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Field Investigations, Technique of Field Observations Including Compaction Control, Soil Stabilization

Recherches et essais du sol sur place, y compris contrôle de la compaction, stabilisation des sols, technique des observations sur le terrain

GENERAL REPORT

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Introduction

Directions for preparation of general reports require, and rightly so, that consideration be given not only to papers submitted to the conference but also to all other papers dealing with the subjects assigned to a particular Session and published since 1948, or in general that the report should present a review of progress since the Second International Conference. This is a rather large order, particularly for Session No. 3, since the scope of field investigations has been increased considerably in later years, and since papers on field compaction and stabilization of soils also have been relegated to this Session. The time and space for preparation and presentation of this report were insufficient for a review of all papers dealing with the subjects assigned to the Session, and it is also possible that some papers, particularly those published outside U.S.A., may have been overlooked.

The reporter takes this opportunity to express his sincere thanks to Dr. *M. Juul Hvorslev* for his valuable and able assistance in preparing this report.

The division of this report into subsections is more or less governed by the number and character of the papers submitted, but it proceeds in general from preliminary field investigations to final observations of the behavior of completed structures. The list of references is restricted to papers mentioned in the report, and in order to shorten this list, papers submitted to the conference are not included but are indicated by the number of the Session and the number of the paper in the Session (for example 3/2).

(1) Geological and Aerial Reconnaissance

An outstanding trend in field investigations is the increasing use of geology, aerial photographs, and to some extent also pedology for estimates of surface and subsurface soil conditions,

preliminary location of structures, and establishing an adequate and economical program for more detailed investigations by geophysical methods, soundings, borings, and sampling.

The value of geology in field investigations for structures in or on solid rock has long been recognized, not only because the engineering geologist usually can prepare fairly reliable estimates of subsurface conditions but also because of his detailed knowledge of the physical and mechanical properties of the numerous types of rocks. Use of geological reconnaissance of unconsolidated sediments is of more recent date and is due not only to increasing interest in geology by foundation engineers, but also to the fact that engineering geologists have learned in their reports to emphasize data of engineering interest and to obtain such data from field reconnaissance, published geological maps, and aerial photographs. The services of an engineering geologist can be utilized to advantage, not only for preliminary investigations, but also in the final interpretation of the results obtained by subsurface explorations in order to avoid misleading interpolations and extrapolations and overlooking significant changes in the continuity of subsurface strata. For examples of recent use of geology for engineering purposes, reference is made to a symposium, called the *Berkey volume*, published by the *Geological Society of America* (1952), to another symposium sponsored by the *American Society of Testing Materials* (1952), and to a paper on highway soil surveys by *Woods* (1952). Use of geology and aerial photographs in surveys of soil conditions and river regimen in broad alluvial valleys is demonstrated in a paper by *Fisk* (1952) and especially in a detailed report by the same author (1947).

Aerial photographs not only permit very quick and economical surveys of geological and surface soil conditions of large areas but also often disclose changes in such conditions which would be very difficult to detect by ground reconnaissance. It can be said that aerial photographs are becoming indispensable

in the planning of all projects involving river regulation, location of highways, railroads, airfields, dams, canals, and large foundation structures. The basis for interpretation of aerial photographs is a thorough knowledge of geomorphology and of the formation of soils and their subsequent segregation and redeposition, changes and movements by wind, water, glaciers, frost, slides, and creep. The value of aerial photographs to the average foundation engineer is increased by publication of keys to and examples of their interpretation. Such keys and examples were contained in papers by *Belcher*, *Woods*, *Frost*, and *Hittle* submitted to the Second International Conference in Rotterdam, 1948, and additional data are presented in some of the references given above and in recent papers by *Belcher* (1952), *Frost* and *Mintzer* (1950), and *Parvis* (1950).

A large amount of information on surface soils is contained in published agricultural soil maps and reports, but these maps are often of but little help to engineers unfamiliar with pedological symbols and terminology and the vast array of local soil names used. However, the value of agricultural soil maps is being recognized, especially for preliminary location of highways and airfields, and directions for their engineering use are contained in the above mentioned paper by *Woods* (1952), the symposium by the *American Society for Testing Materials* (1952), and in a special symposium on the subject sponsored by the *Highway Research Board* (1949).

