SUBSURFACE EXPLORATION AND SAMPLING OF SOILS FOR CIVIL ENGINEERING PURPOSES

REPORT ON A RESEARCH PROJECT OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS

SPONSORED BY THE ENGINEERING FOUNDATION

HARVARD UNIVERSITY

THE WATERWAYS EXPERIMENT STATION

REPORT PREPARED BY M. JUUL HVORSLEV

EDITED AND PRINTED BY WATERWAYS EXPERIMENT STATION VICKSBURG, MISSISSIPPI NOVEMBER 1949
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REPORT ON A RESEARCH PROJECT OF THE
COMMITTEE ON SAMPLING AND TESTING
SOIL MECHANICS AND FOUNDATIONS DIVISION
AMERICAN SOCIETY OF CIVIL ENGINEERS

SPONSORED BY
THE ENGINEERING FOUNDATION
THE GRADUATE SCHOOL OF ENGINEERING
HARVARD UNIVERSITY
THE WATERWAYS EXPERIMENT STATION
CORPS OF ENGINEERS, U. S. ARMY

REPORT PREPARED BY
M. JUUL HVORSLEV

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## SOIL MECHANICS AND FOUNDATIONS DIVISION
### AMERICAN SOCIETY OF CIVIL ENGINEERS

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PREFACE

The following report presents the results of the first major research project organized by the Soil Mechanics and Foundations Division of the American Society of Civil Engineers and is issued under the sponsorship of the Engineering Foundation, Harvard University, and the Waterways Experiment Station. This final report is the result of the personal efforts of M. Juul Hvorslev, who served the project first as research engineer and later as member of the Committee on Sampling and Testing. The report was completed by Dr. Hvorslev late in 1947 and printed in preliminary form early in 1949. Before final printing, an appendix covering recent developments, a name index, and a subject index were added to the report.

In scope this report is an authoritative reference work on subsurface exploration and sampling of soil and rock. Its value to the practicing engineer is that it includes under one cover:

1. Information and general data on all methods of subsurface exploration and sampling, with a complete bibliography for detailed information on specific topics.

2. A clear and logical delineation of factors influencing the quality of samples, and rules covering the design and operation of equipment for obtaining undisturbed samples.

Neither the report nor experienced foundation engineers on the committees advocate requiring undisturbed samples for all soil investigations. Many projects are adequately served by the relatively inexpensive exploratory procedures summarized in the report under the heading "Reconnaissance and General Exploration." More elaborate explorations are warranted only when the character of the project and the results of preliminary explorations indicate that a complete investigation and laboratory tests are required to insure an adequate foundation design.

The committees wish to emphasize that when undisturbed samples and major laboratory tests are required, only the best possible sampling procedures are justified. It is essential that undisturbed sampling operations be performed under field supervision of a competent soils engineer. Necessary variations in sampling methods for different soil types, changes in procedure to improve results as sampling progresses, and the many measurements and records required to insure an adequate return from the operation -- all of which are described in the report -- require a thorough knowledge of soil mechanics for their understanding and proper execution.

The report has been reviewed by all who have been members of the sponsoring committees during the entire period of the research and is enthusiastically endorsed by all reviewers. The report is presented to the engineering profession with the conviction that it constitutes a significant contribution to soils and foundation engineering practice.

The Committee on Sampling and Testing

and

The Executive Committee

Soil Mechanics and Foundations Division

American Society of Civil Engineers

November 1949
FOREWORD

HISTORICAL SUMMARY

The Committee on Sampling and Testing, with Mr. Joel D. Justin as Chairman, was organized in 1937 by the Soil Mechanics and Foundations Division of the American Society of Civil Engineers. The first project undertaken by the committee was a study of exploration and sampling of subsurface materials with the primary purpose of developing better methods for obtaining undisturbed samples of soils. Arrangements were made to obtain the cooperation of other organizations and institutions in this project, and it was decided to engage a research engineer to carry out the work under general direction of the committee. The writer was engaged in this capacity on February 1, 1938. This plan was made possible by the financial assistance of The Engineering Foundation and the offer of the Graduate School of Engineering, Harvard University, to provide office and laboratory facilities for the research engineer.

The first part of the research consisted of a fact finding survey, embracing an analysis of the problems encountered and a critical review of the methods and equipment currently used in sampling of soils. The results of the survey were presented in a report, entitled "The Present Status of the Art of Obtaining Undisturbed Samples of Soils", which was printed in 1000 copies in March 1940 and reprinted in 1200 copies as an appendix to the Proceedings of the Conference on Soil Mechanics and Its Applications, Purdue University, July 1940.

The experimental part of the research was advanced concurrently with the fact finding survey. Methods and equipment were developed for determining the extent and causes of disturbance in soil samples. Preliminary experiments were made during practical sampling operations, but systematic tests in uniform soil deposits were required to segregate and determine the influence of the many factors which govern the disturbance of soil samples and the success of the sampling operation. Uniformly stratified soil deposits, suitable for such experiments, were found near Hartford, Connecticut, and Woods Hole, Massachusetts, and several series of experiments were performed in these localities between May 1939 and February 1941.

In conjunction with these experiments, the Missouri River Division, Corps of Engineers, performed a series of comparative tests with large samplers at Marshall Creek Dam. These tests were started in December 1938; the field work was completed in April 1939 and the laboratory investigation of the samples in September 1939. A report on the results of the experiments was issued by the
Missouri River Division in October 1940; see (112) in the classified bibliography. In these experiments the Committee on Sampling and Testing was represented by its research engineer, who acted as consultant and participated in the writing of the report.

The results of all the above mentioned experiments were applied in practical sampling operations near Boston. New problems appeared, and it became evident that a large additional series of systematic tests in very uniform soil was needed to obtain more detailed data. Special sampling, recording, and testing equipment was designed and built during the fall of 1941, and detailed plans were prepared for experiments to be performed in the spring of 1942. However, the experiments required the cooperation of several organizations and had to be abandoned because of the priority of other activities in connection with the war effort. Likewise, time and circumstances made it impossible to perform a planned and badly needed series of experiments on the use of core boring methods in sampling of soils. The special equipment was, however, used in experiments made in conjunction with practical sampling operations. Such experiments as well as laboratory tests on various methods of preserving and handling samples and on the extent and degree of disturbance in samples were continued until completion of this report. A large amount of new data was obtained, but a detailed analysis was often difficult since the number of variables entering each experiment could not always be controlled under practical working conditions. It is therefore to be regretted that the planned and final series of experiments in uniform soil deposits could not be carried out.

Independent sampling experiments were performed by the Providence District and the Waterways Experiment Station, Corps of Engineers, and recently by the Special Engineering Division, The Panama Canal. The writer acted as consultant on some of these experiments, and the results were made available to the committee.

In addition to the published report on the results of the fact finding survey, four progress reports or papers on special phases of the research were prepared and presented at the following meetings of the American Society of Civil Engineers: Chattanooga, April 20, 1939; Denver, July 25, 1940; New York, January 22, 1942; New York, January 21, 1943. The titles of these papers are given in Section 1 of the classified bibliography (133, 136, 137, 138).

The Committee on Sampling and Testing was reorganized in October 1942, when Mr. Joel D. Justin assumed the Chairmanship of the Executive Committee of the Soil Mechanics and Foundations Division, Mr. Philip C. Rutledge was appointed Chairman, and Messrs. Robert M. German, O. J. Porter, and Willard J. Turnbull became Members of the Committee on Sampling and Testing. The writer resigned as research engineer to the committee in December 1942 to engage in private work. He was appointed member of the committee, in which capacity he continued the research on sampling of subsurface materials whenever time and opportunity made it possible. During the period from December 1942 to March 1946 the research was in part supported by a stipend paid by the Graduate School of Engineering, Harvard University,
and to a large extent performed by the writer without remuneration.

The analysis of the large amount of data and preparation of a final and comprehensive report were greatly delayed by the priority of other activities during the war and later because of the cost of preparing the many figures for reproduction. In March 1946 the Corps of Engineers, through the Waterways Experiment Station in Vicksburg, offered assistance in preparation of the final report, engaged the writer to supervise the work, and entered a cooperative arrangement with the committee for editing and printing the report.

The figures and final draft of the report were essentially completed in the fall of 1947, and reproduction typing was started in January 1948. Therefore, excepting minor revisions and substitutions, the report represents the status of the research at the end of the year 1947.

ACKNOWLEDGEMENTS

The research was made possible through the cooperation of many institutions, organizations, individual engineers, and in particular by the generous assistance of The Engineering Foundation, the Graduate School of Engineering of Harvard University, and the Corps of Engineers of the Department of the Army.

The Engineering Foundation made generous annual research grants to this project during the five-year period from February 1938 to December 1942. Since then some funds from continuing grants have also been allocated to the project for the purpose of printing this and preceding reports. Without the active support of the Engineering Foundation, the research could not have been initiated and carried through the years when the basic experiments were performed.

The Graduate School of Engineering provided office, secretarial, laboratory, and machine shop facilities for the research engineer, bore the cost of reproduction typing of the preliminary reports and of construction of much experimental equipment, and supported the research by a stipend paid the writer during the period from January 1943 to July 1945.

The Corps of Engineers, besides undertaking or participating in several series of experiments, provided facilities for and bore the cost of preparation and preliminary printing of the final report. Without this assistance by the Corps of Engineers, the report could not have been completed and printed in its present form.

The cooperation of various organizations and persons is acknowledged in the following paragraphs, but it is impossible to mention individually the many engineers in this country and abroad who have assisted the committee by furnishing information on sampling methods and equipment. A list of special communications and reports to the committee is found in Section 1 of the classified bibliography, whereas reprints of published reports and papers, received by the committee, are listed in their appropriate sections of the bibliography.
Special recognition and appreciation are due the first chairman of the committee, Mr. Joel D. Justin, who organized the research and obtained the cooperation of other organizations. The arrangement for assistance in preparation and printing of the final report is due to the efforts of Messrs. Frank A. Marston and Philip C. Rutledge, Chairmen, respectively, of the Executive Committee and the Committee on Sampling and Testing, and in particular to the cooperation of James H. Stratton, Member of the Executive Committee and Colonel, Corps of Engineers.

The cooperation of the Graduate School of Engineering, Harvard University, was arranged by Professor H. M. Westergaard, then Dean, and Professor A. Casagrande who also placed departmental and personal facilities and records at the disposal of the committee and its research engineer and furthered the research at every opportunity. Many practical suggestions for construction of sampling and testing equipment were contributed by Mr. Philip Grotjohan, in charge of the machine shop of the Graduate School of Engineering.

Various Divisions and Districts of the Corps of Engineers cooperated individually by furnishing detailed information on sampling methods and equipment, and the Missouri River Division, the Providence District, and the Waterways Experiment Station undertook or participated directly in experiments and development of improved sampling methods and equipment.

The Bureau of Yards and Docks, Department of the Navy, permitted experiments to be performed during sampling operations at the South Boston Dry Dock and at the Charlestown Navy Yard.

The Division of Highways, State of California, through Messrs. T. E. Stanton and O. J. Porter, furnished a one-inch piston sampler and detailed information on sampling methods and equipment developed in their department.

The Raymond Concrete Pile Company, through Mr. H. A. Mohr, has built or paid for the construction of several samplers and parts of the experimental equipment besides participating in the performance of many field tests. Mr. H. A. Mohr contributed personally to the development of new equipment by many helpful suggestions and his ever active interest in the research.

Mr. E. Pola, President of the Pleasant Valley Brick Company near Hartford, Connecticut, gave permission to perform extensive experiments in the clay pits of the company and facilitated the work by loan of laborers and equipment.

Dr. C. S. Piggot and Mr. E. A. Johnson of the Carnegie Institution of Washington permitted observations to be made during their coring experiments near Hartford, lent their equipment, and assisted in special experiments for the committee. Later they placed the results of their own experiments at the disposal of the committee.

Mr. H. C. Stetson of the Woods Hole Oceanographic Institution lent equipment and collaborated personally in experiments near Woods Hole, Massachusetts, and
also made the results of experiments with a new ocean bottom sampler available to the committee.

As already mentioned, the Waterways Experiment Station undertook the preparation and reproduction of the final report. Special recognition is due Messrs. Willard J. Turnbull and Stanley J. Johnson for a critical review of the entire manuscript and for many valuable suggestions; Messrs. Reginald A. Barron, William R. Perret, and Thomas B. Goode for reviewing sections of the report; Mr. William L. Boult and Mrs. Hilda D. Rowe for preparing the figures for reproduction; and the Reports Branch and the Reproduction Branch for final editing and printing of the report.

In conclusion the writer wishes to express his personal and sincere appreciation of the assistance rendered by the organizations and persons mentioned above and by the many engineers who contributed special information, reports, or reprints of their papers.

M. J. H.

November 1948
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INTRODUCTION

The soil or rock and water below the ground surface supports, exerts pressure on, or is utilized in and thereby affects the safety of nearly all civil engineering structures. Technical literature contains numerous examples of costly failures which can be attributed to the action of the soil and ground water and, in the end, to the absence of or to inadequate or unreliable subsurface explorations. A careful investigation of successful projects would probably reveal an equal number of cases in which parts of the structure are over-designed, where uneconomical types of structures or unfavorable locations were chosen, and where considerable savings could have been effected if adequate foundation investigations had been made and the results properly interpreted.

Before the advent of soil mechanics, foundation investigations were confined to the determination of sequence, thickness, and general character of the soil strata, and the suitability of the various strata for foundation or construction purposes was primarily determined on the basis of general or local experience. Explorations were made by means of test pits or simple borings or soundings, and when samples were obtained, they were generally seriously disturbed although adequate for the purpose of identification of and simple tests on the soil. With the rapid development of soil mechanics and laboratory methods for determination of the physical properties of the soils, it soon became evident that some of the physical properties of the soil may be seriously changed during sampling operations or by subsequent storage or handling of samples in the laboratory, and that unreliable or misleading results obtained when the test data were used in the analysis or design of foundation or earth structures. The first task with which the Committee on Sampling and Testing was charged consisted of: (1) an investigation of the causes and effects of the disturbance of soil samples; (2) a critical review of methods and equipment used for soil sampling in this country and abroad; and (3) development of improved methods and equipment for obtaining undisturbed soil samples.

The experimental research and the various progress reports have been confined to the above mentioned subjects. However, in planning the final report, consideration was given to the fact that undisturbed samples are not required for the solution of many common foundation and construction problems, although they generally are needed as a part of the final foundation investigations for important or unusual projects and are a prerequisite for the continued advancement of soil mechanics and foundation engineering. Furthermore, other methods of subsurface exploration which are not based on obtaining samples, such as geophysical and sounding methods, have been subject to significant developments. This also applies
to certain methods of exploration and sampling which should be considered although they are used primarily for other than civil engineering purposes. Therefore, it was decided to enlarge the scope of the report to include a general review of all methods used in subsurface exploration and sampling of subsurface materials; however, the main subject of the report is the securing, preservation, and handling of undisturbed soil samples.

Observation of ground-water levels and performance of minor field tests, which can be considered as an integral part of the exploration or sampling operations, are discussed. On the other hand, descriptions of actual field tests, such as loading and permeability tests, and special installations and methods for determination of movements and pressures of the soil and ground water, are considered to be outside the scope of this report. Likewise, the discussion of examination and handling of samples in the laboratory is limited to operations required to determine the stratigraphical soil profile and the condition of the samples, and does not include actual preparation of test specimens and subsequent tests. The report is divided into two main parts, subject to the delimitations mentioned above.

The first part contains a review of the requirements, general procedures, and various methods of subsurface exploration and sampling. In discussing the latter, stress is laid on the general principles and problems encountered rather than on details of the equipment which are presented in the second part of the report. A series of summary directions for the design of sampling equipment and for sampling operations and handling of samples has been formulated. However, it should be borne in mind that the systematic experiments were made in only a few types of soil, and that the recommendations, of necessity, are broad generalizations. The directions should not be applied indiscriminately, and exceptions to some of the rules are to be expected.

The second part of the report contains a fairly detailed description of the equipment and methods used in obtaining samples of subsurface materials and in the preservation and handling of these samples. Some of the samplers mentioned are now considered obsolete, although they embody features which still are used or may be used again. A description of these samplers is included in order to give proper credit to those who developed original ideas and designs and to prevent the expenditure of time and money on developing methods or details which already have been tried out. Several tentative methods and designs are also described; they are presented, although untried, to call attention to possible new or alternative solutions of the problems encountered.

The second part of the report also contains a review of the principal sampling methods and equipment used in ocean-bottom exploration and in search for oil and minerals. In some respects these methods are advanced beyond those used in subsurface exploration for civil engineering purposes, and they have been or may, under certain conditions, be used to advantage for the latter purpose.
The advantages and disadvantages of the various methods and types of equipment for boring and sampling are discussed in relation to the soil conditions. Because of the great variation in the physical properties of soils, it is unlikely that a single sampling method or type of sampler, which will produce satisfactory samples under all conditions, will ever be developed. On the contrary, best results will be obtained at least cost when several types of samplers are at hand and are used in accordance with the character of the soil and the purpose of the exploration, and when the operators constantly watch out for minor changes in the soil conditions and make corresponding adjustments of the equipment and sampling procedure. Although general directions for the design of samplers and for their operation in various types of soils and for various purposes are given in the first part of the report, definite recommendations of specific samplers and methods, described in the second part, are not made. A first-hand study of local conditions often is necessary before the final selection, and there is often a choice between alternative methods and details which still are in the process of development.

Originally it was intended to add a third part to the report, in which the research methods and equipment and the principal series of experiments would be described in considerable detail, but this material would be of little interest to the practicing engineer. Therefore, this third part was omitted and some of the principal test results are inserted in the first part in order to help explain the causes of disturbance of soil samples and to substantiate the recommendations made.

The report is concluded with an extensive, classified bibliography on subsurface exploration, sampling of soil and rock, and allied subjects.
PART I
PRINCIPLES OF EXPLORATION AND SAMPLING

CHAPTER 1
GENERAL PROCEDURE AND REQUIREMENTS

1.1 Problems and Phases of Foundation Investigations

Investigation of the distribution, type, and physical properties of subsurface materials are, in some form or other, required for the final design of most civil engineering structures. These investigations are performed to obtain solutions to the following groups of problems:

Foundation problems or determination of the stability and deformations of undisturbed subsurface materials under superimposed loads, in slopes and cuts, or around foundation pits and tunnels; and determination of the pressure of subsurface materials against supporting structures when such are needed.

Construction problems or determination of the extent and character of materials to be excavated or location and investigation of soil and rock deposits for use as construction materials in earth dams and fills, for road and airfield bases and surfacing, and for concrete aggregates.

Ground-water problems or determination of the depth, hydrostatic pressure, flow, and composition of the ground water, and thereby the danger of seepage, underground erosion, and frost action; the influence of the water on the stability and settlement of structures; its action on various construction materials; and its suitability as a water supply.

A complete foundation investigation comprises the following three more or less overlapping and interdependent phases:

The stratigraphical survey or subsurface exploration and sampling. The objectives of this survey are: (1) to determine the depth to and pressure of the ground water and the sequence, thickness, extent, and approximate identity of the strata of soil and rock to the required depth below the ground surface; (2) to obtain samples of the ground water, soil, and rock of a size and condition adequate for positive identification of the material and for the tests of the physical survey; and
(3) to make observations and certain incidental or minor field tests which will facilitate determination of the condition of the samples obtained and estimation of the physical properties of the materials or of their action during and after construction of the proposed structures.

The physical survey or field and laboratory tests for the purpose of determining the physical properties of the materials to the extent required for an estimate of the behavior of the materials under the conditions imposed by the proposed structure. It is emphasized that the survey cannot be limited to determination of the physical properties of a few samples but requires, in many cases, a reliable estimate of the average values for the entire stratum or strata under investigation. In other cases, especially for stability problems, it is necessary to locate the weakest or critical strata and determine their physical properties. In case of erratic soil conditions or soils with secondary structure and when satisfactory samples cannot be obtained, recourse is often taken to special or major field tests on the soil in situ.

The evaluation of the data obtained in the stratigraphical and physical surveys and the formulation of definite solutions to the problems mentioned in the first part of this section. This evaluation may be simply an estimate based on the personal experience of the engineer, or on general empirical rules or regional ordinances, or it may require more or less involved computations based on the theories of soil mechanics. When soil conditions or the stresses created by the proposed structure are so complicated that a detailed mathematical analysis of the problem is too difficult or unreliable, recourse is again taken to observation of completed structures, special field tests on the soil in situ, or to model tests.

This report deals only with the first phase of the foundation investigation or the stratigraphical survey and appurtenant observations and minor field tests. However, the methods and requirements of the two other phases must constantly be kept in mind, since they and the general character of the problem to a large extent govern the care and details required and the methods used in the stratigraphical survey.

1.2 General Definitions

Before discussing the general procedure and requirements in subsurface explorations, it is desirable to establish broad classifications of the methods used and results obtained. The definitions and classifications presented in this section and also the foregoing and following sections are summarized in Table 1. These classifications are intended only for a general orientation; more detailed classifications and tables will be found in Chapters 2, 4, 5, and 6.

