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Geotechnical Considerations

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Thomas W. McNeilan
Fugro West, Inc.

James Chai
*California Department
of Transportation*

30.1 Introduction

A complete geotechnical study of a site will (1) determine the subsurface stratigraphy and stratigraphic relationships (and their variability), (2) define the physical properties of the earth materials, and (3) evaluate the data generated and formulate solutions to the project-specific and site-specific geotechnical issues. Geotechnical issues that can affect a project can be broadly grouped as follows:

- *Foundation Issues* — Including the determination of the strength, stability, and deformations of the subsurface materials under the loads imposed by the structure foundations, in and beneath slopes and cuts, or surrounding the subsurface elements of the structure.
- *Earth Pressure Issues* — Including the loads and pressures imposed by the earth materials on foundations and against supporting structures, or loads and pressures created by seismic (or other) external forces.

- *Construction and Constructability Considerations* — Including the extent and characteristics of materials to be excavated, and the conditions that affect deep foundation installation or ground improvement.
- *Groundwater Issues* — Including occurrence, hydrostatic pressures, seepage and flow, and erosion.

Site and subsurface characteristics directly affect the choice of foundation type, capacity of the foundation, foundation construction methods, and bridge cost. Subsurface and foundation conditions also frequently directly or indirectly affect the route alignment, bridge type selection, and/or foundation span lengths. Therefore, an appropriately scoped and executed foundation investigation and site characterization should:

1. Provide the required data for the design of safe, reliable, and economic foundations;
2. Provide data for contractors to use to develop appropriate construction cost estimates;
3. Reduce the potential for a “changed condition” claim during construction.

In addition, the site investigation objectives frequently may be to

1. Provide data for route selection and bridge type evaluation during planning and preliminary phase studies;
2. Provide data for as-built evaluation of foundation capacity, ground improvement, or other similar requirements.

For many projects, it is appropriate to conduct the geotechnical investigation in phases. For the first preliminary (or reconnaissance) phase, either a desktop study using only historical information or a desktop study and a limited field exploration program may be adequate. The results of the first-phase study can then be used to develop a preliminary geologic model of the site, which is used to determine the key foundation design issues and plan the design-phase site investigation.

Bridge projects may require site investigations to be conducted on land, over water, and/or on marginal land at the water’s edge. Similarly, site investigations for bridge projects can range from conventional, limited-scope investigations for simple overpasses and grade separations to major state-of-the-practice investigations for large bridges over major bodies of water.

This chapter includes discussions of

- Field exploration techniques;
- Definition of the requirements for and extent of the site investigation program;
- Evaluation of the site investigation results and development/scoping of the laboratory testing program;
- Data presentation and site characterization.

The use of the site characterization results for foundation design is included in subsequent chapters.

30.2 Field Exploration Techniques

For the purpose of the following discussion, we have divided field exploration techniques into the following groupings:

- Borings (including drilling, soil sampling, and rock-coring techniques)
- Downhole geophysical logging
- *In situ* testing — including cone penetration testing (CPT) and vane shear, pressure meter and dilatometer testing)
- Test pits and trenches
- Geophysical survey techniques

