Soil Investigations and Drilling Programs

In South Dakota it was standard practice for many years to drill every 300 to 500 ft and sample every 1,200 to 1,500 ft on every project. By using soil maps and computerized data, the engineer now plans a much reduced yet more effective soil drilling and sampling program by concentrating his efforts in excavation and borrow areas, in areas where engineering soil data are meager, on soil types where the range of values of engineering properties is extraordinarily wide, or where problem areas appear. With this system, field drilling, sampling, and testing have been reduced substantially. Drilling on the average project now takes about 2½ to 3 days against about 10 days previously.

Materials Inventory

By using a different sorting of the data from the computer, the soils are grouped according to the AASHO Soil Classification System. In other words, all A-1-a soils are grouped together. This allows people involved in materials inventory studies to determine where valuable construction materials have been found throughout the state along existing highway routes.

Engineering Soil Maps

When the engineering properties of each soil are known, it is possible to prepare engineering soil maps by setting up class interval limits for any engineering property and assigning a color or pattern to each class interval. This can be done for any scale or intensity of mapping but is probably most useful when used on large-scale generalized county or state maps. A state engineering soil map has been prepared for South Dakota using mean liquid limits in five class intervals. The base map used is entitled Soil Associations of South Dakota. To date, the South Dakota Department of Highways has hand-colored copies for its own use, but the map has not been published.

Although not directly related to this project, it seems appropriate to mention that the SCS also furnishes other information about soils that is useful to engineers. In addition to published soil surveys, such information can be obtained from soil interpretation sheets that are being prepared to supplement soil series descriptions. The information of most interest to the highway engineer is the ratings of shrink-swell potential, potential frost action, and corrosivity to uncoated steel and concrete. State soil maps are being prepared for the corrosivity factors.

Other Engineering Uses

Other applications of computerized soil data include favorable route selection, aid to right-of-way appraisal, aid in locating various types of soils for use in the soil mechanics classes of engineering schools, and planning roadside improvement projects and rest areas.

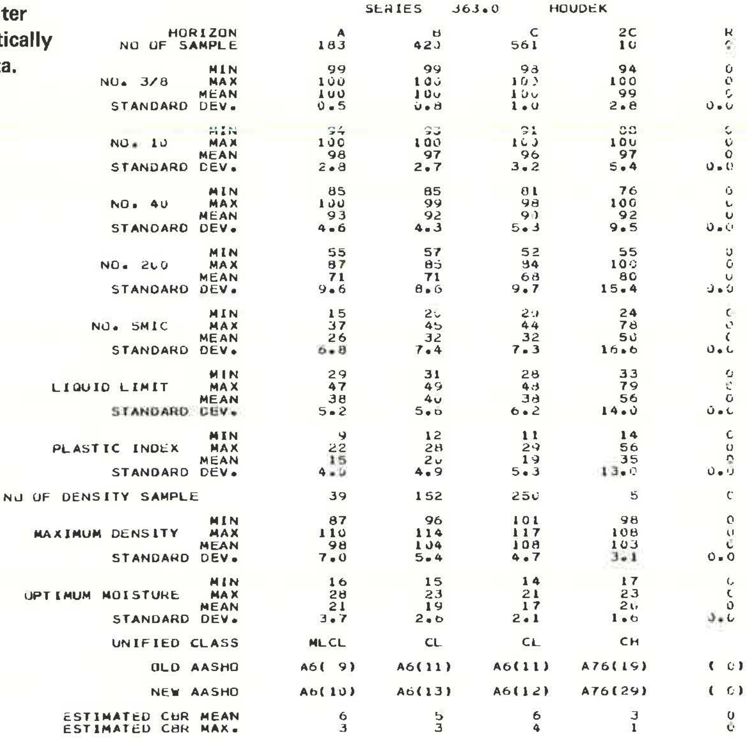
USES OF CORRELATED SOIL DATA BY SCS

A statistical printout of the data for each county allows a comparison of engineering properties of soils from one county to another. The data given in Table 1 indicate that the Houdek series in Davison County is slightly less clayey than in other counties in which the soil occurs. Also the Kyle series in Fall River County is markedly less clayey than the Kyle soils from other counties. This information may indicate the necessity for establishing a new series, reviewing the concept of the Kyle soil in Fall River County, or classifying the soil in a different series.

The data give a more reliable characterization of a soil type than the usual one or two modal samples because of the statistical significance of the larger sample size.

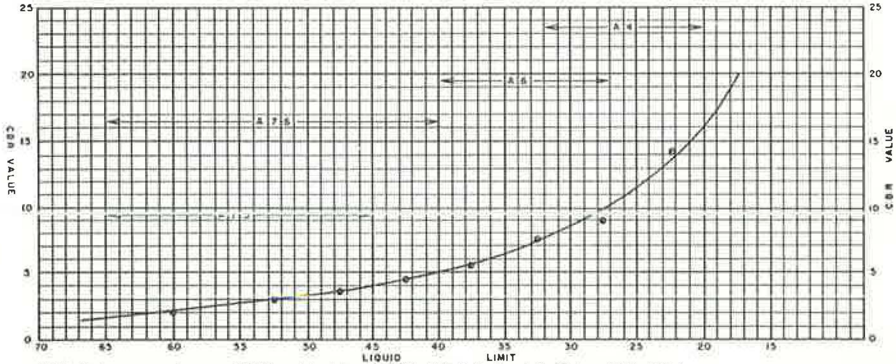
PROJECT COST AND BENEFITS

Total project cost to the South Dakota Department of Highways was $54,000, including data collection and coding, punching cards, preparing printouts and maps for series identification of SCS, tape updating, programming, and producing final printouts of data in several forms. Time spent by the SCS in locating and identifying soil samples is not included in this figure.



```
                                      SERIES    363.0      HOUDEK
              HORIZON           A           B           C          2C          R
         NO OF SAMPLE         183         420         561          10          0

                  MIN          99          99          98          94          0
     NO. 3/8      MAX         100         100         100         100          0
                 MEAN         100         100         100          99          0
       STANDARD DEV.          0.5         0.8         1.0         2.8        0.0

                  MIN          94          93          91          88          0
      NO. 10      MAX         100         100         100         100          0
                 MEAN          98          97          96          97          0
       STANDARD DEV.          2.8         2.7         3.2         5.4        0.0

                  MIN          85          85          81          76          0
      NO. 40      MAX         100          99          98         100          0
                 MEAN          93          92          90          92          0
       STANDARD DEV.          4.6         4.3         5.3         9.5        0.0

                  MIN          55          57          52          55          0
     NO. 200      MAX          87          85          94         100          0
                 MEAN          71          71          68          80          0
       STANDARD DEV.          9.6         8.6         9.7        15.4        0.0

                  MIN          15          20          20          24          0
    NO. 5MIC      MAX          37          45          44          78          0
                 MEAN          26          32          32          50          0
       STANDARD DEV.          6.8         7.4         7.3        16.6        0.0

                  MIN          29          31          28          33          0
 LIQUID LIMIT     MAX          47          49          48          79          0
                 MEAN          38          40          38          56          0
       STANDARD DEV.          5.2         5.6         6.2        14.0        0.0

                  MIN           9          12          11          14          0
 PLASTIC  INDEX   MAX          22          28          29          56          0
                 MEAN          15          20          19          35          0
       STANDARD DEV.          4.0         4.9         5.3        13.0        0.0

NO OF DENSITY SAMPLE           39         152         250           5          0

                  MIN          87          96         101          98          0
  MAXIMUM DENSITY MAX         110         114         117         108          0
                 MEAN          98         104         108         103          0
       STANDARD DEV.          7.0         5.4         4.7         3.1        0.0

                  MIN          16          15          14          17          0
 OPTIMUM MOISTURE MAX          28          23          21          23          0
                 MEAN          21          19          17          20          0
       STANDARD DEV.          3.7         2.6         2.1         1.6        0.0

       UNIFIED CLASS         MLCL          CL          CL          CH

           OLD AASHO       A6( 9)      A6(11)      A6(11)     A76(19)      (  0)

           NEW AASHO       A6(10)      A6(13)      A6(12)     A76(29)      (  0)

  ESTIMATED CBR MEAN            6           5           6           3          0
  ESTIMATED CBR MAX.            3           3           4           1          0
```

Figure 3. Computer printout of statistically processed soil data.



NOTE: Points on curve are the average CBR's for each 5 point increment of liquid limit. For the soil classification as listed a total of 138 CBR tests were used to develop the curve. CBR and liquid limit relationship is not applicable to granular soils (the A1, A2, and A3 and subgroups of these classifications).

Figure 4. California bearing ratio—liquid limit curve.

Table 1. Mean liquid limit variation among counties.

Houdek Series			Kyle Series		
	Horizon			Horizon	
County	B	C	County	B	C
Aurora	43	42	Butte	65	65
Beadle	39	37	Custer	63	60
Bon Homme	40	37	Fall River[a]	52	55
Brule	44	46	Haakon	70	73
Davison[a]	34	34	Jackson	67	72
Douglas	39	39	Lawrence	70	—
Hand	40	40	Meade	68	59
Hanson	38	37	Pennington	64	64
Hutchinson	40	38	Average	66	68
Jerauld	38	35			
McCook	45	43			
Miner	43	43			
Sanborn	38	36			
Spink	43	38			
Turner	40	42			
Yankton	43	36			
Average	40	38			

[a] Mean liquid limit indicates that review of mapping concepts to improve uniformity within a series may be necessary.

Although this project was conceived and carried out intermittently over a period of about 8 years, it is estimated that the total activity, if uninterrupted, could be completed in about 1 year.

A cost analysis indicates that the previous average annual soil survey cost was approximately $68,000; it now averages about $23,000, an annual saving of $45,000.

FUTURE STUDIES

It is anticipated that these data can be made more useful to highway engineers in several ways. An attempt will be made to relate highway performance and highway design to soil series and to soil-moisture relations. In several instances this possibility has appeared promising.

For example, contacts between soils or geologic materials of contrasting textures are often a problem, such as a mantle of windblown silt overlying clay shale or glacial till, a fairly common condition in South Dakota. In this situation, inadequate internal drainage of the underlying layer causes a concentration of moisture in the vicinity of the contact, which in turn can result in distortions and breakups of surfacing due to shrink-swell differentials, frost damage from ice lens buildup, and reduced subgrade strength at high-moisture contents. This is particularly evident where contacts occur on a hillside.

A related problem that has been noted is the high degree of variability of soil textures, which can and often does occur over relatively short distances, particularly where local relief is greater than about 6 percent combined with horizontal contacts within a few feet of the surface. Again, this results in heaving and breakups caused by differences in moisture-holding capacities and permeability rates among soil materials of contrasting textures from one location or level to another. One way of minimizing such differences is by undercutting and compacting the undercut soil or replacing with select soil of uniform texture.

Another problem on soils known to be underlain by clay shales of the Pierre formation is deep-seated bed movements and seeps caused by entry of water into subsurface fractures, faults, and bentonite seams, resulting in sliding or swelling when wet. No satisfactory remedy has been found for this type of movement.

In general, highway distress is seen to be related primarily to swelling, loss of soil strength, and frost heaving due to entry and retention of local drainage moisture in soil materials relatively high in silt and clay. There is obviously considerable variation in the degree to which different soil series contribute to these problems.

Relations of this type will be studied, and, as causes of distress become better understood, relief measures will be incorporated in the design process wherever possible.

IDENTIFICATION OF COLLAPSIBLE SOILS IN LOUISIANA

Ara Arman, Division of Engineering Research, Louisiana State University; and
Samuel I. Thornton, Department of Civil Engineering, University of Arkansas

In southwest Louisiana, experience with widespread surface deposits (as thick as 5 ft) for use in earth structures has shown that some soils can withstand the design load, but others exhibit characteristics of a collapsible soil in the presence of load and moisture. All of these soils are classified as silt; the collapsible soils cannot be distinguished from normal silts by using routine tests. The known and conjectured areas containing collapsible silts fall within a 30-mile band through the coastal prairie terrace, the Mississippi River terraces, and the loessial hills. The dominant clay mineral in the collapsible silts is montmorillonite; kaolinite and illite are also present. These silts attract and suspend moisture in their pores by electrochemical forces. They become virtually impermeable when a polar liquid, such as water or ethylene glycol, is added. If a collapsible silt is mixed in a solution of sodium hexametaphosphate (Calgon) and allowed to settle, the liquid turns black. This color change is attributed to lignin. Along with a determination of the presence and location of collapsible soils in Louisiana, criteria for distinguishing these soils from normal silts are established. When two of the following four conditions are met, these soils may be considered collapsible: in situ unit weight of the undisturbed silt is less than 80 lb/ft^3; maximum dry density is less than 104 lb/ft^3; after the solids of the suspected soil have settled out in a 3 percent solution of sodium hexametaphosphate (used in routine hydrometer analyses), the supernatant liquid is black; and a total strain of at least 15 percent occurs at the end of the 16-tsf loading in a collapse test.

•IN southwest Louisiana, the wooded flats, coastal prairies, and low-profile hills that border salt marshes have surface soils of alluvial silt. A gray soil, classified as silt, covers an area about 30 miles wide and 100 miles long in this region. The thickness of the soil varies from 6 in. to 5 ft. Although this soil has a uniform appearance and gradation, its stability may differ among small areas.

New highway construction through these areas has highlighted the seriousness of these differences in stability. During the early stages of Interstate highway construction, isolated silty areas became unstable; no equipment could travel over the material when it became wet. Yet only a few hundred feet away from an unstable area, equipment could operate, under similar wet conditions, on material that had a gradation, classification, and Atterberg limits like the unstable one. In one section of Louisiana, more than \$2.5 million had to be added to the contract cost of the highway (after construction had started) to remove the unstable silts.

The records of the regional office of the U. S. Department of Agriculture indicate that farmhouses and drainage structures built in this region have experienced considerable damage from failures of foundations on seemingly stable silt. These failures occurred during the rainy season. (The annual rainfall in this region is more than 60 in.)

The problem of soil instability gained considerable prominence as the land use in the area slowly changed from farming to residential and industrial and became intensified because of the lack of methods for identifying the unstable silts.

Sponsored by Committee on Exploration and Classification of Earth Materials.

This report covers the investigation of the engineering properties of the material and a proposed identification method.

INITIAL INVESTIGATION

At the outset of the study, the effect of the soil instability was known, but the cause was unknown. After interviews with highway soils engineers, samples were obtained from small areas, within 30 ft of each other (Fig. 1), known to contain either stable or unstable silt. Moisture, according to early reports from construction engineers, was thought to be the cause of instability. Unstable silts were too wet for construction equipment to traverse (i. e., they underwent large volume changes when subjected to loads), and they could not be drained. These silts seemed to hold moisture suspended in the pores. As a result of the preliminary investigation, the following facts were established:

1. Both stable and unstable silt deposit areas are intermingled in the region. Both types of silts are surface deposits and are massive (homogeneous) in structure and are usually about 3 to 4 ft deep.
2. The AASHO classification of both types of soils is silt.
3. The gradation, Atterberg limits, and appearance of both soils are the same.
4. Failures occur only when the unstable soil is wetted.
5. Structural and slope failures take place soon after the unstable soil is wetted. These same soils, in a dry state, have sufficient strength to support heavy construction equipment or structures.
6. Both types of silts have low permeabilities.

These facts led to the conjecture that the unstable soils are loessial and collapsible.

RESULTS OF EARLIER STUDIES

A collapsible soil is defined as one that undergoes an appreciable amount of volume change on wetting, loading, or both. The magnitude of the collapse is between 4 and 20 percent of the original soil height and depends on the moisture content, load, and nature of the soil. The collapse may take from several minutes to several hours (1).

Both the identification of collapsible soils and the predictions of the amount of collapse have proved to be difficult and indeterminate tasks. A low in-place unit weight has been used as one criterion to identify them. For loess or loess-like materials, an in-place dry unit weight of 80 $\mathrm{lb/ft^3}$ or less indicates a collapsible soil. Dry unit weights of 80 to 90 $\mathrm{lb/ft^3}$ are transitional values. Settlement is negligible in a loessial soil when dry unit weight is 90 $\mathrm{lb/ft^3}$ or more (2). Moisture content has also been used as a criterion. A moisture content of less than 10 percent of dry unit weights indicates stable soil, but greater than 20 percent indicates collapsible soil (3).

Denisov introduced the K-coefficient of subsidence with a range of values that correlates with the degree of collapse. This is expressed as

$$K = \frac{e_L}{e_o}$$

where

e_L = the void ratio at the liquid limit, and
e_o = the natural void ratio.

A value of 0.50 to 0.75 indicates a highly collapsible soil, and 1.5 to 2.0 indicates a noncollapsible soil (5).

Both the dry unit weight and the moisture content were used successfully to identify collapsible soils along the San Luis Canal in the San Joaquin Valley (4). If the voids were sufficient to contain the moisture of the soil at its liquid limit, the soil was collapsible. This criterion applies only if the soil is uncemented and the liquid limit is greater than 20.

The 1962 Soviet Building Code presents a relation between initial void ratio and void ratio at the liquid limit to determine the collapsibility of soils with less than 60 percent saturation (5). Accordingly,

$$\lambda = \frac{e_o - e_L}{1 + e_o}$$

where

e_o = the initial void ratio, and
e_L = the void ratio at the liquid limit.

A value of λ greater than -0.1 indicates collapse.

Milovic suggested the concept of a specific coefficient of settlement in a variation of the consolidation test (6).

The double odometer test was used to identify collapsible soils by Knight and Dahlen (1). A consolidation test is made with one soil sample at its natural moisture content; an identical sample is tested while submerged in the confining ring.

Kassiff and Henkin proposed that the product of the dry density and moisture content be used as a predictor of collapse for loess. When this product exceeds 15, collapse may occur (7).

According to Dudley the only conditions for defining a collapsible soil are loose structure and a moisture content less than saturation. Dudley also discussed a pseudo-consolidation, or collapse, test in which a fabricated sample of fine sand and montmorillonite was loaded and rebounded in a dry state. It was then flooded, and the settlement or collapse was recorded (8).

THE COLLAPSE MECHANISM

Although the addition of water as a triggering action is commonly used to explain soil collapse, it should be emphasized that collapse may also occur without wetting, by an increase of the stress above the compressive strength as well as by a decrease in compressive strength below the stress.

The strength of noncohesive soils is directly related to the effective stress. In partially saturated soils, capillary force causes tension in the pore water (negative stress). A negative pore water stress increases the total effective stress, thereby increasing the shear strength. If the capillary forces are destroyed, as by saturation, the shear strength is reduced, and collapse may occur.

One hypothetical collapse mechanism involves clay-covered silt particles. Because the soil strength would result from the electrochemical bonding capacity of the clay, it would ultimately depend on percentage of clay. If water is added to such a soil, the adsorbed water film becomes thicker, the bond between particles weakens, and the soil thus loses strength (9).

Thus soil particles supported by clay minerals and associated ions may undergo collapse when saturated. Buttresses of clay-sized material, flocculated by ions, may form around silt particles as the saturated soil dries (8). Capillary forces will increase the strength of the partially saturated soil. The addition of water reduces the ion concentration and destroys the capillary forces. In turn, the supporting buttresses are dispersed, and the strength is reduced instantaneously.

TESTS ON COLLAPSIBLE SOILS IN LOUISIANA

Three sites in southwest Louisiana were chosen, at the outset of this study, for sampling and in situ testing. Two of these sites (Iowa and Sulphur) contained extensive deposits of stable and unstable silts, as identified by construction experience. The third site (Chloe) contained silts similar to the first site from the standpoints of sedimentation, formation, and physical characteristics; however, they were known to be stable under all conditions (Fig. 2).

The disturbed samples were prepared according to ASTM 2217 (with drying temperatures held below 60 C) for the following tests: Atterberg limits (ASTM D-423 and

D-424), grain size analyses (ASTM D-442), and the standard compaction test (ASTM D-698). X-ray diffraction, electron microscopy (both scanning and transmission), differential thermal analyses, infrared analyses, and qualitative chemical analyses were used to identify the chemical and mineral composition of the soils and other substances present.

The undisturbed 3-in. core samples were tested both in direct shear and in collapse. The collapse test, patterned after work done by Dudley (8), was performed in accordance with the ASTM D-2435 Consolidation Test, with the following difference: The sample, first oven-dried at 60 C, was loaded in the dry state up to 8 tsf, rebounded to 4 tsf, and then submerged in the consolidometer. The settlement as a result of wetting was recorded for pressures of 4, 8, and 16 tsf. The maximum settlements at 16 tsf were 14.5 percent for stable silts and 23.6 percent for unstable silts (Fig. 3).

Along with a field survey of all known and suspected deposits of collapsible silt (to determine their topographic and geologic features), in-place density and natural moisture content were measured at all sites of collapsible silts and neighboring stable silts. Samples of underlying clays, taken during a subgrade profile survey in the same region, were subjected to routine mechanical, pH, and organic content tests and quantitative and qualitative chemical analyses to determine if a soluble soil binder might have been leached out of the overlying silts and redeposited in them.

During the analyses, it was observed that these silts did not exhibit color or textural differences in either the natural or dried condition. However, after they had been soaked in a 3 percent water solution of sodium hexametaphosphate (the trade name is Calgon), which is normally used to disperse soil particles for hydrometer analyses, each type of soil had a different color.

The mixtures of stable silt and the sodium hexametaphosphate solution produced a light brown suspension that settled and left an almost clear supernatant liquid after 24 hours. However, the mixtures of unstable soil and the stock solution, without exception, produced a permanently black supernatant liquid, indicating the presence of foreign matter that was readily soluble. Infrared and chemical analyses of the black liquid showed that the black color was caused by a form of lignin that was dispersed in the liquid.

Thus the dispersion or Calgon test evolved as a chemical test to indicate instability.

A Calgon-washed test was also devised to determine if the material that dissolves in a Calgon-water mixture is responsible for the unstable condition of the soil. In this test, Calgon powder was mixed on a 3 percent by weight basis with dried soil, and the mixture was dispersed in a solution of 3 ml of distilled water per gram of soil. The water, along with other dissolved solids, was then removed by centrifuging for 15 minutes at 1,850 rpm. The rise with distilled water and centrifuging was repeated two more times to ensure removal of all Calgon and dissolved solids. No suspended solids or clays were removed in this process during the tests. Permeability of remolded specimens was determined in a falling-head permeameter (initial head 2 m).

TEST RESULTS

About 1,800 tests were run to provide the results given in the following discussion.

The AASHO classification of all the soils is silt (averaging 70 percent silt, 18 percent sand, and 12 percent clay) (Fig. 4). Differential thermal analyses and X-ray diffraction indicated that the predominant mineral in the silt and sand portions was quartz (60 percent average); the clay portion of the unstable silt was mostly montmorillonite, with some illite and kaolinite; and the clay in the stable silt was vermiculite and illite. Electron microscopy indicated that the silt grains of both soils are alike in shape and have surface weathering similar to weathered silts elsewhere. Only scattered microfossils having diameters of 1 to 10 microns were observed. They were similar to the siliceous diatoms reported by Beutelspacher and Van der Marel (10).

In the quick, undrained direct shear tests, both the collapsible and noncollapsible soils had an apparent cohesion of 0.4 tsf and an angle of internal friction of 30 deg.

The maximum density, obtained by standard compaction (ASTM D-698), was higher in the stable silts (108 $\mathrm{lb/ft^3}$) than in the unstable silts (102 $\mathrm{lb/ft^3}$). The consistent

Figure 1. Collapsible soils in the United States.

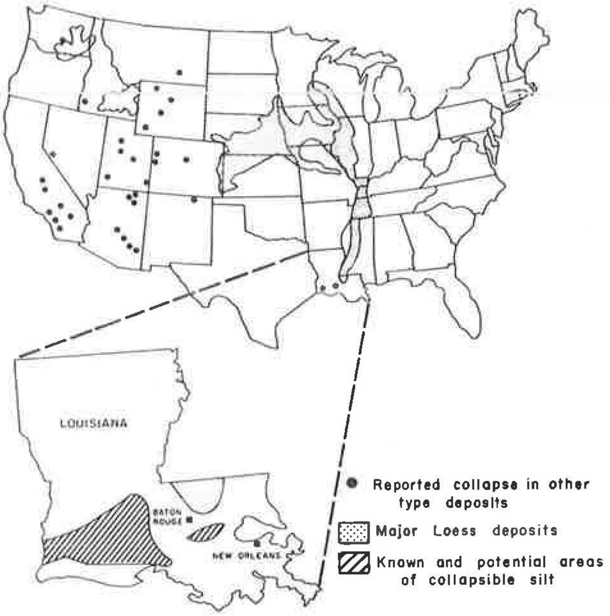


Figure 2. Sample locations and numbers.

Figure 3. Typical double odometer (collapse) test results.

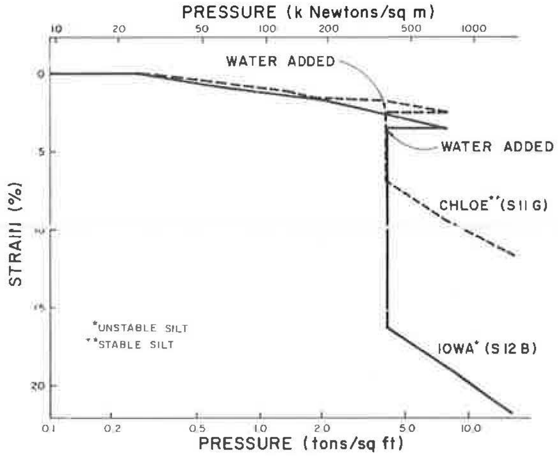
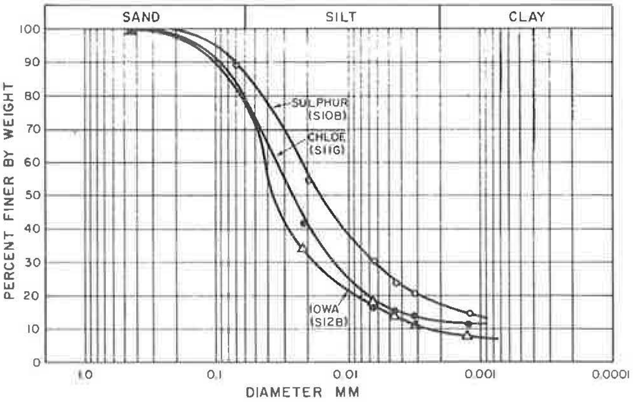


Figure 4. AASHO soil classification.



difference of 6 lb/ft^3 in maximum densities (Fig. 5) was the first mechanical property found to distinguish the two types.

The unit weights of undisturbed, unstable silts, measured in place with a nuclear density device, averaged 80 lb/ft^3 or 8 lb/ft^3 less than those for stable soils. Table 1 gives a sample of the results from tests at three sites. This consistent and uniform difference in unit weight furnished another method of identifying collapsible soils. The liquor produced in a Calgon test of known unstable silts was black in color in all cases. Stable samples produced a brown or gray liquor not much different from plain soil-water mixtures (without Calgon).

DISCUSSION OF TEST RESULTS

The low, in-place, dry unit weights of unstable silts—lower than those of stable silts—indicate a looser structure and greater settlement. Both the unit weights and the gradation of the unstable silts were similar to those for collapsible soils reported by Clevenger (2). The standard compaction test was the most outstanding proof of the difference in the mechanical properties of the remolded silts.

The Calgon test is practical and easily applied. During preparations for the hydrometer analysis (a routine classification test), the color of the Calgon-water-soil mixture can be observed.

The collapse test is another useful indicator of relative stability. The maximum values of collapse in this study showed that unstable silts may subside twice as much as stable silts (Fig. 3).

Electron microscopy indicated that both stable and unstable soils were formed by the same geologic process and contain particles of similar size and shape, microdiatoms, and agglomerated soil particles. The massive (unstratified) deposition of both types and their coincidence in former flood plains of the Mississippi and Red rivers point toward the same or similar geologic processes of formation.

Chemical analyses of underlying deposits failed to show that a soil binder, such as calcium carbonate, had been leached out of the unstable silts and redeposited in lower soil horizons.

Permeability of both collapsible and noncollapsible soils in distilled water decreases with time after initial saturation (Fig. 6). After 30 days, the permeability (k) drops to almost a tenth of the initial values. However, when carbontetrachloride (a nonpolar liquid) was substituted for water it drained quickly through the soil (k about 5×10^{-4} cm/sec), whereas ethylene glycol (an extremely polar liquid) would not drain through at all. Permeability samples using carbon tetrachloride and glycol were mixed with the liquids before being placed in the permeameter. The imperviousness of both stable and unstable silts indicates the presence of strong electrochemical charges that seal the pores. The permeability reduction with time in water (Fig. 6) can also be explained by the gradual polar attachment of water onto these electrochemical charges in fine particles.

As a result of data produced in this study, the Louisiana Department of Highways decided to tentatively adopt the Calgon test as a required test for all silts to determine the presence of collapsible soils; in addition dry unit weight was also used as a second indicator.

Correlation of collapse, Calgon, standard compaction density, and in situ density results (Table 2) show that Calgon color, standard compaction, and in situ compaction tests are in agreement in almost all cases. The collapse test, however, does not follow a definite trend. Although the collapse tests of known and suspected (e.g., S-11B) silts generally produced higher percentages of strain (20 percent), they also produced strain as low as 11 percent, i.e., those obtained from stable (S2G) silts. Thus the collapse test by itself was found to be unreliable for definite identification. This also applies to in situ and other test results. However, the correlation of the data and actual field experience indicates that, if two of the results of the tests given in Table 2 agree, the soil should be identified as a potentially collapsible soil.

During routine investigations on two federal aid projects in Lafayette and New Iberia, Louisiana (Fig. 2), the presence of extensive collapsible deposits was identified by

Figure 5. Typical standard compaction results.

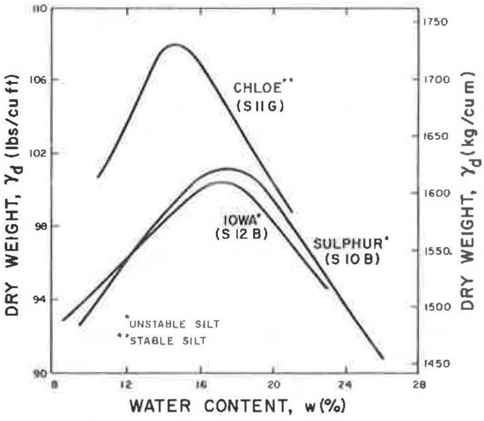


Figure 6. Effect of wetting time on permeability.