In this report the term "stratigraphical survey" is used to designate all field operations, whereas "exploration" refers primarily to the determination of
**TABLE 1 - GENERAL DEFINITIONS AND CLASSIFICATIONS**

<table>
<thead>
<tr>
<th>Stability of subsurface materials</th>
<th>Foundation Problems</th>
<th>Stratifigraph. Survey</th>
<th>Exploration Sampling Identification</th>
<th>Stratigraphical Profiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deformation and consolidation</td>
<td></td>
<td>FOUNDATION</td>
<td>FOUNDAION INVESTIGATIONS</td>
<td>Rock-line, rough, or detailed soil profiles, limited physical profiles</td>
</tr>
<tr>
<td>Pressure on supporting structures</td>
<td></td>
<td>PHYSICAL SURVEY</td>
<td>Physical Survey</td>
<td>Physical Profiles</td>
</tr>
<tr>
<td>Excavation of subsurface material</td>
<td>Construction Problems</td>
<td></td>
<td>Laboratory Tests Major Field Tests</td>
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<tr>
<td>Use of excavated material</td>
<td></td>
<td>Evaluation of Data</td>
<td>Empirical Rules Soil Mechanics</td>
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<tr>
<td>Flow and action of ground water</td>
<td>Ground Water Problems</td>
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<td>Quantity and use of ground water</td>
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</tbody>
</table>

**Foundation Problems**

- Soil from various strata mixed or some soil constituents removed or foreign materials added to sample
- Soil structure disturbed or change in water content or void ratio but no change in the soil constituents
- No disturbance of soil structure, no change in water content, void ratio, or chemical composition

**Construction Problems**

- Non-Representative Samples
- Representative Samples
- Undisturbed Samples

**Ground Water Problems**

- Exploration Samplers
- Drive Samplers
- Core Boring Samplers

**Stratigraphical Profiles**

- Augers, bailers, sandpumps; slit and cup samplers or sampling tubes with a longitudinal or circumferential slit. Non-representative and representative samples
- Sampling tubes driven without rotation or chopping; displaced soil pushed aside. Open drive samplers and piston samplers. Representative and undisturbed samples
- Rotation or chopping action of sampler; displaced material ground up and removed by circulating water or drilling fluid. Representative or undisturbed samples

**Geophysical methods, soil sounding, yielding limited physical profiles.**

- Borings without taking representative samples of principal strata
- Boring - Changes in material detected by action of tools or non-representative samples. Identification by representative samples
- Test pits, trenches, drifts, other accessible explorations or borings yielding fairly continuous, representative or undisturbed samples

**Gathering of data on foundation experience and results of previous explorations at site and vicinity.**

- Semi-direct methods with or without indirect methods, rough ground water observations in permeable strata. Required for all projects. Sufficient for many standard structures, small loads, simple soil conditions
- Continuous undisturb samples of small diameter or large repres. samples of pertinent strata. Ground water observations in fairly pervious strata. Sufficient for common foundation problems, all construction problems
- Large undisturbed samples in borings or in accessible explorations. Ground water levels and pressures in impermeable strata. Required for structures unusual size and character and for difficult foundation conditions

The logical sequence of operations for exploration of a large area in virgin territory is indicated by the four phases or steps, but some of these phases may often be omitted or combined. These phases also show the details required with increasing importance of the structure, departure from accepted design standards, and the foundation difficulties encountered.
the depths to and approximate identity of the subsurface strata, and to the methods used in providing access to these strata for the purpose of obtaining samples or of examining the strata in situ. Likewise, the term "boring" refers only to the bore hole and the methods of advancing such holes. Various methods of sampling may be used in connection with a single method of boring and vice versa. When a bore hole is advanced entirely by sampling, the method of boring or exploration will be called continuous sampling and further designated by the method of sampling. In practice, the term "exploration" is occasionally used to cover all field operations, and this all-inclusive meaning is retained in this report for a few commonly used terms, such as reconnaissance exploration and detailed exploration.

The samples obtained may be classified in accordance with the condition or disturbance of the material, or roughly in the following three groups:

Non-representative samples consist of a mixture of materials from various soil or rock layers or are samples from which some mineral constituents have been removed or exchanged by washing and sedimentation. These samples are also called "wash samples" or "wet samples" because they often are obtained from material which has been washed or bailed out of a bore hole and allowed to settle in a sump at the ground surface. Such samples do not represent the material actually found at the bottom of the bore hole and are unsuitable for positive identification of the material and for laboratory tests, but they often permit a preliminary classification and determination of depths at which major changes in the subsurface strata occur and at which representative or undisturbed samples should be obtained.

Representative samples contain all the mineral constituents of the strata from which they are taken and have not been contaminated by material from other strata or by chemical changes, but the soil structure is seriously disturbed and the water content may be changed. These samples are suitable for general classification tests and positive identification of the material, but they are not suitable for major laboratory tests and determination of the structural properties of the material in situ. These samples are often called "dry samples" in contrast to "wet samples", but this term is very misleading since the samples are not dry but usually have a water content a little above or below that of the material from which they are taken.

Undisturbed samples may be defined broadly as samples in which the material has been subjected to so little disturbance that it is suitable for all laboratory tests and thereby for approximate determination of the strength, consolidation, and permeability characteristics and other physical properties of the material in situ. The term is to some extent misleading since it is impossible to obtain a truly undisturbed sample, but it is firmly established in engineering terminology and has therefore been retained. The term "undistorted sample", proposed by H. A. Mohr (341)*,
in many cases better expresses the actual condition of the sample. Many samples which visually appear to be undisturbed have actually been subjected to considerable disturbance of the soil structure. A detailed discussion of the requirements for "practical undisturbed" samples and of the various types of disturbance and their influence on the physical properties of the soil is presented in Chapter 6.

Samples of soil close to the ground surface or to the bottom or walls of test pits, tunnels, and other accessible explorations may be obtained by digging or carving, or by methods similar to those used for obtaining samples in bore holes. Many types of samplers are used for the latter purpose and they may be classified in the following three principal groups:

**Exploration samplers.** This term is proposed as a group name for augers, bailers, sandpumps, slit tube, and cup samplers, which are used both for advancing the bore hole and for obtaining samples of cohesionless materials and soft to medium stiff cohesive soils. The samples obtained are seriously disturbed and some mixing of adjacent soil layers may occur so that they cannot always be considered as truly representative samples.

**Drive samplers** consist of a tube which is forced into the soil in a unilateral motion. An amount of soil corresponding to the wall thickness of the tube is thereby pushed aside and causes compaction or plastic deformations of the surrounding soil. The drive samplers may be divided into two groups, open samplers and piston samplers. The tube of the former is always open at its lower end, and soil enters the sampler as soon as it is forced into the ground. On the other hand, the tube of the latter group is temporarily closed with a plug or piston, so that the sampler can be pushed through soil of which samples are not desired, and the piston can be released or retracted when a sample is to be taken. Both representative and undisturbed samples of soils can be obtained according to the construction of the sampler and the care used in the sampling operation.

**Core boring samplers** or core barrels are, in contrast to drive samplers, advanced by a chopping action of the barrel or by rotation while being forced into the ground. The material displaced by the walls of the barrel is not pushed aside but is ground up and then removed by circulating water or drilling fluid. Both representative and undisturbed samples can be obtained according to the construction and operation of the core barrel and the character of the material. Core barrels are primarily suited for use in stiff, dense, or partially cemented soils and in rock.

Bearing in mind that subsurface materials can be identified positively only by means of representative or undisturbed samples or by examination in situ, the methods of subsurface exploration may be classified in the following three groups:

**Indirect methods** comprise geophysical methods and sounding methods. The depths to the principal strata are determined by surface measurement of changes in certain physical properties, such as electrical resistivity, seismic wave velocity, or resistance to the penetration of a sounding rod. Samples are not obtained, and
positive identification of the strata requires correlation with the results of semi-direct or direct methods of exploration within the area under investigation. Borings in which representative samples are not obtained may also be classified as indirect methods.

**Semi-direct methods** are common boring and drilling methods combined with intermittent sampling. The depths to the principal strata are determined by the rate of progress, the "feel" or resistance to the advance of the boring tools, or by means of non-representative samples obtained in the course of the boring operations. The major strata can be identified approximately but not definitely by these observations and samples. However, the borings provide access to the strata, so that representative or undisturbed samples can be obtained whenever a change in the character of the material has been observed. In general, only the depths to strata of appreciable thickness and at which major changes in the character of the subsurface materials occur can be determined reliably by the semi-direct methods.

**Direct methods** are boring and sampling methods which provide practically continuous, representative or undisturbed samples, and all accessible explorations, such as test pits, trenches, large-diameter borings, shafts, and tunnels, which permit direct examination and mapping of the strata in situ. The direct methods of exploration provide the most detailed and reliable data of all methods.

The results obtained by the stratigraphical survey are generally presented as a plot showing surface elevation and depths to or elevations of the various strata. When the plot, in addition to these depths, shows only the identity of the strata, it is called a **stratigraphical profile or simple soil profile**. When the plot also shows variations in physical properties or coefficients, as determined during the physical survey, it is called a **physical soil profile**. Profiles obtained by indirect methods of exploration are limited physical profiles which may be transformed into stratigraphical profiles through correlation with other methods of exploration.

The term "profile" is used even if the plot is one-dimensional and only shows the sequence of the strata along a vertical or inclined line, as determined by a single boring or probing. True profiles, or two-dimensional profiles, can be obtained directly by some geophysical methods and in some accessible explorations and are then often called **continuous profiles**. However, two-dimensional profiles are generally determined by interpolation between several one-dimensional profiles. Various methods of plotting the profiles are discussed in Section 7.7. The profiles may, according to the details shown, be divided into the following three groups:

**Rock-line profiles** show only surface elevations and depths to rock or, in some cases, to strata of exceptional bearing capacity such as hardpan, hard clay, very dense sand and gravel, etc. These profiles can often be obtained by indirect methods of exploration.

**Rough soil profiles** show the depths to principal subsurface strata and also the depths to free ground-water level, in case the exploration is extended below this
level. Rough soil profiles are obtained by semi-direct methods of exploration or small-diameter borings in which each of the major strata is identified by means of representative samples.

**Detailed soil profiles** show not only the major strata but also the dip of the strata, thin strata and seams, faults, shear planes, and other details which can be obtained only by means of direct methods of exploration. In addition to the free ground-water level, detailed profiles should also show the piezometric pressure levels at various depths or at least in fairly porous, water-bearing strata. Profiles showing the stratifications and gradual changes in the character of the soil in considerable detail can be obtained by some sounding methods, but the soil in the various strata cannot be identified by these methods alone.

1.3 General Considerations

Two requirements should always be observed in planning subsurface explorations. The first of these requirements is reliability of the work performed. Carelessness or lack of experience may produce inconclusive and often completely misleading results, which may not only prevent selection of the most economical location and design of the proposed structure but may often cause expensive changes in the adopted design or require the use of costly construction methods. The performance of subsurface explorations should be entrusted only to engineers, contractors, and drilling crews of proven experience and reliability.

The second requirement is timeliness. The value of foundation investigations is greatly decreased if they are not completed before major decisions, which may be influenced by the results of the investigations, are made. All too often, the explorations are postponed until changes in the location and general design of the structure can no longer be made or time limitations prevent performance of desirable laboratory tests. It must be borne in mind that certain soil tests require considerable time and cannot be accelerated without seriously impairing the value or reliability of the test results.

**Detailed advance planning of subsurface explorations for large projects is often difficult, since the spacing and depth of profiles or borings and the methods and equipment to be used depend not only on the nature of the project and general purpose of the investigation but to a still larger degree on the subsurface conditions themselves. The exploration is often a series of progressive approximations in which each step is determined by the results of the already completed part of the exploration. It is therefore difficult to formulate definite rules of procedure, but as a guide and for the purpose of discussion, subsurface explorations may be divided into the following four steps or phases:**

1. **Fact finding and geological survey**
2. **Reconnaissance or general exploration**
3. **Detailed exploration -- small undisturbed samples**
4. **Special explorations -- large undisturbed samples**
These four steps, which will be discussed in some detail in the following sections, indicate the logical sequence of large-scale operations in virgin territory. The fact finding and geological survey serves as a basis for preliminary planning of the actual exploration. The reconnaissance exploration furnishes data for a more detailed geological survey and for the required spacing and depth of and the methods and equipment to be used in detailed explorations, if required. Results of the detailed exploration, in turn, will indicate the need of and best location for special borings or test pits, the depths to strata from which large undisturbed samples are required, and the most advantageous methods of advancing test pits or borings and obtaining undisturbed samples.

The above mentioned four phases or steps also indicate the details required with increasing importance of the project or with the foundation difficulties encountered; it is emphasized that one or two of these classes of exploration are sufficient in the majority of cases. Even in large-scale operations it is not always possible or desirable to adhere strictly to the above mentioned sequence of operations. Reconnaissance explorations may be omitted in areas where the soil conditions already are fairly well known and it may, in many cases, be advantageous to combine the detailed and special explorations by taking practically continuous undisturbed samples of such a diameter that they can be used for all laboratory tests.

When the site of exploration is difficult of access or at considerable distance from the laboratory, it may be desirable or necessary to complete all boring and sampling operations before any of the samples can be examined and tested in the laboratory. The depth of the borings should then be extended, their spacing decreased, and the number of undisturbed samples taken increased, in order to cover unforeseen contingencies. The additional cost involved may be less than that of moving drilling equipment and personnel to the site for a second or third time.

1.4 Fact Finding and Geological Survey

The natural first step in the foundation investigation of a given site is a gathering and digest of available data on subsurface conditions and the behavior of other structures in the vicinity of the proposed project. Such data facilitate the planning and will often decrease the required extent of the actual exploration. Valuable data on subsurface conditions can often be obtained from maps and publications of Federal, State and institutional geological surveys, and from the Bureau of Public Roads and State Highway Departments. Detailed data on foundation conditions in highly developed areas may be found in technical periodicals and reports or obtained from local building commissions, engineers, and contractors. Efforts are currently being made to assemble and publish available data on foundation conditions in several regions.

A preliminary geological survey, based on outcroppings and other surface indications, is generally made for large projects in virgin territory. From the data
thereby obtained, and especially when it is supplemented by the results of reconnaissance explorations, an engineer-geologist will often be able to sketch the general geological structure of the site, estimate the character and depth of the overburden, and indicate the location of possible buried channels, faults, etc., where borings first should be made. In accordance with principles recently established by Belcher, Gregg and Woods (202, 901), coupled with a general knowledge of the geology and climate of the region, an estimate of the character of surface deposits can be made from a study of stereoscopic aerial photographs. This method is particularly valuable for preliminary planning of highways and airfields and for location of soil deposits which may be suitable for construction materials. Aerial photographs also greatly facilitate the detection of slide areas, buried channels, faults, and other subsurface irregularities.

1.5 Reconnaissance or General Exploration

The principal objective of reconnaissance or general explorations is to obtain rough soil profiles and representative samples of the principal strata or, in partial substitution thereof, to obtain rock-line profiles or limited physical profiles by means of indirect methods of exploration. The free ground-water levels should be determined if reached by the required depth of exploration.

Auger borings, wash borings or displacement borings with small piston or cup samplers are commonly used and representative samples from 1 in. to 2 in. in diameter obtained. Geophysical methods are often used in the preliminary exploration of sites for large projects, since they are rapid and relatively cheap and facilitate detection of subsurface irregularities which may be missed by individual borings. Sounding methods are being used on an increasing scale in the exploration of sites for small and medium-sized projects and furnish data on the physical properties of the soil which, through proper correlations, can be used directly in the design of the structure. However, these indirect methods of exploration should always be supplemented by borings in which representative samples are obtained, unless adequate correlations already have been made in the area under investigation.

These explorations furnish data for the planning of detailed and special explorations of sites for large and important projects. They are in themselves sufficient for solution of many construction problems and especially those concerning excavation of materials. They are also adequate for solving many simple foundation and stability problems: (1) when the loads are small and the factor of safety is large; (2) when the structure is to be founded on or the design is governed solely by the depth to bedrock or strata of high bearing capacity; and (3) when structures of ordinary character are built in localities where the properties of prevalent soil types are known from long practical experience and this experience has been summarized in empirical rules or building codes. The data obtained by some sounding methods may be adequate for the final design when satisfactory correlations are available for similar soil conditions and structures.
1.6 Detailed Explorations

The purpose of these explorations is to obtain detailed soil profiles and relatively undisturbed samples with a diameter of 2 to 3 in. or to obtain larger and fairly continuous, representative samples of deposits considered for use as construction materials. Appreciable excess hydrostatic pressures in pervious strata should be determined in addition to the free ground-water level or levels.

Test pits and trenches are often used in very shallow explorations, whereas practically continuous sampling by means of open drive samplers, piston samplers, or core boring samplers is used for deeper explorations. Strata of which detailed soil profiles are not required are penetrated by means of one of the various boring methods. In cases where it is difficult to obtain satisfactory samples, the borings are often supplemented by penetration or sounding tests.

Detailed explorations are adequate for the final investigation of deposits to be used as construction materials. Unless it is preferred to combine detailed and special explorations by taking continuous, large-diameter samples, detailed explorations are required in the foundation investigation for the majority of large and important projects; they are in themselves sufficient for the solution of many common foundation and stability problems, especially when the variations of physical properties within individual strata are so great that it is more important to determine reliable averages than accurate values for a particular depth or sample. With the improvement of small-diameter samplers, detailed explorations are being used as a compromise between the relatively inexpensive but inadequate general explorations and the more expensive special explorations in which large-diameter, undisturbed samples are obtained.

1.7 Special Explorations and Undisturbed Sampling

The object of this phase of subsurface exploration is to obtain from critical strata undisturbed samples, 4 in. or more in diameter, which are suitable for special laboratory tests, or to provide large-diameter borings for special field tests or accessible explorations for inspection, mapping, sampling, and testing the materials in situ. Determination of pore-water pressures in critical strata of low permeability may be required.

The bore holes are advanced to the critical strata by means of wash boring, power-driven augers, percussion or rotary drilling according to soil conditions and available equipment. Samples in borings are obtained with large drive samplers or core barrels. Accessible borings, test pits, or tunnels are used to moderate depths when soil conditions permit their construction, and samples are then obtained by advance trimming or block sampling methods. Piezometers or hydrostatic pressure cells are used for determination of the pore-water pressures.

Special explorations are required for the solution of foundation problems
involving either structures of exceptional size and character or difficult foundation and ground-water conditions. Large-diameter samples are needed for accurate determination of the consolidation characteristics of cohesive soils, for certain direct and torsion shearing tests, and when several test specimens for unconfined or triaxial compression tests are to be cut from the same soil layer or depth so that several tests can be performed on identical soil types.

1.8 Location and Spacing of Borings

At the completion of the survey, the location and spacing of geophysical profiles, soundings, and borings should be such that the soil profiles obtained will permit a reasonably accurate estimate of the extent and character of the intervening soil or rock masses and will disclose important irregularities in subsurface conditions.

In exploration of large sites, the first borings or geophysical profiles should not be located in accordance with a rigid pattern or spacing but in such a manner that they will furnish the most necessary data for completion of the general geological survey and thereby facilitate further planning of the exploration. When soil conditions are found to be uniform, a spacing of 400 to 500 ft for the borings will often be adequate; this spacing may be decreased later by intermediate borings where required. A regular spacing of 100 ft, or one bore hole for each 10,000 sq ft of area, is often used in explorations for highways, airfields, and some large dams, especially when results of the exploration cannot be evaluated in detail as the work progresses. The spacing must be decreased to 50 ft or 25 ft, and occasionally to even smaller values when erratic subsurface conditions are encountered, but a spacing of 25 ft will generally provide adequate information even for erratic conditions. Such conditions are likely to exist along rivers, lakes, estuaries, and in many parts of glaciated and mountainous regions.

The great majority of borings are vertical, but inclined borings may be used to advantage in exploration of inclined strata and various subsurface irregularities, such as lenses, buried channels, cavities, and fault zones. Inclined borings are also used when surface obstructions prevent use of vertical holes, as in obtaining soil profiles under existing structures or deep and swift flowing rivers. Each inclined bore hole furnishes information on variations in subsurface conditions in both a vertical and horizontal direction. Inclined bore holes have occasionally been used instead of vertical holes for systematic exploration of dam sites and with such spacing that the top of one bore hole is vertically above the bottom of an adjacent hole, Lynn and Rhoades (336).

Borings for exploration of narrow or elongated areas should not all be located in a single straight line, but there should be a sufficient number of borings outside the main line to determine the dip and strike of the subsurface strata and irregularities in profiles at right angle to the axis of the area.

In exploration of sites for dams, embankments, bridges, and similar structures,
borings should also be made outside the actual site, which has been chosen on the basis of surface conditions and requirements, in order to determine whether a shift in location may be advantageous when subsurface conditions also are taken into consideration.

In exploration of areas of limited extent, as for individual buildings and bridge piers, the initial borings should preferably be located close to the corners of the area, and the number of borings should not be less than three unless subsurface conditions are known to be very uniform. These preliminary borings must be supplemented by intermediate borings as required by the extent of the area and the subsurface conditions encountered.

Borings inside an area, which is to be enclosed by a cofferdam or caisson and unwatered, may become a source of additional inflow of water and thereby increase the difficulties of unwatering. In such cases it is advisable to locate all the borings outside the area to be unwatered; at least, all bore holes within or close to this area should be carefully backfilled with impermeable soil. On the other hand, in exploration of sites for dams to be founded on rock, some of the bore holes are often so located that they later can be used for grouting operations.

1.9 Depth of Exploration

The required depth of exploration depends to some extent on the size and type of the proposed structure and on certain design considerations—such as safety against foundation failure, excessive settlement, seepage, earth pressure, etc.—but it depends to a still larger degree on the character and sequence of the subsurface strata. Unless the general stratigraphy of the area is known, it is difficult to estimate the required depth, and it is very important that reconnaissance explorations or the first of a group of borings be carried to fully adequate depths.

**General rules.**—The borings should be extended to strata of adequate bearing capacity and should penetrate all deposits which are unsuitable for foundation purposes—such as unconsolidated fill, peat, organic silt, and very soft and compressible clay. The soft strata should be penetrated even when they are covered with a surface layer of higher bearing capacity.

When structures are to be founded on clay and other materials with adequate strength to support the structure but subject to considerable consolidation by an increase in the load, the borings should penetrate the compressible strata or be extended to such a depth that the stress increase for still deeper strata is reduced to values so small that the corresponding consolidation of these strata will not materially influence the settlement of the proposed structure.

Except in case of very heavy loads or when seepage or other considerations are governing—see paragraph on dams and levees—the borings may be stopped when rock is encountered or after a short penetration into strata of exceptional
bearing capacity and stiffness, provided it is known from explorations in the vicinity or the general stratigraphy of the area that these strata have adequate thickness or are underlain by still stronger formations. When these conditions are not fulfilled, some of the borings must be extended until it has been established that the still strata have adequate thickness irrespective of the character of the underlying material.

When the structure is to be founded on rock, it must be verified that bedrock and not boulders have been encountered, and it is advisable to extend one or more borings from 10 to 20 ft into sound rock in order to determine the extent and character of the weathered zone of the rock.

In regions where rock or strata of exceptional bearing capacity are found at relatively shallow depths -- say from 100 to 150 ft -- it is advisable to extend at least one of the borings to such strata, even when other considerations may indicate that a smaller depth would be sufficient. The additional information thereby obtained is valuable insurance against unexpected developments and against overlooking foundation methods and types which may be more economical than those first considered.

Specific requirements and simple rules for estimating the required depth of reconnaissance explorations or initial borings for various types of structures are reviewed in the following paragraphs. It is strongly emphasized that these rules should be considered only as a very rough guide for the initial estimate and that they are subordinate to the general rules given above. The depth requirements should be reconsidered when results of the first borings are available, and it is often possible to reduce the depth of subsequent borings or to confine detailed and special explorations to particular strata.

**Foundation structures (Fig. 1A).** Safety against excessive settlements and particularly differential settlements usually governs the design of foundation structures and the required depth of exploration. Settlements of adjacent structures, caused by the proposed structure, must be taken into consideration.