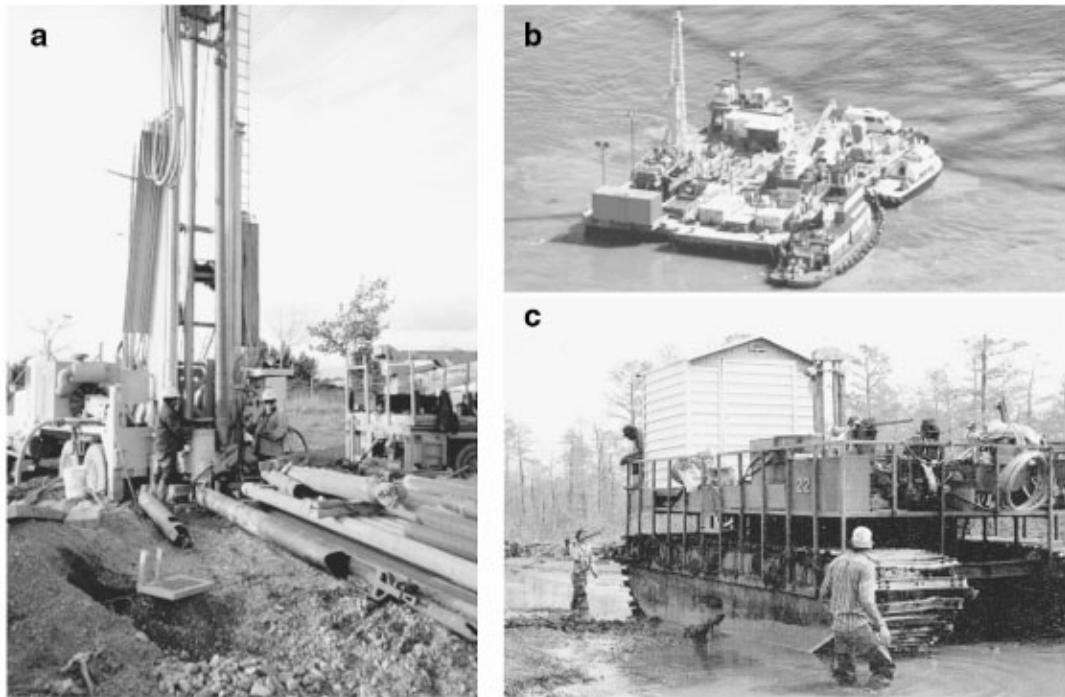


FIGURE 30.1 Drilling methods. (a) On land; (b) over water; (c); on marginal land.

30.2.1 Borings and Drilling Methods

Drilled soil (or rock) borings are the most commonly used subsurface exploration technique. The drilled hole provides the opportunity to collect samples of the subsurface through the use of a variety of techniques and samplers. In addition to sample collection, drilling observations during the advancement of the borehole provide an important insight to the subsurface conditions. Drilling methods can be used for land, over water, and marginal land sites (Figure 30.1). It should be noted that the complexity introduced when working over water or on marginal land may require more-sophisticated and more-specialized equipment and techniques, and will significantly increase costs.

30.2.1.1 Wet (Mud) Rotary Borings

Wet rotary drilling is the most commonly used drilling method for the exploration of soil and rock, and also is used extensively for oil exploration and water well installation. It is generally the preferred method for (1) over water borings; (2) where groundwater is shallow; and (3) where the subsurface includes soft, squeezing, or flowing soils.

With this technique, the borehole is advanced by rapid rotation of the drill bit that cuts, chips, and grinds the material at the bottom of the borehole. The cuttings are removed from the borehole by circulating water or drilling fluid down through the drill string to flush the cuttings up through the annular space of the drill hole. The fluids then flow into a settling pit or solids separator. Drilling fluid is typically bentonite (a highly refined clay) and water, or one of a number of synthetic products. The drilling fluids are used to flush the cuttings from the hole, compensate the fluid pressure, and stabilize borehole sidewalls. In broken or fractured rock, coarse gravel and cobbles, or other formations with voids, it may be necessary to case the borehole to prevent loss of circulation. Wet rotary drilling is conducive to downhole geophysical testing, although the borehole must be thoroughly flushed before conducting some types of logging.

30.2.1.2 Air Rotary Borings

The air rotary drilling technology is similar to wet rotary except that the cuttings are removed with the circulation of high-pressure air rather than a fluid. Air rotary drilling techniques are typically used in hard bedrock or other conditions where drill hole stability is not an overriding issue. In very hard bedrock, a percussion hammer is often substituted for the bit. Air rotary drilling is conducive to downhole geophysical testing methods.

30.2.1.3 Bucket-Auger Borings

The rotary bucket is similar to a large- (typically 18- to 24-in.)-diameter posthole digger with a hinged bottom. The hole is advanced by rotating the bucket at the end of a kelly bar while pressing it into the soil. The bucket is removed from the hole to be emptied. Rotary-bucket-auger borings are used in alluvial soils and soft bedrock. This method is not always suitable in cobbly or rocky soils, but penetration of hard layers is sometimes possible with special coring buckets. Bucket-auger borings also may be unsuitable below the water table, although drilling fluids can be used to stabilize the borehole.

The rotary-bucket-auger drilling method allows an opportunity for continuous inspection and logging of the stratigraphic column of materials, by lowering the engineer or geologist on a platform attached to a drill rig winch. It is common in slope stability and fault hazards studies to downhole log 24-in.-diameter, rotary-bucket-auger boreholes advanced with this method.