(2) Geophysical Methods

The principal geophysical methods used in subsurface explorations for civil engineering purposes are still the electrical resistivity method and the seismic refraction method, although the faster and cheaper magnetometer surveys occasionally can be used to advantage for location of buried dikes and investigations of irregularities of the surface of underlying intrusive rocks. Advances since 1948 consist primarily in simplification and reduction in weight of the field equipment; *Linehan* (1952). New resistivity meters have been reduced to a fraction of their former size and weight, and the adjustments are greatly simplified and much faster to operate. Oscillographs for seismic explorations are provided with a greater number of channels but reduced in size and weight and also combined with a self-contained unit for field development of oscillograms. The size of recent combined oscillograph and development units is that of a small suitcase.

Süsstrunk (3/18) describes the use of seismic refraction methods in Switzerland, presents a table of velocities of longitudinal waves in local sedimentary deposits and rocks, and discusses in detail determination of *Young's* modulus of elasticity by means of the measured wave velocities. He suggests that the dynamic moduli thus determined are more realistic than the static moduli obtained by laboratory experiments on rock cores, because the wave velocities are not influenced by the presence of small fissures and haircracks to the same extent as the results of static laboratory tests, and because the fissures in foundation rock often are closed by grouting during construction.

Several attempts have been made by various agencies including the Waterways Experiment Station, Corps of Engineers, U.S. Army, to use ordinary sonic sounding and depth-finding equipment for determination of the thickness of soft or loose bottom deposits in rivers, lakes or bays, but until recently without much success. However, according to reports in *Engineering News-Record* (August and October 1951) new

and improved sonic depth-finding equipment, developed by the *Edo Corporation* for the U.S. Navy and the U.S. Geological Survey, has made it possible to determine the depth to bedrock through up to 130 feet of overlying mud, sand, and gravel, and the results were in excellent agreement with those obtained by borings. This equipment is still in development and has apparently not yet been released for general use, but it may constitute an important new tool for subsurface exploration of water-covered areas.

(3) Sounding Methods

It can not be questioned that sounding by means of rods or cone penetrometers is a very fast, economical, and useful method of subsurface exploration. Static sounding methods are generally preferable to dynamic methods, but the latter are more economical and may be used to advantage when hard and gravelly soils are encountered, and when the primary objective is to determine the depth to bedrock. Sounding methods provide continuous and very detailed profiles of changes in character of the soil and often disclose stratifications and irregularities which are difficult to detect by boring, sampling, and testing. It has been demonstrated by pile loading tests and statistical correlations that the sounding profiles provide fairly reliable data for determination of the required length and the safe point bearing capacity of piles; *Huizinga* (1951), *Geuze* (1952), *Skempton*, *Yassin* and *Gibson* (1952). Sounding also furnishes qualitative data on the strength, compressibility, and relative density of soils, but considerable uncertainty still exists regarding the reliability of current methods for translating the penetration resistance into definite quantitative values of these properties.

The point resistance of a rod or cone depends on the effective stresses in the ground and on various soil properties such as cohesion, internal friction, compressibility, and sensitivity or relative density. A very useful theoretical basis for the relationship between the point resistance and some of these properties is contained in previous papers by *De Beer*, and excellent reviews are presented in recent papers by *Kantey* (1951) and *Geuze* (1952). In actual practice it is often difficult to separate the influences of the various properties, and recent investigations by *Haefeli*, *Amberg*, *von Moos* (1951), *Kahl* and *Muhs* (1952), *Kahl* (1952), and *De Beer* (1951) demonstrate that minor details in the design and operation of the sounding equipment may exert a very great influence on the penetration resistance. Laboratory tests by *Kahl* and *Muhs* (1952) and field observations also indicate that in uniform cohesionless soils the penetration resistance at first increases linearly with depth, but after reaching a certain depth, which depends on the relative density of the soils, there is no further increase in penetration resistance with increasing depth. Finally, the penetration resistance in stratified or nonuniform soils will be influenced by the properties of the soil at a considerable distance below the cone, and to a smaller extent by the compressibility of the soil above the cone. Therefore, a certain minimum thickness of uniform soil is required in order to obtain a penetration resistance which is truly representative of a particular stratum.

The skin friction on uncased sounding rods is often determined by withdrawal tests or resistance to rotation, and separate diagrams for the point resistance and the accumulated skin friction can be obtained directly by use of encased sounding rods. *Begemann* (3/1) demonstrates that the accumulated skin friction thus determined is too low, since the skin friction de-

creases with continued sliding of metal on soil, and he proposes the addition of a small cylinder above the cone point which will permit determination of the specific skin friction before it has been decreased by excessive sliding. The specific skin friction also can be determined by means of equipment described by *De Beer* in papers published before 1948. *Haefeli* and *Fehlmann* (3/4) describe equipment which can be used for either dynamic or static sounding and which also contains a separate small cylinder for determination of the specific skin friction. Furthermore, these authors demonstrate that the skin friction thus determined increases several fold in course of time. *Huizinga* (1951) also points out that the skin friction determined by sounding tests usually is lower than that ultimately acting on piles. Considering all the above-mentioned investigations, it appears that the skin friction obtained by sounding tests does not represent that acting on piles unless special equipment is used and time-consuming tests are made to determine the increase in skin friction with time.