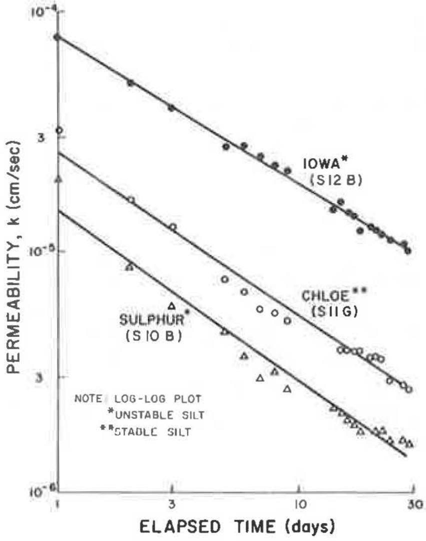


Table 1. Sample test results of silts from Iowa, Sulphur, and Chloe, Louisiana.

Iowa[a]				Sulphur[b]				Chloe[c]			
In-Place Dry Density (lb/ft^3)	Moisture Content (percent)	Calgon Test Color	Type of Silt	In-Place Dry Density (lb/ft^3)	Moisture Content (percent)	Calgon Test Color	Type of Silt	In-Place Dry Density (lb/ft^3)	Moisture Content (percent)	Calgon Test Color	Type of Silt
75	21.3	Black	Collapsible	77	18	Black	Collapsible	88	23	Natural	Noncollapsible
76	22.6	Black	Collapsible	83	14	Black	Collapsible	91	20	Natural	Noncollapsible
82	15.3	Black	Collapsible	78	17	Black	Collapsible	90	22	Natural	Noncollapsible
79	12.2	[illegible]	Collapsible	78	20	Black	Collapsible	87	24	Natural	Noncollapsible
78	20.5	Black	Collapsible								
95	18	Natural	Noncollapsible								
101	21	Natural	Noncollapsible								
104	20	Natural	Noncollapsible								
99	16	Natural	Noncollapsible								
73	20	Black	Collapsible								
83	18	Black	Collapsible								
96	22	Black	Noncollapsible								
67	18	Black	Collapsible								

[a] Stable and unstable deposits intermingled in this region.

[b] Unstable silt deposits only.

[c] Stable silts only.

Table 2. Test results of silts from Iowa, Louisiana.

Sample Number	Calgon Test Color	In-Place Dry Density (lb/ft^3)	Standard Compaction Dry Density (lb/ft^3)	Collapse Test (percent strain)	Type of Silt[a]
S2G	Natural	98.4	113	11	Noncollapsible
S4G	Natural	107	110	6	Noncollapsible
S5G	Natural	101	110	9	Noncollapsible
S6G	Natural	104	112	6	Noncollapsible
S-11B	Black	95	111	17	Collapsible
S-12B-1	Black	78	103	22	Collapsible
S-17B	Black	73	103	20	Collapsible
S-18B	Black	83	105	24	Collapsible
S-19B	Black	67	102	—	Collapsible
S-128-2	Black	—	—	12	Collapsible
S-12B-22	Black	—	—	10	Collapsible

[a] As determined by field and laboratory tests.

using criteria established by this study, and action was taken prior to construction to treat these soils (with hydrated lime) to avoid costly delays and additional work. Field experience on these projects, before treatment, proved that the trafficability and stability of their natural deposits were extremely low.

CALGON TEST

The Calgon test is a color test developed in this study to distinguish between stable and collapsible silts in southwest Louisiana. The test consists of the following steps:

1. One hundred grams of prepared silt is placed in a 500-ml beaker,
2. Nine grams of Calgon and 300 ml of distilled water are added, and
3. The color of the liquid is observed after allowing the sample to settle overnight.

A black color in the liquor indicates that the soil is collapsible.

CONCLUSIONS

The results of the study substantiate the following conclusions:

1. The unstable soils studied are collapsible silts.
2. Collapsible silts in Louisiana have a loose flocculated structure.
3. Based on the preceding conclusions, the following criteria were established for identifying collapsible silts in Louisiana: In situ unit weight of the undisturbed silt is less than 80 lb/ft^3; maximum dry density (standard compaction, ASTM D-698) is less than 104 lb/ft^3; the supernatant liquid in a settled mixture of the silt and stock solution (3 percent Calgon or sodium hexametaphosphate and water), used in hydrometer analyses (or Calgon test), is black; and in a collapse test (modified consolidation test of an oven-dried sample that has been saturated under pressure), a total strain of at least 15 percent occurs at the end of the 16-tsf loading.
4. Both collapsible and noncollapsible soils are of the same origin.

ACKNOWLEDGMENTS

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SIGNIFICANCE OF THE MAGNITUDE OF DIELECTRIC DISPERSION IN SOIL TECHNOLOGY

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A description of the alternating current response characteristics of soils in the radio-frequency range (10^6 to 10^8 Hz) is given. The variation of dielectric constant as a function of frequency of alternating current, called electrical dispersion, for various clays is presented. The magnitude of dielectric dispersion, which is defined as the total amount of decrease in the measured dielectric constant, is shown to be dependent on structure-determining factors such as type and amount of clay, water content, pore fluid composition, and fabric. It is suggested that the value of the magnitude of dielectric dispersion, which takes into account both compositional and environmental factors of a clay-water-electrolyte system, can be used to characterize clays without destroying or separating the soil mass into different sizes.

•SIGNIFICANT progress in the area of soil technology has been somewhat limited because of the slow development of fresh approaches, new techniques, and equipment that could characterize clay-water-electrolyte systems without destroying the clay mass.

The alternating current electrical response characteristics of saturated clay-water-electrolyte systems have been studied in the low-frequency range (50 to 10^5 Hz) (1, 2, 3) and in the radio-frequency range (10^6 to 10^8 Hz) (4, 5, 6, 7) to develop a nondestructive method of characterizing soils.

This paper has as its purposes (a) the description of the alternating current response characteristics of soils in the radio-frequency range (10^6 to 10^8 Hz) and (b) the illustration of the influences of changes in structure-determining factors and fabric on magnitude of electrical dispersion and presentation of a new method for classifying soils.

RADIO-FREQUENCY ELECTRICAL DISPERSION OF CLAY-WATER-ELECTROLYTE SYSTEMS

When an alternating electric field is applied to a clay-water-electrolyte system, a response is produced that can be measured in terms of a resistance, R, and a capacitance, C. The measured value of the capacitance can be converted into a quantity known as the dielectric constant. This value is defined as C/C_o, in which C_o is the capacitance of a condenser with only a vacuum between the electrodes. The dielectric constant is actually a measure of the ability of the clay to store electrical potential energy under the influence of an electric field. From a knowledge of the dimensions of the sample, the dielectric constant can be calculated from the following relations:

$$\epsilon'\epsilon_a = \frac{Cd}{A} \qquad (1)$$

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where

d = length of a specimen,
A = cross-sectional area,
ϵ_a = the dielectric constant of vacuum (8.85×10^{-14} farads/cm)

The dielectric constant of a dry silicate mineral is 4 and that of water is about 80. A mixture of soil and water should, therefore, have a dielectric constant between 4 and 80. When the dielectric constant of a clay-water-electrolyte system is measured with an alternating current in the radio-frequency range, it is found to be far in excess of the dielectric constant of components. This measured value, ϵ', referred to as the "apparent dielectric constant," reflects the heterogeneous nature of the path of the current and the electrical properties of the pore fluid and the clay mineral (4).

When the apparent dielectric constant, ϵ', of a liquid such as water or of an electrolyte is measured as a function of frequency, in the radio-frequency range, it is found that ϵ' does not vary (Fig. 1). The reason is that we are considering the electrical response characteristics of a one-component system. Water and salt are considered as a one-component system. In a one-component system, the current density, which is proportional to the ratio of conductivity to dielectric constant, does not vary from point to point. When we consider a two-component system (clay particles and solution), however, such as a saturated clay-water-electrolyte system, current density varies from point to point because the ratio of conductivity to dielectric constant is different for each of the two components. Charges therefore accumulate at the interface between the clay particle and the surrounding solution (9, 10, 11). Because this buildup of charges takes time, as the frequency is increased, there will be less time for the charges to accumulate at the interface, which in turn decreases the system's ability to store electrical potential energy and thus decreases the dielectric constant. When the frequency reaches a certain value, there will not be enough time for any charges to accumulate at the interface, and, at this point, the dielectric constant becomes independent of frequency. The value of the dielectric constant at this leveling-off frequency is defined as ϵ_∞. Figure 2 shows the change in ϵ' as a function of frequency for a two-component system (saturated illite Grundite). This change in ϵ' is generally referred to as electrical dispersion. The total amount of decrease in the measured dielectric constant is defined as the magnitude of dielectric dispersion, $\Delta\epsilon$. Several classes of materials exhibit this behavior (Fig. 3).

EXPERIMENTAL EQUIPMENT

The Cell

The design of the cell and its connections to the bridge terminal and the evaluation of the capacitance of the sample were similar to those used by Sachs and Spiegler (8). The cell is based on the principle of vectorial subtraction of impedances measured at different electrode distances. This procedure eliminates the influence of the transmission line, the electrodes themselves, and the surroundings of the cell in general.

The Meter

The measuring instrument used was an RX meter, type 250. It is essentially a Schering bridge, with oscillator, amplifier-detector, and null indicator designed to measure equivalent parallel conductance in the range of 0.0 to 0.067 mho, at frequencies of 0.5 to 250 MHz. All tests were performed at a constant room temperature of 22 C. Figure 4 shows the meter and cell.

RELATION BETWEEN MAGNITUDE OF ELECTRICAL DISPERSION AND PHYSICOCHEMICAL FACTORS

The sensitivity of magnitude of dielectric dispersion to variation in clay type, water content, amount of clay, amount and type of electrolyte, flocculated and dispersed saturated illite, method of compaction, and particle orientation was determined to investigate the significance of magnitude of dielectric dispersion to physicochemical properties.

Figure 1. Variation of dielectric constant with change in frequency for 0.01 N sodium-chloride solution.

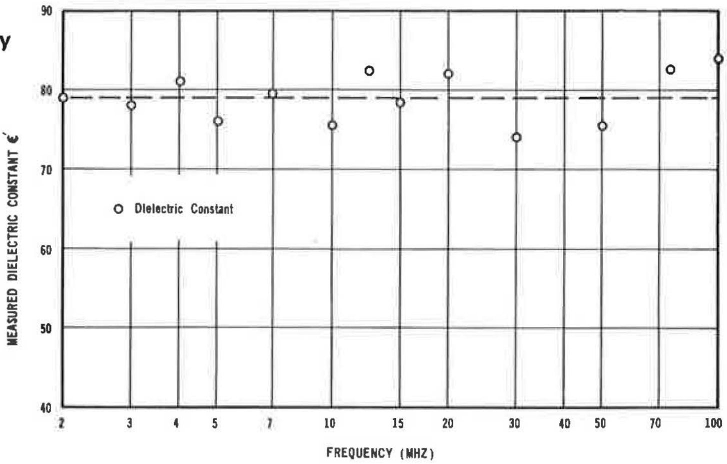


Figure 2. Dielectric dispersion characteristics of saturated illite Grundite.

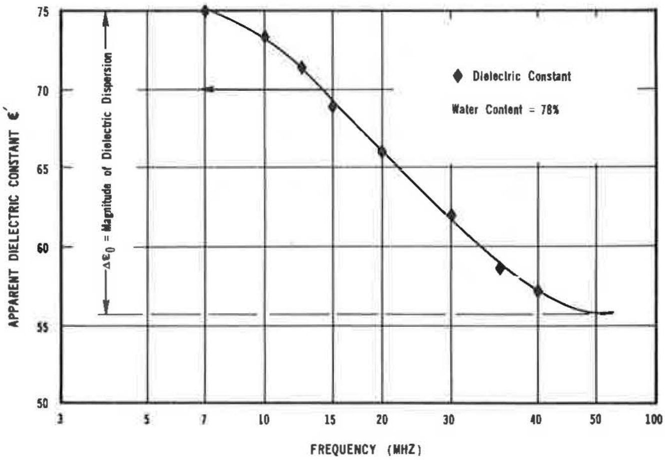


Figure 3. Variation of dielectric constant for solids, solid-liquid mixtures, and liquids in the radio-frequency range.

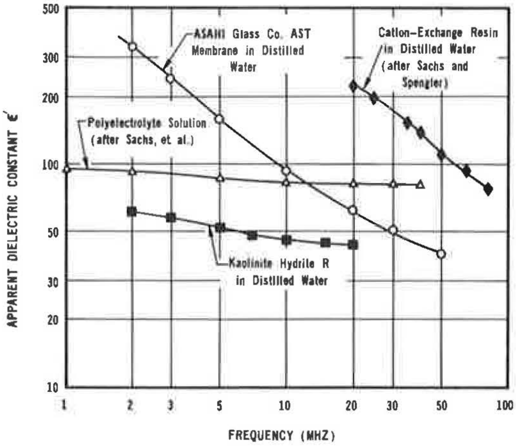
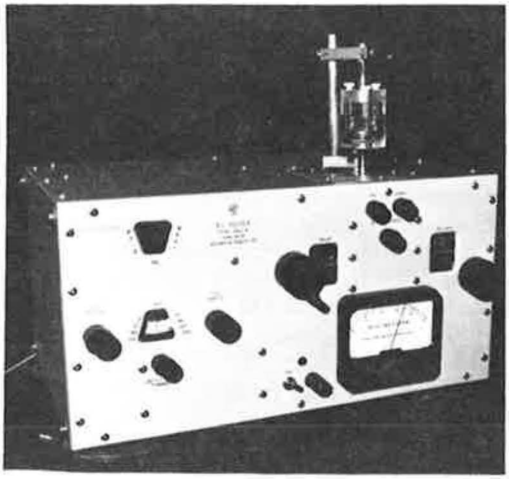


Figure 4. Measuring instrument.



Effect of Type of Clay on Magnitude of Dielectric Dispersion

Three basic clay minerals were studied: montmorillonite, illite, and kaolinite. Each was consolidated from a slurry under a pressure of 1 kg/cm^2, and electrical dispersion curves were then obtained. Figure 5 shows dielectric dispersion curves (in the radio-frequency range) for these three clay minerals. The curves show that the magnitude of the dielectric dispersion decreases for the three clay minerals in the following order: montmorillonite, illite, and kaolinite. This result can be interpreted in the following manner.

The dielectric constant of a medium reflects the magnitude of its polarizability, which is equal to the product of the number of charges per unit volume and the average displacement of particles. The number of charges per unit volume of particles is directly proportional to the number of unsatisfied surface bonding sites, the net electrical charge of the particle itself, and the specific surface area. The amplitude with which the particles will vibrate is directly proportional to the degree of association of the charge with particle surfaces when other factors remain unchanged, such as particle orientation, temperature, strength, and frequency of the electrical field.

We already know that each of the preceding four parameters decreases for the three clay minerals in the following order: montmorillonite, illite, and kaolinite. Hence, montmorillonite will show the greatest polarizability of these three basic clay minerals, and consequently the highest dielectric constant. Kaolinite will have the lowest one at the same frequency of applied electrical field when other factors, such as particle orientation and temperature, are kept constant. This difference would be prominent in the lower end of the radio-frequency spectrum. With increasing frequency, however, the time between alterations decreases and the polarization mechanism ceases to be effective, which means that the magnitude of polarizability will be minimum regardless of the type of clay and that therefore dielectric dispersion curves for all clay types will level off at the higher end of the radio-frequency spectrum. The fact that the dielectric constant decreases in the lower radio-frequency range in the previously given order, whereas all tend to level off at approximately the same level in the higher radio-frequency range, is the reason that the magnitude of dielectric dispersion also decreases in the same order (montmorillonite, illite, and kaolinite). This explains why the type of clay mineralogy is reflected in the nature of dielectric dispersion.