30.2.1.4 Hollow-Stem-Auger Borings

The hollow-stem-auger drilling technique is frequently used for borings less than 20 to 30 m deep. The proliferation of the hollow-stem-auger technology in recent years occurred as the result of its use for contaminated soils and groundwater studies. The hollow-stem-auger consists of sections of steel pipe with welded helical flanges. The shoe end of the pipe has a hollow bit assembly that is plugged while rotating and advancing the auger. That plug is removed for advancement of the sampling device ahead of the bit.

Hollow-stem-auger borings are used in alluvial soils and soft bedrock. This method is not always suitable where groundwater is shallow or in cobbly and rocky soils. When attempting to sample loose, saturated sands, the sands may flow into the hollow auger and produce misleading data. The hollow-stem-auger drill hole is not conducive to downhole geophysical testing methods.

30.2.1.5 Continuous-Flight-Auger Borings

Continuous-flight-auger borings are similar to the hollow-stem-auger drilling method except that the auger must be removed for sampling. With the auger removed, the borehole is unconfined and hole instability often results. Continuous-flight-auger drill holes are used for shallow exploration above the groundwater level.

30.2.2 Soil-Sampling Methods

There are several widely used methods for recovering samples for visual classification and laboratory testing.

30.2.2.1 Driven Sampling

Driven sampling using standard penetration test (SPT) or other size samplers is the most widely used sampling method. Although this sampling method recovers a disturbed sample, the “blow count” measured with this type of procedure provides a useful index of soil density or strength. The most commonly used blow count is the SPT blow count (also referred to as the N-value). Although the N-value is an approximate and imprecise measurement (its value is affected by many operating factors that are part of the sampling process, as well as the presence of gravel or cementation), various empirical relationships have been developed to relate N-value to engineering and performance properties of the soils.

30.2.2.2 Pushed Samples

A thin-wall tube (or in some cases, other types of samplers) can be pushed into the soil using hydraulic pressure from the drill rig, the weight of the drill rod, or a fixed piston. Pushed sampling generally recovers samples that are less disturbed than those recovered using driven-sampling techniques. Thus, laboratory tests to determine strength and volume change characteristics should preferably be conducted on pushed samples rather than driven samples. Pushed sampling is the preferred sampling method in clay soils. Thin-wall samples recovered using push-sampling techniques can either be extruded in the field or sealed in the tubes.

30.2.2.3 Drilled or Cored Samplers

Drilled-in samplers also have application in some types of subsurface conditions, such as hard soil and soft rock. With these types of samplers (e.g., Denison barrel and pitcher barrel), the sample barrel is either cored into the sediment or rock or is advanced inside the drill rod while the rod is advanced.

30.2.3 Rock Coring

The two rock-coring systems most commonly used for engineering applications are the conventional core barrel and wireline (retrievable) system. At shallow depths above the water table, coring also sometimes can be performed with an air or a mist system.

Conventional core barrels consist of an inner and outer barrel with a bit assembly. To obtain a core at a discrete interval; (1) the borehole is advanced to the top of the desired interval, (2) the drill pipe is removed, (3) the core barrel/bit is placed on the bottom of the pipe, and (4) the assembly is run back to the desired depth. The selected interval is cored and the core barrel is removed to retrieve the core. Conventional systems typically are most effective at shallow depths or in cases where only discrete samples are required.

In contrast, wireline coring systems allow for continuous core retrieval without removal of the drill pipe/bit assembly. The wireline system has a retrievable inner core barrel that can be pulled to the surface on a wireline after each core run.

Variables in the coring process include the core bit type, fluid system, and drilling parameters. There are numerous bit types and compositions that are applicable to specific types of rock; however, commercial diamond or diamond-impregnated bits are usually the preferred bit from a core recovery and quality standpoint. Tungsten carbide core bits can sometimes be used in weak rock or in high-clay-content rocks. A thin bentonite mud is the typical drilling fluid used for coring. Thick mud can clog the small bit ports and is typically avoided. Drilling parameters include the revolutions per minute (RPM) and weight on bit (WOB). Typically, low RPM and WOB are used to start the core run and then both values are increased.

Rock engineering parameters include percent recovery, rock quality designation (RQD), coring rate, and rock strength. Percent recovery is a measure of the core recovery vs. the cored length, whereas RQD is a measure of the intact core pieces longer than 4 in. vs. the cored length. