SOIL ENGINEERING

Testing, Design, and Remediation

Fu Hua Chen

SOIL ENGINEERING: TESTING, DESIGN, AND REMEDIATION

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To my wife Edna, with love and appreciation;
she took care of me during the preparation of this book while
I was suffering severely from emphysema.

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Foreword

A true Renaissance man, Fu Hua Chen was educated in both China and the United States. Returning to his homeland to contribute to its struggle against Japanese attrition, he was chief engineer on the Burma Road. That artery held together the victorious Allied campaign to end World War II on the Asian mainland.

After the Tibet Highway, the Ho Chi Minh Trail, and other large China projects, Dr. Chen brought his family to the U.S. to build a better life. Successful in that, he then devoted his remaining years to returning to his community, his society, and his profession some of the benefits American life had provided for him.

Acknowledged as the world's authority on expansive soils, Dr. Chen published books on that and other aspects of geotechnical engineering, and a riveting autobiography. He wanted the top rung of his career ladder to be his guide for constructors and consultants to demystify soils and foundation engineering. It is a plain-talk effort to help builders understand and deal with that complex facet so vital to construction.

With the publication of this book, Dr. Chen has achieved that goal, to top off a monumental career that ended peacefully among his family in his 87th year.

M.D. Morris, P.E.
Advisory Editor

Chen, Fu Hua
21 July 1912 — 5 March 1999
Civil Engineer, Author, Educator, Humanitarian

Introduction

When I was at the University of Michigan in 1935, I took a course on soils with Professor Hogentogler. He had just completed a book entitled *The Engineering Properties of Soil.* At that time, soil mechanics was not known. I talked to Dr. Terzaghi at Vienna in 1938; he assured me that he had nothing to do with the term "soil mechanics." We all realized that the term "mechanics" is associated with mathematics. By using the term "mechanics" with soil, the academicians firmly linked engineering with mathematics. It appears that in order to understand soil, one must understand "elasticity," "diffusion theory," "finite element" and other concepts. After several years of dealing with foundation investigation, most consultants realize that soil engineering is an art rather than a science as the academicians depicted.

In the last 40 years, no fewer than 50 books have been written on the subject of soil mechanics. Most of them were written for use in teaching. Only a few touched on practical applications. When engineers dealt with major complicated projects, such as the failure of the Teton Dam or the Leaning Tower of Pisa, high technology was required. However, 90% of the cases in which consulting engineers are involved do not require mathematical treatment or computer analysis; they mostly need experience. Consulting soil engineers are involved primarily with the design of foundation for warehouses, schools, medium-rise buildings, and residential houses. With such projects, the complete answers to soil engineering problems cannot be resolved solely with textbook information.

The purpose of this book is to provide consulting engineers with the practical meaning of the various aspects of soil mechanics; the use of unconfined compression test data; the meaning of consolidation tests; the practical value of lateral pressure; and other topics.

In addition to the technical aspect of foundation investigation, in the real world one should be aware that the shadow of litigation hangs over the consultant's head. A careless statement may cost the consultant a great deal of time and money to resolve the resulting legal involvement.

It is expected that the academicians may find many inconsistencies in this book. However, at the same time, I expect that the book will find its way to the consulting engineer's desk.

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1 Site Investigation

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The stability and performance of a structure founded on soil depend on the subsoil conditions, ground surface features, type of construction, and sometimes the meteorological changes. Subsoil conditions can be explored by drilling and sampling, seismic surveying, excavation of test pits, and by the study of existing data.

Elaborate site investigation oftentimes cannot be conducted due to a limited assigned budget. For very favorable sites, such investigation may not be warranted. However, if the area is suspected of having deep fill, a high water table, or swelling soil problems, extensive soil investigation will be necessary even for minor structures. The soil engineers should not accept jobs in problem areas without thorough investigation. Bear in mind that in court of law, limited budgets or limited time frames are not excuses for inadequate investigation. Differing site conditions are a favorite tool of the contractors. They are used as the basis for extra claims on their contracts.

Since a consulting soil engineer cannot afford to treat each site as a potential hazard area, the amount of investigation required will generally be dictated by the judgment and experience of the engineers. If the project is completed on time and under budget, the consultant may still be criticized for being too conservative. On the other hand, if problems are encountered in the project, no number of excuses can relieve consultants of their responsibility.

1.1 GENERAL INFORMATION

The content of this chapter has very little to do with soil engineering. However, as a consultant, site investigation is probably one of the most important parts of the total inquiry or the report. Average owners know very little about engineering, but they do know a great deal about the property they own. Misrepresentation of the observations can often cause a great deal of trouble. For instance, describing the property as located in a low-lying area may devalue the property. Pointing out the cracks in the building owned by someone else in the neighborhood may induce the buyer to decrease the offer and in extreme cases may result in litigation.

Valuable information about the presence of fills and knowledge of any difficulties encountered during the building of other nearby structures may be obtained from talking to older residents of the area.

Much of the site investigation depends on the experience and good judgment of the field engineer or the technician. An experienced field engineer has the sense of a bloodhound; he is able to smell or sense a problem when he visits the site. A red flag will be raised to call for thorough investigation. In a potential swelling soil area, special attention should be paid to the condition and foundation system of the existing structures.