The skin friction greatly increases the difficulties in operating ordinary sounding equipment at great depths below the ground surface, but these difficulties are eliminated in a new equipment developed by the Waterways Experiment Station and described in a paper by *Hvorslev* (3/5). The sounding rod proper passes through a rotating drill rod and its auger-type bit to a conical drive point, and it is advanced automatically with the drill rod but not rotated. Circulating drilling fluid removes cuttings, stabilizes the walls of the hole, and practically eliminates skin friction on the drill rod so that the equipment can be operated by a standard rotary drilling rig.

The *Swedish Geotechnical Institute* (1949) has also developed sounding equipment in which the skin friction is reduced by rotation of an uncased sounding rod and by use of drilling fluid. The cone point is connected to the rod by a swivel so that it will not rotate with the rod, and drilling fluid is allowed to seep down into the annular space between the rod and the soil. The torque in the rod is measured, and the corresponding vertical component of the skin friction is automatically subtracted from the recorded total penetration resistance. The rod is advanced and rotated by means of friction rollers, and this arrangement permits coupling of new rods without interruption of the sounding.

The various soil strata can not be identified by penetration resistance diagrams unless the results of boring and sampling operations in the vicinity are available. This limitation of soundings is partially eliminated by modifications in sounding equipment, described in a recent paper by *Buisson* (1952), which permit intermittent sounding and sampling.

In summary, it can be said that sounding methods have great potential advantages and uses, but a considerable amount of basic research remains to be performed before the maximum benefits from use of the methods can be realized.

(4) Vane Tests

In a paper presented at the Second Conference in Rotterdam, 1948, *Carlson* (name later changed to *Cadling*) described a vane test for determination of the shearing resistance of soft cohesive soils in situ. Independently thereof, similar vane tests were developed in England by *Evans* and *Sherrat* (1948) and described in greater detail in a paper by *Evans* (1950), but the original equipment was primarily intended for determination of the traffic-bearing capacity of surface soils. Since that time the vane test has gained greatly in popularity, a variety of improved equipment has been developed, and many tests and

correlations of the results have been performed and are described in papers by *Cadling* and *Odenstad* (1950), *Skempton* (1948), *Hansen* (1950), *Murphy* (1952), *Trow* (1952), and *Kantey* (3/6).

Exploration by vane tests is slower than by sounding and a continuous profile is not obtained. However, the results of vane tests can be translated into fairly reliable values of both the maximum and residual shearing resistances of the soil in situ. Correlations show that the shearing resistances obtained by vane tests generally agree well with the unconfined compressive strength of undisturbed samples from shallow depths, but in contrast to the compression tests, the vane tests indicate a continued increase in shearing resistance with depth, and this resistance is fairly close to computed average values along actual surfaces of failure in soft cohesive soils.

Skempton and *Henkel* (3/17) demonstrate that the shearing resistances of certain normally consolidated clays obtained by vane tests are in close agreement with those obtained by unconsolidated, undrained triaxial tests on undisturbed samples from all depths, whereas the unconfined compressive strengths of the deeper strata are too low and corresponding strengths obtained by consolidated, undrained triaxial tests are too high. The authors emphasize, and this reporter agrees, that the enthusiasm for the new vane tests in some cases has led to unjustified mistrust of the reliability of standard sampling and testing procedures—see also the section on “Density and Strength of Soil in Situ”—and to the use of vane tests under unsuitable soil conditions. The vane test is undoubtedly a very valuable method for determination of the shearing resistance of the soil in situ, but it also appears that there is need of a definite and authoritative statement of its limitations and the conditions under which it can be used to advantage.

(5) Field Loading Tests

One of the earliest methods devised for direct determination of the bearing capacity of soils is the field loading or plate bearing test. This method has the serious limitation that it indicates only the bearing capacity of the soil to a depth equal to a few times the diameter of the plate, and in some cases it is also necessary to make tests with plates of various diameters in order to eliminate dimensional effects. These limitations are now known and taken into consideration to a greater extent than formerly.