One of the first proposed and still used rules for estimating the required depth of exploration, \( D \), below a loaded rectangular area is,

\[
D = CB
\]

in which the coefficient \( C \) is given values ranging from 1.0 to 2.0 and \( B \) variously is specified as the average diameter or the minimum width of the area. The German Committee on Foundation Investigations (315) proposed in its Manual of 1937 a series of rules which in condensed and slightly transcribed form may be expressed as follows:

- **Squares and Short Rectangles** \( L < 2B \) \( D = 0.8 \, p \, B_a \)
- **Long Rectangles and Strips** \( L > 2B \) \( D = 1.0 \, p \, B \)

where \( L \) is the length and \( B \) the width of a rectangular area or strip; \( B_a \) is the average diameter of a short rectangular or irregular area but is not definitely defined. It is further specified that the unit load, \( p \, \text{kg/cm}^2 \), should not be less than
**Fig. 1 - Required Depth of Exploration**
1.0 kg/cm² or greater than 3.0 kg/cm², and that the depth of exploration, D, should never be less than 10 m below the actual foundation level unless rock is encountered. The width, B, and the average diameter, Bₐ, refer normally to the entire loaded area, and p is therefore the average unit load on this area and not the actual footing pressure. Only when the spacing of the footings is very great may the rules be applied to a single footing, but the critical spacing is not defined; however, Brennecke and Lohmeyer (206) suggest that the rules may be applied to a single footing or strip instead of the entire loaded area when the spacing, S, of the footings or strip loads is greater than 5B.

Except for the requirement that the depth of exploration should be never less than 10 m unless rock or strata of exceptional bearing capacity are encountered, these rules have been subject to considerable criticism, because they do not take properly into consideration the shape of the loaded area, load intensities and distribution, and the character and depth of the strata at which exploration is terminated. Much more reliable estimates of the required depth of exploration are obtained by computing the approximate stress distribution diagram for a vertical line through the center of the loaded area, or the center of the footing with the greatest load, and then by means of this diagram determining the depth at which the increase in vertical stress, caused by the proposed structure, is reduced to a value below which material consolidation of the soil will not occur.

For preliminary estimates, the Geotechnical Institute of Belgium -- personal communication by E. De Beer, Director -- has recently introduced the general rule that the above mentioned increase of vertical soil stresses at the required minimum depth of exploration shall not exceed 10 percent of the original vertical stress at this depth. This rule is easy to remember and apply, Fig. 1A, and seems to give reasonable results in many cases; however, a single rule cannot cover all the varied conditions encountered. The stiffness and coefficient of compressibility of the strata, the relation of current soil pressure to preconsolidation pressure, and the sensitivity of the proposed structure to settlements must be taken into consideration in the final determination of the limiting stress increase at the required depth of exploration. It is again emphasized that all the above mentioned specific rules are subordinate to the general rules enumerated in the first part of this section.

Retaining and quay walls (Fig. 1B).—Safety against foundation failure is usually governing, but the influence of settlements may also have to be considered. Explorations should be extended to depths beyond which it is unlikely that surfaces of failure or sliding will occur. Such surfaces tend to follow the weaker strata, even when such strata are found at considerable depth. Explorations should therefore be continued until firm strata are encountered and should be extended into such strata for a distance sufficient to verify that these strata are of adequate thickness. For preliminary estimates a depth D = 0.75 to 1.5 H below the bottom of the wall or end bearing piles, where H is the net height of the wall, is suggested. This depth may have to be increased to D = 2H or more when the wall is founded on thick, compressible strata which may cause excessive settlements and tipping of the wall,
especially when the backfill is not a replacement of excavated material but represents an additional load on the subsoil.

**Terraces and fills (Fig. 1C).**—Safety against foundation failure is usually governing, although settlements caused by consolidation of the subsoil may have to be considered in some cases. Explorations should be extended to depths beyond which surfaces of failure and sliding are unlikely to occur. Maximum shearing stresses are encountered approximately at a depth \( D = 1.25 L \) for terraces and \( D = 0.5 L \) for triangular fills, where \( L \) is the average horizontal length of the slope. Except when slopes are very flat, it is suggested that these depths may be used for preliminary estimates of the required depth of exploration. A surface of sliding may occur at still greater depths, and objectionable consolidation and settlements may take place when soft materials are encountered at the above mentioned depths, in which case the exploration should be continued until firm strata of adequate thickness are reached.

**Deep cuts (Fig. 1D).**—Stability of the slopes is governing. The soil below a cut is subjected to a double terrace loading, but the depth of a probable surface of sliding is limited by the bottom width, \( B \), of the cut. When this width is relatively small compared to the depth, \( H \), of the cut, the required depth of exploration will be smaller than for a true terrace loading. For preliminary estimates a depth of exploration \( D = 0.75 B \) to \( 1.0 B \) is suggested unless the depth determined on basis of a true terrace loading is smaller. When the bottom of the cut is below the ground-water level, the stability may be seriously affected by uplift and seepage, and the extent of pervious strata and the pore-water pressures in such strata should therefore be fully explored. On the other hand, when the cut is above the ground-water level and in stable materials, and especially when there is a definite increase in the strength of the soil with depth, exploration to a depth of 6 to 10 ft below the cut may often be sufficient, as in normal highway explorations.

**Dams and levees (Fig. 1E).**—Safety against foundation failure and seepage is governing. Seepage conditions control not only loss of water but also uplift under and beyond the structure and thereby influence the danger of piping and complete foundation failure. Borings should therefore penetrate not only soft and unstable soils but also permeable materials, and they should be extended to such depths that seepage and hydrostatic pressures can be estimated with reasonable accuracy. It should be noted that seepage and uplift depend not only on soil conditions below the structure but also on those below the inundated area.

For preliminary estimates depths of exploration \( D = L \) for levees and earth dams and \( D = 1.5 H \) to \( 2.0 H \) for small concrete dams, where \( 2L \) is the bottom width and \( H \) the net height, are tentatively suggested. The borings may be stopped after a penetration of 10 to 20 ft into strong and tight strata, provided the number of borings is sufficient to verify the continuity of such strata under the inundated area. In case of large dams, rock will often be encountered within the above suggested depths, but the borings should be extended for a distance sufficient to establish the
character and stratigraphy of the rock foundation. In general, the required depth of exploration for large dams is governed by the character and sequence of subsurface formations to a greater extent than for other structures.

Highways, railroads, and airfields (Fig. 1F).- Borings should penetrate the weathered strata and reach a depth sufficient to disclose the general stability and drainage conditions and the danger of frost action. Excepting major fills and cuts, a depth of exploration -- measured from original ground surface in fills and from finished grade in cuts -- of \( D = 3 \) to \( 5 \) ft for light loads and \( D = 6 \) to \( 10 \) ft for heavy loads represents current practice and is usually sufficient, but strata of unsatisfactory character should, as always, be fully explored.

Tunnels (Fig. 1G).- Stability of the materials and the pressure they exert against the tunnel lining are the governing considerations. Based on current methods of stability analysis -- Terzaghi (972, 973) and Housel (936) -- it is suggested that the preliminary explorations be extended to a depth \( D = B \) below the invert elevation, where \( B \) is the gross width of the tunnel. If the soil conditions are unfavorable at this depth, the borings should be extended to determine whether a lowering of the tunnel grade will be more economical. Greater depths of exploration may also be required when the tunnel is to be built in materials which are subject to considerable swelling.

1.10 Sample Requirements

The required condition and the quantity or dimensions of samples to be obtained during various phases of the subsurface exploration and for various groups of laboratory tests are summarized in Table 2. Major physical tests are still in development and continuously undergoing changes, and the requirements for samples for such tests therefore depend to a considerable extent on the methods used and equipment available in the laboratory in which the tests are to be performed.

In reconnaissance borings representative samples with a volume of at least \( 1/5 \) pt, and preferable \( 1/2 \) pt, should be obtained from each distinctive stratum; in thick and apparently uniform strata it is advisable to take such samples at intervals of not more than \( 5 \) ft. Fairly continuous samples with a diameter of about \( 1 \) in. are obtained by some methods of exploration -- small piston samplers -- and are satisfactory for reconnaissance explorations.

In detailed explorations practically continuous samples should be obtained, with the possible exception of surface deposits which obviously are unsuitable for foundation or construction purposes. Samples with a diameter of about \( 2 \) in. are generally satisfactory for foundation investigations, but \( 3\)-in. sampling tubes are often used and furnish less disturbed samples and more reliable test results. When undisturbed tube samples of very soft soils or cohesionless soils are too difficult to obtain, representative samples with a volume of \( 1 \) to \( 2 \) qt should be taken of the particular strata so that tests on remolded soil may be performed. Still larger
<table>
<thead>
<tr>
<th>PHASE OF EXPLOR.</th>
<th>TYPE OF TEST</th>
<th>CONDITION OF SAMPLE</th>
<th>QUANTITY OF SOIL OR WATER OR DIAMETER OF SAMPLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconnoisseur, Explor.</td>
<td>Visual Classification</td>
<td>Repres.</td>
<td>Augers, cup, or 1 to 2 in. samples. Preserve at least 1/5 pint and preferably 1/2 pint in case of tests</td>
</tr>
<tr>
<td></td>
<td>Occasionally approx. Water Content, Limits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detailed Exploration Minor Physical Tests</td>
<td>Liquid and Plastic Limits</td>
<td>Repres.</td>
<td>Fine-grained soils 1/2 pint minim. Mechananalyses of coarse-grained to gravelly soils 1 pint to 2 quarts</td>
</tr>
<tr>
<td></td>
<td>Mechanical Analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Specific Gravity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detailed Exploration Minor Physical Tests</td>
<td>Water Content</td>
<td>No vol. change</td>
<td>1-3/4 to 2 in. samples usually adequate; 2-1/8 to 2-7/8 in. samples often used. In test pits 3 to 4 in. samples or field volume tests plus 1 to 2 quarts representative sample of coarse-grained to gravelly soils</td>
</tr>
<tr>
<td></td>
<td>Unit Weight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detailed Exploration Minor Physical Tests</td>
<td>Unconfined Compression</td>
<td>Undist.</td>
<td>2 in. samples occasionally used but 2-7/8 in. diam. advisable minimum and 4 to 6 in. diam. preferable</td>
</tr>
<tr>
<td></td>
<td>Direct Shear, Double, Rd. Slicing, Partial Drying</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Special Exploration Major Physical Tests</td>
<td>Permeability</td>
<td>Undist.</td>
<td>4-3/4 in. diam. advisable minimum 5 to 6 in. diam. often used. In test pits 5 to 8 in. round or 10 in. cubes</td>
</tr>
<tr>
<td></td>
<td>Consolidation</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Triaxial Compression</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Special Exploration Major Physical Tests</td>
<td>Multiple Compres. Tests</td>
<td>Undist.</td>
<td>From single strata or holes 100 lb to 500 lb. Composite sample for a complete series of tests 500 lb. Samples for aggregates see text</td>
</tr>
<tr>
<td></td>
<td>Direct Shear, Single, Sq. Torsion Shear, Ring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction Materials Exploration</td>
<td>Mechanical Analysis</td>
<td>Repres. or Composite</td>
<td>Density 2 to 4 in. diam. samples or field volume tests. Others 5 in. min. diam., CBR mold, or 10 in. cubes</td>
</tr>
<tr>
<td></td>
<td>Compaction and CBR Tests</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Triaxial Compression</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Concrete Aggregate Tests</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction Materials Control</td>
<td>Dry Density, Water Cont. California Bearing Ratio Triaxial Compression</td>
<td>Undist.</td>
<td>1 quart to 1 gallon depending on laboratory method and equipment</td>
</tr>
<tr>
<td>Water</td>
<td>Chemical Analysis</td>
<td>Repres.</td>
<td>Minim. 7/8 or 1-1/8 in. (EX, AX) 1-5/8 or 2-1/8 in. (BX, NX) preferred because of better recovery. In soft or broken rock 3 to 6 in. diam.</td>
</tr>
<tr>
<td>Rock Drilling</td>
<td>Visual Inspection</td>
<td>Undist.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mineralogical Tests</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Compression, Shear Porosity, Permeability</td>
<td></td>
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</tr>
</tbody>
</table>
diameters and quantities of representative samples are required in the detailed explorations of materials to be used for construction purposes; see Table 2 and the further discussion at the end of this section.

Some of the major physical tests, such as permeability and consolidation tests, are occasionally performed on samples about 2 in. in diameter, but a sample diameter of about 2-7/8 in., as taken with a 3-in. OD. thin-wall sampler, is the advisable minimum for this purpose. Undisturbed samples 4-1/4 in. to 5-3/4 in. in diameter are required by some soils laboratories for major physical tests and are, in general, to be preferred, since the influence of the surface disturbance is decreased thereby and the test specimen may be prepared from the central and least disturbed part of the sample. Larger samples also permit preparation of several smaller test specimens from a single soil layer in a section of the sample and the consequent performance of multiple unconfined or triaxial compression tests on the same soil but with varying testing conditions.

When large undisturbed samples are taken, it is advisable also to preserve small representative samples of at least 1/2 pt from each distinctive stratum. These samples may be composed of material obtained by trimming the larger samples or, if necessary, they may be cut from the top or bottom of the large samples. In test pits small representative or undisturbed samples may be taken at the same levels and close to the large samples. Small samples permit laboratory examination and classification tests to be performed without breaking the seals of the large undisturbed samples. Routine laboratory work is thereby facilitated; the danger of disturbing the large samples is decreased; and additional data are obtained for the proper planning of the tests on the large samples.

Continuous or composite representative samples are generally required for investigation of soil deposits or rock ledges considered for use as construction materials. Composite representative samples should represent the stratum or deposit to be used. They are obtained by preserving all the material excavated between the appropriate depths in a bore hole or from a narrow channel in the walls of a test pit, or they may be prepared by mixing samples taken at various depths and from various bore holes and test pits. Both the individual samples and the final composite sample may, when too large, be reduced in size by mixing and quartering in either the field or laboratory.

The required size of composite samples varies greatly with both the composition of the material, its intended use, and the extent of the laboratory investigation. Only very approximate indications of the requirements can be given here, and whenever possible, the laboratory should be consulted before samples are taken.

When the soil is to be used in earth dams, fills and backfills, base courses for airfields and roads, or for asphalt aggregate, a sample weighing about 500 lb will usually be adequate for a standard series of tests. This amount must be increased when several series of tests are to be performed, or when a part of the material may be discarded as unsuitable for the actual tests. On the other hand, a
much smaller amount may be sufficient when only specific tests are to be performed. When the final sample is prepared by mixing composite samples from various levels or bore holes, the individual composite samples should weigh from 100 to 200 lb.

In the Standards of 1946 by the American Society of Testing Materials, it is specified in Designation D75-46T that for preliminary investigation of a source of supply, samples of pit run gravel and sand for use as highway materials should not be less than 100 lb in total weight and so large that each sample will contain not less than 25 lb of sand and/or 50 lb of gravel. For example, a 200-lb sample should be taken when the deposit contains only 25 per cent gravel.

In Bulletin 27 (Revised), Concrete Analyses Testing and Research, Waterways Experiment Station, Vicksburg, Miss., July 1947, it is specified that the total amount of unprocessed aggregate from gravel pits and rock ledges, submitted for analysis and concrete mixture design, should not be less than the following amounts:

| Size of coarse aggregate in concrete, in. | 3/4 | 1-1/2 | 3 | 6 |
| Size of total sample, lb                | 1000 | 1500 | 2000 | 3000 |

When the aggregate is to be prepared by crushing of rock cores, the diameter of the core should not be less than 6 in. and the length not less than 8 ft for each ledge investigated, and the diameter should be increased to at least 10 in. when 6-in. aggregate is to be prepared.

The requirements for undisturbed samples of soil and the influence of unavoidable disturbances are discussed in greater detail in Chapter 6, and the requirements for samples of water in Section 3.10.
CHAPTER 2
METHODS OF SUBSURFACE EXPLORATION

2.1 General

The purpose of this chapter is to present a brief outline of the various methods of exploration in such a manner that it will serve as a background for sampling operations, the main subject of the report. Only general principles and not details of the various methods of exploration are described, and greater stress is laid on a discussion of their advantages and disadvantages, the accuracy with which changes in the character of the material can be determined, and features which may affect sampling operations and the quality of the samples obtained. A general classification and summary of the principal features of the various methods of subsurface exploration is shown in Table 3. The methods will be described in the order shown in this summary, progressing from indirect through semi-direct to direct methods of exploration.

2.2 Geophysical Methods -- General

Geophysical methods of exploration consist in identifying changes in the character of subsurface materials by measuring changes in certain physical characteristics of the earth at or near its surface. The major geophysical methods involve measurement of surface anomalies in the gravitational, magnetic, and electric fields of the earth and measurement of changes in electrical resistance and rate of propagation of elastic waves in the earth. They are classified as gravitational, magnetic, electrical, and seismic methods.

These methods have been developed primarily for and are used extensively in prospecting for oil and minerals, but some electrical and seismic methods are also being used on an increasing scale in subsurface explorations for civil engineering purposes. In addition, a special method has been developed for use in the latter field. It is basically a seismic method but it differs from other seismic methods in so many respects that it may be placed in a separate category and called the continuous vibration method. Several minor geophysical methods, utilizing radioactive, thermal, and other properties of subsurface materials, are used to a limited extent and under special conditions. For a detailed description of the theory and practice of geophysical methods of exploration see references 211, 214, 221, 227 and the publications listed in Section 4 of the classified bibliography.
<table>
<thead>
<tr>
<th>GROUP</th>
<th>TYPE</th>
<th>METHOD</th>
<th>MEASUREMENTS OR METHODS OF ADVANCE</th>
<th>INDICATION OF CHANGE IN MATERIAL</th>
<th>TYPE OF FORMATION</th>
<th>USE IN CIVIL ENGINEERING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geophysical</td>
<td>Methods (1)</td>
<td>Resistivity</td>
<td>Current and potential drop</td>
<td>Variations in resistivity</td>
<td>Rock, soils, and ground water; horizontal and inclined strata at shallow to medium depths</td>
<td>Reconnaissance, general stratigraphy; detection of irregularities. Rapid, fairly reliable with correlation of borings, incl. represent. samples</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pot, Drop Ratio</td>
<td>Ratio pot. drop betw. three points</td>
<td>Variations in pot. drop ratio</td>
<td>Rock, soils, and ground water; horizontal and inclined strata at shallow to medium depths</td>
<td>Reconnaissance, general stratigraphy; detection of irregularities. Rapid, fairly reliable with correlation of borings, incl. represent. samples</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seismic</td>
<td>Refraction</td>
<td>Velocity, compress. waves</td>
<td>Deposits at depths over 2000 ft</td>
<td>Not used in Civil Engineering</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Reflection</td>
<td>Velocity, compress. waves</td>
<td>Deposits at depths over 2000 ft</td>
<td>Not used in Civil Engineering</td>
</tr>
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<td></td>
<td></td>
<td>Continuous Vibration</td>
<td>Contin. waves, variable frequency phase, amplitude, power, settlement</td>
<td>Variations in wave</td>
<td>Soil and rock, shallow depths, horizontal and inclined strata</td>
<td>Reconnaissance, general stratigraphy, dynamic properties; in development</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rod alone</td>
<td>Simple Point</td>
<td>Driving by drop hammer</td>
<td>Blows : penetration</td>
<td>All soils without large stones; rapid not always reliable</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Screw Point</td>
<td>Static pressure and rotation</td>
<td>Rev's : penetration</td>
<td>Medium to hard cohesive soils</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cone or Disk</td>
<td>Static pressure, constant speed</td>
<td>Force : penetration</td>
<td>Soft to stiff and dense soils</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rod with a Sleeve Pipe</td>
<td>Wash Point</td>
<td>Alternating jetting and jacking</td>
<td>Variations in point</td>
<td>Primarily cohesionless soils</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Large Core Point</td>
<td>Alternating jacking and driving of rod and sleeve pipe. In some cases concurrent jacking of rod and sleeve pipe</td>
<td>Variations in point</td>
<td>Primarily cohesionless soils</td>
</tr>
<tr>
<td></td>
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<td>Flash Cone Point</td>
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<td></td>
<td>Cone and Collar</td>
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<td></td>
<td></td>
<td>Kjellman &quot;In situ&quot; Method</td>
<td>Insertion and withdrawal of resistor</td>
<td>Withdrawal resistance</td>
<td>Primarily soft and loose soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Displacement Boring</td>
<td>Silt, Cup Sampler</td>
<td>Driving closed sampler into the soil, rotation, release of piston, sampling</td>
<td>Blows or static force versus penetration</td>
<td>Loose to medium cohesionless soils; stiff to stiff cohesive soils</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Piston Samplers</td>
<td></td>
<td></td>
<td>Reconnaissance and detailed exploration. Rapid under favorable conditions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wash Boring (3)</td>
<td>Light chopping, strong jetting; removal of cuttings by circulating water</td>
<td>Cuttings in water, rate of progress (2)</td>
<td>Soft to stiff cohesive and fine to coarse cohesionless soils</td>
<td>Reconnaissance, to special explorations, ground water; inexpensive equip.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Percussion Drilling -- also called Cable-Tool Drilling</td>
<td>Power drilling; periodic removal of slurry with bailers or sandpumps</td>
<td>Cuttings in slurry, rate of progress (2)</td>
<td>Soil and rock but difficult in soft sticky clay or loose sand</td>
<td>Penetration, gravel, boulders, rock; supplementing wash, auger borings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rotary Drilling</td>
<td>Power rotation of bit; cuttings removed by circulating drilling fluid</td>
<td>Cuttings in fluid, rate of progress (2)</td>
<td>Soil and rock, except stony or very porous soil, fissured rock</td>
<td>Detailed and special exploration; fast; water observations difficult</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Auger Boring</td>
<td>Hand or power operat. with periodic withdrawal or use of contin. auger</td>
<td>Soil removed constitutes representative sample</td>
<td>Medium to stiff cohesive soils; part. saturated sand and silt</td>
<td>Shallow reconnaissance, detail explor. Power operat., fast; special explor.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continuous Sampling</td>
<td>Alternating sampling and cleaning with drive samplers or core barrels</td>
<td>Samples obtained are representative or undisturb.</td>
<td>All soils and rock -- cohesionless soils may require freezing</td>
<td>Best method for detail soil expl. Majority of explorations in rock</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accessible Borings (1)</td>
<td>Test Pits and Trenches, Caissons, Drifts, Tunnels</td>
<td>Excavation by hand and power tools, use of explosives; sheeting of walls</td>
<td>Inspection, mapping, sampling, and testing material in situ</td>
<td>Soil and rock; unstable soils require ground water control, compressed air, or freezing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accessible Borings</td>
<td>Wash Boring</td>
<td>Light chopping, strong jetting; removal of cuttings by circulating water</td>
<td>Cuttings in water, rate of progress (2)</td>
<td>Soft to stiff cohesive and fine to coarse cohesionless soils</td>
</tr>
</tbody>
</table>

(1) Only principal methods listed. (2) Samples of cuttings, settled from wash water, slurry, or drilling fluid, are called "Wet Samples". They are non-representative and inadequate for positive identification of soil strata; however, the borings make separate sampling operations possible. (3) Wash borings with representative samples taken each stratum often called "Dry Sample Borings".
Gravitational methods are based on differences in density of subsurface materials. They consist in determining either the vertical intensity (by pendulum or gravimeter) or the curvature and gradients (by torsion balance) of the gravitational field at various points of the area under investigation. Any anomalies existing after correction has been made for terrain, planetary, and other effects indicate changes in the density of the subsurface materials. These methods are particularly valuable in tracing the boundaries of steeply-inclined subsurface irregularities, such as faults, intrusions, domes, and ridges. The methods are not suited for depth determinations to fairly horizontal strata and are rarely used in subsurface explorations for civil engineering purposes.