Effect of Amount of Clay on Dielectric Dispersion

Several samples of montmorillonite, illite, and kaolinite were mixed with different percentages of sand. Each was consolidated from a slurry under pressure of 1 kg/cm^2. A summary of the electrical dispersion characteristics obtained on illite and kaolinite sand mixtures is given in Table 1. With increasing sand content (decreasing clay content), the dielectric dispersion curve shifted downward, and the magnitude of dielectric dispersion decreased (Table 1). This may be interpreted in the following manner. With increasing sand content in a soil, the average specific surface area of the constituent soil particles decreases, reducing the number of charges associated with particles per unit volume, thus lowering the magnitude of dielectric dispersion. At the lower end of the radio frequency, of course, this phenomenon is prominent. At the higher end, the time available for charge distortion during any single current alteration decreases and may be insufficient for the polarization mechanism to operate, which means that the magnitude of polarizability will be minimum regardless of the percentage of clay content. Therefore, at the higher end of the radio-frequency spectrum, dielectric dispersion curves will level off and tend to merge together (Fig. 6). This explains why the dielectric dispersion curve shifts downward and the magnitude of dielectric dispersion decreases with decreasing amount of the clay fraction in a particular type of soil.

Therefore, adding sand to a soil changes the water content (after consolidation), which might affect the magnitude of dielectric dispersion. To investigate this, electrical dispersion tests were performed on several samples of a particular soil consolidated under different pressures to obtain different water contents (Table 2). The magnitude of dielectric dispersion of a soil proved independent of water content (discussed further in the following section). Therefore, variation in water content does not explain the change in dielectric dispersion values for different clay minerals.

Effect of Water Content on Magnitude of Dielectric Dispersion

Samples of montmorillonite, illite, and kaolinite were brought to three different water contents by consolidating them under different pressures, and electrical dispersion curves were determined. With two of the soils, the entire dielectric dispersion curves shifted downward with decreasing water contents, whereas with montmorillonite they shifted upward (Fig. 7). The results of the magnitude of dielectric dispersion with changing water content have only a very little effect on the magnitude of dielectric dispersion.

Effect of Cation Type on Dielectric Dispersion

The main types of ions existing in natural soils are sodium, calcium, and magnesium ions. Their amount in soils can be expressed in terms of sodium-adsorption ratio (SAR), which is given by

$$\mathrm{SAR} = \frac{\mathrm{Na^+}}{\sqrt{\tfrac{1}{2}\,(\mathrm{Ca^{++}} + \mathrm{Mg^{++}})}}$$

Used in the investigation was Yolo loam (a naturally silty soil commonly found in Yolo County, California). Several samples having different SAR's but the same electrolyte concentration were prepared and then consolidated under pressure of 1 $\mathrm{kg/cm^2}$. The dielectric dispersion characteristics of the soil samples were determined, and the magnitude of dielectric dispersion $\Delta\epsilon_0$ is given in Table 3. They demonstrate that the dielectric dispersion curve is affected by SAR, which reflects the type and amount of exchangeable cations in the soil. The magnitude of dielectric dispersion increases with increasing SAR. The explanation may be as follows: Univalent sodium ions have weaker bonds with the clay particle surface than do bivalent magnesium or calcium ions. Therefore, when a field of alternating current is passed through a soil, average displacements are much greater for sodium ions than for magnesium or calcium ions. Hence, with increasing SAR (i.e., increasing amount of sodium ions or decreasing amount of magnesium or calcium ions) in the soil, the magnitude of polarizability increases, resulting in increased dielectric dispersion.

Effect of Electrolyte Concentration on Dielectric Dispersion

The dielectric dispersion characteristics of two samples of Yolo loam having the same SAR but different electrolyte concentrations were obtained, and the results are summarized in Table 4. With increasing electrolyte concentrations, the dielectric dispersion curve shifts downward, and the magnitude of dielectric dispersion is reduced slightly. This relation has been explained as follows. A high concentration of electrolyte reduces the double-layer thickness surrounding each clay particle. This reduction results in low interparticle repulsion, causing a tendency toward flocculation, i.e., edge-to-face arrangement of particles. This arrangement causes a relocation of charges associated with particle surfaces. There is a high concentration of surface charges around the junction between the edge of one particle and the face of another. Therefore, the average displacements of the surface charges are reduced. Because of this, the polarizabilities of the surface charges are also reduced, thus accounting for the reduced magnitude of dielectric dispersion.

Effect of Structure on Dielectric Dispersion

Two series of tests were carried out to investigate the effect of the structural arrangement of particles on dielectric dispersion characteristics.

Flocculated Illite and Dispersed Illite—One illite sample was flocculated by using an NaCl solution of comparatively high concentration (0.05 N) as electrolyte. Another illite sample was dispersed by using a dispersing agent (Calgon). Each was consolidated

Figure 5. Effect of type of clay on dielectric dispersion.

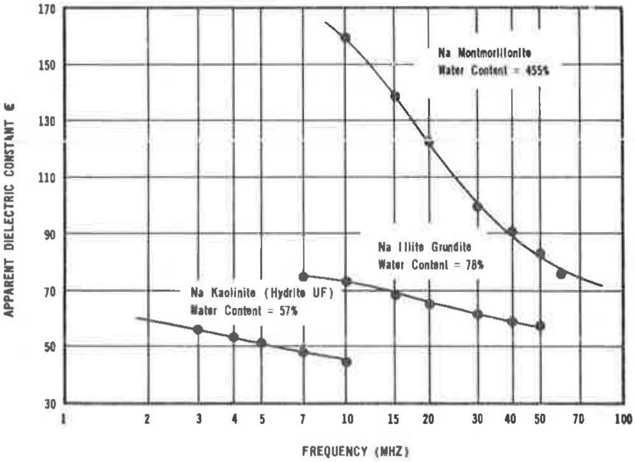


Table 1. Effect of clay content on dielectric dispersion.

Type of Soil	Water Content (percent)	Clay Content (percent)	Dielectric Dispersion
Sodium montmorillonite and sand	295	100	134
	230	83	110
	300	80	108
	255	70	94
	350	60	80
	182	55	72
Illite Grundite and sand	71.4	50	33
	40	47	30
	31.5	39	27
	25	34	17
	18.8	29	12
Kaolin UF and sand	70	100	14
	45	80	4
	39.3	60	5
	35.4	50	6
	28.7	40	4
	20.8	20	2

Figure 6. Effect of clay content on dielectric dispersion of sodium montmorillonite.

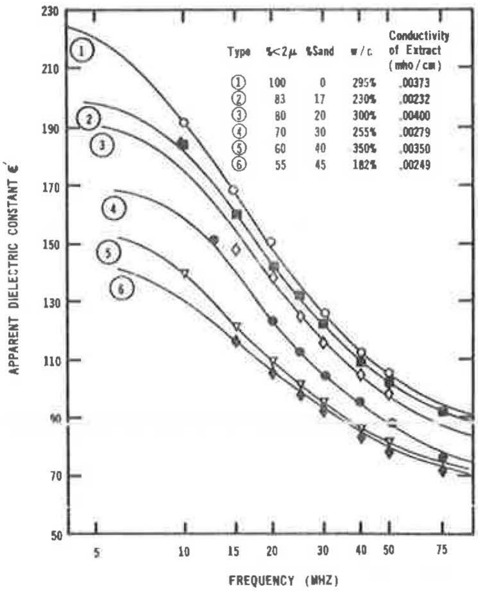
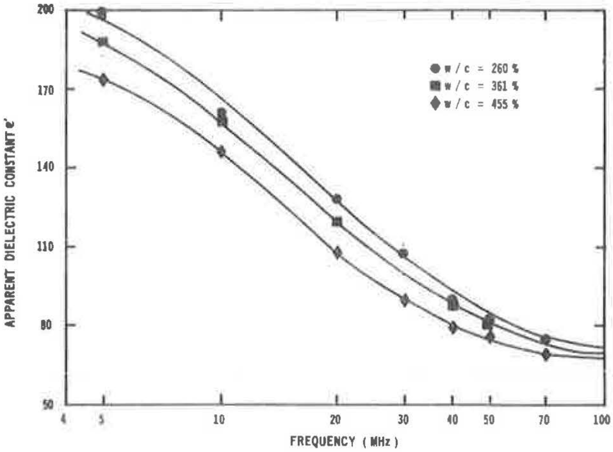


Table 2. Effect of water content on dielectric dispersion.

Type of Soil	Water Content (percent)	Dielectric Dispersion
Montmorillonite	260	127
	361	128
	455	112
Illite Grundite	48.6	24
	52.0	26
	78.0	25
Kaolin UF	51.2	16.0
	61.0	17.5
	80.2	14.5

Figure 7. Effect of water content on dielectric dispersion of sodium montmorillonite.



under a pressure of ½ kg/cm², and electrical dispersion tests were performed. The results (Fig. 8) show that a dispersed structure gives a higher dielectric dispersion than does a flocculated structure.

Yolo Loam Samples—Because Yolo loam is a structure-sensitive soil, as evidenced by the stress-strain curve shown in Figure 9, kneading compaction disperses the soil structure, whereas static compaction leaves the particles in a flocculated state (12). The two samples tested were not saturated but were good examples of soils having different structures but otherwise identical in all respects. Dielectric dispersion tests on these two samples (Fig. 10) demonstrate that kneading compaction (i.e., dispersed structure) gave rise to a higher dielectric dispersion than did static compaction (i.e., flocculated structure).

From these two series of tests, it is quite obvious that with increasing dispersion of particles, the dielectric dispersion curve shifts up and the magnitude of dielectric dispersion increases. The reason is that dispersion increases the specific surface area of particles and hence the number of bound charges per unit volume, which dictates the dielectric dispersion characteristics.

Effect of Particle Orientation on Dielectric Dispersion

Kaolinite Hydrite UF was consolidated under a pressure of 1 kg/cm². Two samples were taken from the consolidated soil, one perpendicular to the direction of consolidation (i.e., horizontal) and the other parallel to the direction of consolidation (i.e., vertical). Figure 11 shows that dielectric dispersion is higher when particles are aligned parallel to the direction of current. Clearly, particle orientation has an effect on the dielectric dispersion characteristics.

CONCLUSIONS

The results of this study give evidence that the radio-frequency dielectric dispersion characteristics of a saturated fine-grained soil are controlled by various compositional and environmental factors that determine the soil properties. A summary of the influences of these factors on the magnitude of dielectric dispersion is given in Table 5.

It can be noted that the magnitude of dielectric dispersion is mainly a measure of the clay mineral composition and percentage of clay content (Table 5). Consideration must also be given, however, to the second-order dependence of dielectric dispersion on water content, cation type, pore fluid concentration, structure, and particle orientation. The magnitude of dielectric dispersion may thus be of value in developing a soils classification method that takes into account both compositional and environmental factors and that can be used to characterize a soil without destroying or separating the soil mass into different sizes. The relation between the magnitude of dielectric dispersion and percentage of clay fraction is examined (Fig. 12) by plotting the results given in Table 1. Dielectric dispersion and percentage of clay fraction appear related linearly when increasing amounts of sand are added to a particular soil. Thus, three straight lines are obtained corresponding to the three basic clay minerals: montmorillonite, illite, and kaolinite. Figure 12 also shows the values of dielectric dispersion against clay fractions of 18 other natural soils investigated. The mineralogical composition, the percentage of clay content, water contents, and magnitude of dielectric dispersion for all experimental natural and artificial soils are given in Table 6. These soils fall under different zones according to their mineralogical compositions. These zones can be separated by the three lines corresponding to the three clay minerals, montmorillonite, illite, and kaolinite. For example, soil 1PB has a large amount of montmorillonite and illite (Table 6) and plots between the montmorillonite line and the illite line (Fig. 12). Similarly, other soils can also be placed appropriately in the classification table according to the amount and type of clay content.

ACKNOWLEDGMENTS

The research described in this paper is part of a continuing investigation into the relation between electrical and mechanical properties of soils supported by a Davis

Table 3. Effect of sodium-adsorption ratio on dielectric dispersion of Yolo loam.

Electrolyte Concentration	Conductivity of Pore Fluid (mho/cm)	Sodium-Adsorption Ratio	Dielectric Dispersion
0.01 N	0.00160	8.5	33
0.01 N	0.00150	4.8	30
0.01 N	0.00110	2.1	26
0.10 N	0.00930	154	50
0.10 N	0.00980	23.2	50
0.10 N	0.01000	12.4	50

Table 4. Effect of electrolyte concentration on dielectric dispersion of Yolo loam.

Sodium-Adsorption Ratio	Electrolyte Concentration	Conductivity of Pore Fluid (mho/cm)	Dielectric Dispersion
1.3	0.01 N	0.00115	30
1.3	0.10 N	0.00850	28
9.0	0.01 N	0.00160	35
9.0	0.10 N	0.01000	30

Figure 8. Effect of structure on dielectric dispersion of illite Grundite.

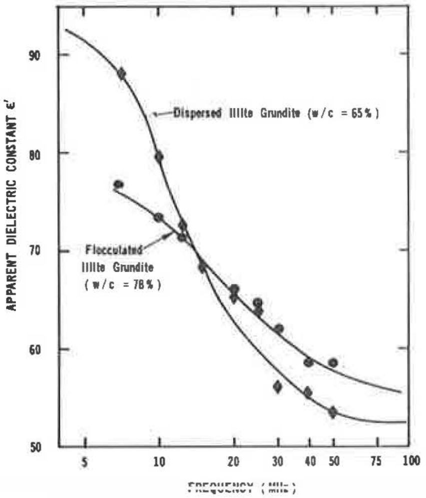


Figure 9. Effect of method of compaction on stress-strain relation of compacted Yolo loam.

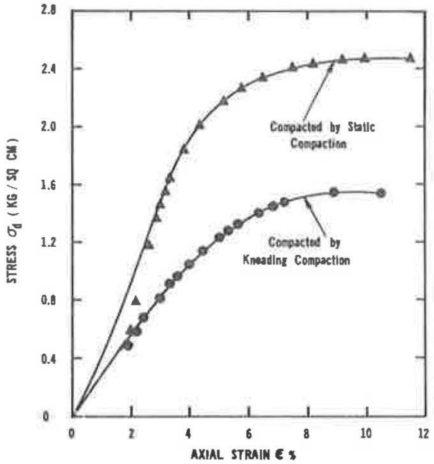


Figure 10. Effect of method of compaction on dielectric dispersion of Yolo loam.

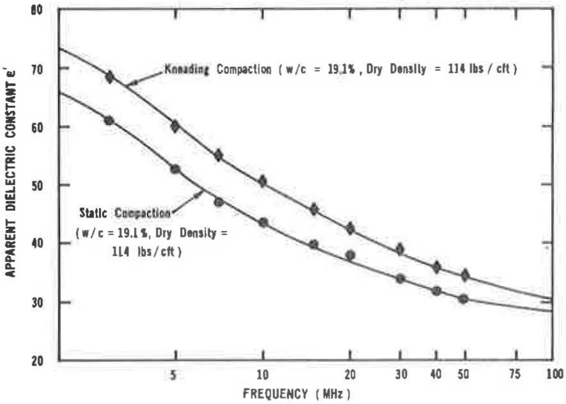


Figure 11. Dielectric dispersion of kaolinite Hydrite UF.