Recent advances in plate bearing tests consist mainly in improvement of mobile testing equipment. Even with such improvements, plate bearing tests require considerably more time than soundings and standard penetration tests with soil samplers. In order to enable substitution of the latter type of tests for plate bearing tests, an extensive series of correlations has been performed by *Khanna*, *Varghese*, *Hoon* (3/7), and satisfactory results were obtained. These authors also present comparisons between load-settlement curves and stress-strain curves obtained by triaxial compression tests.

Pile loading tests may also be classified as field loading tests, but such tests will presumably be discussed in Session No. 5. Here it shall only be mentioned that improved equipment for performance of such tests has been developed by the Swedish Geotechnical Institute and described by *Kjellman* and *Liljedahl* (1951), and that particular efforts are being made by several organizations to determine the division of the total load between point resistance and skin friction as well as variations of the latter with depth.

requires periodic determinations of water contents or moisture gradients in the ground. The data can be obtained by boring, sampling, and standard laboratory tests, but this procedure is time-consuming and expensive, and it has the further disadvantage that each sample is obtained from a slightly different location, which introduces an additional disturbing factor in the analysis of the results obtained. Several fast but indirect methods for continuous determination of changes of water content of soil in situ have been in progress of development during the last decade and especially since 1948.

The so-called electrical moisture meters measure changes in resistivity of gypsum blocks, fiberglass, or nylon plates buried in the soil. The resistivity depends on the water tension, which in turn varies with the moisture content of the soil, but the relationships are not unique, and it is generally necessary to calibrate each meter for each type of soil and often in situ. The design and use of these meters are described in papers by *Colman and Hendrix* (1949), *Aitchison and Butler* (1951), *Croney* (1952), and *Bouyoucos* (1952).

The more recent nuclear meters, developed by *Belcher, Cuykendall, Sack* (1950, 1952) permit fast indirect determination of either water content or density of the soil. A neutron source is used for determination of moisture content; the fast neutrons emitted are changed into "slow neutrons" when they collide with hydrogen nuclei; some of the transformed neutrons return to and are counted by the meter, and the count is correlated with the water content of the soil. A source emitting gamma rays is used for density determinations. The gamma rays are scattered by atoms in their path; the scattering increases and the reflection of rays, measured by the meter, decreases with increasing density of the soil. These meters are still in process of development but have already been used successfully on practical projects; *Belcher* (1952), *Torchinsky* (1952), *Horonjeff* and *Goldberg* (1953).

(12) Density and Strength of Soil in Situ

Several papers submitted for presentation at Session No. 3 describe results of field and laboratory investigations of the density and strength of soils in situ and also correlations between these properties and classification indices of the soil.

Kantey (3/6) describes results of field and laboratory strength tests on normally consolidated, soft clay deposits, and also the construction of a test bank designed to produce failure in the clay. The results indicate that the shearing resistance increases linearly with depth and agrees with the *Coulomb* equation, $s = c + n \tan \Phi$, where c is the cohesion, n the effective normal stress, and Φ an apparent angle of internal friction. Good agreement existed between values of Φ obtained by vane tests, direct shear tests, and stability analysis of the test bank, but triaxial tests gave deviating results, and there was also considerable difference in values of c obtained by the different types of tests. Some of these differences are attributed to disturbance of the sensitive clay and to its content of shells.

Skempton and Henkel (3/17) present first a summary of previously published data and hypotheses, *Skempton* (1948), and then amplify these data with the results of detailed field and laboratory investigations of the strength characteristics of postglacial, normally consolidated clays. It was found that the ratio of shearing resistance to the effective normal pressure is nearly constant for the individual strata, and that there is a linear relationship between this ratio and the plasticity index.

The investigations by *Skempton and Henkel* indicate that the

frequently reported differences between the results of vane tests and various laboratory strength tests may be ascribed to differences in type and technique of laboratory tests rather than to disturbance of the soil during sampling. The authors conclude that good agreement between the results of vane tests and unconsolidated, undrained triaxial tests can be expected for non-fissured, overconsolidated clays and also for normally consolidated clays when the plasticity index is low and when a newly defined activity ratio, i.e., plasticity index over clay-size fraction, is high.

(13) Stress and Strain of Soil in Situ

Soil stresses in earth dams and in compacted bases for roads and airfields, caused both by the weight of the soil and by surface loads, have been investigated by several organizations, and the results of stress measurements below loading plates are described in a paper by *Plantema* (3/15). Such investigations are still in progress at the Waterways Experiment Station and include both homogeneous and layered systems. More reliable results are now being obtained because of improvements of earth pressure cells, particularly in regard to their sensitivity and ability to retain their calibration characteristics under adverse conditions and over long periods.