The magnetic method is based on differences in the magnetic properties of subsurface materials. The vertical intensity and occasionally also the inclination and the horizontal intensity and declination are measured at various points and corrected for normal variations in the magnetic field and other effects. The interpretation of the remaining magnetic anomalies yields primarily qualitative results, although quantitative results, such as depth determinations, can be obtained under special conditions. The method cannot yield the detailed information obtainable by other methods, but it is the simplest and quickest of all geophysical methods, and is used extensively as a reconnaissance method in searches for oil and minerals. It has also been used successfully in the general exploration of dam sites underlain with igneous or crystalline rocks, which often are strongly magnetic compared to sedimentary deposits.

The general principles and special features of electrical, seismic, and dynamic vibration methods are discussed in the following three sections, but their common advantages and limitations and fields of application are summarized here.

In comparison with borings, large areas or projects of great linear extent can be explored more rapidly and economically by geophysical methods. These methods have the further advantage that they indicate average conditions within a limited area and not along a single vertical or inclined line. This facilitates detection of subsurface irregularities which often are missed by borings. The results obtained are generally satisfactory when only the depth to rock or the location of subsurface irregularities or deposits materially different from the surface soil is desired. The general character of subsurface materials can often be estimated, but the materials cannot be definitely identified by geophysical methods alone; these methods should therefore always be supplemented by borings in which representative or undisturbed samples are obtained.

Geophysical methods are especially well suited for reconnaissance exploration of large areas to be used for dams and reservoirs, tunnels, highways, airfields, and large groups of buildings. They have also been used successfully for location of gravel deposits and other construction materials. The presence of and depth to ground water can be determined under favorable conditions, but the influence of the water may be obscured by the character and sequence of strata adjacent to the water table and by varying contents of mineral salts dissolved in the water.
2.3 Electrical Methods

The majority of electrical methods of exploration are based on differences in electrical conductivity or resistivity of the subsurface materials. The resistivity of dense, igneous rocks is much larger than that of loose, saturated sediments; however, dry sedimentary deposits may have a fairly large resistivity. In general, resistivity depends mainly on the quantity and salinity of the water in the pores and less on the mineral constituents of ordinary soils and rocks. Evaluation of field results obtained by electrical methods of exploration is therefore based more on the relative than on the actual values of the resistivity. A great variety of electrical methods of exploration has been developed, but only two, the potential-drop-ratio or PDR method and especially the resistivity method, are used to any extent in explorations for civil engineering purposes.

The resistivity method (412 to 415, 419 to 422, 431, 432) consists in producing an electrical field in the ground by means of two current electrodes, Fig. 2. By measuring this current and the potential drop between two intermediate or potential electrodes, the apparent resistivity of the soil to a depth approximately equal to the spacing, a, of the electrodes can be computed. The resistivity unit is often so designed that the apparent resistivity can be read directly on the potentiometer. In "resistivity mapping" or "transverse profiling" the electrodes are moved from place to place without changing their spacing, and the apparent resistivity and any anomalies within a depth equal to the spacing of the electrodes can thereby be determined for a number of points. In "resistivity sounding" or "depth profiling" the center point of the set-up is stationary whereas the spacing of the electrodes is varied. A detailed evaluation of the results of resistivity sounding is rather complicated, but preliminary indications of subsurface conditions may be obtained by plotting the apparent resistivity as a function of the electrode spacing. The resultant diagram will generally show a more or less pronounced break or change in curvature when the electrode spacing reaches a value equal to the depth to a deposit with a resistivity materially different from that of the overlying strata.

In the potential-drop-ratio method (214, 427) the two current electrodes are placed very far apart, 5 to 10 times the desired effective depth penetration of the survey, and the measurements are carried out in the vicinity of one of the current electrodes, Fig. 3. Three equidistant potential electrodes are used and placed in lines through the current electrode. Only the potential drop, or rather the ratio between the potential drops A-B and B-C, is measured. The center distance, R, is
varied, whereas the electrode spacing, \( b \), is kept constant or is a definite fraction, generally \( 1/3 \), of \( R \). The observed potential-drop-ratios are first multiplied by a correction factor, which depends on the relative values of \( b \) and \( R \), and are then plotted as a function of \( R \). A break or change in curvature of the diagram obtained indicates strata with a resistivity different from that of the surface soil. The ratio between the corresponding value of \( R \) and the depth to the stratum varies between 1.5 and 3.5 according to the electrode spacing and the conductivity of the various strata.

The principal measurements are usually carried out along a line at right angle to the line between the two current electrodes, but profiles radiating from one of the current electrodes are used for determination of the dip and strike of the subsurface strata. In other PDR methods the base length is relatively small, and the three potential electrodes are placed between the current electrodes and with a spacing which is a function of the base length.

The potential-drop-ratio method gives sharper indications of vertical or steeply-inclined boundaries and, under certain conditions, more accurate depth determinations than the resistivity method. However, it is more susceptible to surface interference and to small irregularities in the surface soil. The resistivity method is generally preferred in explorations for civil engineering purposes. Both methods have been used extensively in obtaining rock-line and preliminary rough soil profiles for large projects and in prospecting for gravel deposits and other construction materials.

### 2.4 Seismic Methods

Seismic methods are based on the fact that the velocity of propagation of a wave or impulse in an elastic body is a function of the modulus of elasticity, the Poisson ratio, and the density of the material, and that very great differences exist between wave velocities in solid rock and in loose, sedimentary deposits. An impulse will produce longitudinal or compression waves, transverse or shear waves, and various types of surface waves. It is primarily the velocity of longitudinal or compression waves which is utilized in the seismic methods of exploration. The range of velocities for such waves is indicated in Fig. 4.

The elastic impulse is produced by exploding a small charge of high velocity dynamite placed in a shallow bore hole. The time required for the impulse to travel from the shot point to various points on the ground surface is determined by means
of small vibration detectors or "geophones" which transform the vibrations into electrical currents and transmit them to a recording unit or oscillograph, equipped with a timing mechanism. There are two principal types of seismic methods of exploration, one which depends on the refraction of the elastic waves between the various strata, and one which utilizes the reflection of the waves at the interfaces between the strata.

The refraction method of seismic exploration (420 to 426) is based on the fact that an elastic wave in travelling across a boundary between materials is refracted toward the plane of the boundary when it enters a material which transmits the wave with a higher velocity and toward the perpendicular to the boundary when it passes from one material to another with a lower velocity of wave propagation. The detectors are placed at various distances from, but generally along a straight line through, the shot point, Fig. 5. In actual practice several shots are fired successively at various distances from each set-up of three to four detectors. The distance from the last shot to the farthest detector, or the maximum shooting distance, must be from three to twelve times the desired depth of penetration.

Only the arrival time of the initial impulse at each geophone is utilized. If the successively deeper strata transmit the waves with increasingly greater velocities, the paths traveled by the first impulses will be similar to those shown in Fig. 5. Those recorded by the nearest detectors pass entirely through the overburden, whereas those first reaching the
farther detectors travel downward through the lower-velocity material, horizontally within the higher-velocity stratum, and return to the surface as shown. By plotting the travel times as a function of the distances between the geophones and shot points, Fig. 5, a curve is obtained which indicates the wave velocity in each stratum and which may be used to determine the depths to the boundaries between the strata.

It should be noted that the seismic refraction method can be used only when the wave velocity is greater in each successively deeper stratum. The presence and thickness of a stratum which transmits the waves at a lower velocity than the overlying stratum cannot be determined by this method. Complications are occasionally encountered when the wave velocity in the overburden or loose deposits increases gradually with depth. The path of the first impulses and the travel-time diagrams will then be curved, and it may be difficult to determine the actual wave velocities and the thickness of the non-uniform strata. When inclined strata are encountered, only the average depths can be determined by a single travel-time diagram, and it is necessary to reverse the positions of the shots and detectors and shoot "up-dip" and "down-dip" in order to determine the actual depths and the dip of the strata along the shot line. The strike and maximum dip of the strata are determined by comparing parallel profiles or by taking profiles along two or three intersecting lines.

Several variants of the basic refraction method have been developed. By special arrangements of the shot points, detectors, and shooting lines, and by special methods of evaluating the data obtained, it is often possible to decrease the required shooting distance and the number of shot points, and to obtain increased accuracy in determining the depth to subsurface strata below specific points instead of average depths.

The reflection method of seismic exploration utilizes impulses reflected from the boundaries between deep strata, Fig. 6. This method requires a shooting distance of only one-tenth to one-half of the depth of penetration and smaller explosive charges than the refraction method. However, the reflected impulses are weak and easily obscured by the direct surface and shallow refraction impulses, and arrangements to screen out the latter impulses has not yet been fully successful. The reflection method is therefore used to determine the depths to deep strata so that the reflected impulses
will arrive at the geophones after the stronger surface and shallow reflected impulses have been dissipated. The minimum depth of penetration, at which reliable results can be obtained by the reflection method, is about 2000 ft. The method is therefore not applicable to the relatively shallow explorations for civil engineering purposes.

The refraction method of seismic exploration is well suited for determination of the depth to rock and other strata substantially different from the surface materials. For this purpose it is now used to a greater extent than the electrical methods, because it is less influenced by surface irregularities and structures, and it also has the advantage that it can be used on water-covered areas. Nevertheless, the electrical and seismic methods are in several respects complementary; when definite results cannot be obtained with one of these methods, the other one can often be used successfully.

2.5 Continuous Vibration Method

Seismic methods of subsurface exploration utilize longitudinal or compression waves, produced by a single elastic impulse. As indicated, these methods may be used for determination of the depth to rock or to strata in which the wave velocity is materially greater than in the overlying strata, but they furnish only limited information on the physical properties of the materials. Additional information on these properties can be obtained by the continuous vibration method, which was developed by the engineers of the Deutsche Gesellschaft für Bodenkunde (Degebo) and the Geophysical Institute of Göttingen, see references 407 to 410, and 416. Brief descriptions of the method are also given by Brennecke and Lohmeyer (206), Heiland (214), Loos (229), and Terzaghi (245).

The continuous vibration method utilizes continuous transverse or shear waves -- probably Love waves -- of controllable amplitude and frequency. These waves are produced by a mechanical vibrator, which in principle consists of a pair of counter-rotating disks on parallel shafts. The disks are eccentrically weighted or mounted in such a manner that the centrifugal forces thereby produced cancel each other in one direction and produce a sinusoidal variable force in a direction perpendicular thereto. The vibrator is generally used in such a position that the two parallel shafts with the disks are in a horizontal plane, and sinusoidal vertical forces are then produced, Fig. 7A, but horizontal forces can be produced by up-ending the vibrator so that the two shafts then are located in a vertical plane. Pure moments in either a horizontal or vertical plane can be
produced by using two pairs of disks with the eccentricity of one pair 180 degrees out of phase. The vibrator used by "Degebo" has a base area of about 10 sq ft and weighs from 4500 to 6000 lb. The frequency can be varied from 5 to 60 cycles per second. For a given frequency the impulse or amplitude can be varied by changing the eccentric weights or the eccentricity of these weights or the disks. The dead weight of the vibrator can be changed by means of removable weights.

The waves imparted to the soil are picked up and recorded by seismic detectors, which are placed at various distances from the vibrator; usually with one detector on the vibrator itself. Tests are performed at various frequencies and with various loads on the vibrator. The observations include: (1) the phase shift at the various detectors; (2) the amplitude as a function of frequency and distance; (3) settlement of the vibrator as a function of the frequency and the load on the vibrator; and (4) the power input as a function of the frequency.

The travel times of the waves to the various detectors can be computed from the phase shifts. When they are plotted as a function of the distance, the depths to or thickness of the strata may be determined as shown in Fig. 5 for a shallow seismic refraction survey. However, the computations are often complicated by changes in wave velocity due to dispersion at certain combinations of frequencies and depths to the boundaries of the substrata.

The amplitude plotted as a function of the frequency will show a distinct maximum at the resonance frequency or natural period of vibration of the ground, Fig. 7B. The settlement and power input vary with the frequency, increasing toward and with the maximum gradient at resonance. The settlement curve shown in Fig. 7B indicates the accumulated settlement obtained by gradually increasing the frequency. The power transmitted to the soil is the difference between the actual power input and the power consumed at no load or balanced rotating disks. This difference, plotted as a function of the frequency, reaches a maximum value at the resonant frequency of the system. The natural period of vibration of the ground can thus be determined in several ways with reasonable accuracy. Knowledge of the natural period of vibration is very important in the design of foundations for machines or structures subject to induced vibrations.

The amplitudes permit an estimate of the coefficient of dynamic subgrade reaction, and the decrease of amplitude with distance indicates the damping effect of the soil. These two physical properties as well as the velocity of the waves and the natural period of vibration give some indication of the soil type. In homogeneous soil the amplitude decreases rapidly but uniformly with the distance from the vibrator, Fig. 7C, but in layered soil the refracted or reflected waves cause interference with the directly transmitted waves. In the latter case the amplitude-distance curve will show distinct maxima and minima, the spacing of which depends on the depth to the substrata. This spacing is constant when the layers are parallel to the ground surface, but it increases or decreases with distance in case of inclined strata.

By combining the continuous vibration method with the seismic refraction
method, the velocities of both the compression waves and the slower shear waves can be determined. These velocities can be expressed by two independent equations, involving the modulus of elasticity, the Poisson ratio, and the density of the material. When the velocities are determined and one of the above mentioned physical coefficients is known or estimated, the other two coefficients can be computed.

Based on empirical correlations of collected data, tables have been prepared which give directly the allowable bearing capacity of the soil as a function of either the velocity of the shear waves or the natural period of vibration, BRENNENCKE and LOHMeyer (206), LOOS (229) and Terzaghi (245). Such tables should, of course, be used only with great caution, especially in case of exploration outside the region for which the correlations have been made. It should also be noted that whereas the continuous vibration method can give some indication of the density and prospective compaction of cohesionless or partially saturated materials, it cannot furnish any information on the consolidation characteristics of saturated cohesive soils.

As will be seen from this brief review, it is theoretically possible to obtain considerable information on both the soil profile and certain physical properties of the soil by means of the continuous vibration method. However, conditions are often considerably more complicated than outlined above, and with exception of the natural period of vibration, it is not always possible to determine these physical properties and the soil profile with satisfactory accuracy. The depth of penetration of the continuous vibration method is reported to be about 40 m under favorable conditions, but the practical limit of this depth has not yet been reliably established, and it is, in any case, small compared to that of the seismic refraction method. The continuous vibration method has been used to a considerable extent in Germany, but so far only in a few cases in this country. The method must be considered as still in the stage of development, but it has interesting possibilities.

2.6 Sounding Methods -- General

Soil sounding or probing consists in forcing a rod, a rod encased in a sleeve pipe, or a wire and resistor body into the soil and observing the penetration or withdrawal resistance. Variations in this resistance indicate dissimilar soil layers, and the numerical values of the resistance permit an estimate of some of the physical properties of the strata. Soil sounding can therefore be considered as a method of both exploration and field testing. Similar data can also be obtained by observation of the penetration resistance of a drive sampler, discussed in Section 4.10.

Recent advances in design and operation of soil sounding apparatus and in methods of evaluating the results obtained have increased the use of sounding. The development and principal types of soil sounding equipment will be described in the following three sections, but space limitations permit only reference to the various theories and empirical correlations which have been advanced for interpretation of the data obtained. The advantages and limitations of soil sounding methods may be
summarized as follows:

When the soundings are properly performed with recently improved equipment, the sounding profiles obtained will generally furnish consistent data on the depths to different soil strata, but very misleading results can also be obtained by some of the sounding methods and when the soil contains stones and boulders.

Continuous sounding profiles may indicate the presence of thin strata which often remain unobserved in boring operations, but the strata encountered cannot be definitely identified by soundings alone. Soil soundings should therefore be supplemented by borings unless the soil types found in the area under investigation already are known.

Soundings are generally considerably faster and cheaper than borings. In case of erratic soil conditions, it may be advantageous to replace some of the borings with a greater number of soundings and thereby obtain more complete data on variations in the soil profile.

Sounding profiles give indications of the consistency of cohesive soils and the compactness of cohesionless soils in situ. This information is very valuable when undisturbed samples are difficult and too expensive to obtain, as in saturated cohesionless soils.

In regions where sufficient correlations of soundings with borings, laboratory tests on prevalent soil types, and field loading tests or the behavior of completed structures have been made, and where soil conditions are favorable for the use of sounding methods, it has been possible on the basis of soundings alone to estimate the approximate bearing capacity of soil strata, the length and bearing capacity of piles, and in case of some foundations on cohesionless soils, even the approximate settlements of the proposed structure. However, it should be noted that sounding profiles do not give information on the permeability of the soil or the consolidation characteristics of relatively impermeable cohesive soils.

Correct interpretation of sounding profiles requires considerable experience, especially when estimates of bearing capacity and settlements are attempted. Very misleading results can be obtained by inexpert execution of the work and interpretation of the data. Great caution should be exercised in applying the results of correlations outside the region or area for which the correlations were made.

In general, small and large areas can be explored rapidly and economically by soil sounding methods, especially when the depth of exploration is moderate and the soils penetrated are soft or loose. Soundings furnish data which in several respects supplement those obtained by borings, but soundings alone cannot provide sufficient data for the final design of important or unusual foundation and earth structures, and in any case, not when consolidation, seepage, and earth or groundwater pressures must be taken into consideration.
2.7 Simple Sounding Rods

**Dynamic resistance.** - The oldest and simplest form of soil sounding consists in driving a rod into the ground by repeated blows of a hammer, Fig. 8 and 9. The penetration of the rod for a given number of blows with a hammer of constant weight and drop, or the number of blows required per foot penetration of the rod, may be used as an index of the penetration resistance and correlated directly with local foundation experience (219, 225, 319). However, the numerical value of this index depends not only on the character of the soil but also on the diameter, length, and weight of the rod in relation to the weight and drop of the hammer, and more reliable results are obtained when the index is translated into the dynamic force resisting penetration or into a pressure per unit area of the rod by means of formulas similar to the pile driving formulas (225, 351, 931).

Since the skin friction acting on the rod is cumulative with depth, the penetration resistance does not directly represent the strength or density of the strata encountered. In recent years the skin friction is often determined at short intervals of penetration by the resistance to withdrawal and/or rotation of the rod, and separate diagrams for the point resistance and accumulated skin friction can thereby be obtained. However, the dynamic friction during driving may not always be equal to the static friction during withdrawal or rotation. The approximate point
resistance may in some cases be determined directly by use of an oversize drive point, Fig. 10, but the method is not reliable when the depth is great and when the soil is soft or loose and saturated. A great reduction in withdrawal resistance can generally be obtained by use of a clearance sleeve, Fig. 10B, which is left in the ground upon withdrawal of the rod.

**Penetration by rotation.** In 1917 the Geotechnical Committee of the Swedish State Railroads (967) -- see also 332 and 353 -- introduced a sounding rod which is forced into the soil in part by a static load and in part by rotation of the rod, Fig. 11. This method is used extensively in the Scandinavian countries, and the following description is based on minor modifications introduced by the Danish State Railroads, see Godskesen (323, 324, 206, and 615). The rod is provided with a screw point with a diameter about 50 per cent greater than that of the rod. The penetration is first recorded for successive static loads of 5, 15, 25, 75, and 100 kg. The rod with the final static load of 100 kg is then rotated, and the penetration is observed for each 25 half turns. A diagram of the variations of this penetration with depth is then compared with similar diagrams obtained in the same region and under conditions for which the bearing capacity of the soil strata or the required length and bearing capacity of piles have been determined by other means.

According to Godskesen (323, 324), fair foundation conditions, suitable for spread footings, exist when the penetration is less than 50 cm for each 25 half turns, and end-bearing piles can be used when the penetration is less than 5 to 10 cm. However, these rules should not be applied indiscriminately, and the general character of the soils in the region, the depth to the strata under consideration, and the possibility that skin friction may be active and decrease penetration in spite of the oversize drive point must be taken into consideration. The method is relatively fast and inexpensive, even when compared with other sounding methods, but it is not suited for exploration of coarse and gravelly soils or very compact or hard soils. Neither does the method furnish adequate details on the soil profile when soils are so soft that they are penetrated by the sounding rod without rotating it but simply by placing the above mentioned static loads on the self-locking clamp.

**Static resistance.** Variations in static penetration resistance of a sounding rod, which is pushed or jacked slowly into the soil, can be determined with greater accuracy than variations in dynamic resistance. The numerical values of the static resistance are also easier to correlate with the strength and bearing capacity of the soil. Static rather than dynamic penetration resistance is therefore measured in the majority of the recently developed soil sounding methods, especially when these methods are used in exploration of relatively soft soil deposits.

The test rod shown in Fig. 12 was developed by A. Casagrande for detection of soft spots in shallow hydraulic fills covering large areas. The washer at the bottom of the rod provides outside clearance and is left in the ground, thereby facilitating withdrawal of the rod. The penetration resistance is measured by a simple commercial spring scale. For each type of fill this resistance is correlated with
the water content and degree of compaction of the soil, as determined by laboratory tests on samples obtained in borings or test pits. For example, it was found that a fill of silty clay was satisfactory when the penetration resistance exceeded 40 lb, whereas a resistance of 20 lb or less indicated soft or loose materials which should be replaced.

A cone penetrometer built and used by Keith Boyd for determination of the bearing capacity of subgrades for roads and airfields has been further developed by the Waterways Experiment Station in Vicksburg and is shown in Fig. 13. It is used for shallow explorations in relatively soft deposits and determination of the capacity of such deposits to sustain various types of loads and traffic. At depths at which

it is desired to determine the penetration resistance, the pressure on the handle is slowly increased until there is a perceptible but very slow and uniform downward movement of the cone. The corresponding pressure is measured by means of the proving ring. The small deformations of such a ring, compared to those of an ordinary spring dynamometer, greatly facilitate detection of a slow, downward movement of the cone.

2.8 Encased Sounding Rods

Soft or cohesionless soils may close in on a sounding rod in spite of an
oversize drive point or washer. The partial skin friction thereby established makes it very difficult to evaluate the results properly. These difficulties are frequently encountered when soundings are extended to considerable depths. The influence of skin friction in determining point resistance may be eliminated by encasing the sounding rod proper in a sleeve pipe. Encased sounding rods were first developed by Terzaghi (968) and Barentsen (601). They may be designed and operated for: (1) determination of point resistance alone; (2) additional determination of total skin friction on the sleeve pipe; or (3) determination of the specific skin friction exerted by the individual strata.

Point resistance. - When point resistance alone is to be determined, the skin friction on the sleeve pipe is usually decreased by means of jetting or use of an oversize cone point, thereby facilitating both the driving and withdrawal of the sounding assembly. Jetting is used in the method developed by Terzaghi (246, 353, 968), which also is called the Wash Point Method since the encased sounding rod is hollow and provided with a vented cone point to permit washing or jetting, Fig. 14. The method is intended for exploration of sand deposits and determination of variations in density or compaction within the deposit. A cycle of operations is as follows.

The cone is jacked 10 in. into the soil and the penetration or point resistance is measured by means of the manometer connected to the oil pump. Water is then pumped through the rod and the vents in the cone point, flowing upward both inside and outside the sleeve pipe. The upward flow of water causes temporary liquefaction of the sand immediately above the cone and removes some of this material through the sleeve pipe. The water flowing from the pipe is collected in a bucket and samples are taken later from the settled material. These samples are similar in character and value to the wash samples described under wash boring, Section 2.13. The sleeve pipe is then forced down until it touches the cone; the flow of water is stopped, and the entire operation is repeated. The sand above the zone of temporary liquefaction will by arch and wedge action relieve the pressure on the sand below the cone. The penetration resistance determined during the advance of the cone will therefore be more or less independent of depth below the ground surface and thereby indicative of the actual density of the soil.

A light and simple, encased sounding rod, developed by Barentsen (601), is shown in Fig. 15. It has been used extensively for exploration of soft surface deposits in Holland. The penetration resistance is determined by pushing the cone into the soil at a speed of about 1 cm per sec and measuring the corresponding pressure by means of a hydraulic dynamometer. The cross-sectional area of the piston in the dynamometer is equal to the base area of the cone, 10 cm², and the Bourdon gage therefore directly indicates the unit load on an area equal to that of the base of the cone. After a 10- to 15-cm advance of the cone, the sleeve is pushed down until it touches the cone, and the entire assembly is then advanced until a new determination of the penetration resistance is to be made. Such determinations are generally made for each 50-cm advance in depth. The sounding rod is operated by one or two men, and the maximum pressure is limited to 10 kg/cm² or a total...
penetration resistance of 100 kg.

Further development of sounding rods of the above mentioned type has been made by the Soil Mechanics Laboratory in Delft under direction of T. K. Huizinga (132, 218). The medium-size apparatus shown in Fig. 16A has a manually-operated rack feed, whereby it becomes possible to exert greater pressure and to obtain a more uniform rate of penetration than with the Barentsen sounding rod. The base area of the cone is 10 cm² and the maximum thrust 300 kg. A heavier sounding rig, Fig. 16B, is used for deep soundings and in dense or stiff soils. The cone has a base area of 20 cm² and the jack a maximum capacity of 10 tons. The lower end of the sleeve pipe is reinforced with a short collar, but the outside diameter of this collar is still slightly smaller than the base diameter of the cone. A bushing inside the sleeve pipe and a collar on the sounding rod proper limit the advance of the latter with respect to the pipe. A special coupling permits transfer of the force from the jack to either the rod or the sleeve pipe. A heavy steel frame with the jack and operating platform is attached to a base platform, which is placed in a 1-m deep hole and covered with soil to obtain necessary anchorage. When used on water-covered areas, the sounding apparatus is operated from the adjustable mast shown in Fig. 18.

"Point resistance and total skin friction." - Determination of skin friction in addition to but separate from point resistance has the advantage that two complementary
resistance diagrams are obtained and thereby additional data on the character of the soil and the bearing capacity of piles. When the sleeve pipe is given the same outside diameter as the base of the cone, the accumulated or total skin friction for the entire depth of penetration is determined by the force required to advance the sleeve pipe. This method is widely used in Holland and Belgium although the specific skin friction is determined directly in some cases; see Fig. 16.

Both simple and encased sounding rods are used to a considerable extent in Switzerland. The dynamic rather than the static method is generally preferred on account of the prevalence of coarse-grained and dense soil deposits. Haefeli (931) initiated the use of a simple sounding rod for snow surveys and adapted the method for soil sounding in cooperation with Münger and Knecht. The latter use a 1-1/4 in. rod and a 140-lb hammer with 20-in. drop; the skin friction is determined by rotation of the rod and other methods not specified, and the specific point resistance is computed in a similar manner as the point resistance of a pile. An encased sounding rod is used by Stump (350), who determines not only the driving resistance but also the resistance to rotation and withdrawal of the sleeve pipe. Three different diagrams for the accumulated skin friction with depth are thereby obtained, and a more detailed estimate of variations in the skin friction is made possible. The specific point resistance is determined by means of the Stern pile driving formula.

Point resistance and specific skin friction. - The specific skin friction, or the skin friction exerted by the soil at a specific depth, can be determined as the rate of increase with depth from the diagram representing the total skin friction but not always with satisfactory accuracy. Furthermore, the accumulated skin friction increases rapidly with depth and may reach such values that the relatively slender sleeve pipe cannot be driven to or withdrawn from the desired depth of exploration. These difficulties can be eliminated by providing the lower end of the sleeve pipe with a collar of limited length and the same outside diameter as the base of the cone, whereas the sleeve pipe proper has a smaller diameter.

Experiments by De Beer (916) indicated that both point resistance and skin friction, expressed as unit forces on the base area of the cone and the surface area of the collar, vary to some extent with the length of the collar when this length is small. De Beer suggests that the length of the collar should be about 100 cm when its outside diameter is 5 cm. Results of tests with two sounding rods are shown in Fig. 16C. The diagrams of point resistance and skin friction marked (1) were obtained with a 10-cm² cone and a sleeve pipe with the same diameter and area, whereas the diagrams marked (2) were obtained with a 20-cm² cone and a sleeve pipe with a smaller diameter but provided with the 1-m long collar of the same diameter as the cone. It will be observed that the point resistance, expressed as a force on the unit base area of the cones, is nearly identical in the two cases. Diagram (1) of the skin friction indicates the accumulated skin friction, and changes in the friction exerted by individual strata are discernible only as changes in slope of the diagram, whereas such changes are prominently displayed in diagram (2), which indicates the skin friction on the 1-m long collar. In case of deep soundings in soft or cohesionless
soils, there is a possibility that the soil may close in on the sleeve pipe, in spite of the clearance provided by the collar, and thereby interfere with accurate determination of skin friction on the collar.

A recent improvement of sounding rods used in Holland and Belgium consists in connecting the top of the rod to the sleeve pipe by means of a coupling with a hydraulic or electrical dynamometer for measuring the point resistance. The force from the jack is applied to this coupling and determined by another dynamometer. The skin friction is the difference between the two forces measured or the distance between the two depth-force diagrams obtained. With this arrangement it is possible to advance the cone and sleeve pipe concurrently and to obtain continuous diagrams for the point resistance and skin friction. Furthermore, the cone is provided with a tapered sleeve which prevents reduction of the lateral pressure above the cone as well as entrance of soil into the space between the sleeve pipe and the rod and cone.

Another method for determination of point resistance and specific skin friction has been developed by Ostenfeld (957), but it should be classified as a field testing method rather than a method of exploration since the tests are performed in a 4-1/2-in. cased bore hole. The testing equipment consists of a pipe with 6.1-cm outside diameter, a flat piston with 4.8-cm diameter, and a piston rod. It resembles a piston sampler but is not used for obtaining samples. After being seated on the
bottom of the bore hole, the piston is subjected to increasing loads, and a regular load settlement diagram is obtained. The pipe is then forced a given distance into the soil and its withdrawal resistance -- and thereby the skin friction -- determined, whereupon the bore hole and casing are advanced until a new test is to be performed.

**Evaluation.** - As already indicated, determination of individual values of both point resistance and skin friction has the advantage that two diagrams are obtained which supplement each other and permit a more accurate estimate of the identity of the soil strata and their properties than can be obtained by determination of the point resistance alone.

The point resistance or the penetration resistance of the cone depends not only on the coefficient of internal friction and the cohesion of the soil but also on the stress conditions or the depth below ground surface. A theory covering the influence of these three factors on the cone penetration resistance has been advanced by Buisman (207) and is also described by Barentsen (601), Huizinga (218), and De Beer (916). Laboratory correlation tests are often made on selected samples from the general area under exploration and include cone penetration tests with various surface loads on the confined test specimen. These tests are furthermore supplemented by field observations of completed structures and general foundation experiences within the region. In this manner it has been possible to estimate the approximate values of the internal friction and cohesion as well as the compactness of soil strata and the bearing capacity for direct foundations and piles. Both the general theory -- see De Beer (916), Huizinga (218), and Kollbrunner (225) -- and field and laboratory correlations have also been extended to include estimates of the elastic properties of cohesionless soils and the settlement of structures founded on such soils. However, it should be noted that results of soundings cannot give information on consolidation characteristics of saturated cohesive soils.

### 2.9 Swedish Sounding Methods

An entirely new method of sounding has recently been developed by the Swedish Geotechnical Institute under direction of W. Kjellman (147, 332, 940). The principal part of the sounding apparatus, Fig. 17A, is a small resistor or "deadman" which is hinged in the center and attached to a wire rope. The resistor is folded and pushed down to the maximum sounding depth by means of a rod with an oval collar and a slot for the wire rope. The resistor is then opened by a 90° rotation of the rod and by pulling the resistor up against the rod collar by means of the wire rope, whereupon the rod is withdrawn. The actual sounding is now performed by withdrawing the resistor. The wire rope is attached to a small winch and a recorder which furnishes a diagram of the withdrawal resistance as a function of depth. The winch may be motor-operated as shown in Fig. 17A, but a smaller hand-operated model, which can be carried by one man, has also been developed. Since the diagram indicates the relative shearing resistance of soil strata in situ, it has been called the "Insitu Apparatus". The method is primarily suited for use in soft soils and has the advantages
"INSITU" APPARATUS IN OPERATION

KJELLMAN "INSITU" APPARATUS

FIG. 17-A

CARLSON WING AUGER

FIG. 17-B
that the equipment is light, anchorages are not required, and a continuous resistance record is obtained. The withdrawal resistance may in some cases be influenced by a squeezing-in of the hole and friction between wire and soil.

Currently the Swedish Geotechnical Institute is conducting experiments with a wing type auger, shown in Fig. 17B and developed by Lyman Carlson (631). The casing with the auger abutting against the bottom cover plate is driven to the desired depth; the auger proper is then pushed down until it is beyond the zone of disturbance below the casing; the torque transmission and measuring equipment is attached to the rod, and the torque required to rotate the auger is determined and the corresponding shearing resistance computed. The method appears to give more reliable results than the wire and resistor method; it indicates a consistent increase in shearing strength with increasing depth in uniform soils, and good agreement between the computed, average shearing strength in actual slides and that obtained with the wing auger has been obtained in two cases so far investigated.

2.10 Borings -- General

In accordance with the method used in displacing or removing material in advancing a bore hole, the commonly used boring methods may be classified in the following six groups:

1. Displacement Boring
2. Wash Boring
3. Percussion Drilling
4. Rotary Drilling
5. Auger Boring
6. Continuous Sampling

The principal characteristics of these methods are summarized in Table 3 and will be discussed in greater detail in the following sections.

The efficiency of the various boring methods varies greatly with the character of the material to be penetrated and with the diameter and depth of the hole; several methods are often used in advancing a single bore hole. In selecting the boring method to be used, consideration should be given to (1) the material encountered and the relative efficiency of the various boring methods, (2) the facility and accuracy with which changes in the soil and ground-water conditions can be determined, and (3) possible disturbance of material later to be sampled.

The essential equipment for boring consists of: (1) the actual drilling or sampling tools and clean-out equipment; (2) drill rods or cables connecting these tools to the operating equipment at the ground surface; (3) casing when required to stabilize the hole and a drop hammer for driving the casing; (4) motors and winches for lowering, operating, and withdrawing drilling tools, drill rods, and casing; (5) a tripod or mast of wood or pipe sections to permit handling of reasonably long sections of drill rods and casing; and (6) a pump when required for circulation of water or
drilling fluid to remove material from the bore hole.

The operating machinery and the pump may be used as independent units, but they are often assembled in a single drilling rig which may be mounted on skids or on a truck, on which a collapsible mast also may be erected. Truck-mounted drilling rigs are being used on an increasing scale because of their mobility and the reduction in time required for setting up and dismantling the equipment, but skid-mounted drilling rigs or independent units must be used in locations inaccessible by motor vehicles. Drilling rigs are generally designed for one particular boring method and examples of such rigs will be given in the following sections; however, these rigs can, as a rule, also be used for other boring methods and for operation of samplers.

For exploration of water-covered areas the drilling equipment may be erected on a platform supported by piles; on a raft consisting of a platform supported by small boats, pontoons, or empty oil drums; or on a barge or drill boat. The raft or barge is generally provided with a well in the center through which boring operations are performed. Casing is used, at least through the open water. The raft or barge must be securely anchored and in such manner that it can rise or fall with changing water levels; the casing must also be shortened or extended in accordance with these levels. These operations may be very time consuming in case of great tidal fluctuations of water levels, and drilling operations from a raft or barge may become impossible in case of swift currents and considerable wave action.

Under the above mentioned difficult conditions a boring tower or mast, supporting the operating platform, may be erected on pontoons which are ballasted and sunk to the bottom. The mast or tower must be sufficiently high to bring the platform above high-water level. A slight slope or minor irregularities of the bottom may be compensated for by varying the amount of water in the individual pontoons or compartments and thereby the settlement of the pontoons in fairly soft deposits. In case of a considerable slope of the bottom or firm deposits, it may not be possible to bring the mast or tower into vertical position by this method, and it will then be necessary to change the angle between the mast and the pontoons or between the mast and the platform in order to bring the latter into horizontal position.

An adjustable mast with platform for use in sounding operations on water-covered areas has been developed by engineers of the Soil Mechanics Laboratory in Delft -- Huizinga (937) -- and is shown in Fig. 18. The platform is supported by a heavy pipe which in turn is connected to a heavy triangular concrete
footing by means of a universal joint. The pipe is brought into vertical position by means of three guy ropes and winches. The assembly is moved to a new location by placing a barge on each side and lifting the footing slightly off the bottom. The same principles can, of course, also be used for supporting a boring platform.

An arrangement used by the Corps of Engineers for exploration through deep water with a maximum tidal range of 28 ft, currents up to 8 knots an hour, and 6-ft high waves is described by Dow (318) and shown in Fig. 19. The platform is carried by a 21-in. heavy pipe, which in turn is supported by a circular plate or spud pad and by a short penetration into the bottom deposits. A large boat is anchored alongside the pipe, and lateral forces on the pipe are taken up by guy ropes or tackles to hand-operated winches on the boat. These winches are constantly manned so that the guy ropes will always be adjusted to varying water levels and currents.

2.11 Stabilization of Bore Holes

Common to all boring methods is the problem of preventing caving of the sides and bottom of the hole and to avoid disturbance of the soil to be sampled.

Uncased, dry bore holes are generally stable when they are shallow and above the groundwater table, but danger of caving increases rapidly with depth and the presence of free ground water. In firm, cohesive soils the hole may nevertheless remain open for a limited length of time. Bore holes without any provisions for stabilization and extending below groundwater level are often used in displacement boring and continuous sampling with piston samplers and slit samplers.

Stabilization with water.—Bore holes are often filled with water to stabilize the hole and, when the water is circulated, to remove material ground up by the boring tools. Water in the bore hole counteracts soil and pore-water pressures, but its ultimate effect depends on whether the soil is partially or fully saturated. In the partially saturated zone above groundwater level the soil derives a great part of its strength from capillary forces and the resultant apparent cohesion. Free water in the bore hole will eliminate this apparent cohesion and cause an increase in water content of the soil in the vicinity of the hole. The resultant loss in strength will generally be greater than the increase in strength caused by seepage pressure, and the ultimate result may be sloughing and collapse of the hole. On the other hand,
the water will exert a stabilizing effect on the parts of the hole extending below ground-water level; it will temporarily increase the rate of swelling but decreases the ultimate amount of swelling of the soil in the vicinity of the hole; see also Section 4.2. Water alone cannot prevent caving of borings in soft or cohesionless soils nor a gradual squeezing-in of a bore hole in plastic soils. Uncased bore holes filled with water are generally used in rock and often in stiff, cohesive soils.

**Stabilization with drilling fluid.**—An uncased bore hole can often be stabilized by filling it with a properly proportioned drilling fluid or "mud", which when circulated also serves to remove ground-up material from the bottom of the hole. A satisfactory drilling fluid can occasionally be obtained by mixing locally available fat clays with water, but it is usually advantageous and often necessary to add commercially prepared products such as Volclay or Aquagel. When suitable native clays are not available, the drilling fluid is prepared with commercial products alone. These mud-forming products consist of highly colloidal, gel-forming, thixotropic clays—primarily bentonite—with various chemicals added to control dispersion, thixotropy, viscosity, and gel strength. Special chemicals must be added to prevent flocculation when formations containing salt or anhydrite are encountered, or a drilling fluid consisting of a saturated solution of salt or sodium sulphate is used. A drilling fluid prepared of water and Aquagel requires from 5 to 10 percent by weight of Aquagel, but this amount may be reduced to 1 to 5 percent when suitable native clays also are used. Additional Aquagel should be mixed with the drilling fluid from time to time to replace losses of colloids by formation of the "mudcake" and by adherence of colloids to the cuttings which are removed from the bore hole.

The stabilizing effect of the drilling fluid is caused in part by its higher specific gravity, in comparison with water alone, and in part by the formation of a relatively impervious lining or "mudcake" on the side walls of the bore hole. This lining prevents sloughing of cohesionless soils and decreases the rate of swelling of cohesive soils. The drilling fluid also facilitates removal of cuttings from the hole on account of its greater specific gravity and viscosity. The required velocities and volume of circulation are smaller than for water alone, and the danger of uncontrolled erosion at the bottom of the hole is thereby decreased. Furthermore, the drilling fluid is thixotropic; that is, it stiffens and forms a gel when agitation is stopped, and it can be liquefied again by resuming the agitation. It is thereby better able than water to keep the cuttings in suspension during the time required for withdrawal and re-insertion of boring and sampling tools. It also reduces abrasion and retards corrosion of these tools.

Weighting materials, consisting of ground barite, hematite, galena, or other heavy minerals, are added to the drilling fluid to increase its specific gravity and prevent caving of the hole in troublesome soils or when the fluid must carry very coarse-grained materials in suspension. These weighting materials are available in specially prepared form and sold under various trade names, such as Baroid and Colox. The unit weight can in this manner be increased up to 150 lb per cu ft, but this is rarely required in the relatively shallow borings for civil engineering purposes.
Drilling fluid may be lost when cavities or highly permeable strata, such as clean gravel, are encountered, especially when there is also a strong ground-water flow. This loss can often be stopped and circulation regained by adding cement, straw, cotton seed hulls, or special, commercially prepared fibrous materials to the fluid. These materials will be deposited in and seal off the pervious strata.

Countering the above mentioned advantages of drilling fluid and in comparison with clear water are the following disadvantages: (1) it makes identification of the cuttings and thereby of the soil at the bottom of the hole more difficult and uncertain; (2) it hinders observation of ground-water levels and pressures and field determinations of the permeability of the soil; and (3) it requires greater fluid passages in pumps, drill rods, and core barrels. Drilling fluid is primarily used with rotary drilling and core boring methods.

**Stabilization with casing.**—Casing or the lining of the bore hole with steel pipe provides the safest, though relatively expensive, method of stabilizing the bore hole. Many types of standard and special pipe are used as casing and are described in detail in Chapter 8. Standard or Extra Strong Black Pipe is generally preferred for exploratory borings in soil since it is readily available.

Some typical joint details are shown in Fig. 20. Recessed outside couplings, A and B, provide the strongest joint and are commonly used in soils. The open joint, A, is used under normal conditions, but the butt joint, B, is often preferred when the casing is to be driven through hard ground and ahead of the boring. Repeated use will damage the threads of open joints and cause beading and upsetting of butt joints. After a certain depth of bore hole is reached or when difficult ground conditions or obstructions are encountered, it is often impossible to advance the original string of casing any further. A smaller casing is then inserted through the one in place, and the diameter of the extension of the bore hole must be decreased accordingly. Flush or practically flush jointed casing, C, is often used in order to minimize the required decrease in diameter. Flush jointed casing has a smaller resistance to driving and withdrawal than casing with outside coupling. The joint detail shown in Fig. 20D is often used in cohesionless soils when the casing is to be advanced by rotation, jacking, and jetting instead of by blows of a drop hammer.

The lower end of the casing is generally protected by a casing shoe of hardened steel, Fig. 21A and B, and with an inside bevel so that displaced material will be forced into the pipe.
Removal of this material instead of pushing it aside decreases friction between the casing and the surrounding soil. In case of flush jointed casing, the shoe may simply consist of a short section of pipe. It is often bevelled or, when the casing is advanced by combined rotation and jacking, provided with rough cut teeth, Fig. 21C and D.

Except when undisturbed samples are to be obtained of soils which are sensitive to vibration, the casing is generally driven by repeated blows of a drop hammer, Fig. 22. The hammer is guided by a pipe or rod, and the blows are transmitted to the casing through a drive head. The upper end of the guide tube in Fig. 22A has a heavy coupling or jar collar, so that withdrawal of the casing can be facilitated by upward blows of the hammer. When used with wash boring, the drive head often has a side outlet for the wash water, and the hammer may be slotted so that it can be used without withdrawing the drill rod, Fig. 22B. These features facilitate concurrent advance of casing and bore hole. Heavy casing is lifted into driving position by means of a casing elevator, Fig. 23, but a hoisting plug, similar to that shown in Fig. 26, is generally used for light casing. The casing clamp, Fig. 24, serves to prevent uncontrolled downward movement of casing inserted in an oversize bore hole or when there is danger of undercutting. It also facilitates the use of jacks in pulling the casing.

Casing will prevent caving of the sides but not always of the bottom of a bore hole. The stability of the bottom can be increased by keeping the casing filled with water or drilling fluid. However, the casing should not be filled with water when
the bottom of the bore hole is above the ground-water level and undisturbed samples are to be obtained. Casing is used extensively with wash borings, percussion drilling, and deep auger borings. It is generally required for all borings in very soft soils, when large open drive samplers are used, and when accurate observations of the ground-water levels or incidental field permeability tests are to be made.