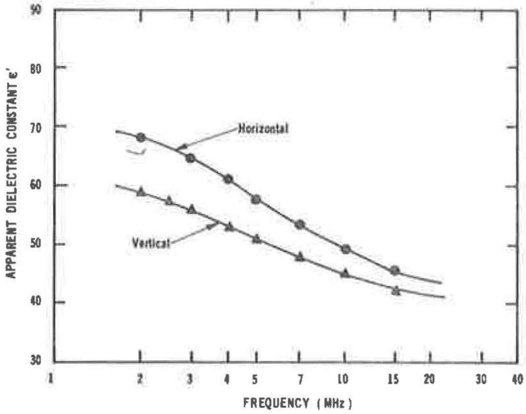


Table 5. Effects of compositional and environmental factors on magnitude of dielectric dispersion.

Factor	Effect
Type of clay	Dielectric dispersion is different for different clay types. Of the three basic clay minerals, it significantly decreases in the following order: montmorillonite, illite, and kaolinite.
Clay content	Dielectric dispersion increases significantly with increasing clay content.
Water content	Water content has a very little effect on dielectric dispersion (in the radio-frequency range).
Cation type (SAR)	Dielectric dispersion increases slightly with increasing SAR.
Electrolyte concentration	With increasing electrolyte concentrations, dielectric dispersion decreases slightly.
Structure	With increasing dispersion of particles, dielectric dispersion increases slightly to moderately.
Particle orientation	Dielectric dispersion is slightly higher when current is flowing perpendicular to direction of consolidation pressure than when current is flowing parallel to the direction of consolidation pressure.

Figure 12. Relation between dielectric dispersion and percentage of clay fraction.

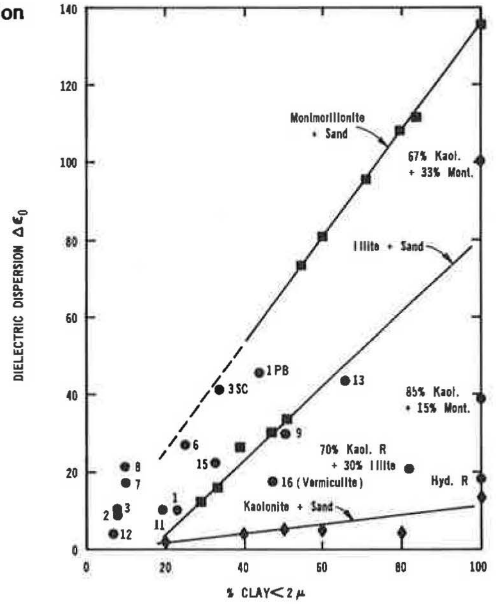


Table 6. Composition of soils.

Type of Soil	Water Content (percent)	Dielectric Dispersion	Clay Content (percent)	Clay Mineralogy[a] (percent)			
				Montmorillonite	Mixed Layer	Illite	Kaolin
85 percent kaolin and 15 percent montmorillonite	157	39	100	—	—	—	—
70 percent kaolin and 30 percent illite	53.8	21	82	—	—	—	—
1	38.7	10	23	0	5	0	0
1PB	105.6	46	44	0	52	5	0
2	24.8	9	8	0	10	0	0
3	38.5	10	8	10	5	0	0
3SC	75	42	34	35	5	0	0
6	64	27	25	0	13	0	0
7	31.7	18	10	0	5	0	5
8	47	22	10	0	20	0	0
9	69	31	50	20	5	0	5
11	53	11	19	0	20	0	0
12	23.3	4	7	0	10	0	0
13	65.2	44	66	20	5	0	7
15	46.3	23	33	15	0	0	0
16 (vermiculite)	114	16	48	—	—	—	—
Hydrite R	65	18	100	—	—	—	—
67 percent kaolin and 33 percent montmorillonite	244	100	100	—	—	—	—

[a] The percentages of different clay minerals present in each soil are based on the total weight of the soil (data supplied by the California Division of Highways).

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DEVICE FOR MEASURING SUBSIEVE SIZES IN THE FIELD

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A device for measuring percentage finer by weight of subsieve sizes in the field is described. The device measures the specific gravity of a soil-water dispersion with a small hydrometer (called a urinometer) inside a plexiglass tube. To determine the percentage finer than a certain size, the dispersion is sampled at a predetermined depth and time after mixing, and the specific gravity of the sample is measured. Results using the new device agreed with results using the standard ASTM hydrometer technique. Graphs for four nonplastic soils are presented showing typical comparisons of particle size distributions measured by both techniques. Application of the device to decrease the time required for wet sieving is discussed. Possible modification of procedures when using the device for plastic soils is noted.

•MONITORING particle size distribution of soils used for construction often requires information on the amount of particles finer than a subsieve size. For example, in a region subject to frost, information on the percentage finer by weight than 0.02 mm may be desired as an indicator of the susceptibility of a soil to frost heave. The standard method of making subsieve measurements requires equipment not well suited for use in the field.

In the technique described here, a small hydrometer is used in a device that can be easily handled in the field. This technique was designed to make measurements of the percentage finer than one or two subsieve sizes in the field. The technique can also be used in the laboratory to decrease the time required for wet sieving.

DESCRIPTION OF THE FIELD HYDROMETER DEVICE

The basic apparatus used in the test has two main components: a field hydrometer device and a 1-gallon widemouthed, polyethylene bottle. The field hydrometer device (FHD), shown in Figure 1, consists of a small hydrometer, sold commercially as a urinometer, inside a plexiglass tube. Attached to the bottom of the plexiglass tube is a glass stem having horizontal openings for withdrawing a sample of dispersion. The stem is made from 6-mm tubing. At the upper end of the plexiglass tube is attached a rubber bulb that allows the correct amount of suspension to be withdrawn and held within the chamber while the hydrometer is read. A plastic screen is placed in the tube above the stem to allow the flow of dispersion into and out of the chamber without any hindrance from the urinometer. The openings in the screen are about 5 mm wide.

To make the dispersion, approximately 450 g of soil are weighed and then mixed in the polyethylene bottle with 3,000 cc of water containing a suitable dispersant. At the appropriate time after mixing, the stem of the FHD is inserted into the soil-water dispersion to a predetermined depth and a sample of the dispersion extracted. The specific gravity of the extracted sample is read on the hydrometer, and the percentage of the sample finer by weight is computed in the usual way (6). The particle size of interest fixes the time and depth at which measurement is made and can be computed by Stoke's Law (p. 329, 5). The plexiglass tube has an inside diameter just slightly

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larger than that of the urinometer. This allows a measurement to be made with a minimum amount of suspension being withdrawn. The scale on the urinometer used in the tests described here measures specific gravities from 1.000 to 1.020. Commercial urinometers are also available to measure specific gravities from 1.020 to 1.040 and from 1.000 to 1.060.

DESIGN CONSIDERATIONS

Several features of this technique have been adopted from recommended procedures and methods previously published (1, 2, 6; 7, p. 386). The basic techniques are from the Andreason pipette method (2) and the standard ASTM method for soils passing the No. 200 sieve (3, 4). Hydrometers have been used for many years to determine the subsieve size gradation in soils. The standard method requires a large hydrometer, which is difficult to use when making a measurement in the field. When using the Andreason pipette method of particle size analysis, a portion of the dispersion is extracted from a measured depth and the amount of solids determined, usually by drying (2). Because of the great amount of water in the sample, this method is time-consuming. The method using the FHD combines the feature of extracting a portion of dispersion by utilizing a pipette, with a more rapid determination of solid content by the hydrometer.

Other investigators have reported that a horizontal withdrawal of the sample may give different results than a vertical withdrawal (2). Both of these stem types were tried, and their results were compared. No discernible differences in results were noted.

The specific gravity of the dispersion changes rapidly near the top surface. If the sample is withdrawn too close to the surface of the dispersion, the measurement will be in error. Each measurement required 40 cc of dispersion. The extreme possible shapes of a sampled volume are shown in Figure 2. The configuration shown in Figure 2b is a thin disk-shaped volume proposed by Heywood (2) and indicates a thickness of 0.6 cm for the sampled volume. The other extreme of sampled volumes is the spheres shown in Figure 2a. The spheres have a diameter of 1.79 cm. The shapes of actual sampled volumes probably fall between these two extremes. To ensure good resolution of particle size, the thickness of the sampling zone must not exceed one-sixth of the mean depth (2). The case of spherical sampled volumes was assumed, and the depth of sample withdrawal was set at 11.7 cm for the tests reported here. The total depth of dispersion in the polyethylene jug is about 17 cm. At a depth of 11.7 cm, the sampled volumes are not influenced by sediment on the bottom.

This depth of sampling proved to be a convenient one. A dispersion sample from the depth of 11.7 cm, taken 5 min after mixing shows the percentage finer than 0.02 mm, when the temperature is 20 C, and the specific gravity of the soil solids is 2.7. By sampling at this depth, the distributions of subsieve sizes were determined in shorter times than by standard methods.

Rapid sampling is also not recommended because preferential sampling may result. Small particles outside the sampling zone may be drawn in because of their lower inertia. Allen (2) mentions Johnson's experiments; however, Allen varied the sampling times between 12 and 140 sec. Johnson recommends a sampling time of about 20 sec. The "quick" test sampling time is about 10 sec, which is felt to be sufficient considering the small amount of dispersion withdrawn. The final verification of the technique is the comparison of the results using the FHD method with those using the ASTM method (3).

VERIFICATION OF FHD RESULTS

The object of the laboratory tests was to show that the FHD gives results comparable to the standard ASTM hydrometer technique. Comparison of results from the two techniques required identical soil samples. For purposes of verification, it was decided, therefore, to use only the soil passing the No. 10 sieve as recommended by the ASTM procedures (3). The particle size distributions of 13 soils were measured by both the FHD device and the standard ASTM hydrometer technique. The soils were limited to types that might be used in highway construction in Connecticut and showed little or no plasticity.

Sodium pyrophosphate was selected as the dispersant to be used in the tests. Trials using various concentrations of dispersant indicated that a 0.5 percent solution was adequate to disperse the particles.

The recommended ASTM procedures are designed to be adequate for a broad spectrum of soils. Part of the experimental verification of the FHD was to determine which parts of the standard procedures could be shortened to save time in the field. The steps that required checking when the FHD is used with plastic soils are covered in the following discussion.

Experimental Procedure

Sample Preparation—Each soil was air-dried and then split with a No. 10 sieve. Of the soil passing the No. 10 sieve, two representative samples were removed. One sample was tested in accordance with the ASTM Tentative Method for Grain-Size Analysis of soils (3). The other was tested with the FHD. Hydroscopic moisture was determined by drying a sample in an oven at 105 C for 12 hours. Specific gravity of solids was determined for each soil by using the ASTM procedure (3).

Testing the FHD—Approximately 450 g of air-dried soil weighed to 0.1 g were added to 3 liters of dispersing solution in the polyethylene bottle. A series of measurements was run, with the soaking time for the soil varied from 10 min to 24 hours. The soil was dispersed in the solution by end-over-end mixing for 1 min. No differences in measurements could be ascertained for the tested soils between the shorter and longer soaking times with the FHD, and the results agreed with standard hydrometer method. The minimum soaking time for the FHD was taken as 20 min on the basis of these results. During the soaking time the dispersion was mixed end over end twice. The specific gravity of the dispersing solution was checked with the FHD before each measurement. The hydrometer was always read at the top of the miniscus. Time was measured from the end of mixing. The stem of the FHD was marked with a piece of tape 11.7 cm above the center of the horizontal openings, and all measurements were made at this depth.

With a dispersion of 450 g of soil and 3,000 cc of deflocculant, the polyethylene bottle is about three-quarters full. This allows the dispersion to be easily mixed. The dispersion and bottle weigh less than 8 lb and can be easily handled.

A series of tests was run to determine the percentage finer curve for each soil for sizes ranging from the No. 200 sieve to clay. The FHD disrupts the dispersion with each measurement. As a result the sample withdrawn was replaced after each measurement, and the entire dispersion was remixed for 1 min and the timing begun for the next measurement. Time from mixing to measure at a depth of 11.7 cm was computed for each desired particle size.

RESULTS AND DISCUSSION

Typical results for the particle size distributions measured by each of the two methods are compared in Figures 3 through 6. The graphs shown are for the tested samples having the greatest and least amounts passing the No. 200 sieve. Two intermediate samples are also shown. The results shown in these figures, which are typical of all soils tested, indicate that the two techniques produce essentially the same curve for each soil. The results are reported as percentages finer by weight based on a wet-sieve analysis of the total sample.

The data of each curve seem to diverge a little above the 0.05-mm size or a Reynolds number of 0.10. A possible reason for the divergence of test data may be counterflow. This phenomenon is most pronounced at short times after mixing when a large quantity of particles are settling out of suspension. While they are moving downward, the volume of water that they displace is rushing upward. The resulting particle velocity is somewhat less than that calculated by Stokes' equation. Retardation due to counterflow occurs for a longer period in the hydrometer jar than in the polyethylene bottle for the field test.

Figure 1. Field hydrometer device.

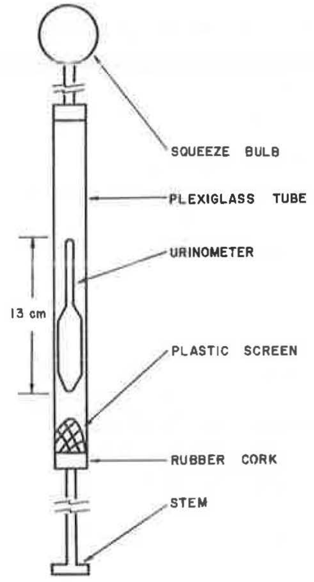


Figure 2. Extreme possibilities of sampled volume shapes.

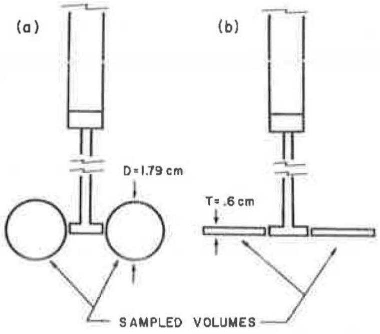


Figure 3. Distribution of particles smaller than the No. 200 sieve from silty sand No. 1 (USCS SM).

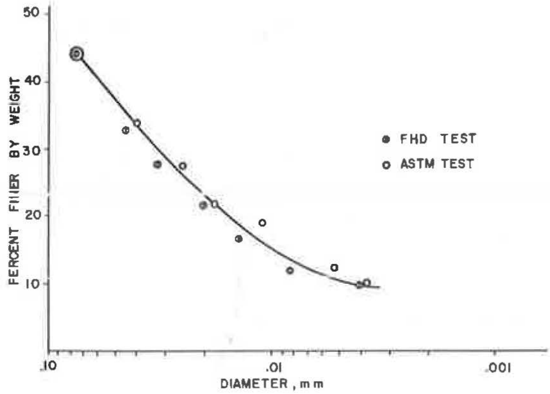


Figure 4. Distribution of particles smaller than the No. 200 sieve from a silt (USCS ML).