Plantema (3/14) describes an earth pressure cell consisting of a very thin and flexible face plate or membrane, tightly attached to a ribbed base plate. The space between the membrane and the base plate is filled with oil, which transmits the pressure on the membrane to a diaphragm in the base plate. The strains in the diaphragm are measured by means of electrical resistivity strain gages and a dummy gage. A new and ingenious apparatus for calibration of the pressure cells also has been developed by the author. This apparatus resembles a triaxial chamber, and the pressure cell is placed in the center of a huge test specimen of sand. The calibration indicated excellent characteristics of the pressure cell under uniformly distributed loads. It is possible, however, that the characteristics may not be retained under nonuniform loads, since the Waterways Experiment Station found it necessary to increase the thickness of the face plate of the WES earth pressure cell in order to minimize the effect of a nonuniform distribution of loads.

A pressure cell which is nearly identical to the one developed by *Plantema* is described by *Lecoy* (1952). Several improvements have been made in the design and construction of the earth pressure cell developed by the Waterways Experiment Station (1951-A). Stronger and more corrosion-resistant steels are used, and the oil film between the face plate and the base plate is replaced with mercury, since the latter has thermal volume change characteristics which are in better agreement with those of steel. The diaphragm is provided with four strain gages, two in compression and two in tension, which form a complete bridge. The sensitivity of the cell is thereby increased four times in comparison with the usual arrangement with a dummy gage and strain gages in compression or tension only.

The influence of slow plastic flow or creep of soils under retaining walls and similar structures has long been recognized, and several papers on the creep of soil, snow, and ice have been published by Professor *Haefeli* and his collaborators. The existence of creep in natural soil deposits, and the consequent danger to structures built on or in such deposits, is often overlooked during preliminary subsurface explorations. Slow lateral movements may be determined by the methods devised

by Professor *Haefeli*, and also by observing changes in inclination at various depths of a hole, lined with an armored rubber hose or a flexible metal hose, by means of the inclinometers described in the section on "Observations of Completed Structures".

(14) Special Investigations in Cold Regions

Possible destructive action of frost in foundation soils for buildings, roads, and airfields is of great concern to all practicing engineers. Many papers and some books on the subject have been published, and a comprehensive bibliography and review of existing literature dealing with this subject has recently been compiled by *Johnson* (1952). Attention may also be called to a recent book on frost action in foundations by *Ruckli* (1950), to a symposium held under the auspices of the Highway Research Board, U.S. National Research Council (1952), and to a recent paper by *Carlson* and *Kersten* (1953). Definite progress is being made in investigation of the characteristics of soils subject to destructive frost action and in correlating the frost penetration in soils with meteorological data and type of surface cover.

Increased construction activities in arctic regions have emphasized many new problems which require special field investigations. Credit should be accorded to Professor *Haefeli* and the Swiss Institute of Snow and Avalanche Research as material contributors to the founding of the new science of snow and ice mechanics and for demonstrating that many of the results obtained in the study of snow and ice also can be applied to frozen and unfrozen soils. Intensive research on these problems is currently being performed or sponsored by the Associate Committee on Soil and Snow Mechanics of the National Research Council of Canada and by the Snow, Ice and Permafrost Research Establishment of the Corps of Engineers, U.S. Army. Available space in this report permits only an enumeration but not a discussion of the principal special field investigations in arctic regions.

(15) Field Compaction of Soils

Papers on compaction of soils, submitted for presentation at this Session, deal in part with laboratory tests, and it is difficult to separate completely laboratory and field work in a discussion of compaction of soils. So many factors influence the compaction of soils and so many papers have been published on the subject that it is not possible to cover the field in this report, and reference is made to general reviews in recent papers by *Philippe* (1952), *Wilson* (1952), and *Bjerrum* (1952).

It is often difficult to duplicate the results of laboratory compaction tests in field compaction because of differences in confinement, compactive effort, and method of compaction. A variety of laboratory compaction tests utilizing impact and static forces, kneading and vibrations, and combinations thereof have been developed in an effort to obtain agreement between the results of laboratory and field tests. Very coarse material is often removed from the soil tested in the laboratory or the size of the molds or test specimens is varied in accordance with the maximum size of grains or stones in the soil. Practical miniature equipment for compaction tests on fine-grained soils has been developed by *Wilson* (1950), compaction by kneading is described by *McRae* and *Rutledge* (1952), and

an excellent discussion of the influence of coarse aggregate and use of large molds is contained in a paper by *Walker* and *Holtz* (1951). Whenever feasible, and particularly when large structures are involved, it may be advisable to make full-scale field compaction tests with various types of equipment. Such tests can often be made on cofferdams, approach fills, and similar structures which will serve other purposes in addition to that of a test fill.