**Stabilization by freezing.** - A bore hole may be stabilized by freezing the soil around it as the boring progresses. This may be accomplished by replacing wash water with kerosene or brine, cooled by means of "dry ice." The method cannot be used when the ground is dry or nearly so and when there is a strong ground-water flow. So far, it has only been used in a few cases and primarily for experimental purposes.

Another freezing method consists in circulating the cooling liquid through a series of pipes, driven or bored into the ground in a circle around the main bore hole, which subsequently is advanced by core boring. This method is expensive, but it has been used successfully when large undisturbed samples of gravelly soil or weak and fissured rock could not be obtained by other and cheaper means.

**Stabilization by grouting.** - A bore hole passing through a troublesome zone in rock -- cavities, faults, fissured and broken rock, etc. -- may be stabilized by filling the lower part of the hole with cement grout and thereafter re-drilling the hole through the concrete plug. The method can be used only when the hole remains open until the grouting is completed and the setting started. Grouting is often preferred to the use of casing, since the diameter of the hole then can be maintained, whereas it must be reduced for any extension of the hole below the casing.

2.12 Displacement Boring

The simplest of all boring and sampling methods consists in forcing a closed sampler -- slit, cup, or piston sampler -- into the soil until the desired depth is reached, whereupon the sampler is rotated or the piston released or withdrawn and a sample taken. After withdrawal of the sampler and removal of the sample, the sampler is again inserted into the hole and forced down to the depth where a new sample is to be taken. The bore hole is uncased and no attempt is made to stabilize it. The sampler acts as a close-fitting piston, and its withdrawal creates a temporary, partial vacuum which often causes failure of bore holes in soft or cohesionless soils. The closed sampler can generally be forced through the caved part of borings in soft soils without much difficulty, but caving in cohesionless soils often makes it necessary to use casing and advance the bore hole by other means until the troublesome zone is passed. In stiff or dense soils it is necessary to use fairly continuous sampling, otherwise the sampler may be damaged, or it requires objectionably heavy construction.

Major changes in the character of the soil can be detected by means of the penetration resistance of the sampler, but the determination of such changes and
thereby the depths at which samples should be taken is not always as accurate and reliable as when other boring methods are used. The forcing of a closed piston sampler into the soil will cause disturbance of the soil below the sampler but, in contrast to the disturbance caused by other boring methods, there is no mixing of the soil layers or segregation of the soil constituents, and the disturbance seldom extends to a depth below the sampler greater than three times the outside diameter of the sampler.

Displacement borings are generally from 1 to 3 in. in diameter. Larger diameters are impractical since they require samplers of too heavy construction. The method should not be confused with the use of piston samplers in cased bore holes or in uncased holes, which have been advanced by other means and reamed out so that clearance between the sampler and the walls of the hole is provided, and so that the hole can be stabilized with water or drilling fluid. Displacement boring is simple and economical when excessive caving of the hole does not occur. It is being used extensively in the Scandinavian countries, California, Louisiana, and other regions. It is well suited for reconnaissance explorations and, when soil conditions are favorable, for detailed explorations.

2.13 Wash Boring

A wash boring is advanced partly by a chopping and twisting action of a light bit and partly by jetting with water which is pumped through the hollow drill rod and bit, Fig. 25. Cuttings are removed from the hole by the circulating water. The drill rod and bit are moved up and down by pulling and slackening the rope and are at the same time rotated back and forth by means of the tiller. These operations, as well as the pumping, may be performed entirely by hand, but a small motor-driven winch and pump are generally used. The water may be pumped from a river or pond or taken directly from local water supply lines, when such sources are near the bore hole, but a closed circulating system is generally preferable. In the latter case water is pumped from a small sump or a tub, and the soil-laden water from the bore hole is discharged into the same reservoir, where the coarse material settles out and from which the so-called "wet samples" can be secured.

The drill rod is generally 1/4-, 1-1/2-, or 2-in. Standard Black Pipe with recessed couplings, Fig. 27, but Standard Diamond Core Drill Rods, see Section 8.4, are occasionally used. During coupling and uncoupling the drill rod is supported by a fork, Fig. 28, resting on the casing. The straight bit, Fig. 29, is commonly used, but the other bits shown in the same figure are useful when obstructions or special soil conditions are encountered and for increasing the diameter of the hole below the casing and thereby facilitating its advance. Casing is required in soft or cohesionless soils, but is often omitted in stiff, cohesive soils when only small representative samples are desired.

Changes in the character of the soil are determined partly by the feel of the
tiller or the resistance to penetration and rotation of the bit and partly by examination of the cuttings in the wash water as it emerges from the casing; but definite identification of the soil can only be made when representative samples are taken from the bottom of the bore hole. When such samples are taken, the method is often called "dry sample boring" to distinguish it from "wet sample boring" or more appropriately "wash sample boring", during which only samples from the washed and segregated material in the tub are taken. These samples are worthless and non-representative unless special arrangements are made to preserve all the material from a particular stratum and to exclude material from other strata.

The soil below the bottom of the bore hole may be disturbed by careless handling of the bit and by excess erosion when the flow of the wash water is not properly controlled. Coarse, segregated material tends to collect at the bottom of the hole, and sticky soils may adhere to the casing instead of being removed by the wash water. Careful cleaning of the hole is therefore required before samples are taken.

The principal advantages of the wash boring method are that it can be used in borings of both small and large diameter, that the equipment is inexpensive and light, and that the method does not cause sealing of the bottom of the hole and therefore does not obstruct ground-water observations. The rate of progress is relatively slow except in very soft soils and fine- to medium-grained cohesionless soils. It can be
used in all common soils which do not contain numerous stones or boulders, but it is not suitable for boring in hard and cemented soils or rock.

Drillers with adequate experience in wash boring can determine changes in and estimate the general character of the soil with satisfactory accuracy, especially when both the drill rod and the pump are operated entirely by hand. On the other hand, very serious mistakes may be made by inexperienced or careless drillers, who often fail to recognize changes in the character of the soil, do not clean the bore hole properly, and take samples of the coarse and segregated material settled at the bottom, instead of the undisturbed material below the bottom. The results of such errors are very misleading soil profiles which often indicate strata of coarse materials at depths where soft soils of low bearing capacity actually exist.

Wash boring is used extensively for reconnaissance explorations and, in some regions, also for advancing and cleaning the bore hole between samples taken in detailed and special explorations. However, the method should not be used above ground-water level when undisturbed samples are desired of the soil above this level, since the water will enter the soil below the bottom of the hole and change its water content.

2.14 Percussion Drilling

Advance of a bore hole by percussion drilling is accomplished by alternately raising and dropping a heavy drilling bit -- also called a churn bit, Fig. 34 -- which is attached to a drill stem, Fig. 32. In caving soil or broken rock, where there is danger of the bit becoming stuck, a jar and sinker bar are connected to the top of the drill stem, Fig. 30. Such a "string of tools" for a 6-in. hole may weigh from 1000 to 2000 lb and is attached to and operated by a "soft laid" cable or wire rope. The method is therefore often called "cable tool drilling". Other names for the method are "churn drilling" on account of the churning action of the drilling bit, or "well drilling" because it was one of the principal methods used in sinking water and oil wells, but it has been replaced by other methods to a large extent.

The chopping action of the drilling bit may be obtained by taking a few turns with the main cable around the cathead of a winch and varying the pull on the free end of the cable, as in operating a wash boring bit. However, the up and down motion of the cable is generally imparted by means of a "jerkline" or by attaching it to a crank, a spudding arm, or a walking beam. Compact, motorized, and truck- or skid-mounted drilling rigs are now used extensively. The spudding arrangement of one such unit is shown diagrammatically in Fig. 30 and a photograph of another and slightly different unit in Fig. 31. The spudding arm is provided with a heavy coil spring or dash pot, which lessens the shock transmitted to the cable and operating machinery and starts the lifting of the bit immediately after the blow has been delivered. Strokes vary from 18 to 40 in. in length and from 35 to 65 per minute according to the soil or rock conditions.
CROWN SHEAVE — SAND SHEAVE — CASING SHOE

NOTE: THE SPUDGING ARRANGEMENT SHOWN HERE IS ONLY ONE OF MANY IN ACTUAL USE. IN FIG. 31, THE POSITION OF THE SPUDGING ARM SHAFT AND CRANK AND THAT OF THE SPUDGING SHEAVE IS THE REVERSE OF THAT SHOWN HERE.

FIG. 30 - PERCUSSION DRILLING
FIG. 31 - KEYSTONE PERCUSSION DRILLING RIG
FIG. 32 - DRILL JARS AND STEM
FIG. 33 - CASING DRIVE CLAMP
FIG. 34 - PERCUSSION DRILLING BITS
FIG. 35 - BAILERS
FIG. 36 - SANDPUMPS
The bore hole is generally kept dry except for a small amount of water which forms a slurry with the material ground up by the bit. When the carrying capacity of the slurry is reached, the bit is withdrawn and the slurry removed by means of a bailer or sandpump, Fig. 35 and 36, which are operated by a separate winch and light cable, also called a "sandline". In soft soils and cohesionless soils it is often possible to advance the hole by means of the bailer or sandpump alone, especially when they are provided with a dart valve or bit bottom. A small amount of sand is sometimes added to increase the cutting action of the bit in fat clays, whereas clay may be added to increase the carrying capacity of the slurry when drilling in coarse, cohesionless soils. Specially prepared drilling fluid is also used for the latter purpose, particularly when there is danger of excessive loss of water in pervious formations.

Casing is generally required, except in stable rock, and is driven by attaching a drive clamp, Fig. 33, to the main drill stem. Whenever possible, the bore hole is advanced ahead of the casing for a depth somewhat less than the length of a string of tools, but it is difficult and often impossible to advance the hole ahead of the casing in soft soils or cohesionless soils. Caving in such soils may occur even when the casing is advanced ahead of the hole. Stabilization may then be obtained by filling the boring with water or drilling fluid, but the efficiency of the method is thereby decreased, and other boring methods and especially rotary drilling are generally preferred where such troublesome formations are prevalent.

Changes in the character of subsurface materials are determined by the rate of progress, action of the drilling tools, and composition of the slurry. However, the character of the material cannot be determined as accurately as with wash boring and especially not when foreign materials have been added to the slurry. Furthermore, the cuttings are removed only intermittently and therefore represent the average material over a considerable depth. The slurry may enter the soil below the bottom of the hole thus hindering ground-water observations. The main drilling bit and bailers or sandpumps with dart valves or bit bottom may disturb the soil to a considerable depth below the bottom of the hole, and the suction caused by operation of a sandpump may cause caving or mixing of strata of soft or cohesionless soils.

Percussion drilling is the oldest of all methods for drilling deep bore holes. Its principal advantages are simplicity of equipment and operation, use of a cable instead of drill rods, and that only a small amount of water is required. The method can be used in most soils and rock, and it is superior to other methods in penetrating coarse gravel deposits, in formations containing numerous boulders and chert nodules, and in cavernous rock. The method is relatively slow in clay and sticky shale and is often impossible to use in fine, loose sand or quicksand. The pure cable tool method is not economical for borings less than 4 in. in diameter, and it is not well suited as a general method for exploratory boring on account of difficulties in detecting thin strata and small changes in the character of the soil, and because drilling tools may disturb the soil to be sampled. In combination with auger or wash
borings, the method may be used to advantage for penetrating occasional hard layers, coarse gravel, boulders, and other obstructions. It may also be used for extending such borings into rock when undisturbed samples or cores of the rock are not required. A combination of auger boring and percussion drilling is often used for foundation explorations in Europe.

2.15 Rotary Drilling

In rotary drilling the bore hole is advanced by rapid rotation of the drilling bit, which cuts, chips, and grinds the material at the bottom of the hole into small particles. The cuttings are removed by pumping water or drilling fluid from a sump down through the drill rods and bit and up through the hole, from which it flows first into a settling pit and ultimately back to the main pit. Water alone may be used when the depth is small and the soil is stable, but drilling fluid is generally preferred since the required flow is smaller and it serves to stabilize the hole. A section of casing is used to start the hole, but the remaining part of exploratory bore holes advanced by rotary drilling is usually uncased except in soft soils.

When rotary drilling is used for exploratory boring, the motors, rotary driving mechanism, winches, pump, etc., are generally assembled as a unit and with a folding mast mounted on a truck or tractor, or the unit may be mounted on intermediate skids so that it can be placed on a raft or moved into places inaccessible by motor vehicles. A diagrammatic sketch of such a drilling rig is shown in Fig. 37 and a photograph of a similar unit -- manufactured by the George E. Failing Supply Co., Enid, Oklahoma -- in Fig. 38. The skid-mounted drilling machines shown in Fig. 127 and 129 can also be used for rotary drilling. In large stationary drilling rigs, as used in production drilling for oil, the drill rod is rotated by means of a rotary table, and this method is occasionally used in portable drilling rigs, Fig. 56 and 57.

The rotary drive of the commonly used, portable, rotary drilling rigs, Fig. 37, consists of a "drive quill" with a hexagonal bore and connected to the drive shaft from the motor by spiral bevel gears. A hollow, hexagonal drive rod can slide through and is rotated by the drive quill. A swivel joint connects the upper end of the drive rod to a yoke which can be moved in a vertical direction by two hydraulic cylinders. The drill rod slides through the hollow drive rod and is gripped by a chuck at the lower end of this rod. The bit pressure and the rate of feed can then be controlled by means of the hydraulic cylinders.

The upper section of the drill rod is often replaced with a "kelly" or "grief stem" which is a thick-walled pipe with external, longitudinal grooves. Keys or drive pins in a kelly drive bushing on top of the drive rod fit into these grooves and rotate the kelly, even when the latter is not clamped to the drive rod. The assembly can then be operated by gravity and the rate of feed controlled by a wire line to the hoist. Clamping of the drill rod and re-setting of the hydraulic cylinders after
completion of each stroke is thereby avoided and a greater rate of progress obtained in soft materials. When firm materials are encountered, the kelly is clamped to the drive rod by means of the chuck and additional feed pressure is exerted through the hydraulic cylinders.

The upper end of the drill rod or kelly is connected to a water swivel, Fig. 40, and through the hose and standpipe to the mud pump. The drill head, comprising the rotary drive and the hydraulic feed mechanism, can be moved back, or in other drill rigs swung aside, to permit addition or removal of drill rod sections. The mast is hinged and can be folded down over the truck when the rig is to be moved to a new location. The movement of a sliding drill head and the raising and lowering of the mast are performed by means of separate hydraulic cylinders.

Standard diamond core drill rods, Fig. 39, are generally used in relatively shallow borings for civil engineering purposes, but heavier drill rods are required for deep borings of large diameter; see Sections 8.4 and 8.5. During the removal and addition of new sections, drill rods in the hole may be supported by a fork, Fig. 28, if they have outside couplings, and external flush drill rods may be gripped by a wrench or chain tong if they are light and the boring is shallow, but a long string of heavy, external flush rods is supported by either a safety clamp, Fig. 45, or by a spider and slips, Fig. 46. The latter are also used when inserting a string of casing in an oversize bore hole. The section of drill rod immediately above the bit often consists of pipe with a greater outside diameter and wall thickness than other sections and is called the drill collar. The increase in stiffness and weight, thereby acquired, lends stability to the bit, decreases whip and vibration, and helps to keep the bore hole straight and uniform.

Many types of rotary drilling bits are used in accordance with the character of the material to be penetrated. Fishtail bits, Fig. 42, and two-bladed bits, Fig. 43, are used in relatively soft soils and three- or four-bladed bits in firmer soils and soft rock. The cutting edges are surfaced with tungsten carbide alloys or formed by special hard-metal inserts. The bits used in rock all have several rollers with hard-surfaced teeth, Fig. 44. The two-cone bits are used in soft or broken formations, but the tri-cone and roller bits provide smoother operation and are more efficient in harder rocks. The number of rollers and also the number and shape of the teeth are varied in accordance with the character of the rock. Relatively few and large teeth are used in soft rock, and the teeth are interfitting so that the bit will be self-cleaning. The teeth in all bits are flushed by drilling fluid flowing out of vents in the base of the bit.

Rotary drilling is best suited for borings with a diameter of not less than 4 in., and a diameter of 6 to 8 in. is generally preferred when the method is used for exploratory boring. In most soils and rocks the rate of progress is greater than can be obtained by other methods. However, rotary drilling is not well suited for use in deposits containing very coarse gravel, numerous stones and boulders or chert nodules, or in badly fissured or cavernous rock or very porous deposits with a strong
ground-water flow since an excessive amount of drilling fluid may be lost by seepage in such formations.

A uniform, clean hole with relatively little disturbance of the soil below the bottom of the hole is generally produced. An experienced driller can detect changes in the character of the soil or rock by the rate of progress and the action of drilling tools and by cuttings in the drilling fluid. However, such changes cannot be determined as accurately as with wash borings, since power operation is required, and since drilling fluid, when used, makes identification of the cuttings more difficult. The fluid also hinders ground-water observations and the performance of incidental permeability tests.

Rotary drilling was originally developed for production drilling of deep oil wells and is generally associated with this use. However, with the development of light and compact drilling rigs, the method is now also used extensively in explorations for oil and minerals and for drilling water wells. In recent years, rotary drilling has been used to a considerable extent in subsurface explorations for civil engineering purposes, but primarily as a method of advancing and cleaning the bore hole between samples of large diameter and less as a method for determination of the rough soil profile. However, light rotary drilling rigs are employed on a much larger scale than rotary drilling proper, since these rigs also can be used for wash boring, occasional percussion drilling, operation of large augers, drive samplers, and core barrels, in drilling of shot holes for seismic methods of exploration, and for dewatering bore holes and field permeability tests. In general, these drilling rigs constitute very flexible and useful units for subsurface exploration.

2.16 Auger Borings

In auger boring the hole is advanced by rotating a soil auger while pressing it into the soil and later withdrawing and emptying the soil-laden auger. Soil augers are used in subsurface exploration for three purposes: (1) general exploration and obtaining of representative samples in reconnaissance surveys; (2) advancing and cleaning bore holes between depths at which undisturbed samples are to be taken by drive sampling methods; and (3) drilling large accessible bore holes which permit direct inspection of the soil in situ. Augers are also used for various construction purposes, such as drilling drainage wells, pre-excavation for piles, and excavation for piers and caissons of relatively small diameter.

Augers used for the first purpose are generally small helical augers, Fig. 47, and post hole or Iwan type augers, Fig. 48. They are used primarily in soils in which the bore hole can be kept dry and uncased, and are hand-operated in shallow explorations. The rate of progress is slow, but the method is employed extensively in subsurface exploration for highways, railroads, and airfields on account of its simplicity and the light and inexpensive equipment. The augers are occasionally used at depths up to 100 ft and are then often power operated so that a much greater
rate of progress is obtained.

Large helical or worm type augers, Fig. 49, and spoon augers, Fig. 50, in many different forms are used for the second purpose. A recent addition to this group is a hinged auger, Fig. 51, developed by the Waterways Experiment Station in Vicksburg. It has a bit similar to that of the Iwan auger and is split in two halves, which are held together by a hinge in the bit and a ring at top. This auger is very sturdy and seems to retain the soil better than other augers, and it is easily emptied of soil after opening the auger. Auger borings are kept dry, as far as possible, since water in the hole increases the danger of losing the soil in the auger, and since the soil-laden auger acts as a piston and tends to force water above it out of the hole. Casing is required for auger borings in unstable soil and especially when the boring is extended below the ground-water surface.

Boring with large, hand-operated augers is slow and cumbersome and seldom used in this country but to some extent in Europe. However, the augers can be operated by portable rotary drilling rigs, described in the foregoing section, or by the drilling machines used for core boring, and they are then very efficient for boring in medium soft to stiff cohesive soils and in moist cohesionless soils with some apparent cohesion. On the other hand, these augers are not well suited for use in very hard or cemented soils, and they often fail to retain very soft soils and fully saturated cohesionless soils. When the last mentioned soil types are encountered, the casing is generally driven ahead of the hole and then cleaned out by means of barrel augers or, if there is water in the hole, with bailers or sandpumps.

Barrel augers, Fig. 52, consist of a short auger of the flat spiral or Iwan type surmounted by a barrel which serves as a reservoir for the soil. The auger bits or shoes are interchangeable; the flat spiral is used in fine to coarse sand and the Iwan type in coarse sand, gravel, and stony soil. The barrel can be emptied of soil either by unscrewing the shoe, for small augers, or through a removable or hinged section of the barrel. In the latter case the auger is also called a "door" or "window" sampler -- Sprague and Henwood (174, 175). Barrel augers are seldom used as a primary means of advancing the bore hole but mainly for penetrating relatively thin strata of troublesome soils, for cleaning the bore hole of coarse sand, gravel, and stones, and for obtaining fairly representative samples of these materials.

A series of augers and special drilling machines for their operation has been developed by the Buda Company, Harvey, Illinois. These augers are primarily intended for construction purposes, but they are also used for foundation exploration. The continuous flight, helical augers, Fig. 53, are used for drilling holes with a diameter of 6 to 8 in. and a depth up to 100 ft. As depth increases, new auger sections are added instead of drill rods. The material is thereby automatically transported to the ground surface, repeated withdrawals of the auger are eliminated, and the rate of progress increased. However, it is more difficult to determine definitely the depth from which the soil, discharged by the auger, was excavated. The auger has interchangeable heads or bits for use in various types of material. It is operated by the
drilling machine shown in Fig. 54, which has a folding mast with chain-operated feed and lift. Relatively short helical augers with interchangeable cutters, upper left-hand corner in Fig. 54, are used for medium-sized holes, 12 to 16 in. in diameter, whereas holes up to 42 in. in diameter are excavated by means of a disc auger, Fig. 55.

Large-diameter, accessible bore holes may be excavated by the above mentioned disc augers, but bucket augers are generally used when these holes are deep. The bucket auger consists of a relatively short barrel, which is open at the top. The bottom is split and bent to form a flat spiral and provided with a hinge and latch so that it can be opened for easy emptying of the barrel. The bucket auger shown in Fig. 56 and 57 has an outside diameter of 24 in., but by attaching a reamer it can drill holes up to 48 in. in diameter. The auger is operated by a combination drilling rig with a 30-in. rotary table; drilling rigs of the type shown in Fig. 37 and 38 can also be used. The combination drilling rig, Fig. 56 and 57, was developed by the Materials and Research Department, California Division of Highways, Porter (162, 347). In addition to the rotary table, the rig is provided with a spudding arm, winches, and pumps. It can be used for percussion drilling, rotary drilling and core boring, auger boring, operation of drive samplers, dewatering of holes, and field permeability tests.
Auger boring has the great advantage over wash boring, percussion, and rotary drilling that the soil removed by the auger, although considerably disturbed, generally is suitable for positive identification. The soil profile and depths at which undisturbed samples should be taken can therefore be determined with greater accuracy by this method than with any of the previously described methods. Since the bore hole is kept dry, auger boring is particularly well suited for advancing borings in partially saturated materials above the ground-water level, especially when undisturbed samples are to be obtained of these materials. Furthermore, determination of the free ground-water level is also facilitated by auger boring. Due to these advantages and the development of light and compact, motorized drilling rigs, power-operated augers are being used on an increasing scale in foundation explorations.