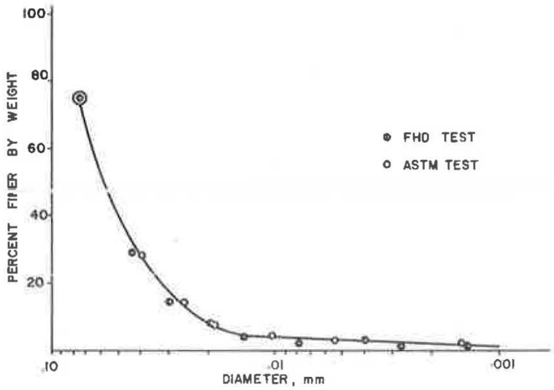


Figure 5. Distribution of particles smaller than the No. 200 sieve from silty sand No. 2 (USCS SM).

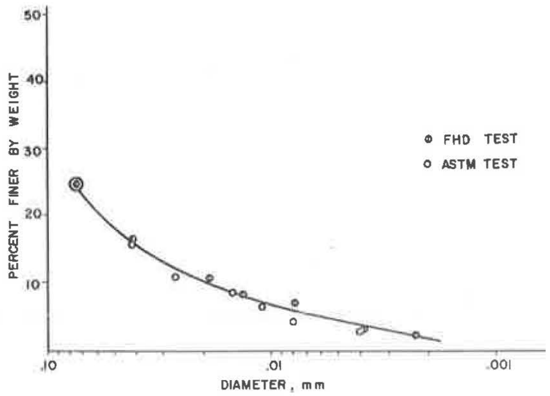
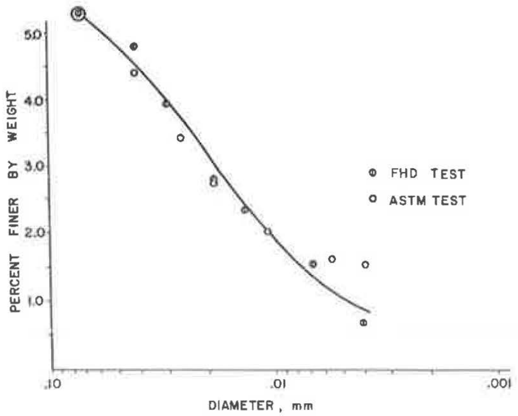


Figure 6. Distribution of particles smaller than the No. 200 sieve from a well-graded sand (USCS SW).



Another source of error is the small amount of dispersion from near the surface that is trapped in the stem of the FHD when it is submerged. This error tends to lower slightly the "percentage finer than" as measured by the FHD.

The scale of the urinometer inside the FHD is smaller and, therefore, less precise than the larger ASTM hydrometer. This difficulty may also account for some of the divergence shown in the curves.

When making each measurement, the specific gravity of the sodium pyrophosphate solution must be determined. An error of 0.001 in the reading of the specific gravity of the deflocculant solution will affect the percentage finer determination of the soil suspension. This error would be largest for soils with small amounts passing the No. 200 sieve. All readings with the FHD must be made carefully. The experimental results show that the FHD used properly produces the same particle size distribution curve as the larger hydrometer.

When using the FHD with plastic soils, the most important items to check are the soaking and mixing times. For the tests reported here, short soaking times and little mixing were required. Both of these may have to be increased for plastic soils. Use of a mortar and pestle to break up aggregations of particles might be helpful for plastic soils.

USE OF THE FHD IN THE FIELD AND FOR WET SIEVING

Splitting a field sample on the No. 10 sieve may be difficult. Perhaps a better sieve for field use would be a No. 4. The sample passing the No. 4 sieve could be mixed with deflocculant solution in the polyethylene bottle. The Bureau of Reclamation (7) has used hydrometer tests to measure soil passing a sieve of about the same size.

Use of the FHD in the field requires equipment in addition to the polyethylene bottle. A balance to weigh the sample and some means of drying the soil are needed. Other accessories, such as bowls and thermometers, are also required. Perhaps the best way to include all the necessary equipment in a kit for the field is to run one test outdoors near the laboratory and bring out equipment as needed until the test can be made. Then a list of all the items can be made. In the process of checking the FHD, one test was run outdoors with a minimum of equipment.

A complete wet-sieve analysis can be made by treating the soil in three ranges: the portion retained on the No. 4 sieve, the portion passing the No. 4 but retained on the No. 200 sieve, and the portion passing the No. 200 sieve.

The analysis of the particles finer than the No. 200 sieve is made using the portion passing the No. 4 sieve in the polyethylene bottle and the FHD, as previously described. In many instances information on one subsieve particle size will be sufficient. After determining this information by using the FHD, the next step is to wash all the soil contained in the polyethylene bottle on a No. 200 sieve so that the finer particles will pass through. To facilitate the washing, the sample in the jar is again mixed and immediately poured over the sieve. The mixing action suspends the fine particles that, once the dispersion is poured, will reach the sieve first and proceed through with little resistance. The last particles of soil in the jar will tend to cling to the sides. These particles can be washed out and onto the sieve with a standard laboratory wash bottle. After all the particles are on the sieve, tap water should run over the soil, and the sieve should be agitated lightly by hand until the water coming through the sieve is clean. The soil particles remaining on the sieve are those passing the No. 4 sieve but retained on the No. 200 sieve. The No. 200 sieve and the soil contained on it should be dried and weighed to determine the amount of the total sample in each of the two size ranges. The portion passing the No. 4 but retained on the No. 200 sieve may now be sieved to determine the distribution of sizes in this range. The portion of the soil retained on the No. 4 sieve can also be analyzed after drying, by using a nest of sieves having openings larger than the No. 4 size, to determine the distribution of sizes in this range.

CONCLUSIONS

The report data substantiate the following conclusions:

1. The FHD gives particle size distribution curves comparable to those from the standard ASTM hydrometer procedure, and
2. The technique can be used in the field to monitor subsieve sizes of soil or in the laboratory to decrease the amount of time required for a wet-sieve analysis.

ACKNOWLEDGMENT

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ENGINEERING VALUES FROM SOIL TAXONOMY

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Many properties of engineering interest can be deduced from the connotative nomenclature of Soil Taxonomy, the pedological soil classification system adopted for use by the National Cooperative Soil Survey in 1965. The system is based on soil properties that have been defined quantitatively and named. Each soil class name, in turn, is composed of word elements taken from the names of those properties that are diagnostic for the soil class. The major features of a soil placed within any class are signified directly by the specific formative elements appearing in the soil class name. The descriptions and formative elements of six surface horizons (epipedons), 17 subsurface horizons, 56 special features, and the 10 soil classes at the highest level of the system (orders), are provided. Because the basis of this paper is use of Soil Taxonomy by engineers, emphasis is placed on the nomenclature rather than the structure of philosophy of the system. The 39 formative elements considered to be most informative for general engineering analysis are highlighted for handy reference.

•SINCE 1965, all U.S. Department of Agriculture soil survey reports have correlated soils into the new Soil Taxonomy (11, 12), until recently referred to as the 7th Approximation (10). In contrast to the qualitative nature of the previous pedological classification system (2, 8, 14), Soil Taxonomy provides a quantitative framework in which to place soils of the United States as well as many soils of the world. Authors, attempting to point out the engineering value of the previous system, have been forced to treat the general merits of pedological soil surveys (4, 5, 6) or to confine themselves to specific soil series encountered in their particular project (7, 13). Although soil series convey the most specific soil property information and are therefore the most valuable class for engineering investigations, their number and variability preclude their use for more than local investigations. The new Soil Taxonomy, as Arnold Suggests (1), provides the first practical basis for interchange of a broad range of quantitative soil information between the soil scientist and the engineer.

For engineers, the most important aspect of the new taxonomy is that information can be derived from soils classes according to the system with little understanding of pedology, the mechanics of the system, or soil series. The user need only recognize key formative elements in the soil class names. That Lithic Cryopsamments are classed at the subgroup level is of little concern to the engineer; that elements in the name Lithic Cryopsamments signify shallow, sandy soils in cold climatic regions is of definite concern. Consequently, Soil Taxonomy is summarized, emphasizing the connotative nomenclature of the system and omitting much purely agricultural information. Throughout the discussion, those properties and their formative elements that are considered to be of interpretive value to engineers will be highlighted as follows: An asterisk (*) indicates possible interest, a dagger (†) indicates definite interest, and a double dagger (‡) indicates major importance.

This rating scheme is subjective and directed toward a range of engineering problems; a rating scheme for, or by, any specific engineering group (e.g., highway engineers) would likely be different. It should also be recognized that Soil Taxonomy is not an engineering soil classification system. Although much engineering information

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can be derived from soils mapped and classed according to the system, the diagnostic soil properties and categorical levels of the taxonomy do not correspond to priority levels of engineering interest.

THE SOIL TAXONOMY

Soil Taxonomy is a multi-categoric, pedological soil classification system (3, 9). The system recognizes 10 soil orders at the highest level, each order being subdivided into suborders, great groups, subgroups, families, and series. Approximately 10,000 soil series have been recorded in the United States (11). Preliminary reports on Soil Taxonomy have been available since 1960 (10), and the complete details of the system are being published as a two-volume set (11, 12).

DIAGNOSTIC HORIZONS

Because certain soil horizons and layers are basic to the separation of soil classes in Soil Taxonomy, a brief description of each diagnostic surface horizon (epipedon) and subsurface horizon follows.

Epipedons

1. Mollic: dark surface horizon, at least 18 cm thick, with at least 1 percent organic matter and without a massive or hard structure.
2. Anthropic: similar to mollic but different chemically.
3. Umbric: similar to mollic but different chemically.
4. Histic†: surface or near surface horizon(s), 20 to 60 cm thick, with at least 14 percent organic matter; unless artificially drained, saturated for at least 30 consecutive days.
5. Plaggen: not found in United States; man-made surface layer, more than 50 cm thick, produced by long continuous application of manure.
6. Ochric: pedogenic surface horizon, usually light colored, which does not qualify for one of the preceding.

Subsurface Horizons

1. Agric: thin horizon of silt, clay, and humus; formed by cultivation immediately below plow layer.
2. Albic: bleached horizon.
3. Argillic: horizon of silicate clay accumulation.
4. Calcic*: horizon of calcium carbonate, or calcium and magnesium carbonate, accumulation; calcium carbonate equivalent more than 15 percent; more than 15 cm thick; may be in C-horizon or other horizons; found primarily in arid and semiarid regions.
5. Cambic: altered horizon with significant amounts of weatherable minerals; little evidence of accumulations of clay, iron, aluminum, organic matter, or of rock structure.
6. Duripan†: horizon cemented to the point that air-dry fragments will not slake in water or acid; largely restricted to areas of vulcanism, primarily subhumid Mediterranean or arid regions.
7. Fragipan†: horizon seemingly cemented when dry, having hard or very hard consistency; dry fragments slake or fracture in water; when moist, has moderate or weak brittleness; high bulk density relative to soil above it; upper boundary commonly within 40 to 80 cm of surface, with horizon thickness varying from about 15 to 200 cm; found primarily in humid regions.
8. Gypsic†: horizon of calcium sulfate accumulation; at least 5 percent more gypsum than C-horizon or underlying stratum; more than 15 cm thick; product of thickness (cm) and percentage of gypsum is 150 or more; found primarily in arid and semiarid regions.
9. Natric*: special kind of argillic horizon; in some subhorizon, has more than 15 percent saturation with exchangeable sodium or more exchangeable magnesium plus sodium than calcium plus exchange acidity; normally prismatic or columnar structure.

10. Oxic[†]: extremely weathered horizon; hydrated oxides of iron and/or aluminum, variable amounts of 1:1 lattice clays, and highly insoluble minerals (e.g., quartz); more than 15 percent clay; at least 30 cm thick; stone lines and/or ironstone pebbles common; soils exhibit low clay activity, high permeability, and low erodibility; generally found in soils of very old, stable surfaces, seldom beyond tropics or subtropics.

11. Petrocalcic[‡]: continuously cemented or indurated calcic horizon; when dry, fragments do not slake in water and material cannot be penetrated by spade or auger; when moist, very firm to extremely firm; permeability moderately slow to very slow; usually much thicker than 10 cm; found primarily in arid to semiarid regions.

12. Petrogypsic[‡]: rarely found in United States; a gypsic horizon cemented to the point that dry fragments do not slake in water; gypsum content usually exceeds 60 percent; restricted to arid climates and to parent materials rich in gypsum.

13. Placic[*]: thin layer, cemented by iron; generally 2 to 10 mm thick; usually within 50 cm of, and roughly parallel to, surface; slowly permeable; sometimes found in tropical or cold regions but always in very humid or perhumid climates.

14. Plinthite[†]: technically not a diagnostic horizon; material changes irreversibly to ironstone layer or irregular aggregates on exposure to repeated wetting and drying (nonindurated form of material that has been called laterite); once indurated, can be broken or shattered with a spade but cannot be cut; normally forms in various subsurface horizons but may form at surface; restricted to tropics and subtropics.

15. Salic[†]: horizon of accumulation of salts more soluble in cold water than gypsum; at least 2 percent salt; at least 15 cm thick; product of thickness (cm) and percentage of salt (wt) is 60 or more; generally restricted to arid regions.

16. Spodic: horizon in which mixtures of organic matter and aluminum, with or without iron, have accumulated; may have a continuously cemented subhorizon more than 2.5 cm thick; found most often in coarse-textured materials; found only in humid regions.

17. Sulfuric[†]: horizon of mineral or organic materials with pH less than 3.5; forms as a result of artificial drainage.

SOIL ORDERS

Ten soil classes have been established at the highest level of Soil Taxonomy. These orders relate to the complete soil profile, being differentiated largely with regard to the aforementioned horizons. Although each order represents a defined central concept (11, 12), property variations are possible. Features common to, or absent from, soils classed at the order level are reported here rather than the central concepts:

1. Alfisols—have an argillic or natric horizon, or have a fragipan in, below, or similar to an argillic; no spodic or oxic horizon over argillic; no continuous plinthite in upper 30 cm.

2. Aridisols—have an ochric or anthropic epipedon; no spodic or oxic horizon; found principally in arid regions.

3. Entisols—have few or no diagnostic horizons; may have ironstone at any depth but no continuous plinthite in upper 30 cm; no salic horizon in upper 75 cm; no calcic, petrocalcic, gypsic or petrogypsic horizon or duripan in upper 1 m; no fragipan.

4. Histosols[‡]—organic soils; range from undecomposed to highly decomposed materials; unless over fragmental or rock material, at least 40 cm deep; found generally in swamp or marsh, but may be artificially drained.

5. Inceptisols—any epipedon possible; no continuous plinthite in upper 30 cm; no salic horizon in upper 75 cm; no gypsic or petrogypsic horizon in upper 1 m; commonly have cambic horizon; no spodic, oxic, argillic, or natric horizon, unless buried.

6. Mollisols—with few exceptions, have a mollic epipedon; have bulk density of at least 0.85 g/cc and less than 60 percent pyroclastic materials; no continuous plinthite in upper 30 cm; no spodic horizon in upper 2 m; no oxic horizon; found generally in subhumid to semiarid regions, being most extensive in midlatitudes.

7. Oxisols[†]—have an oxic horizon, normally in upper 2 m, or have continuous plinthite in upper 30 cm and are saturated at some time in most years; no spodic or argillic horizon over the oxic; found in tropics or subtropics (see "oxic horizon").