Properly performed laboratory compaction tests will generally furnish adequate data for design of the structure, but possible differences in the results of laboratory and field compaction should be taken into consideration when writing specifications for execution of the work. Many specifications prescribe that the density obtained by field compaction should be a certain percentage of the optimum density obtained by a standardized laboratory compaction test, but slight changes in soil conditions or adverse weather may make it very costly or impossible to comply with such requirements. Furthermore, a soil compacted to a specified density may not have other desired physical properties, and it should be realized that properties such as strength, compressibility, and permeability do not depend alone on the density but also on moisture content, compactive effort, and method of compaction; see *Wilson* (1952). Compaction specifications tend to be of either one of two general types. One type, in general, specifies the end product and the other specifies methods, control, equipment, and procedures. Either type may possess advantages depending on specific local soil and climatic conditions. Both types require the exercise of moisture control. Military compaction work in the U.S.A. is controlled both as to moisture and density by a family of strength curves which show the full range in strength of a soil with changes in moisture and density; *Turnbull* and *McRae* (1950).

Lewis (3/9) discusses difficulties in adhering to specified limits of moisture content and corresponding densities by field compaction of soils in Great Britain, primarily because of the humid climate and the prevalence of cohesive soils. Under these conditions it is generally necessary to use the soils at their natural water content, and *Lewis* proposes that specifications for the final state of compaction be based on the air content or a certain percentage of the density for complete saturation of the soil at the prevailing water content. In other areas of humid climate where drying is difficult, the soil is compacted at the existing moisture content with the design of the earthen structure being based on the reduced strength of the soil in its semi-compacted and high moisture state. Limited compaction is often obtained only by the hauling and spreading equipment.

A large series of laboratory and field compaction tests with different soils and types of equipment has been performed by the *Waterways Experiment Station* (1949-50). Results of compaction of a lean clay soil with sheepfoot and rubber-tired rollers are reported in a paper by *Turnbull* and *Shockley* (3/19).

The behavior of a sheepfoot roller depends on the strength of the soil, and the *Waterways Experiment Station* (1951-B) has performed a series of penetration or loading tests with small circular plates which were attached to the hydraulic stem of a power drill rig in order to develop simple methods for estimating the behavior of sheepfoot rollers and to determine the optimum foot area. It is believed that this procedure will prove sufficiently feasible so that expensive compaction test sections can be eliminated.

The paper by *Lewis* (3/9) contains interesting details of a

available correlations of the penetration resistance of penetrometers or samplers with the density and strength of soil in situ are subject to definite limitations. More reliable data on the strength of soil in situ can often be obtained by vane tests. Equipment and techniques for vane tests have been improved, and the tests are being used on an increasing scale, but additional basic research is needed on possible limitations of the test or on the reliability of the results obtained in various types of soils.

Comparisons of soil strengths obtained through vane tests or by analysis of actual slides with the results of triaxial tests on undisturbed samples indicate that formerly reported differences often can be traced to improper techniques in laboratory testing.

Lighter and more mobile equipment for field loading or plate bearing tests has been developed, but these tests are still relatively time-consuming and are often replaced with faster and less expensive methods of investigation, especially since the limitations of results of plate bearing tests are becoming better known.

Explorations show that honeycombed structures, vertical pipes, solution channels, and cavities can be formed not only in limestone and other rocks but also in certain silty and calcareous soils.

Sources of error in determination of ground-water levels and pore-water pressures are better known than formerly, and definite improvements have been made in measuring equipment and techniques, especially in the design and installation of piezometers and hydrostatic pressure cells for use in less permeable soils. These advances are important since determination of pore-water pressures and their changes during and after construction is becoming a practical necessity for proper design and control of construction for many large foundations and earthen structures.

Attempts are being made to replace field pumping tests for determination of the permeability of soil in situ with simpler and less expensive methods, such as observation of flow from or to shallow trenches, borings, or piezometers. These latter methods are theoretically feasible, but the measurements may be subject to significant errors, and additional research and improvements in techniques are needed to determine the influence of or eliminate sources of error.