2.17 Continuous Sampling

Each sampling operation advances the bore hole, and the boring may be accomplished entirely by sampling. In this case the method becomes one of both exploration and sampling and may be called continuous sampling and further designated by the particular method of sampling used.
Continuous sampling by means of core boring is nearly always used in exploration of rock. Borings in soil may also be advanced entirely by sampling when the bore hole is uncased and core barrels or piston samplers are used. When these samplers and open drive samplers are used in cased bore holes, the sampler will produce a hole slightly smaller than that of the casing. It is therefore necessary to clean the casing after advancing it to the bottom of the hole and before taking a new sample; the method is one of alternate sampling and cleaning. Withdrawal of the sampler and separation of the sample from the subsoil will generally disturb the soil below the bottom of the bore hole. When the primary purpose is to obtain undisturbed rather than fully continuous samples, it is therefore desirable to advance the hole a short distance -- say two to three times its diameter -- before taking a new sample. A still greater advance may be required when withdrawal of the sampler causes caving of the bottom and lower part of the hole.

A soil boring method which was developed by Burkhardt (307, 505) and called the "Pile Boring Method" may be classified as fully continuous sampling. The method consists in driving a heavy steel pipe or tubular steel pipe into the ground, Fig. 58. A split steel liner with a core catcher and trigger mechanism is held in firm contact with the shoe of the drive pipe. After advancing the pipe 6 to 7 ft, the liner is withdrawn with the soil sample, and an empty liner is then inserted and the driving resumed. Borings have been extended to depths of about 130 ft in this manner and samples with a diameter of 21 cm obtained of sand, gravel and glacial till. The method has been used only to a limited extent since it requires pipe with large diameter and thick walls and consequently very heavy driving equipment, and since the samples obtained usually are seriously disturbed by the heavy walls of the pipe and shoe and vibrations caused by the pounding of a heavy drop hammer.

Continuous sampling in soils is generally slower and more expensive than intermittent sampling in combination with one of the previously described boring methods, but there are exceptions to this rule. When modern rotary drilling rigs or power-driven augers are not available, continuous sampling may be used to advantage for advancing large-diameter borings in stiff and tough strata of clay and mixed soils, Fehlmann (521, 522). According to Shannon (171), the Boston District, Corps of Engineers, has made faster progress and reduced costs by use of continuous sampling in advancing 3-in. diameter borings through compact, gravelly glacial till, which is difficult to penetrate by any boring method. A simple thick-walled sampler, similar to the one shown in Fig. 177, is used, and particularly tough strata are broken up by exploding one or two sticks of dynamite in the hole before each sampling operation.

The greatest advantage of continuous or nearly continuous sampling is that
it provides more reliable and detailed information on soil conditions than any other method with the exception of accessible explorations. Continuous sampling is therefore used extensively in detailed and special foundation explorations for important structures.

2.18 Accessible Explorations

Accessible explorations are test pits, test trenches, caissons, borings, shafts, tunnels, and drifts large enough to permit entrance of a man and inspection and sampling of subsurface materials in situ. The minimum dimensions are usually determined by the space required for efficient work rather than by accessibility.

**Test pits.** - Square or circular pits with a diameter of about 4 ft or unsheeted rectangular pits, 3 by 5 ft, are often used; however, a rectangular cross section of 4 by 6 ft permits easier and often cheaper excavation. This rectangular section is also the minimum required when vertical sheeting is driven ahead of the excavation and large undisturbed samples are to be taken. The dimensions are net dimensions at the bottom of the pit and do not include the space required for sheeting, wales, and special arrangements for drainage. Starting dimensions at the ground surface may be much greater for deep test pits requiring several offsets or lifts.

Test pits are generally excavated by hand, but a considerable saving in time and expense can often be effected by use of a clamshell or orange-peel bucket in excavating shallow, unsheeted test pits. However, power equipment should be used only for rough excavation and not when approaching the depths at which undisturbed samples are to be taken.

Shallow test pits in fairly firm ground can generally be excavated without any support of the pit walls, but sheeting is required in unstable ground and for deep pits. Arch action in the surrounding soil will materially decrease the earth pressure acting on the sheeting, at least when dimensions of the pit are small and when material displacements in the surrounding soil can be avoided during the excavation and the short period of actual use of the pit. The dimensions of the sheeting are in such cases based on practical experience rather than on theoretical earth pressures. The dimensions shown in Fig. 59 to 65 are adequate only under such favorable conditions; they must be increased when the pit is large, when the soil is soft and hydrostatic pressures are to be resisted, and when there is danger of soil movements on account of rough methods of excavation, vibrations, etc.

Horizontal or box sheeting is the simplest of all types of sheeting. It is easy to install, permits offsets when obstructions are encountered, and requires less excavation than other types for given net dimensions of the pit. In contrast to vertical sheeting driven ahead of the excavation, box sheeting permits inspection of the soil strata in the walls of the pit and is less likely to disturb the soil to be sampled. The boards are supported on each other either by notching -- Fig. 59 shows one of several methods of notching -- or by full end bearing on alternate boards and partial support
NOTE. IN GOOD GROUND THE BOARDS NEED NOT BE PLACED CLOSE TOGETHER.

NOTCHED BOX SHEETING

BOX SHEETING WITH CLEATS

BOX SHEETING WITH LOUVERS

A - SPACERS B - SLOTS

PRENTIS & WHITE, UNDERPANING IN.

NOTE ALL BOARDS ARE ALIKE

BOX SHEETING WITH CLEATS

BOX SHEETING WITH LOUVERS

A - INCLINED BOARDS B - VERTICAL BOARDS

FIG. 62 - POLING BOARDS

WOOD OR STEEL SHEET PILING

NOTE THE DIMENSIONS OF SHEETING, WALES, ETC. IN FIGS. 59 TO 65 APPLY ONLY TO SMALL TEST PITS IN FAIRLY STABLE SOIL - SEE TEXT.

VERTICAL SHEETING - ONE LIFT

FIG. 63

VERTICAL SHEETING - TWO LIFTS

FIG. 64

VERTICAL SHEETING - THREE LIFTS - WELL POINTS

FIG. 65

WELL POINTS
of the other boards by cleats, Fig. 60 and 61 — Mohr (341), Prentiss and White (234). Small openings or louvres between the boards, Fig. 61, facilitate drainage and permit repacking the space behind the boards with soil or salt hay in case cavities are formed by soil movements or seepage. Salt hay is less liable to rotting and better suited for packing than ordinary hay. Notched sheeting or cribbing can also be installed with openings between the boards simply by making the depth of the notch smaller than half the width of the board. Careful excavation and full and uniform contact between the soil and the boards are essential to avoid earth movements, which may increase the pressure on the sheeting, cause failure of the bottom of the pit, and disturb the soil to be sampled.

It is difficult and often impossible to use box sheeting in very soft or loose soils. Inclined poling boards, which are driven slightly ahead of the excavation, may then be used, Fig. 62A. The inclined boards may be changed to vertical boards, Fig. 62B, when firmer ground, permitting temporary unsheeted excavation, is encountered. Steel liner plates, as used in tunneling, have recently been used successfully in test pits instead of poling boards of wood. Poling boards and liner plates cannot be driven far ahead of the excavation and, although they can be used in soft soil and loose soil, they require somewhat firmer ground than true vertical sheeting. On the other hand, they permit maintenance of the original dimensions of the pit, irrespective of its depth.

Vertical sheeting may consist of plain boards, tongue and groove boards or steel sheet piling, Fig. 63, and has the advantage that it can be driven far ahead of the excavation when required to prevent loss of ground in soft soils or loose, cohesionless soils. In firm soils the sheeting is generally advanced more or less concurrently with the excavation. The pit may even be advanced a little ahead of the sheeting, but the excavation must then be very carefully performed to avoid cavities behind the sheeting. Loose boards or sheet piles, also called runners, should be wedged to insure full bearing against both the bracing or wales and the soil. The length of runners which can be handled conveniently is limited, and an offset is generally required for every 12- to 18-ft advance in depth, Fig. 64 and 65. In planning the starting dimensions of a pit with several lifts it must be taken into consideration that the sheeting of a lower lift should be at least 2 to 3 in. inside the wales of the upper lift in order to facilitate the driving of the sheeting. The vibrations caused by driving of the sheeting may disturb the soil to be sampled, especially when the sheeting is driven ahead of the excavation. The samples should therefore be taken near the center of the pit and not closer than 12 in. to the vertical sheeting.

Various methods of sheeting may be used in a single deep test pit. Vertical sheeting may be required in penetrating soft strata near the ground surface, but poling boards or box sheeting may be adequate when firm strata are reached, and an offset and decrease in the dimensions of the pit can thereby be avoided. A pit started in firm soil with box sheeting may be advanced through relatively soft soil by means of poling boards or liner plates.

Extreme care must be taken in control of ground water, especially when a
pit is advanced through soils with little or no cohesion. Cohesionless soils should be under capillary pressure when undisturbed samples are to be taken; that is, the ground-water level in the central part of the pit should be depressed below the bottom elevation of the samples. Pumping directly from a sump and drainage ditches in the pit may be used in cohesive soils or mixed and gravelly soils but in sand and silt only when the depth below the original ground-water level is slight. Even then it may be necessary to maintain a layer of gravel in the drainage ditches and to protect the central part of the pit by sheet piling extending below the bottom of the ditches. Dewatering by means of well points, Fig. 65, is the safest method of control, and it should be used when pits in cohesionless soils are extended well below ground-water level.

**Test trenches.**—The practical minimum bottom width of test trenches is 30 to 36 in., but a width of 24 in. is occasionally used. Trenching or ditching machines can often be used to advantage. In comparison with test pits, test trenches have the advantage of providing a continuous or two-dimensional soil profile. They are primarily used for very shallow explorations in soil requiring little or no support of the sides of the trench and especially when the depth to rock or strata of exceptional bearing capacity is very shallow.

**Caissons.**—Cylindrical caissons with a steel or concrete shell are occasionally preferred instead of sheeted test pits when the caissons also can be used as a part of the proposed foundation structure. The practical minimum bottom diameter is about 3 ft, but a diameter of 4 ft or more is generally used. Caissons have the great advantage that water level can be controlled by means of compressed air in the caisson. This method is generally the most practical and often the only one by means of which deposits of very pervious, cohesionless soils deep below ground-water level can be examined in situ. When undisturbed samples of such soils are to be obtained, the air pressure in the caisson should be greater than the hydrostatic pressure so that capillary forces will be called into action and produce an apparent cohesion.

**Accessible borings.**—A boring with a diameter of 24 in. is accessible, but a diameter of about 36 in. is preferable, and bore holes up to 6 ft in diameter have been drilled for special field tests. Accessible borings in soil and very soft rock are drilled with power-operated augers of various types, some of which were described in Section 2.16. Other types, specially designed for pre-excavation for piles and shaft piers (219, 614), are also used. Shot core barrels and steel-toothed, single tube core barrels are used in rock or frozen soils (321, 348, 537, 948); see Sections 13.2 and 13.4.

When modern drilling rigs and core barrels are used, accessible borings can often be made in a fraction of the time and cost required for sinking test pits in soil and shafts in rock by hand methods. A rate of progress of 25 ft per hr has been attained in soil under favorable conditions. The borings are uncased and dry and therefore require fairly stable soil conditions. However, many soils remain stable.
for the short period required to complete the boring and inspection and sampling of the soil strata, whereas a slowly advanced test pit in the same soil may require sheeting. The method has also been used successfully in unstable soils by first freezing the soil around and below the bore hole (911), Fig. 252. Accessible borings in soil have been extended to a depth of 120 ft and in rock up to 150 ft. By use of rodless core boring, in which the rotative power unit is suspended immediately above the core barrel, mine shafts have been sunk to depths of over 1000 ft.

**Tunnels and drifts.**—Exploratory tunnels and drifts are primarily used in the final exploration of dam sites. The economical minimum dimensions are 3.5 by 6.5 ft or 4 by 6 ft.

**Advantages and limitations.**—Of all methods, accessible explorations provide the most reliable and detailed information on soil and rock conditions along a specific vertical, inclined, or horizontal line. They make it possible to examine, sample, and perform special field tests on the material in situ. Furthermore, the very act of advancing such an exploration gives valuable information on the difficulties to be encountered in and the probable costs of excavation for the proposed structure.

Larger and usually less disturbed samples can be obtained in accessible explorations than in bore holes of relatively small diameter, but certain causes of disturbance should be recognized and proper measures taken to ascertain and reduce their influence on the condition of the samples obtained. Stress changes in the soil below the bottom of an ordinary bore hole can be reduced by filling the hole with water or drilling fluid, but accessible explorations must be kept dry, and there is therefore greater danger that a slow plastic flow and consequent disturbance of the soil may occur in the vicinity of the bottom of a deep test pit or accessible boring or the face of a tunnel. This danger is, of course, decreased when a tunnel or caisson is advanced under compressed air.

Unless soil is very stable, the extent and rate of soil displacements should be investigated so that it can be determined if the soil to be sampled already has been partially disturbed, and so that the samples may be taken where there is a minimum of disturbance. Observations of the movements of soil surface will indicate displacements, but more reliable results are obtained by "squeeze measurements" in which the movements of a rod or spearhead, driven into the soil ahead of the excavation, are observed -- Terzaghi (973), Peck (620). Loss of ground, or the difference between the volume of the excavated material and the volume of the pit or tunnel, will also give an indication of plastic movements, but this difference is difficult to determine with satisfactory accuracy.

The soil may also be disturbed by swelling, caused by stress reduction, migration of water from the surrounding soil, and expansion of gas and air in the soil; see Section 5.9. Exposure to air may cause oxidation and, combined with the effect of stress changes and contact with free water, complete disintegration of certain partially cemented soils and soft rocks. However, these processes, as well
as loss of water by evaporation, take place over a period of time, and it is therefore essential that samples be taken as soon as possible after the rough advance and immediately after the final trimming and preparations for sampling.

With favorable soil conditions and depending upon available equipment, shallow test pits and trenches and large-diameter borings may in some cases be used to advantage instead of ordinary borings, but accessible explorations are generally considerably more expensive than other methods of subsurface exploration. The results of reconnaissance and detailed explorations should be available before expensive accessible explorations are undertaken, not only to establish the need of such explorations but also to make it possible to determine the proper location, type, depth, dimensions, methods of excavation and control of water, etc.
CHAPTER 3
GROUND-WATER OBSERVATIONS

3.1 General

A detailed ground-water survey, involving determination of the free ground-water level or levels, hydrostatic pressures in various strata, flow, yield, quality, sources, etc., requires considerable time and often special methods and equipment. In common foundation explorations it is usually sufficient but also very essential to determine the free ground-water levels and conspicuous excess hydrostatic pressures in pervious strata. Furthermore, a subcommittee of the Committee on Earth Dams, Am. Soc. Civ. Eng., has been appointed to study and develop methods for determination of pore-water pressures in soils. A detailed description of special methods and equipment for this purpose is therefore considered outside the scope of this report, and the following review is limited to general principles and to observations which can be made with simple, standard equipment and without serious interruption of boring and sampling operations.

3.2 Ground-Water Levels and Pressures

A free ground-water table or level is defined as the contact surface between the free ground water and the capillary zone, Fig. 66; that is, the level ultimately assumed by the water in a hole extended a short distance below the capillary zone. Ground-water conditions may be called regular when there is only one free ground-water surface, and when the hydrostatic pressure increases linearly with depth, as in an open body of water; that is, the piezometric pressure level is the same as the free ground-water level at any depth below the latter.

In making ground-water observations, it must constantly be borne in mind that regular ground-water conditions as defined above are not always the normal conditions and that irregular conditions, Fig. 67, often are encountered. In some localities there may be one or more isolated bodies of water or perched ground-water tables above the main ground-water table. The formation of perched ground-water tables is caused by impervious strata which prevent the water from seeping down to the main body of ground water.

Hydrostatic pressure does not always increase uniformly with the depth below the main ground-water table. Subnormal pressures, or piezometric pressure levels below the main ground-water level, may be caused by downward seepage to more porous and better drained strata. They may also be caused, temporarily, by
a decrease of the stresses in the soil below the main ground-water table.

Water is said to be under excess hydrostatic pressure when the piezometric pressure level is above the main ground-water level. Such a pressure is also called "artesian pressure", and a well drilled to strata with excess hydrostatic pressure is called an artesian well. The term artesian is sometimes, popularly but erroneously, interpreted to mean that the piezometric pressure level rises above the ground surface. A well drilled to strata with water having a piezometric pressure level above the ground surface is called a free-flowing artesian well. Artesian pressures may be found in strata which are confined between impervious strata and are connected to a source of water at higher elevation. Temporary excess pressures may also be caused by an increase of the stresses in the soil.

The ground-water levels and pressures may be subject not only to seasonal but also to diurnal changes. These changes are caused by precipitation, evaporation, seepage, pumping, and the water levels in nearby rivers, lakes, estuaries, and the sea. The influence of tidal changes may be observed at distances up to several miles from rivers and estuaries, the range depending upon the topographical and geological conditions. Atmospheric or barometric pressure changes may also cause minor changes in ground-water levels and pressures. It is therefore important that not only the day but in some cases also the exact time of ground-water observations be
noted in the exploration records; the water levels in nearby open bodies of water should also be recorded.

It is seldom necessary to make detailed ground-water observations in each one of a group of closely spaced bore holes, but sufficient observations should be made to establish the general shape of the ground-water table, and it is important that observations be made in the first boring of a group. When observations are made later, ground-water levels and pressures in strata with different piezometric pressure levels may be changed by seepage through the already completed bore holes, unless these holes are carefully backfilled.

3.3 Time-Lag in Ground-Water Observations

During normal boring operations, the water level in the bore hole will seldom correspond to the hydrostatic pressure in the surrounding soil, and water will then flow into or out of the hole. Reliable determination of ground-water levels and pressures requires that the hydrostatic pressures in the bore hole and in the soil be equalized and that the water in the holes reaches a stable level. The time required for this equalization is the time-lag.

When the void ratio and water content of the soil in the vicinity of the hole or its bottom remain constant, the total flow or volume of water required to equalize the difference in hydrostatic pressures in the soil and the hole depends only on the dimensions of the hole or pressure measuring device and on the hydrostatic pressure difference. The corresponding time-lag may be called the hydrostatic time-lag.

The stress conditions in the soil near the bottom of the hole are changed by advance of the hole, installation of pressure measuring devices, and by a flow of water to or from the hole. A permanent and/or transient change in water content of the affected soil will then take place, and the time required for the corresponding volume of water to flow to or from the soil may be called the stress adjustment time-lag. This time-lag affects primarily observations made immediately after advance of the bore hole or installation of pressure measuring devices, and it is difficult to evaluate. The stress adjustment time-lag is insignificant in fairly pervious and incompressible, fully saturated soils, but it may increase or decrease the total time-lag to a considerable extent when the soil is compressible and relatively impervious, and when it contains air and other gases in the pores or dissolved in the pore water.

The time required for complete equalization of hydrostatic pressure differences is theoretically infinite, but practical equalization may be considered attained when the difference in pressure has been reduced to a certain definite, small value, or when 90 to 99 percent of the original pressure difference has been eliminated. The practical hydrostatic time-lag depends on: (1) the diameter of the bore hole or the type and dimensions of the pressure measuring device; (2) the intake area or the depth of the bore hole below ground-water level or below the edge of the casing; and (3) the permeability of the soil. The time-lag also depends on the original pressure
difference when this difference must be reduced to a definite value, but is independent thereof when the allowable, final pressure difference is defined as a percentage of the original difference. To illustrate the order of magnitude of the practical hydrostatic time-lag, the times required for 90 percent equalization of the original pressure difference have been computed by the writer for various borings, intake areas, pressure measuring devices, and are shown in Table 4. The computations are based on

TABLE 4 - APPROXIMATE HYDROSTATIC TIME-LAGS FOR 90 PERCENT EQUALIZATION

<table>
<thead>
<tr>
<th>Approximate Soil Type</th>
<th>SAND</th>
<th>SILT</th>
<th>CLAY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of Permeability in cm/sec.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 2&quot; Casing, Soil in Casing</td>
<td>6m</td>
<td>1h</td>
<td>10h</td>
</tr>
<tr>
<td>2 2&quot; Casing, Soil Flush Bottom Casing</td>
<td>0.6m</td>
<td>0.6m</td>
<td>1h</td>
</tr>
<tr>
<td>3 2&quot; Casing, Hole Extended</td>
<td>1.5m</td>
<td>1.5m</td>
<td>2.5h</td>
</tr>
<tr>
<td>4 2&quot; Casing, Hole Extended</td>
<td>6m</td>
<td>1h</td>
<td>10h</td>
</tr>
<tr>
<td>5 3/8&quot; Piezometer with Wall Point</td>
<td>3m</td>
<td>30m</td>
<td>5h</td>
</tr>
<tr>
<td>6 3/8&quot; Piezometer with Wall Point and Sand Filter, D = 6&quot;, L = 36&quot;</td>
<td>12m</td>
<td>2h</td>
<td>20h</td>
</tr>
<tr>
<td>7 1/16&quot; Mercury Manometer, Single Tube Porous Cup Point</td>
<td>2m</td>
<td>20m</td>
<td>3.3h</td>
</tr>
<tr>
<td>8 1/16&quot; Mercury Manometer, Single Tube with Well Point, D = 1.5&quot;, L = 18&quot;</td>
<td>6m</td>
<td>1h</td>
<td>10h</td>
</tr>
<tr>
<td>9 3&quot; W.E.S. Hydrostatic Pressure Cell Direct Contact with Soil</td>
<td>16m</td>
<td>2.5h</td>
<td>22h</td>
</tr>
<tr>
<td>10 3&quot; W.E.S. Hydrostatic Pressure Cell Sand Filter D = 6&quot;, L = 24&quot;</td>
<td>14m</td>
<td>2.4h</td>
<td></td>
</tr>
</tbody>
</table>

Symbols: m = minutes, h = hours, d = days. Assumptions: Isotropic permeability; no air in system; no clogging; secondary or "stress adjustment" time-lag negligible. All Cases: Time-lag inversely proportional to permeability; 70% equalization at half and 90% equalization at double the times required for 90% equalization. Cases 1 to 4: The time-lag increases linearly with the diameter provided the values of L/D are not changed. Cases 7 and 8: According to tests by A. Warlam, the volume change of a 4-1/2" Bourdon gage is 0.5 to 1.0 cm³ for 1 kg/cm² change in pressure or roughly one-half of that for a 1/16" single tube mercury manometer. Cases 9 and 10: Refer to hydrostatic pressure cell by the Waterways Experiment Station in Vicksburg; diameter of diaphragm 2.315"; deflection of diaphragm 0.008" for 60 lb/sq in. The computed time-lags have been rounded off to convenient values.

the assumptions that the soil is uniform and has isotropic permeability; that there is no air or gas in the system and no clogging of the intake area; and that the actual ground-water level or pressure remains constant during the equalization. The influence of the stress adjustment time-lag is not included in the values given in the table.