8. Spodosols—have a spodic horizon in upper 2 m or a placic horizon over a fragipan; principally coarse-textured materials found in humid regions.

9. Ultisols—have an argillic horizon, or have a fragipan below, or similar to, an argillic; no continuous plinthite in upper 30 cm; no spodic horizon; no oxic horizon over an argillic; mean annual soil temperature at least 8 C; found principally in warm, humid regions, from low latitudes to midlatitudes.

10. Vertisols[‡]—have at least 30 percent clay (primarily expanding lattice) to at least 50-cm depth; unless irrigated, have cracks at or near surface that are at least 1 cm wide at a depth of 50 cm at some period in most years; mean annual soil temperature at least 8 C; generally found in subhumid to arid regions.

NOMENCLATURE AND FORMATIVE ELEMENTS

With the exception of soil series, the name of each soil class within each order is composed of formative elements that connote properties common to soils in that class. Although soil class names may contain more than one word, it is the final word that reflects those properties considered to be most important for the pedological classification. This final word contains two or three formative elements. All other modifying words (i.e., adjectives, ending with "ic") indicate whether the soil represents the central concept of the class, whether the soil is an intergrade to another class, or whether some special property is associated with the soil.

Classes Related to Orders

Ten soil orders have been outlined. The names of all soil classes within a particular order are related to their order by an element from the order name.

Order	Element	Order	Element
Alfisols	Alf(s)	Mollisols	Oll(s)
Aridisols	Id(s)	Oxisols[†]	Ox(s)
Entisols	Ent(s)	Spodosols	Od(s)
Histosols[‡]	Ist(s)	Ultisols	Ult(s)
Inceptisols	Ept(s)	Vertisols	Ert(s)

The elements form the suffixed base to every soil class name. With this base, each name records the soil's classification at the order level and, thus, the basic properties exhibited by the soil. The following serve as illustrations:

Soil Class	Order
Aquents	Entisols
Fragiaquepts	Inceptisols
Hydric Borohemists	Histosols
Vertic Haploborolls	Mollisols

Elements of the order names may also modify the final word in a soil class name. In the class Vertic Haploborolls, "olls" indicates that the soil is a Mollisol, but "Vertic" indicates that the soil has certain properties associated with Vertisols. Other examples of this usage are as follows:

Soil Class	Order
Ultic Paleustalfs	Alfisol grading to Ultisol
Entic Chromuderts	Vertisol grading to Entisol
Alfic Sideraquods	Spodosol grading to Alfisol

Classes Related to Horizons

Epipedons and various subsurface horizons have been described. If a soil has one or more of these horizons, and if the horizon is not required (or indicated) by the soil's order classification, the soil class name will contain elements from the names of those horizons present. Formative elements representing the most commonly recognized horizons are as follows:

Horizon	Element	Horizon	Element
Agric	Agr	Gypsic†	Gyps
Albic	Alb	Natric*	Natr
Anthropic	Anthr	Ochric	Ochr
Argillic	Arg	Placic*	Plac
Calcic*	Calc	Plaggen	Plag
Cambic	Camb	Salic†	Sal
Duripan†	Dur	Sulfuric†	Sulf
Fragipan†	Frag	Umbric	Umbr

Examples of soil class names that signify the presence of horizons listed previously are as follows:

Soil Class	Horizons Indicated
Ochrepts	Ochric
Fragiochrepts	Fragipan and ochric
Natric Durixeralfs	Duripan (also natric or similar)
Calcic Argixerolls	Argillic (also calcic or similar)

With the last two examples, Natric Durixeralfs and Calcic Argixerolls, it is noted that horizon names may also be used to modify the final word. Three other horizon modifiers are petrocalcic, petrogypsic, and nadur. Petrocalcic and petrogypsic horizons have been described; "nadur" signifies that both a natric horizon and a duripan occur in the soil profile. When used as modifiers, "mollic," "spodic," and "oxic" relate to both soil horizons and soil orders, in that these horizons are also diagnostic for the orders. "Histic," on the other hand, relates only to the presence of a histic epipedon.

Classes Related to Other Features

Formative elements that are indicative of properties other than those associated with the soil's order classification or with particular horizons exhibited by the soil are as follows. Their common interpretation, where significant, and examples of their usage in soil class names are provided. As noted, the dominant soil properties are signified by the two or three formative elements that are contained in the final word in each soil class name. When used in the final word, a formative element connotes a characteristic soil property; when used as an adjective to modify the final word, it merely modifies those properties signified by elements in the final word. For example, "Aqu" in "Aquents" indicates complete profile saturation at some period (unless drained), but "Aquic" in "Aquic Calciorthids" indicates a Calciorthid that is wetter than a Typic Calciorthid.

Element	Common Interpretation	Example
Abruptic*	Abrupt clay increase; generally more than 20 percent (absolute) change in 7.5 cm or less, from ochric or albic to argillic (near surface charge)	Abruptic Tropaqualfs Abruptic Durixeralfs Abruptic Durargids
Acr*	Extreme weathering; only used with Oxisols	Acrohumox Plinthic Acrorthox
Aeric	Only used with "aqu"; soil drier than normally associated with "aqu"	Aeric Haplaquents Aeric Umbric Tropaquults

Element	Common Interpretation	Example
And*	Pyroclastic materials; upper horizon of textures finer than loamy fine sand; bulk density of 0.95 g/cc or less	Andepts Andic Cryochrepts Andeptic Ochraqualfs
Aqu‡	Wetness; generally, at least temporary saturation	Aquents Aquic Calciorthids
Ar	Mixed horizons, usually destroyed by plowing	Arents
Arenic*	Sandy surface (loamy fine sand or coarser) 50 to 100 cm thick	Arenic Haplastults Arenic Argiaquolls
Bor	Cold or properties associated with cold; normally mean annual soil temperature below 10 C	Boralfs Typic Fragiboralfs Borollic Haplargids
Chrom	Only used with Vertisol; surface browner and drier than that of "pell"	Chromusterts Chromic Pelloxererts
Cry	See "bor"; normally mean annual soil temperature 0 to 8 C	Cryofolists Cryic Rendolls
Cumulic	Epipedon more than 50 cm thick; organic matter may decrease irregularly with depth	Cumulic Haplumbrepts Cumulic Haplustolls
Dystr	Relates to lower base saturation	Dystrochrepts
Epiaquic*	Characteristics approaching those associated with "aquic"	Epiaquic Palehumults Epiaquic Tropudults
Eutr	Relates to higher base saturation	Eutrorthox
Ferr*	High iron-to-carbon ratio in spodic horizon; or iron-cemented nodules (2 to 30 cm in diameter) in argillic horizon	Ferrods Ferrudalfs
Fluv†	Recent alluvial deposits	Fluvents Fluvaquentic Cryohemists
Gibbs†	In upper 1 to 1.25 m, have cemented sheets or subhorizon with at least 20 percent (vol) gravel-size aggregates, containing 30 percent or more gibbsite (Al_2O_3)	Gibbsihumox Gibbsiaquox Typic Gibbsiorthox
Gloss	Albic horizon tongues into argillic or natric horizon	Glossudalfs Glossic Natrudalfs
Grossarenic†	Sandy surface (loamy fine sand or coarser) more than 1 m thick	Grossarenic Paleaquults
Hal‡	Salty; only used with "aquept" (wet-salty soil); at least 15 percent sodium saturation in at least half of upper 50 cm; decreases below 50 cm	Halaquepts Aeric Halaquepts Fluvaquentic Halaquepts
Hapl	Normal horizon development; "Haplic" indicates minimal horizon development	Haplorthods Haplic Durargids
Hum	Organic matter content higher than normal	Humox Humic Cryorthods
Hydr‡	Thixotropic in some horizon between 25 and 100 cm (relatively low bearing capacity); may have clays that dehydrate irreversibly to sand or gravel-size aggregates; normally	Hydraquents Hydrandepts Hydric Tropofibrists (with Histosols, indicates water layer below 30 to 60 cm)

Element	Common Interpretation	Example
	low bulk density and high water content	
Lithic‡	Rock contact in upper 50 cm	Lithic Rhodustalfs
Orth	Common horizon development	Orthox
Pachic	Epipedon thicker than that of "Typic"; normally more than 50 cm thick	Pachic Argiborolls Pachic Xerumbrepts
Pale*	Older soil development; have petrocalcic and/or thick, fine-textured argillic horizon; may have some plinthite in subhorizons; normally old, stable surfaces	Palexeralfs Paleorthids Spodic Paleudults
Paralithic‡	Lithic-like contact, or altered rock retaining its structure, within 50 cm of surface	Paralithic Vertic Haplustolls
Pell	See "chrom"	Pelleusterts
Pergelic‡	Have permafrost; mean annual soil temperature below 0 C	Pergelic Cryopsamments
Petroferric‡	Petroferric contact (ironstone) within upper 1 m	Petroferric Acrohumox
Plinth†	Plinthite is continuous, or constitutes more than one-half soil matrix, in upper 1.25 m; "Plinthic"—more than 5 percent (vol) plinthite in upper 1.5 m	Plinthaquepts Typic Plinthaquox Plinthic Tropudults
Psamm†	Below plow layer or 25 cm, have sandy textures to 1 m or to lithic or paralithic contact	Psamments Psammentic Haploxeralfs
Quartz*	Only used with "psamm"; sand fraction has at least 95 percent quartz or other insoluble minerals	Quartzipsamments Quartzipsammentic Haplumbrepts
Rend*	Have at least 40 percent calcium carbonate equivalent in or below epipedon	Rendolls Rendollic Eutrochrepts
Ruptic* (Ruptic-Lithic‡)	Intermittent or broken horizons; commonly shallow soils; with "Lithic," indicates horizons interrupted by bedrock	Ruptic-Vertic Albaqualfs Ruptic-Lithic-Entic Hapludults
Sider	Spodic horizon has ratio of free iron to carbon of 0.2 or more	Sideraquods Sideric Cryaquods
Sulf‡	Waterlogged or organic soil materials with at least 0.75 percent sulfur (mostly sulfides) and less than 3 times as much carbonate as sulfur in upper 1 m; drainage normally produces sulfuric horizon	Sulfihemists Sulfic Fluvaquents
Thapto* (Thapto-Histic‡)	Buried horizon or buried soil within 50 to 100 cm of surface	Thapto-Histic Fluvaquents Thapto-Histic Cryaquolls
Torr	Dry soil moisture regime; found primarily in arid and semiarid climates	Torrerts Torriorthentic Haplustolls
Trop	See "ud"; properties associated with humid tropical climates	Tropudalfs Tropic Fluvaquents

Element	Common Interpretation	Example
Typic	Typical profile of soil class (subgroup level)	Typic Medisaprists Typic Placohumods
Ud	Soil moisture regime dry less than 90 days in most years; properties associated with humid temperate climates	Uderts Entic Vermudolls Udic Ustrochrepts
Ust	Soil moisture regime between "torr" and "ud"; properties associated with wet-dry climates, usually warm	Ustox Lithic Ustorthents Ustertic Argiborolls
Verm	Below plow layer or 25 cm, at least 50 percent of volume is worm holes, casts, or filled burrows	Vermustolls Haplic Vermiborolls Vermic Udorthents
Vitr*	Only used with "and"; large amounts of vitric ash (glass) and pumice; commonly found near active volcanoes	Vitrandepts Plaggic Vitrandepts
Xer	Soil moisture regime and properties typified in Mediterranean climates; wet-dry, nontropical	Xerults Durixerollic Natrargids

Classes Related to Histosols

Nine formative elements are employed to distinguish various classes of the order Histosols. Recognition of these elements will assist the engineer who is forced to deal with organic soils as well as the engineer who must decide whether to design around such soils. The elements are summarized as follows:

Element	Common Interpretation	Example
Fibr	Least decomposed state; commonly have bulk densities less than 0.1 g/cc, fiber contents (unrubbed) more than two-thirds of volume, and saturated water contents of 850 to 3,000 percent (oven-dry)	Fibrists Cryofibrists Fibric Borohemists
Fol	Never saturated more than a few days after heavy rains; lithic or paralithic contact within 1 m of surface, and/or fragmental materials with organic materials in interstices	Folists Cryofolists Typic Tropofolists
Hem	State of intermediate decomposition (values between "fibr" and "sapr")	Hemists Hemic Borofibrists
Limnic	Organic and inorganic materials deposited in water or derived from aquatic plants (marl, diatomaceous earths, sedimentary peat, etc.)	Limnic Borofibrists Limnic Medihemists
Luv	Unknown in U.S.; horizon of humus materials, at least 2 cm thick, derived from higher in profile	Luvifibrists Luvihemists

Element	Common Interpretation	Example
Med	Less than three-quarters fiber volume derived from sphagnum peat; temperate climate	Medifibrists Lithic Medihemists
Sapr	Most decomposed state; relatively stable; commonly have bulk densities of 0.2 g/cc or more, fiber contents (unrubbed) less than one-third of volume, and saturated water contents below 450 percent (oven-dry)	Saprists Cryosaprists Sapric Tropofibrists
Sphagn	At least three-quarters fiber volume derived from sphagnum peat	Sphagnofibrists Sphagnic Medifibrists
Terric	Have mineral layer, at least 30 cm thick, with upper boundary within 60 cm of surface	Terric Troposaprists Sphagnic Terric Borofibrists

FAMILIES AND SERIES

All of the examples previously listed represent soils classed at the order, suborder, great group, and subgroup levels of the Soil Taxonomy. Subgroups are divided into families, and each soil family name consists of the subgroup name and several additional adjectives. These adjectives include class names for texture and contrasting texture, mineralogy, reaction or calcareousness, soil temperature, permeability, depth, slope, consistence, and coatings. For example, a "sandy, mixed, thermic" family of any subgroup indicates sand or loamy sand with less than 35 percent rock fragments by volume in a specified control section of the profile; a mixture of minerals, each less than 40 percent, in the 0.02- to 2.0-mm fraction of the control section; and a mean annual soil temperature at 50 cm depth between 15 and 22 C, with at least a 5 C difference between mean summer and winter soil temperatures. Class names, definitions, and recommended use of family characteristics are provided in the two volumes of the Soil Taxonomy (11, 12).

Soil series, when identified and classified in a survey, convey the greatest amount of soil property information and are of special value for local investigations. Series, however, are commonly named for geographic locations that seldom indicate soil properties. In most cases, the previously recognized series of the National Cooperative Soil Survey are classified in the hierarchy of the taxonomy (11).