The erection of a structure or placement of a pavement or other covering on the ground surface usually causes a change in temperature and moisture conditions in the foundation soil, which in turn may result in detrimental heaves or settlements of buildings or pavements. This problem is under active investigation by several organizations, but adequate data for formulation of safe design rules have not yet been obtained. The periodic determinations of changes in soil moisture are facilitated by use of several types of electrical resistivity meters and recently developed neutron moisture meters.

Investigations of the magnitude and distribution of residual and induced stresses in soil masses are being continued by several organizations. New or improved soil pressure cells have been developed, but it is not yet certain that any of these cells, when buried in moist soil, will remain completely reliable or retain their calibration characteristics over protracted periods of time.

(c) *Strengthening of soils by compaction and stabilization.* Field and laboratory investigations of the compaction of soils are commanding the keen interest and efforts of many investigators. One of the principal difficulties in laboratory testing is practical duplication of the soil structure, density, and

strength obtained by field compaction. Fully satisfactory testing equipment and techniques have not yet been developed, but laboratory compaction by kneading shows greater promise of success than static, impact, or vibratory compaction.

Methods of field compaction vary with the type of structure and soil, climatic conditions, and local preferences. Sheepfoot rollers are used extensively for compaction of more or less cohesive soils, but agreement has not been reached on the optimum weight of the roller, of the foot area and pressure, and corresponding variations in the required number of passes. Heavy rubber-tired rollers, with tire pressures up to or even above 100 lbs./sq.in. are being used on an increasing scale, especially in the U.S.A. for compaction in depth and of soils with little or no cohesion. Smooth steel rollers are often preferred in Great Britain because climatic conditions usually require compaction of the prevalent cohesive soils at their natural water content.

Vibrations unquestionably increase or facilitate the compaction of cohesionless soils, and utilization of vibrations in compaction is under active investigation, but really successful vibrating compaction rollers have not yet been developed. Heavy plate vibrators give excellent compaction in depth and can be used to advantage in confined spaces and on special and smaller jobs.

Field compaction is usually accomplished with water contents at slightly above, or somewhat below, the optimum for the soil, depending on the type and general design of the structure. In very humid climates it may be necessary or preferable to use the soils at their natural moisture content and tolerate a corresponding lower strength of the compacted soil. Significant advances have been made in methods of moisture control, execution of control tests, and statistical evaluation of the results.

Intense research and practical development of stabilization of soils by admixture with other soils or with various inorganic and organic products are in progress. Cements and bituminous products are the most commonly used additives. Recent investigations indicate that the addition of small amounts of lime or soluble calcium salts extends successful stabilization with cement to relatively plastic clays and organic soils. An increase in strength or a decrease in the required amount of cement can be obtained by proper selection and blending of local soils, proper moisture control and compaction, and by thorough mixing of additive and soil.

Many other chemicals and natural or synthetic organic materials are being investigated and also used in experimental and practical soil stabilization. Some of these materials are expensive but also very effective, and they may ultimately become economical in use because the amounts required are small and current prices of the additive may be reduced through mass production on increased demand.

(d) *Observations on completed structures.* Continued basic research on soil properties, in both field and laboratory, is required for real progress in the design of foundations and earthen structures, but equally and possibly more important are observations of the behavior of the structure and the foundation soil during and after construction. Such observations may permit corrections in design to meet unforeseen difficulties, and they furnish much needed data for verification or improvement of general theories and design procedures.

Recent advances consist primarily in the assembling and amplification of widely scattered data on equipment and techniques of field observations. The design, methods of installation, and observation of settlements points in the interior of

earth masses have been improved; equipment for surface measurements of very small and slow displacements has been developed, and inclinometers have been built or adapted for checking the position of pile points or determination of horizontal movements or creep. Advances in methods for determination of changes in water content, pore-water and soil pressures are discussed in the foregoing section on field studies.

Far too few sufficiently detailed observations of the behavior of foundation and earth structures are being made, and it is to be hoped that the importance and value of such observations will be given increased recognition by foundation and construction engineers and by owners of structures.

Proposals for Discussion

It would be desirable if all discussions of papers or questions concerning the subjects assigned to this session could be presented for consideration during the Session. This may not be possible, and it is suggested that preference be given to certain topics which appear to have commanded the greatest interest in the papers submitted to the conference or published since 1948. These topics are:

- (1) *Determination of density, strength, and other properties of soil in situ by means of cone penetrometers or vane tests;*
- (2) *Factors to be considered in selecting placement water contents and exercising proper density and moisture control during field compaction of soils;*
- (3) *Detrimental heavings or settlements of light structures caused by interference with and consequent changes in the natural moisture regime of the foundation soil.*

This Reporter also feels that the problems of obtaining, preserving, and preparing undisturbed soil samples for testing are worthy of additional discussion and, in general, should be given greater consideration and thought than they have received from many engineering and construction organizations.