When the site is located out of town, consulting engineering firms sometimes assign site investigation to a technician or a field man, who has little geotechnical experience. He may ignore some important features which should be pointed out in the geotechnical report. An experienced technician with many years of training in a geotechnical company can be worth more than an engineer freshly out of college with a Ph.D. degree.

Generally, it is a small building with inadequate funding, poor planning, and a low-bidding contractor that presents the most trouble. The owner of such a project generally considers soil investigation as a requirement fulfillment rather than a protection against foundation failure. Geotechnical engineers should ask for more details regarding the site condition and proposed construction before accepting such assignments.

1.1.1 Property

In most cases, the owner's property is well defined. However, one often comes across property that is not surveyed and not clearly marked. It is quite possible that the field man located his test hole outside of the property line. There would be a great deal of argument on the liability of such an incident. It is not unusual that the engineering company has to pay for the damage. There are cases when the upper portion of the retaining wall is within the property line, but the base of the wall extends to the neighboring property. There are cases when the surveyor's monument is intentionally moved for the benefit of the owner. If the owner is on good terms with his neighbor, nothing will happen. Otherwise, the case may wind up in court, and the engineers may be involved.

Errors in property lines may lie undetected long after the project is completed and forgotten. The mistake may involve the demolition of the existing structure. It is also possible that the client did not acquire the final title to the property and moved ahead of schedule to order the soil test. The result in one case was the field engineer being chased by an angry owner with a shotgun.

After the property lines have been established, permission should be obtained from the owner to enter the property with drilling equipment. This should be in writing, although oral permission in front of a witness may be enough. The following is a summons filed by the owner:

> "…None of the defendants asked for or obtained plaintiff's permission to enter into and to explore his leasehold estates, did not ask plaintiff for permission to drill or have drilled a rotary hole into his leasehold, and did not ask plaintiff for permission to have geophysical and geological testing conducted pertaining to his leasehold…"

It is obvious that in this case the engineering company is liable.

1.1.2 Accessibility

Not all properties are accessible to drilling equipment. Oftentimes, the site is covered with crops. It is a sad sight to see crops ruined by a drilling vehicle. The engineering company, not the owner, will wind up paying for the damage.

In mountain sites, access usually presents a problem. Before sending the drilling equipment to the site, a general survey of the route to enter the site should be made. Sometimes, trespassing on the neighboring properties cannot be avoided. In such cases, permission should be obtained.

If the property is fenced, permission should be obtained to open the gate. Be very sure that the gates are properly closed after entering or leaving. The loss of cattle or prize horses certainly can add to the liability bill. In the eyes of the attorney, anything lost is not replaceable.

In soft ground, as at the time of spring thaw or after continuous rain, it is a lost effort to move the drilling equipment to the site. In order to avoid loss of time or the cost of towing, it is always advisable to evaluate the accessibility first. An all-terrain drill rig is able to move into places where conventional drill rigs cannot gain access. In this case, the client should agree to pay for the additional cost or wait until the ground has dried up.

During winter months, it is better to move the rig in the early morning when the ground is frozen and move out before thawing. Profit and loss on a project depend sometimes on the intelligent planning of the field engineer. Accessibility problems should be considered before a cost estimate is offered. The margin of profit for a consulting firm is very thin.

1.1.3 Records

A complete record of the site investigation should be maintained by the field engineer. This includes the time, date, the names of all parties involved, and all letters and notes. Such records appear to be so obvious and unnecessary at the time, but may turn out to be invaluable in a court of law at a later date. Dates are important in that conditions such as water tables and climates change with time.

Some field engineers are required to describe the site by filling out standard questionnaires. Such lengthy questionnaires may not be desirable. Most items listed in the questionnaires are unrelated and unnecessary, while vital issues can be neglected. A field engineer should treat each site as an individual case and use his observation and judgment in recording all pertinent details.

1.1.4 Utility Lines

Before sending the drill rig to the site, subsurface utility lines should be checked out thoroughly. Standard contracts between the consulting engineering company and the client usually specify that the company will not be responsible for subsurface structures not indicated on the plans furnished to the engineer. However, in the case of accident, the information furnished to the engineering company cannot protect the geotechnical engineer from being named as a defendant. For projects near a metropolitan area where the site is crisscrossed with utility lines in addition to those indicated in the existing plans, it is important to notify the telephone company, the public service company, the water works, and the city engineer on the project. The concerned parties will send agents to the site to accurately delineate the location of the various lines.

In one project at the Stapleton Airport in Denver, the engineer was provided with the location of the underground cable and all utility lines. The engineer did not check the date on the plot, which was made several years before. During drilling, a main fuel line was damaged, causing the delay of all air traffic. The incident was finally settled out of court. Luckily, the geotechnical company was a relatively new firm with few assets and was able to get away with limited payment.

In residential areas, the location of a sprinkler system should also be checked out. The chance of hitting a 1-in. utility line with a 4-in. auger in several acres of open field appears to be remote, but in fact such incidents have taken place over and over.

1.1.5 Existing Structures

The behavior of the existing structures has an important bearing on the selection of the proposed structure. All possible information should be obtained concerning structures at the site and in the immediate proximity. Inquiry should be made as to the condition of the structure, age, and type of foundation. If adjacent existing structures have experienced water seepage problems, the possibility of a high water table condition or a perched water condition in the area is likely to exist. The best way to determine such a condition is to enter the lower level of the building and look for watermarks on the wall.

It is not often that a geotechnical engineer has an opportunity to examine the cracking of the existing building located on or near the project site. By studying the condition of the existing structure, one will be able to tell the adequacy of the existing foundation system. If there are cracks in the foundation system, it is certainly important to try to determine the cause of the cracking. The cracking can be caused by foundation settlement, swelling of the foundation soils, or even from an earthquake. The age of the structure may provide the potential for distress. An experienced geotechnical engineer treats the cracking as if it is the writing on the wall.

If the existing building is in excellent condition, this does not mean that the existing building system can be used for the design of the new structure. The existing structure's foundation system could have been overdesigned. This is especially true in the case of old structures where massive foundation systems were traditionally used.

1.1.6 Additions

A portion of a geotechnical consultant's project is in addition to the existing structures. Building owners may not want to use the initial consultant and will approach a new consultant for the geotechnical study for one of the following reasons:

The initial geotechnical firm is not available.
The fee charged by the initial engineering company is too high.
The initial recommendation of the foundation system cost is too high.
The possibility of using another foundation system.
The initial building suffered damage.

If the cost of consultation is the main reason, consideration should be given to rejecting the job. This is on account of breaching the ethical practice. If the structure suffered damage, the field engineer should determine as closely as possible the following:

Damage caused by using the wrong foundation system
Damage caused by reasons other than soil
Damage caused by poor maintenance

Bearing in mind that the geotechnical engineer cannot guarantee the performance of the structure, the second consultant should be prepared to defend the initial consultant in a court of law rather than condemn him. It is a mistake to brag about one's knowledge by pointing a finger at one's fellow engineer.

Realizing the importance of site conditions to a geotechnical consultant and the responsibility the engineer is confronting, the Associated Soil and Foundation Engineers (ASFE) proposed an agreement between the owner and the engineers as follows:

1. The owner shall indicate to the soil engineer the property lines and is responsible for the accuracy of markers.
2. The owner shall provide free access to the site for all necessary equipment and personnel.
3. The owner shall take steps to see that the property is protected, inside and out, including all landscaping, shrubs, and flowers. The soil engineer will

not be responsible for damage to lawns, shrubs, landscapes, walks, sprinkler systems, or underground utilities and installations caused by movement of earth or equipment.

4. The owner shall locate for the soil engineer and shall assume responsibility for the accuracy of his representations as to the underground utilities and installations.

Such an agreement when signed should be sufficient to protect the engineering company, yet a talented lawyer may still find loopholes that involve the engineer.

At the same time, a large portion of geotechnical investigation is carried out without a written contract. Small projects are carried out based on a single-page letter or even oral agreement. In such cases, the roles of the field engineer become more and more important. Unfortunately, the importance of the field engineer is seldom realized by the consulting firm until a summons is served.

1.2 TOPOGRAPHY, GEOLOGY, HYDROLOGY, AND GEOMANCY

Topography, geology, and hydrology should be treated as an integral part of soil engineering. No soil engineer can be considered knowledgeable if he lacks information on these subjects. No soil report can be considered complete without touching on these subjects. No investigation can be considered satisfactory without having such subjects in mind.

Such information can be obtained by reviewing available data, studying existing maps, or making a reconnaissance survey. Care must be taken as to the accuracy of such information. Oftentimes, site grading can completely alter the topography, and development in the neighborhood can alter the hydraulic balance.

1.2.1 Topography

Topography is defined as the features of a plain or region. Generally, for larger projects a topographic survey is available. Care must be taken with the date of the survey and the bench mark referred to. Sometimes site grading can completely alter the original ground features. Topography can be different if the original photogrammetric survey was taken when the site was vegetated.

Outdated contour elevation should not be used for elevation of the top of the drill holes without careful checking.

The shape of gullies and ravines reflects soil textures. Gullies in sand tend to be V-shaped with uniform straight slopes. Gullies in silty soils often have U-shaped cross-sections. Small gullies in clay often are U-shaped, while deeper ones are broadly rounded at the tops of the slopes.

The location of natural and man-made drainage features is also of importance. Erecting a structure across a natural gully always poses a future drainage problem. The water level in any nearby streams and ponds should be measured and recorded.

Irrigation ditches can be dry during most of the year but can carry a large amount of water during irrigation season. Water leaking out from the ditches and ponds can supply moisture to the foundation soil and cause settlement or heaving of footing and slab. The lifting of drilled piers in an expansive soil area due to the infiltration of water from ditches and ponds is not uncommon. The source of water may not be detected for a long time.

Water leaking out from the ditches can also cause the cracking and dampness of the basement slab. The location and elevation of the ditches should be included as part of the engineering report.

Streams and nearby runoffs are important parts of the investigation. Engineers should pay special attention to the extent of the flood plain. Such preliminary information can usually be obtained from the U.S. Geological Survey, or the U.S. Department of Agriculture Soil Survey reports.

The steepness of valley slopes is of special concern for sites chosen in mountain areas. Some environmental agents classify valley slopes in excess of 30° as potential hazard areas. Slope stability depends upon the slope's angle, rock and soil formations, evidence of past slope movement, and drainage features. The field engineer should be aware of the possible slope problems associated with landslides, local slope failure, mud flow, and other problems. The vegetative cover on the slope, shapes of tree, and the behavior of any neighboring structures should also be known.

1.2.2 Geology

Geology is the science of the earth's history, composition, and structure. Branches include mineralogy, petrology, geomorphology, geochemistry, geophysics, sedimentation, structural geology, economic geology, and engineering geology. The last category is of utmost concern to the foundation engineers.

The science of geology existed long before the advance of soil engineering. Colleges offer geology to most civil engineering students. However, some professors in geology may have little knowledge of engineering. Consequently, the relationship between geology and soil mechanics is seldom stressed. Students do not pay much attention to geology and give such courses the same weight as astronomy or chemistry.

It is not until an engineer enters the field of consulting that he realizes the close relationships between soil mechanics and geology. For average small structures that do not require special foundation designs, geology information may not be required. It is a mistake for consultants to put a section in their reports on geology if the content has no bearing on the project. A section on geology in the consultant's report is necessary only when such information is vital to the project. Consulting firms should have qualified staff geologists to conduct and study such projects. If the soil engineer is not a qualified geologist, he or she should not attempt to touch the subject.

A geological assessment based on prior knowledge of the area may be required before the study can be completed. The geological assessment can describe any geological conditions that have to be considered before any soil testing is initiated and recommendations for the foundation design are presented.

General surficial geology of the area includes the study of slopes, tributary valleys, landslides, springs and seeps, sinkholes, exposed rock sections, origin of deposit, and the nature of the unconsolidated overburden.

An inspection of upland and valley slopes may provide clues to the thickness and sequence of formations and rock structure. The shape and character of channels and the nature of the soil may provide evidence of past geologic activity. An engineering geologist should identify and describe all geologic formations visible at the surface and note their topographic positions. The local dip and strike of the formations should be determined and notes made of any stratigraphic relationships or structural features that may cause problems of seepage, excessive water loss, or slide of embankment.

Some of the geological concerns to the foundation engineers are as follows:

The bearing capacity of bedrock
The bearing capacity and settlement of windblown deposits
The expansion potential of shale
The orientation of the rock formation
The excavation difficulty
The drilling problem
The slope stability

In the mountain areas, the mapping of surficial geologic features is highly desirable. Features to be shown on the map should include:

Texture of surficial deposits
Structure of bedrock, including dip and strike, faults or fissures, stratification, porosity and permeability, schistosity, and weathered zones
Area of accelerated erosion deposit
Unstable slopes, slips, and landslides
Fault zones

Geologists as well as experienced engineers should be able to recognize a potential swelling soil problem. For instance, the red siltstone formation in Laramie, Wyoming will not pose a swelling problem, while a few miles to the west where claystone of Pierre formation is observed, swelling can be critical. In the front range area west of the foothills, claystone shale dips as much as 30° with the horizontal. The joints within the rock can allow easy access of water and cause volume change. Such problems should be carefully studied.

To assure adequate planned development of a subdivision, some state laws require the subdivider to submit such items as:

Reports concerning streams, lakes, topography, geology, soils, and vegetation
Reports concerning geologic characteristics of the area that would significantly affect the land use and the determination of the impact of such characteristics on the proposed subdivision
Maps and tables concerning suitability of types of soil in the proposed subdivision

Careful discussion between geotechnical engineers and geologists should be maintained during the writing of the report. The report should be presented as a whole. It should give the client the impression that the report is from one author. Contradictory opinions between geologists and geotechnical engineers should be settled before the report is completed.

1.2.3 Hydrology

Hydrology is defined as the scientific study of the properties, distribution, and effects of water on the earth's land surface in the soil and rock. Geotechnical engineers are dealing with water all the time. As Terzaghi stated, "without any water there would be no use for soil mechanics." The most common issues a geotechnical engineer encounters are permeability, seepage, and flow in connection with ground water. For major projects such as dams and canals, the geotechnical engineer should seek advice and consultation from a hydrologist.

The permeability property of soil cannot be separated from the soil drainage characteristics. The former has been researched both in theory and in the laboratory by the academicians, yet the design and construction of the drainage installation seldom receive proper attention from the architect. Long drainage facilities are often shown on the design drawing by mere dotted lines. Construction of the drain facilities is often left in the hands of the builders. It is not uncommon to see that the drains were constructed with reverse grade or without proper outlet. Since drainage facilities are generally installed below ground surface, the defective systems are seldom revealed.

Details of drainage and soil moisture control will be discussed in the subsequent chapters.