SUMMARY

The previous U.S.D.A. system for soil classification has been replaced by the new Soil Taxonomy, a comprehensive, multi-categoric, pedological soil classification system. Although it may appear complex, the new Soil Taxonomy can be used by engineers who have little understanding of the mechanics of the system, of pedology, or of soil series. With the exception of soil series, each soil class name in Soil Taxonomy is composed of words or formative elements that connote properties expressed by the soil. Specific information about the soil is thereby obtained directly from the soil class name. Those formative elements and soil orders considered to be most informative for engineering analysis are listed as follows:

Element or Order	Brief Interpretation
Abruptic*	Abrupt textural change
Acr*	Extremely weathered (see Oxisols)
And*	Pyroclastic materials
Aqu‡	Wetness; possible saturation
Arenic*	Sandy surface
Calc*	Calcic horizon with or without gypsic horizon

Element or Order	Brief Interpretation
Dur†	Duripan
Epiaquic*	Surficial wetness
Ferr*	May have iron-cemented nodules
Fluv†	Alluvial deposits
Frag†	Fragipan
Gibbs†	Cemented sheets or aggregates (Al_2O_3)
Grossarenic†	Thick sandy surface
Gyps†	Gypsic horizon
Hal‡	Salty (wet)
Histic†	Organic surface
Histosols, ist(s) fibr, sapr, hem, med, limnic, sphagn, luv, fol, terric‡	Organic soils (fol: less than 1 m deep) (terric: mineral soil layer within 60 cm of surface)
Hydr‡	Thixotropic, clays may dehydrate irreversibly to aggregates (possible wetness)
Lithic‡	Bedrock within 50 cm of surface
Nadur†	Natric horizon and duripan
Natr*	Natric horizon
Oxisols, ox(s), Oxic†	Extremely weathered, stable soil, commonly deep; oxic horizon
Pale*	Petrocalcic or thick argillic horizon
Paralithic‡	Lithic-like contact within 50 cm of surface
Pergelic‡	Frozen soil or permafrost
Petrocalcic‡	Petrocalcic horizon
Petroferric‡	Ironstone contact within 1 m of surface
Petrogypsic‡	Cemented gypsic horizon
Plac*	Placic horizon
Plinth†	Plinthite within upper 1.25 m
Psamm†	Sandy soil
Quartz*	Sand fraction predominantly insoluble minerals
Rend*	Material with high $CaCO_3$ equivalent
Ruptic* (Ruptic-Lithic‡)	Broken horizon, commonly by shallow bedrock
Sal†	Salic horizon
Sulf†	Sulfuric horizon or sulfidic material
Thapto* (Thapto-Histic‡)	Buried horizon or buried soil
Vertisols, ert(s), Vertic‡	Swelling clay soil
Vitr*	Volcanic glass; nonthixotropic

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SOIL ENGINEERS AND THE NEW PEDOLOGICAL TAXONOMY

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Soil engineers and pedologists can benefit by extending their training and sharing their knowledge of the soils of the world. Future cooperative endeavors can be made easier and more successful if engineers learn more about the new pedological system of classification and soil scientists learn more about the methodology and interpretations employed by soil engineers. Two features of the new soil taxonomy that facilitate a transfer of information are the quantification of major soil characteristics and the system of connotative nomenclature. These features are described, as are the structure and selected classes of the system. The concepts of soil series and mapping units are also discussed in the context of the Soil Taxonomy.

•ENGINEERS and soil scientists no longer deal with highways or farms as independent phases of development. The worldwide concern for an environment that permits mankind to survive and to achieve an overall improvement in the quality of life requires a new scientific conscience and a better integration of human and natural resources.

Soil scientists are pleased that engineers find pedological classification and soil survey of value in their work. That soil scientists have also learned from engineers is evidenced by the engineering interpretation sections of any recent soil survey report. These sections contain information that may assist in studies for developing industrial, business, residential, and recreational sites. In addition, they provide preliminary estimates of engineering properties of soils relevant to water management systems, location of construction materials, possible ground conditions affecting construction, and designate map units useful for correlation with performance of engineering structures. Soil surveys do not provide information about highway design or construction; such decisions require utmost attention to on-site conditions and involve the latest technology developed for such purposes. By soliciting a broader understanding of soil behavior, soil scientists have found that there is much information of mutual concern and benefit.

Traditionally, soil scientists have directed their studies of pedological units toward plant production, whereas engineers have amassed a wealth of engineering data based on the same pedological units—for the most part, at the soil series level of classification. As one's experience with soils expands—from one's own backyard to the next county, to another state, and, finally, to various parts of the world—so do the problems of keeping track of the many kinds of soils, their individual properties, and the correlations of known or expected behavior. Only a computer can recall data on the approximately 10,000 soil series recognized in the United States, and the need arises for a comprehensive, yet practical, soil classification system.

During a recent project in Venezuela, the author was overwhelmed by the numerous potential soil series. Although most did not have series names, it was possible to recall their major properties because they had been classified in the new Soil Taxonomy. When comparing the response of soils whose classifications were similar to soils of New York, the author found that the predicted and experienced behaviors were also similar. In many instances, the agronomic and engineering interpretations were so similar that it was like dealing with soils of New York.

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Such transfers of knowledge are possible with the new Soil Taxonomy because information on soil characteristics has been quantified; the transfer is facilitated by a systematic application of names that indicate major soil properties.

THE NEW CLASSIFICATION SYSTEM

Soil scientists and engineers have steadily improved their methodology for studying and classifying soils. When soil scientists first recognize soil engineering, they discover a new universe related to their sacred pedological units. The engineers' conceptual framework includes a different terminology, several classifications, and a seemingly endless desire to produce numbers. Soil engineers, on the other hand, are undoubtedly aware of the changes that have occurred in pedological soil classification during the past decade. At times, the only item that appears remotely familiar is the soil series. The long-standing engineering experience with soil series has been well chronicled in various publications; now, when soil scientists refer to "Typic Fragiochrepts," the "7th Approximation," and the "new Soil Taxonomy," any feeling of cooperative endeavor might seem lost.

In brief, the previous pedological classification system (1, 7, 10) was not precise enough in its definitions to make consistent generalizations about soil properties or taxa. About 1950, steps were taken to develop a system that would be more quantitative as well as more systematic. By 1960, the system had undergone seven approximations—the 7th Approximation (8)—involving hundreds of changes to accommodate known soils of the United States. Since the official adoption of the 7th Approximation by the National Cooperative Soil Survey in 1965, there have been additional modifications as more worldwide information was considered. The final version will soon be available as U.S.D.A. Handbook No. 436, Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. Its companion volume, which contains the list and classification of soil series in the United States, Puerto Rico, and the Virgin Islands, is now in print (9). Together, these documents will serve as the basic references for the new Soil Taxonomy.

OBJECTIVES AND APPROACH

Soil Taxonomy has two major objectives: (a) to organize available information and thereby assist the understanding of relations among similar as well as dissimilar soils and (b) to serve the needs of a soil survey program in which geographic areas of soils are identified, named, and correlated.

Two significant aspects of the new Soil Taxonomy are the classification of soils based on field investigations supplemented by laboratory investigations and the recall of important properties based on the name of a taxonomic unit.

The taxonomy is a comprehensive system for classifying soils based on properties that have been quantitatively defined in terms of conventional field and laboratory measurements (8, 9). Cation exchange capacity, for example, is commonly the sum of cations extractable with ammonium acetate at pH 7. The degree to which a soil profile is saturated with basic cations (base saturation) is used as a criterion for classification. The quantitatively defined soil features that are diagnostic in the system are then supplied names or name elements, most of which are derived from Latin or Greek and are, therefore, somewhat familiar. "Eutro," for example, is the name element used to indicate a high base saturation soil, while "dystro" denotes a soil of low base saturation.

Overall, the new Soil Taxonomy is designed to facilitate communication and understanding. The systematic naming of quantitatively defined properties provides a means with which to generalize major features of soils in a region, thereby making it easier to share knowledge and experience with other regions.

CATEGORIES OF THE TAXONOMY

Orders

Soil Taxonomy contains six categories: order, suborder, great group, subgroup, family, and series. The highest category has 10 classes, or orders, whose properties are thought to reflect the dominant kinds and strengths of soil-forming processes. To illustrate, recent alluvium, sand dunes, and tidal marshes rarely have evidence of significant alteration of the soil materials. The soils may be so recent that processes have not had time to develop recognizable horizons, or the materials may be so resistant that internal changes are relatively small. These soils are classed together as the order Entisols; the element "ent" connotes recent, and the ending "sols" means soils. At the other extreme are soils whose properties indicate the most advanced state of weathering. These soils have residuals of resistant minerals, crystalline clays of very low activity, and an "oxic" horizon that is dominated by iron and aluminum oxides and is diagnostic for the order Oxisols.

Some soil orders have sets of properties that are thought to be a consequence of specific conditions affecting horizon development. Soils in arid zones (Aridisols) have little water to promote weathering or move components, clayey soils that churn and invert themselves (Vertisols) have little opportunity to develop definite horizons, and organic materials composed of decaying plant tissues (Histosols) do not develop the same kinds of horizons as do mineral soils. Other orders have horizons of clay accumulation (argillic horizons) as a primary diagnostic feature. Those with a high base reserve, like Pedalfers of the old system, are called Alfisols; those with a low base reserve, indicative of an ultimate stage of base removal, are referred to as Ultisols.

Suborders

At the suborder level, properties were selected to indicate the existing stage of horizon development or to indicate conditions affecting future horizon development. For example, all orders except Aridisols, Histosols, and Vertisols have suborders of wet soils, such as Aquents of Entisols and Aquox of Oxisols. Additional suborders are based on soil climate. Alfisols occur from the Arctic to the tropics; but at the suborder level, Boralfs are restricted to cold boreal regions, Udalfs to cool humid regions, Ustalfs to areas that have hot dry summer periods, and Xeralfs to areas of winter rainfall and summer drought, where xerophytic vegetation is common. All wet Alfisols are subclassed as Aqualfs, regardless of their environment, because the internal moisture regime is thought to be more significant than differences of soil water temperature.

Entisols have little horizon development, and their suborders are designed to indicate the main conditions for this lack. Wet Entisols are Aquents, those that are very sandy and either resist change or are young are Psamments, recent fluvial sediments are Fluvents, and most of the remaining kinds of Entisols are Orthents. For the Entisols, soil climate is indicated in the next lower category.

Great Groups

Most classes at the great group level (the third category) are designed to indicate the degree of development of the particular horizons considered to be diagnostic for their order and suborder. In some cases, great groups indicate the presence of additional horizons, bedrock at shallow depth, or soil climate. In the humid temperate, glaciated regions, for example, many well-drained soils with textural B-horizons are classed as Hapludalfs at the great group level. They are Alfisols because of their argillic horizon and high base reserve, they are Udalfs because the profile is usually moist, and they are Hapludalfs because their horizon sequence is relatively simple. Within the same area, however, there are related soils that have a fragipan below the textural B-horizon. These soils are called Fragiudalfs to indicate the presence of both a fragipan and the diagnostic argillic horizon.

Subgroups

At the subgroup level it is possible to indicate features that grade to properties that are diagnostic for other kinds of soils, or features that are extra and not diagnostic for other kinds of soils. Associated with the well-drained Hapludalfs previously noted are Hapludalfs exhibiting some gray mottles, indicative of wetter conditions for some periods of the year. The well-drained Hapludalf would be classed in the Typic subgroup, and the Hapludalf intergrading to a wet soil would be classed in the Aquic subgroup. If bedrock occurred at shallow depth (an extragrade feature), the subgroup would be Lithic.

Modifiers at the subgroup level are applied as separate words, and each ends in "ic." This allows quick recognition of both the categorical level and the kinds of intergrade or extragrade features, distinguishing one soil from another. The previous examples may be summarized as follows:

1. Alfisols—a soil order (sols) with a diagnostic argillic horizon and a high reserve of bases (alf);
2. Udalfs—a soil suborder (two syllables) indicating Alfisols having a humid temperature soil climate;
3. Hapludalfs—a soil great group (three or four syllables) indicating Alfisols in a humid temperate zone, which have a simple sequence of diagnostic horizons;
4. Fragiudalfs—a similar soil great group except that the soils also contain a fragipan;
5. Typic Hapludalfs—a soil subgroup (great group word modified by one or more "-ic" words) indicating that these are the typical well-drained Hapludalfs;
6. Aquic Hapludalfs—a subgroup of Hapludalfs that have evidence of periodic wetness (a property diagnostic of Aqualfs);
7. Lithic Hapludalfs—a subgroup of Hapludalfs that have bedrock at shallow depths (less than 50 cm); and
8. Aquic Lithic Hapludalfs—a subgroup of Hapludalfs that have evidence of periodic wetness (a feature intergrading toward Aqualfs) and are shallow to bedrock (an extragrade feature).

Families

In addition to orders, suborders, great groups, and subgroups, soils in the taxonomy are further subdivided into a fifth category, the soil family. Properties selected at the family level are those believed to have further significance to plant production, namely, the supply of air, water, and nutrients. For most soils, the family includes specific information about the internal soil temperature, the texture in a defined control section of the soil profile, and the mineralogy of clays in fine-textured soils or the mineralogy of silts and sands in medium- and coarse-textured soils. In other soils, reaction and calcareousness, depth, slope, consistence, and permanence of cracks have been used to increase the precision of definitions and separation of soils.

By the time all criteria from an order to a family are accumulated, there are many statements and interpretations that can be made. Particle size classes at the family level have been particularly useful for grouping soils of similar parent materials, thereby producing units of greater familiarity to engineers and pedologists alike (3). It is also possible to examine relations among soils of similar textures even though they may have different kinds of diagnostic horizons; for one interpretation, the soils may be grouped together, yet for another their expected behavior may suggest they be kept separate.

Series and Mapping Units

Refinements of the limits of properties accumulated at the family level, or additional properties of local importance, are used to provide the present concepts and descriptions of soil series. Since 1965, the National Cooperative Soil Survey has been redefining the soil series of the United States to conform with the new Soil Taxonomy. In most instances, there has been little change, but in some areas there has been a drastic overhaul of the pedological units (9). This is not a subterfuge to undermine the long-time confidence in soil survey and pedological classification; it is an attempt to improve accuracy and precision as more information becomes available.

Soil surveys have always had to resolve the variations observed in the field with the scales at which delineations are made and units named. Soil borings and pits are conceded to be samples of some larger body of interest. The sample volumes are now referred to as pedons, the smallest sampling unit that exhibits genetic relations among the horizons. By arbitrary agreement, the surficial area of a roughly circular pedon ranges from about 1 to 12 sq m, depending on the amount of horizon variability. The geographically associated collection of pedons having properties within a specified range is referred to as a polypedon. The limits of polypedons are fixed first by the criteria accumulated in the highest five categories of the taxonomy and are further restricted by the criteria used to define soil series. The sum of characteristics used to define soil series fixes the allowable range for polypedons observed in the field.

In the standard detailed soil surveys of the National Cooperative Soil Survey, delineations are named for the dominant series that occurs in the mapped area. Inclusions in a mapping unit refer to pedons or polypedons of different series or phases that cannot be separated at the mapping scale of about 1:20,000. Soil types are no longer considered as a category in the classification; rather, they are treated as surface-texture phases of their respective series and continue to be a significant part of the designated map units. It is important to realize that, although the characteristics of pedons at geographic points are the basis for classifying and delineating polypedons, when reference is made to soils delineated on a map, the statements relate only to geographic areas (4). On-site investigations are required before accurate statements can be made about geographic points—whether for fertilizer recommendation or for highway route location.

CONCLUSIONS

In 1950, Olmstead (2) indicated the need to place greater emphasis on engineering correlations, and one measure of the value of any soil map is the number and precision of interpretations that can be made about each mapping unit (5). Because the definitions of soil classes at all levels of the new Soil Taxonomy are substantially more specific than in the previous system, there is potential to increase the value of soil maps with a greater number of engineering correlations. In addition, the systematic nomenclature of the taxonomy provides an excellent aid for information transfer. Given quantitatively defined soil properties and a systematic nomenclature, engineers can easily derive information from regions mapped and classified according to the system (6). It is hoped, however, that present and future engineers will supply information to the system and work with soil scientists toward a better understanding and use of the soil resources of the world.

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