In conclusion, this Reporter wishes to express his admiration of the excellent work performed by the organizing committees and his appreciation of the co-operation and efficient handling of all details concerning acceptance, editing, and preprinting of the papers by the General Secretary, Dr. A. von Moos.

Sommaire

a) Reconnaissance du terrain et prise d'échantillons

L'usage de plus en plus répandu de la géomorphologie et de la photographie aérienne pour le repérage des constructions, l'observation de la nature du terrain superficiel et l'organisation de campagnes de sondages détaillées a contribué davantage au développement général de l'exploration des sols que d'autres méthodes récentes.

Des appareillages de chantier plus simples et d'un usage plus commode ont été mis au point pour la mesure de la résistivité électrique et de la réfraction des ondes sismiques, ce qui entraîne une réduction du poids et des dimensions de ces appareils.

Des modèles perfectionnés de cônes et de sondes de pénétration ont amené de nouveaux progrès, en particulier une détermination plus précise des frottements ou, pratiquement, leur élimination. Cela a eu pour conséquence d'augmenter la pro-

fondeur que l'on peut atteindre avec ces sondes. Des relations empiriques et théoriques entre la résistance à la pointe et la capacité portante ou résistance au cisaillement des sols ont donné des résultats satisfaisants pour certaines conditions, mais des recherches récentes montrent que ces relations ne sont pas simples et que la résistance à la pointe est fonction de plusieurs autres facteurs, de la forme des appareils et du mode d'utilisation. Les sondages de reconnaissance à l'appareil de pénétration présentent de grands avantages, mais plusieurs points importants restent à élucider.

La résistance à la pénétration d'appareillage de prélèvement d'échantillons est aussi fonction de plusieurs facteurs et les limites de validité des relations entre cette résistance et la résistance au cisaillement, ou la compacité des sols, est mieux connue actuellement. La recherche et la mise au point de ces lois se poursuit aux U.S.A. et au Canada principalement.

La stabilisation des parois (des trous de sondage) au moyen d'une boue de forage à la place d'un revêtement s'est développée; cette méthode étant souvent meilleure et moins coûteuse, elle diminue les dangers de dérangement des terres et facilite l'élimination des graviers et la conservation des échantillons mous et de sols sans cohésion.

Des progrès importants ont été réalisés pour l'élaboration de prescriptions ainsi que pour le perfectionnement de l'appareillage et de la technique de prélèvement des échantillons intacts, en particulier pour les sables saturés. Mais aucune méthode satisfaisante n'a encore été trouvée pour la prise d'échantillons graveleux intacts.

Le perfectionnement des appareillages de prélèvement d'échantillons indique un réel progrès, mais il faut dire aussi que les résultats des essais exécutés sur des échantillons prélevés avec de mauvais appareils peuvent être très trompeurs, si de tels échantillons sont considérés comme intacts.

Récemment mis au point, un appareil de prises de vues dans les trous de sondages permet d'obtenir des photographies de toute la surface de la paroi des trous, et de déterminer la position et la forme des fissures, des défauts et des cavités.

b) Etude des sols «in situ» et de leurs propriétés

Comme indiqué plus haut, les relations existant entre la résistance à la pénétration des pénétromètres et la densité ou la résistance au cisaillement des sols en place ont des limites de validité. Des résultats plus sûrs pour la résistance au cisaillement des sols en place peuvent être obtenus par les essais au moulinet sur place. L'appareillage et la méthode d'exécution de ces essais ont été perfectionnés et ils sont de plus en plus utilisés, mais d'autres recherches sont encore nécessaires pour connaître les limites de validité de l'essai et des résultats obtenus pour différents types de sols.

La comparaison entre les valeurs obtenues pour la résistance au cisaillement, par les essais au moulinet sur place ou par les cisaillements classiques, et les résultats des essais à l'appareil triaxial sur des échantillons intacts, montrent que des différences souvent constatées précédemment peuvent provenir d'une mauvaise technique d'essai de laboratoire.

Un appareillage plus simple et plus mobile pour les essais de charge ou de portance sur plaques a été mis au point, mais ces essais sont encore relativement longs et sont souvent remplacés par des méthodes plus rapides et moins coûteuses, notamment depuis que l'on connaît mieux les limites de validité des résultats des essais de portance sur plaques.

Les explorations montrent que les structures cellulaires, les canalicules verticaux, les renards et canaux de solution, et les

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