1.2.4 Geomancy

Geomancy, or as what the Chinese refer to as "feng shui" or "Wind and Water" is defined as the art of adapting the residence of the living and the dead so as to harmonize with the cosmic breath.

The ups and downs of the profile of the land is of vital importance to the quality of the site. The ground must be hard and solid and must have a good profile like that of the real dragons if it is rated as a good site. The sand on the ground and the water sources are also of great importance to the geomancer. From a geotechnical point of view, the ideal site would be one with hard bedrock overlain by granular deposits.

In fact, no family or business will consider building on a piece of land without the consultation with a geomancer.

In the Western world, feng shui has been considered dogmatic faith or superstition. However, this art has been under intense study in recent years in the U.S. as well as in European countries. It is not surprising that one will find a link between feng shui and geotechnical engineering.

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2 Subsoil Exploration

CONTENTS

Subsoil exploration is the first step in the designing of a foundation system. It consists essentially of drilling and sampling. The process of subsoil exploration took place long before soil mechanics was born. Present-day engineering requires thousands of exploratory test borings to build a structure like the Great Wall of China. The wall actually winds around the mountains, avoiding problem soil areas. Somehow its ancient builders had a sense in selecting the good foundation soils.

Chinese legend tells the story of a commandeered laborer who died while building the Great Wall. His wife's lament at the foot of the wall was so moving that the wall collapsed. We suspect now if the story is true, the wall collapsed due to foundation failure.

Experienced engineers use soil mechanics to *confirm* their conclusions rather than to reach their conclusions. Many factors affect the choice of a subsoil exploration program; the judgment of the engineer is deemed necessary.

2.1 DIRECT METHODS

The most suitable method to perform subsoil exploration depends on the type of soil in the general area; type of equipment available; ground water condition; type of proposed structure; and the amount of money allocated for the exploration.

Direct methods of exploration include the digging of test pits and the use of auger drilling or rotary drilling. Each method has its merits and its drawbacks. The engineer must use his or her judgment based on experience and the evaluation of the site conditions to select the best method. Unfortunately, in most projects there is very little choice. The driller and the available equipment are the only choices. The engineer often must help the driller in solving the drilling problems.

2.1.1 Test Pits

Probably the most accurate subsoil investigation method is the opening of test pits. In a test pit, the engineer can examine in detail the subsoil strata, stratification, layer and lens, as well as take samples at the desired location. However, the use of test pits is limited by the following:

When the depth of the test is limited to the reach of a backhoe, generally 12 ft.
When the investigation involves basement construction that extends below the ground level
When the water table is high, which prevents excavation
When the soil is unstable and has the tendency to collapse, this prevents the engineer from entering the pit. Entering a test pit can involve certain risks and the regulations of the Occupational Safety and Health Administration (OSHA) should be observed
When the standard penetration resistance test is required

In locations where subsoil consists essentially of large boulders and cobbles, the use of test pit investigation is most favorable. Auger drilling through boulders and cobbles is difficult. The cost of rotary drilling may not be warranted for small projects.

The layman's conception of subsoil investigation generally assumes that drilling to a great depth constitutes the main portion of the cost. After drilling, the layman thinks the remaining task of the engineer, such as testing and preparation of the report, is of minor importance. Consequently, when no drill rig shows up at the project site, the client feels that he has been cheated and the money paid for the investigation is not justified. With such a philosophy, the engineering company usually attempts to drill each project when possible instead of resorting to the use of a backhoe.

Another possible investigation method is to drill a large-diameter caisson hole to the required depth; a caisson rig is shown in Figure 2.1. By entering the hole, the engineer can clearly examine the subsoil strata and undisturbed samples can be obtained at the desired depth. However, such practice is frowned upon by OSHA for safety reasons.

If deep excavation is required or if the soil cannot maintain the steep side slope, sometimes the use of sheeting is necessary. The minimum size of the pit is 4 × 4 ft, so that a man can enter the pit. Pit excavation in this case must be carried out entirely by manpower. The cost of such an operation is high.

2.1.2 Auger Drilling

In auger drilling, the hole is advanced by rotating a soil auger while pressing it into the soil, and later withdrawing and emptying the soil-laden auger. A series of augers

FIGURE 2.1 Caisson rig with a rock bit.

and a special drilling machine for their operation have been developed by many specialized soil exploration equipment companies.

A series of augers, or a continuous flight helical auger (Figure 2.2), are used for drilling holes with diameters of 4 to 8 in. to a depth of 100 ft. An auger boring is made by turning the auger the desired distance into the soil, withdrawing it, and removing the soil for examination and sampling. As the depth increases, new auger sections are added. It is difficult to determine the depth from which the soil discharged from the auger is excavated. Consequently, in order to obtain a representative sample or an undisturbed sample, it will be necessary to stop the drilling and replace the auger with a sampler. The sampler can then be pushed or driven into the soil at the desired depth.

Auger drilling can be successfully conducted in almost all types of soils and in shale bedrock. For hard bedock such as limestone, sandstone, and granite, rotary drilling is necessary.