The practical time-lag may be reduced materially by progressively emptying or filling the bore hole with water until a falling water level changes to a rising level, or vice versa. By observing the decreasing rate of fall or rise of the water level, it is also possible to estimate roughly the depth to the ultimate stabilized level, provided the influence of the stress adjustment time-lag is not too great. As shown in Fig. 68, the computations are very simple when the observations are made at equal time intervals. Even when the practical time-lag is reduced by such methods, considerable time and special equipment are required for accurate determination of ground-water levels and pressures in relatively impervious soils. Therefore,
ground-water observations during normal boring operations are generally confined to fairly pervious soils and strata.

### 3.4 Observation of Loss or Gain of Water

As indicated above, determination of ground-water levels and pressures in a simple bore hole causes serious interruption of the boring operations unless fairly pervious strata are encountered. Such strata can be recognized in part by the character of the cuttings and samples, and in part by a fall or rise of the water level in the bore hole or in the sump or main mud pit. A loss of water indicates pervious strata or cavities in rock. A rise or gain indicates not only pervious strata but also the presence of water with a pressure greater than that corresponding to the current water level in the bore hole.

When pervious, water-bearing strata are encountered, it is desirable to clean out the bore hole and determine the stabilized water level as discussed in the following sections. When the boring schedule does not permit interruption of operations for a sufficient length of time, the depth of the hole at the time of conspicuous loss or gain of water should be noted in the boring record. It is also desirable to record the water level or pressure in the hole and the rate of its rise or fall, since these data may serve as a basis for a rough estimate of the stabilized level and of the permeability of the strata.

### 3.5 Measurement of Depth to Water Surface

The depth to the water level in a bore hole may be determined by means of a float attached to a measuring tape. The float may consist of wood with a waterproof coating or of a hollow metal cylinder. The float must be sufficiently heavy to cause a distinct change in the pull on the measuring tape when the float is buoyed-up by the water. A correction must be made for the temporary rise of the water level caused by displacement of water by the float. This method is satisfactory for rough measurements, but the tension in the tape is decreased gradually, and it is difficult to determine accurately the degree of submergence or the depth at which the entire weight of the float is carried by the water. Some floats are therefore equipped with a whistle which is sounded by air forced out of the lower part of the float when it is submerged in water. Greater accuracy is obtained with a float consisting of an outer shell in which the actual float slides and closes an electrical circuit after it has been moved upwards a short distance.
Simpler than a float with electrical indication of contact with water, and more accurate than an ordinary float, is the wetted tape or rod method. A small lead weight is attached to the measuring tape, the lower part of which is coated with chalk or keel, Fig. 69A. The weight is lowered into the water until a part of the chalked section of the tape is submerged. After withdrawal the wetting line on the tape can easily be read to a fraction of an inch and the corresponding depth to the water surface computed. Depending upon the diameter of the bore hole and the accuracy desired, a small correction may have to be made for the water displaced by the weight. This correction can be eliminated by attaching a thin graduated rod to the weight, Fig. 69B, and lowering the rod but not the weight into the water. Furthermore, the chalk or keel will adhere better to the unfinished surface of the rod than to the highly polished surface of a steel tape. The wetted tape or rod method also has the advantage that it can be used in borings and standpipes of very small diameter, but it has the disadvantage that the approximate depth to the water surface must be known in order to get a wetting line on the chalked part of the tape or rod.

The above mentioned disadvantage of the wetted tape or rod method can be eliminated by providing the weight with electrical indication of contact with the water surface. Such an electrical depth gage, developed by A. Casagrande (105) and especially designed for use in standpipes and piezometers of small diameter, is shown in Fig. 69C. The measuring tape is replaced with two insulated wires with tape markings for measurement of depth. The lead weight is divided into short sections to prevent wedging in the pipe. The contact point is formed by removing the insulation from the ends of the wires and spacing them about 1/4 in. apart by a plug of sealing wax. The wax plug and the lower weight sections are covered with grease to prevent adhesion of water when repeat measurements are made. The wires are connected to a small battery and ohmmeter. This depth gage has been used successfully in piezometers with an internal diameter of only 3/8 in.

3.6 Determination of the Free Ground-Water Level

The depths to free ground-water levels, whether perched or main levels, should preferably be determined as soon as it is estimated that such levels have been reached. Further extension of the boring may lead to erroneous results, since impervious strata below a perched body of ground water may be penetrated, or strata
with artesian pressures may be reached. The depth to free water is most easily determined when the boring is kept dry while being advanced through the overlying, partially saturated or capillary zone. Entrance of water into the hole can then be observed, and the danger of extending the hole too far below the free water table is reduced.

Casing is generally used when the boring is advanced with water in the hole. At the estimated free ground-water level, or when the first pervious stratum below this level is encountered, the hole should be extended a short distance below the edge of the casing, if this is possible without causing caving. The hole should then be thoroughly cleaned and washed until the water is clear in order to avoid increasing the time-lag by sedimentation and formation of a filter skin. The hole is then emptied to the estimated free water level, and the movement of the free water surface observed until a sufficiently close estimate of the stabilized level can be made.

When the boring is filled with drilling fluid, both the sides and bottom of the hole will be sealed with the "mudcake", which will be broken only when cavities in rock, clean coarse gravel, or pervious strata with strong artesian pressures are encountered. The approximate location of the free ground-water level must then be estimated by the character of the cuttings and samples or on the basis of the general stratigraphy of the area. When pervious strata below the estimated water level are reached, the drilling fluid should be replaced with clean water, the bore hole extended a short distance below the sealed bottom, thoroughly cleaned, and then emptied to the estimated ground-water level. The replacement of drilling fluid with water may cause caving of the hole, in which case casing will be required for a reliable determination of the ground-water level.

The procedure in determining the free ground-water level in strata below a perched ground-water table is the same as described above, but a cased bore hole will then be required, since seepage from the perched body of water would raise the stabilized water level in an uncased bore hole extended to a lower ground-water table.

3.7 Determination of Hydrostatic Pressures

A reliable determination of excess or subnormal hydrostatic pressures in strata below the free ground-water level requires a cased bore hole, since the stabilized water level in an uncased hole would be influenced by leakage to or from the overlying strata. The procedure is otherwise the same as in determining the depth to the free ground-water level; that is, the hole should be extended a short distance below the casing, cleaned out, and filled with clean water to the estimated piezometric level, whereupon stabilization is awaited before making the final depth measurements.

When free-flowing artesian strata are encountered but the piezometric level is only slightly above the ground surface, it may be determined by adding one or two sections to the casing. If the pressure is great, it may be necessary to close the top of the casing and attach a manometer. An air outlet valve should then also be
provided in order to prevent accumulation of air and other gases in the upper part of the casing.

There is danger, even in a cased bore hole, that the stabilized water level will not indicate accurately the hydrostatic pressure in the soil at the bottom of the hole, and that this level may be influenced by leakage along the casing and through the joints of the casing. The influence of such a leakage is generally small when the work is carefully executed and the soil is so permeable that the practical time-lag does not exceed a few hours, but the danger that the results may be influenced seriously by leakage increases rapidly with the time-lag and decreasing permeability of the soil.

Knowledge of pore-water pressures in relatively impervious soils is assuming increasing importance with the progress in soil testing and methods of design of important foundation and earth structures, but these pressures cannot be determined with satisfactory accuracy during normal boring operations on account of the time-lag and the danger of leakage. Carefully installed observation wells, small-diameter piezometers, or hydrostatic pressure cells must then be used.

3.8 Observation Wells

Casing is often left in the bore hole when it is desired to continue groundwater observations over a period of time or when the ground-water levels and pressures in relatively impervious soils are to be determined. The casing joints should be tightly made up and, if necessary, sealed with wicks and pipe dope. The casing should fit tightly in the bore hole to decrease outside leakage; therefore, the diameter of the casing shoe should not be larger than that of the casing proper. The bore hole should be advanced a couple of feet below the casing or the casing withdrawn a similar distance. If there is danger of caving of the uncased part of the hole, it may be filled with well graded gravel. The hole should be carefully cleaned both before and after being filled with gravel, and the water left in the hole should not contain any suspended matter. The casing should extend a sufficient distance above the ground surface and also be provided with a ventilated cover to prevent entrance of surface water, rain, and dirt. Even with these precautions there is danger of ultimate clogging of the gravel or formation of a filter skin, and the method is therefore not suitable for protracted observations of rapidly fluctuating ground-water levels and pressures.

A standard well point and pipe, driven or jetted into the ground, is often used as an observation well when the soil is relatively porous and ground-water conditions are fairly regular.

For protracted and detailed observations, especially in the less permeable soils and with irregular or rapidly changing ground-water levels and pressures, it is preferable to use a specially installed observation well, an example of which is shown in Fig. 70. A well point or section of porous concrete or sintered pipe is
attached to the lower end of the standpipe and is surrounded by a filter of well graded gravel or sand. The hole must be carefully cleaned and filled with clear water before the standpipe with its porous point and filter are installed. Extreme care must be taken in obtaining tight joints in the standpipe, and jointless tubing should preferably be used when the diameter is small. The diameter of the standpipe should be as small as possible in order to decrease the time-lag. A diameter of 4 to 6 in. may be required when special floats and recording depth gages are to be used, but a diameter of 1 to 2 in. is sufficient for insertion of a wetted tape or rod gage, and the depth gage shown in Fig. 69C can be used in tubing with an internal diameter of 3/8 in. The internal diameter should not be smaller than 3/8 in., since bubbles of air or other gases then may be retained in the standpipe instead of rising to the surface, and since it then becomes difficult to clean the tubing and the porous point should this become necessary after the installation is completed.

The annular space around the standpipe must be carefully backfilled and the lower part adequately sealed as the casing is withdrawn. The seal should be located in or extended to impervious strata. The casing may also be left in the ground, and the seal between the casing and a small-diameter standpipe may then be confined to the lower part of the casing and backfilling omitted. The seal may consist of compacted clay or bentonite or a mixture of the two materials. Bentonite provides the tighter seal, but there is danger that its great tendency to swelling may cause changes of stresses and pore-water pressures in the surrounding soil. The effect of this swelling may be reduced by placing intermediate layers of sand or concrete in the seal.

An excellent piezometer, developed by A. Casagrande (105), consists of 1/2-in. O.D. Saran tubing, which is connected to a porous point of sintered, non-metallic material by means of a Neoprene rubber bushing. The elimination of metals decreases the danger of electrolysis and development of gases. The entire assembly is filled with water before installation by immersing the porous point a few feet in the water filled bore hole and connecting the free end of the tubing to a vacuum tank. The seal is placed by rolling the clay or bentonite into small balls, which are dropped into the boring to form 3- to 4-in. thick layers around the tubing, and each layer as well as intermediate sand layers is compacted by means of an annular tamper.

As will be seen in Table 4, when the intake or porous point is placed in clay, there is considerable time-lag even when the diameter of the standpipe is only 3/8 in. When the piezometric pressure level is near or above the ground surface, the standpipe
can be connected to a manometer or Bourdon gage and the time-lag greatly decreased thereby, but hydrostatic pressure cells are required when the pressure level is appreciably below the ground surface and rapidly changing pore-water pressures in clay are to be determined.

3.9 Yield and Permeability

The approximate yield of water can be determined by bailing or pumping and observing the corresponding stabilized draw-down level in the bore hole. However, the yield of a single, small-diameter boring does not always give a reliable indication of the pumping requirements for a proposed foundation pit, and better results are obtained by means of a caisson or test pit.

A very rough estimate of the average permeability of the material around the bottom of a cased bore hole may be obtained by lowering or raising the water level in the casing and observing the rise or fall of the level as a function of time and with respect to the stabilized piezometric water level. The depth of the bore hole below the casing, or the amount of soil in the casing, should be carefully determined, and the bore hole should be thoroughly washed with clean water before such experiments are undertaken. The permeability determined by means of a single bore hole is primarily governed by the permeability of the soil in the immediate vicinity of the bottom of the hole, and results of permeability determinations are often subject to serious errors on account of local geological irregularities, disturbance of the soil caused by boring, sedimentation, internal erosion, and difficulties in determining the effective intake area. The average permeability of a deposit is best determined by large-scale pumping tests, in which a given flow is maintained until the draw-down has become stabilized, and in which the corresponding water levels in the soil are determined by several auxiliary borings or observation wells.

3.10 Sampling of Ground Water

Samples of ground water, intended for laboratory analysis, must be uncontaminated by foreign substances. Such samples are easily obtained from borings into free-flowing artesian strata or when pumping tests are performed. In other cases the bore hole must be thoroughly cleaned and completely emptied of the water or drilling fluid used in advancing the boring. When the ground water has risen to a sufficient depth in the hole, a sample may be obtained by means of a thoroughly cleaned bailer.

The quantity of water required for a chemical and bacteriological analysis varies with the laboratory technique. A common requirement is one liter or quart, but some laboratory techniques require up to one gallon. Therefore, unless the requirements of the laboratory in which the water is to be analyzed are definitely known, it is advisable to take a one-gallon sample, which should be preserved in a thoroughly cleaned and sterilized glass container, adequately sealed and packed for shipment.
### TABLE 5 - METHODS OF SAMPLING SUBSURFACE MATERIALS

<table>
<thead>
<tr>
<th>GROUP</th>
<th>TYPE OR PURPOSE</th>
<th>SAMPLER OR METHOD</th>
<th>ID BORING OD SAMPLER</th>
<th>SAMPLE DIAMETER (in)</th>
<th>MATERIALS IN WHICH USED</th>
<th>CONDITION OF SAMPLES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clean-out Tools</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bailer</td>
<td>2.9 - up</td>
<td>-</td>
<td>Very soft soils, loose cohesiveless soils, and strata of all materials</td>
<td>Often non-representative with soil constituents mixed and segregated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sandpumps</td>
<td>2.0 - up</td>
<td>-</td>
<td>Soft soils, silt, and loose sand</td>
<td>Representative of average conditions but adjacent strata are often mixed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sit Samplers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Longitudinal Silt</td>
<td>1.3 - 4.0</td>
<td>-</td>
<td>Medium soft to stiff cohesive soils Partially saturated sand and silt</td>
<td>Seriously disturbed and often partially mixed but generally representative of the average condition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Circumferential Silt or Cap</td>
<td>2.3 - -</td>
<td>-</td>
<td>All soils including gravelly soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Augers</td>
<td>Helical or Worm Type Augers</td>
<td>1.5 - 16</td>
<td>-</td>
<td>All soils including gravelly soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Iwan or Post Hole Augers</td>
<td>4 - 9</td>
<td>-</td>
<td>All soils including gravelly soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Barrel Augers, Helical or Iwan</td>
<td>2.5 - 5.6</td>
<td>-</td>
<td>All soils including gravelly soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Disk and Bucket Power Augers</td>
<td>12 - 40</td>
<td>-</td>
<td>All soils including gravelly soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Open Drive Samplers</td>
<td></td>
<td></td>
<td></td>
<td>All soils except coarse gravel, Remainers req'd in soft or loose soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thick-Wall, Solid-Barrel</td>
<td>1.4 - 8.0</td>
<td>1.0 - 7.0</td>
<td>All soils except coarse gravel, Remainers req'd in soft or loose soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thick-Wall, Split-Barrel</td>
<td>2.0 - 5.6</td>
<td>1.4 - 5.0</td>
<td>All soils except coarse gravel, Remainers req'd in soft or loose soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thin-Wall Samplers</td>
<td>1.0 - 8.0</td>
<td>0.94 - 7.6</td>
<td>Core materials of medium dense soils, Special methods to prevent loss required in some soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Composite Samplers - Liners</td>
<td>1.3 - 8.0</td>
<td>0.94 - 7.0</td>
<td>Core materials of medium dense soils, Special methods to prevent loss required in some soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Piston Samplers</td>
<td>Thin-Wall or Composite</td>
<td>Retracted Piston</td>
<td>7/8 - 6.0</td>
<td>3/4 - 4.9</td>
<td>As above but incl. very soft soils</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Free Piston</td>
<td>3/4 - 6.0</td>
<td>5/8 - 5.9</td>
<td>As above but incl. very soft soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Core Barrels</td>
<td>Retracted Piston</td>
<td>7/8 - 6.0</td>
<td>3/4 - 4.9</td>
<td>As above but incl. very soft soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stationary Piston **</td>
<td>3/4 - 6.0</td>
<td>5/8 - 5.9</td>
<td>As above but incl. very soft soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Soil Core Barrel</td>
<td>Hard-Metal Teeth</td>
<td>3.8 - 8.9</td>
<td>2.8 - 7.4</td>
<td>Stiff to hard clays, brittle soils, dense sand, partial cemented soils</td>
<td>Probably less disturbance than by drive sampling, Method in develop.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flush or protruding inner tube with liner</td>
<td>3.8 - 8.9</td>
<td>2.8 - 7.4</td>
<td>Stiff to hard clays, brittle soils, dense sand, partial cemented soils</td>
<td>Probably less disturbance than by drive sampling, Method in develop.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chilled steel shot in soft steel bit, Single tube with calyx</td>
<td>2.8* - 4.8</td>
<td>1.5* - 3.4</td>
<td>All except very soft, fissured, or cavernous rock; slow in hard rock</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>36 - up*</td>
<td>34 - up*</td>
<td>All except very soft, fissured, or cavernous rock; slow in hard rock</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diamond Bit</td>
<td>Single tube or double tube barrel with retracted inner tube</td>
<td>1.5* - 1.9</td>
<td>7/8* - 1.1</td>
<td>All soft rock but best suited for small cores of medium to hard rock</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Single tube</td>
<td>3.0 - up*</td>
<td>2.1 - up*</td>
<td>All soft rock but best suited for small cores of medium to hard rock</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hard-Metal Teeth</td>
<td>Tungsten Carbide Surface or Inserts</td>
<td>2.5 - 38</td>
<td>2.0 - 36</td>
<td>Soft to medium rock and frozen soil occasionally hard and dense soils</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Single Tube</td>
<td>2.5 - 38</td>
<td>2.0 - 36</td>
<td>Soft to medium rock and frozen soil occasionally hard and dense soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Double Tube</td>
<td>2.5 - 8.9</td>
<td>1.8 - 7.4</td>
<td>Soft to medium rock and frozen soil occasionally hard and dense soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Retracted Piston</td>
<td>7/8 - 6.0</td>
<td>3/4 - 4.9</td>
<td>As above but incl. very soft soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stationary Piston **</td>
<td>3/4 - 6.0</td>
<td>5/8 - 5.9</td>
<td>As above but incl. very soft soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stationary Piston **</td>
<td>3/4 - 6.0</td>
<td>5/8 - 5.9</td>
<td>As above but incl. very soft soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Oilfield Core Barrels</td>
<td>Standard, stationary inner tube</td>
<td>3.9 - 12</td>
<td>1.2 - 5.5</td>
<td>Bladed Bit: Hard soils or soft rock, Roller or Cone Bit; Hard formations</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wire-Line, retractable inner tube</td>
<td>5.4 - 8.0</td>
<td>1.0 - 2.5</td>
<td>Developed for sampling of oil sands</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pressure, inner tube with valves</td>
<td>6.25</td>
<td>1.5 - 1.7</td>
<td>Fluid and gas pressure maintained</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Percussion Core Barrel</td>
<td>Double Tube, Sliding inner barrel</td>
<td>3.8 - 7.3</td>
<td>1.6 - 3.8</td>
<td>Medium soft to medium hard rock</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>with hard-surfaced steel bit</td>
<td>3.8 - 7.3</td>
<td>1.6 - 3.8</td>
<td>Medium soft to medium hard rock</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Side Wall Samplers</td>
<td>Open Drive Samplers. Operation hydraulic, wire-line, or shooting</td>
<td>4.0 - 6.8</td>
<td>7/16 - 1 1/4</td>
<td>Stiff and compact soils to soft or medium rock; side walls of borrow</td>
<td>Fair recovery, but the cores are often broken into small sections</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bag Sample, Field Density Tests</td>
<td>4 - 10</td>
<td>-</td>
<td>Primarily sandy and gravelly soils</td>
<td>Representative but natural density</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Short Open Drive Samplers</td>
<td>2 - 6</td>
<td>1.9 - 5.9</td>
<td>Soft to medium stiff clayey soils, loose sand and silt. Control tests</td>
<td>As below but occasionally some disturbance and especially compaction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Short Piston Samplers</td>
<td>3/4 - 6</td>
<td>5/8 - 5.9</td>
<td>Soft to medium stiff clayey soils, loose sand and silt. Control tests</td>
<td>As below but occasionally some disturbance and especially compaction</td>
</tr>
<tr>
<td></td>
<td>Exploration, Earth Structures</td>
<td>Sampling by Advance Trimming</td>
<td>-</td>
<td>-</td>
<td>Stiff, brittle or dense soils. Compacted or partially saturated soils</td>
<td>Undisturbed excepting influence of stress changes and soil movements before or exposure during sampling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Auger Core Barrels</td>
<td>6.3 - 6.9</td>
<td>3.7 - 6.0</td>
<td>Coarse, dense, brittle or hard soil</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Block or Box Samples</td>
<td>-</td>
<td>-</td>
<td>Coarse, dense, brittle or hard soil</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Submarine Bottom Explorations</td>
<td>Scarpers and Clamshell Buckets</td>
<td>-</td>
<td>-</td>
<td>Only materials from bottom surface</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Restricted Gravity</td>
<td>Composite Open Drive Samplers</td>
<td>1.8 - 3.3</td>
<td>1.0 - 4.4</td>
<td>All sorts to soft rock. Samples of hard and gravelly soils short but of very soft soils up to 18 ft long</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Free-Fall Gravity</td>
<td>Composite Open Drive Samplers</td>
<td>1.8 - 3.3</td>
<td>1.0 - 4.4</td>
<td>All sorts to soft rock. Samples of hard and gravelly soils short but of very soft soils up to 18 ft long</td>
</tr>
</tbody>
</table>

The dimensions shown are approximate and are used mainly for design purposes. A drive sampler with liner and inner tube is used in situations where the formation is soft, friable, or where it is necessary to maintain the recovery of the sample. A drive sampler with inner tube for undisturbed samples is used for sampling of soft and plastic materials.