The drilling machine has a folding mast with a chain-operated feed and lifts. In wet and spongy terrain where a tire-mounted rig is not accessible, a tractor-mounted type rig is available (Figure 2.3). More than 90% of soil exploration study today is conducted by such a device or similar devices.

Relatively short helical augers with interchangeable cutters are used for medium-size holes, whereas large-diameter holes up to 24 in. are excavated by means of a disc auger.

FIGURE 2.2 Continuous flight hollow stem auger.

FIGURE 2.3 Tractor-mounted auger drilling rig.

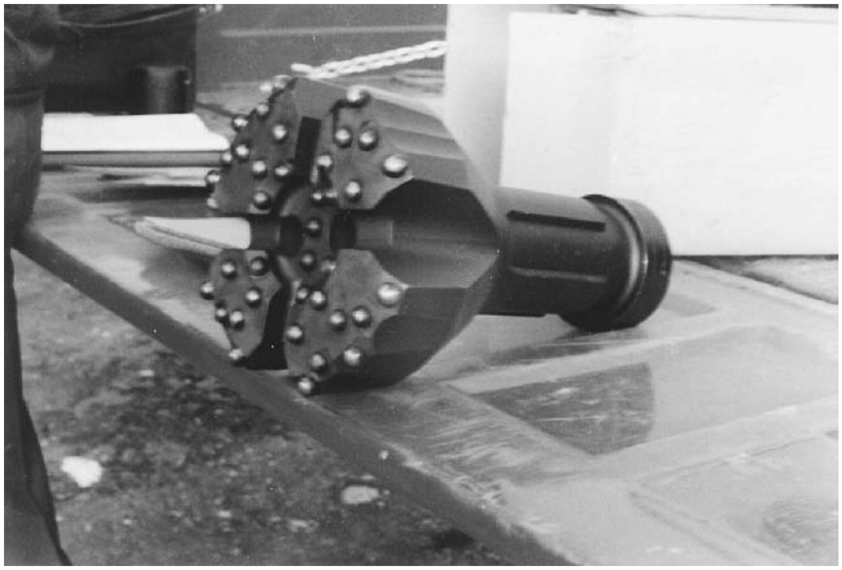

FIGURE 2.4 Diamond drill bit.

2.1.3 Rotary Drilling

In rotary drilling the bore hole is advanced by rapid rotation of the drilling bit, which cuts and grinds the material at the bottom of the hole into small particles. The cuttings are removed by pumping drilling fluid from a sump down through the drill rods and bit, up through the hole from which it flows first into a settling pond, and then back to the main pit.

Rotary drilling with a diamond bit (Figure 2.4) can be used efficiently for drilling through semi-hard rocks. Most truck-mounted drill rigs (Figure 2.5) can be used for rotary drilling with little modification. Core samples are brought up by the drill and can be visually examined. The general characteristics, particularly the percentages of recovery, are of importance to foundation design and construction.

For consultants with limited experience with drilling, it is better to study catalogs from various companies before deciding on the type of equipment best suited for the job. An experienced operator is essential for handling and maintaining the costly equipment.

2.2 INDIRECT METHODS

The geophysical method of exploration is the main indirect method of subsoil exploration.

In subsoil investigation, the seismic method is most frequently used. Seismic methods are based on the variation of the wave velocity in different earth materials. The method involves generating a sound wave in the rock or soil, using a sledge-hammer, a falling weight, or a small explosive charge, and then recording its reception

FIGURE 2.5 Truck-mounted drilling rig.

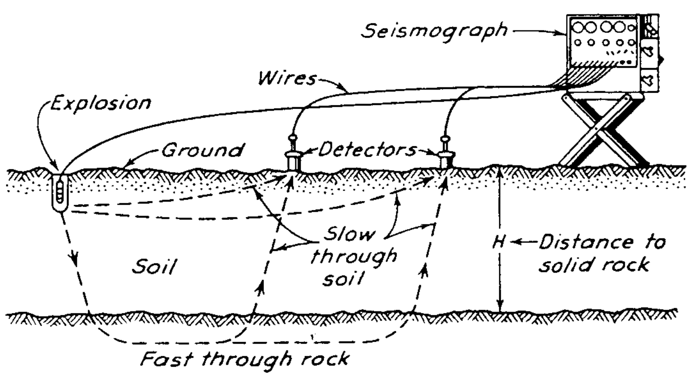

FIGURE 2.6 Diagram of seismic refraction test (after Moore).

at a series of geophones located at various distances from the shot point, as shown in Figure 2.6. The time of the refracted sound arrival at each geophone is noted from a continuous reader. Typical seismic velocities of earth materials in ft/sec are shown in Table 2.1.

TABLE 2.1
Seismic Velocities of the Wave Velocity in Different Earth Materials

Dry silt, silt, loose gravel. loose rocks, talus, and moist fine-grained soil	500–600
Compacted till, indurated clays, gravel below water table compacted clayey gravel, cemented sand, and sandy clay	2500–7500
Rock, weathered, fractured, or partly decomposed	2000–10,000
Sandstone, sound	5000–14,000
Limestone, chalk, sound	6000–20,000
Igneous rock, sound	1200–20,000
Metamorphic rock, sound	1000–16,000

(after Peck, Hanson, and Thornburn)

Seismic exploration requires the following:

1. Equipment to produce an elastic wave, such as a sledgehammer used to strike a plate on the surface;
2. A series of detectors, or geophones, spaced at intervals along a line from the point of origin of the wave;
3. A time-recording mechanism to record the time of origin of the wave and the time of arrival at each detector.

The setup is shown in Figure 2.6.

The advantage of seismic exploration is that it permits a rapid coverage of large areas at a relatively small cost. The method also is not hampered by boulders and cobbles which obstruct borings. Seismic survey is frequently used in regions not accessible to boring equipment, such as the middle of a rapid river.

The disadvantage of the exploration method is the lack of unique interpretation. It is particularly serious when the strata are not uniform in thickness nor horizontal. Irregular contacts often are not identified and the strata of similar geophysical properties sometimes have greatly different properties.

Whenever possible, seismic data should be verified by one or two borings before definite conclusions can be reached. As advice to young engineers, seismic data when used in a geotechnical report should be qualified as to possible error and the margin of error.

2.3 TEST HOLES

The number of the test holes and the depth required for a project depend on the type of foundation system, uniformity of the subsoil condition, and to some extent the importance of the structure.

2.3.1 Test Hole Spacing

If preliminary investigation indicates that shallow footings will be the most likely type of foundation, then it will be desirable to have the drill holes closely spaced to better evaluate the subsoil condition within the loaded depth of the footings. If, however, a shallow foundation system is not feasible and a deep foundation is likely to be required, then the number of test holes can be decreased and the spacing increased.

As a rule of thumb, test holes should be spaced at a distance of 50 to 100 ft. In no case should the test holes be spaced more than 100 ft apart in an expansive soil area or in a problem soil area.

It is a common misconception that drilling of test holes is the major cost of the subsoil investigation. Consequently, there is the tendency to drill as few holes as possible, preferably only one. The risk involved in such an undertaking is enormous. Erratic subsoil conditions can exist between widely spaced test holes.

For the foundation system of a high-rise building in Chicago, a renowned engineer drilled only one test hole, which was the owner's requirement. For a complete investigation, at least four test holes were required. Fortunately, the subsoil within the building area was unusually uniform, and nothing happened to the building.

Closely spaced test holes are especially important where the presence of expansive soils is suspected. For instance, if sandstone and siltstone bedrock are present at a shallow depth, a logical recommendation is to found the structure directly on the bedrock, with spread footing designed for high pressure.

Geotechnical engineers in the Rocky Mountain states, when conducting foundation investigation in a subdivision, insist on drilling one test hole for each lot. This is to ensure that the swelling potential and water table conditions are adequately covered.

Engineers should use special care when dealing with a site containing man-made fill. Since man-made fill is placed at random, it is not possible to delineate the extent of the fill. Field engineers should locate the test holes based on their experience and judgment. Such conditions should be clearly documented in the soil report to avoid possible legal problems.

In one commercial project, the engineer drilled one test hole at each corner on the site of the proposed structure and found the subsoil very uniform. No further drilling appeared to be necessary. During construction, the owner found deep garbage fills at the middle of the site. Such a finding not only required further drilling but also upset the entire recommendations given in the report.

2.3.2 Test Hole Depth

The depth of the test hole required is generally governed by the type of foundation. Before drilling, the field engineer has little conception of the probable foundation system. Therefore, the first hole drilled should be deep enough to provide information pertinent to both shallow and deep foundation systems. Samples in the hole should be taken at frequent intervals, preferably not more than 5 ft apart. After the completion of the deep test hole, the field engineer should have a fairly good idea of the possible foundation system. Consequently, for the subsequent holes, more attention should be directed to the upper soils if a shallow foundation system is likely. If, however, a deep foundation system is contemplated, drilling to bedrock would be necessary for all holes.

Often, the depth to bedrock is the criterion as to the depth of all test holes. Where bedrock is within economical reach, say within 40 ft, it is advisable to drill a few holes into bedrock, irrespective of the foundation system. In the Rocky Mountain region, the depth to the top of the shale is extremely erratic, and the depth to bedrock can increase as much as 30 ft within a short distance. This should be taken into consideration when determining the location and depth of the test holes.

In some cases, deep holes are required, not for the foundation system requirement but for the determination of the water table elevation. For deep basement construction, the depth of the test holes should be at least 20 ft to preclude the possibility of groundwater becoming a problem on the lower floor.

At times, the architect or the structural engineer wants to dictate the location and depth of the test holes. They want to do that as they think the consulting fee for the geotechnical engineers can be better controlled. An established firm should not accept such a restriction. The geotechnical engineers should have a free hand in planning the investigation.

2.3.3 Water in the Test Hole

The depth of the water table as measured during drilling should be carefully evaluated. It is always necessary to wait for at least 24 hours to check on the stabilized water table for the final measurement. Property owners sometimes will not allow open drill holes. The technician should plug the top of the drill holes and flag them for identification.

If the water level in the drill holes is allowed to drop below ground level, when the drill rods are removed rapidly, an upward hydraulic gradient is created in the sand below the drill hole. Consequently, the sands may become quick and the relative density may be greatly reduced. The penetration resistance value will be accordingly much lower than that corresponding to the relative density of the undisturbed sand. Care is required to ensure that the water level in the drill hole is always maintained. Any sudden drop or rise of the water table or a sudden change in the penetration resistance should be carefully recorded in the field log.

2.4 SAMPLING

The purpose of drilling test holes is not only for the observation of the subsoil conditions but also for obtaining representative samples. Both disturbed and undisturbed samples are valuable to geotechnical engineers. The undisturbed samples can be used for the determination of the stress strain characteristics of the material. Certain amounts of disturbance during sampling must be regarded as inevitable.

After accepting the foundation investigation assignment the geotechnical consultant should draft a program of field investigation for the field engineer to follow. The instruction should consist of the frequency and spacing of the test holes, the depth of the test holes, the field test required, etc. The field engineer should use his or her own judgment to determine whether the instruction should be modified. It is important that the field engineer not leave the site until all the information is gathered. The consultant cannot usually afford to investigate the site twice. Unlike some government projects where cost overruns can be tolerated, the consulting business is highly competitive; undue expense generally results in financial loss.

2.4.1 Disturbed Samples

Disturbed samples can be collected during the drilling process. Sometimes they can be collected without interrupting the operation. Samples can be collected from the auger cuttings at intervals. The field engineer should be sure that soils from different strata will not become mixed during drilling. Samples collected must represent soils from each different stratum. Disturbed samples can be stored in fruit jars. They should be sealed to retain the in situ moisture content and properly labeled.

In test pit excavation, large samples will sometimes be required in order to fulfill the laboratory testing requirements. Such samples should be at least 12 × 12 in. in size, wrapped in wax paper, and carefully transported to the laboratory. After it is carefully trimmed to the desired size, such a sample can be considered as undisturbed.

Representative samples can usually be obtained by driving into the ground an open-ended cylinder known as "Split Spoon." Spoons with an inside diameter of about 2 in. consist of 4 parts: a cutting shoe at the bottom; a barrel consisting of a length of pipe split into one half; and a coupling at the top for connection to the drill rod.

2.4.2 Undisturbed Samples

A very simple sampler consists of a section of thin-walled "Shelby" or seamless steel tubing which is attached to an adapter, as shown in Figure 2.7. The adapter or the sampler head contains a check valve and vents for the escape of air or water. A sample can be obtained by pushing the sampler into the soil at the desired depth. The operation must be performed carefully so as to experience minimum deformation. The principal advantages of the Shelby tube sampler are its simplicity and the minimal disturbance of soil.

A modification in the design of the split spoon sampler allows the insertion of brass thin-wall liners into the barrel. Four sections of brass liners (each 4 in. long) are used. Such a device allows the sampling and penetration test at the same time. This method was initiated in California by Woodward, Clyde and Associates and is known as the "California" sampler. It has been adopted throughout the Western U.S.

Samples of rock are generally obtained by rotary core drilling. Diamond core drilling is primarily in medium-hard to hard rock. Special diamond core barrels up to 8 in. in diameter are occasionally used and still larger ones have been built.

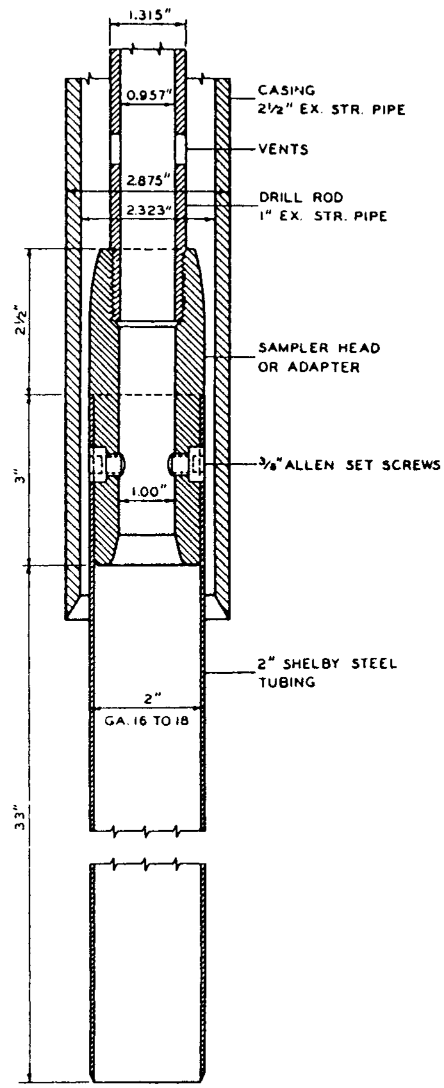

FIGURE 2.7 Shelby Tubing Sampler (after Moore).

In China, during the foundation investigation of the world's largest dam, the Three Gorges Dam, a special coring machine was used. The cores were up to 42 in. diameters and were taken at depths of about 200 ft deep, as shown in Figure 2.8. Such large samples enable the geologist to study the formation and texture of the foundation rock in detail.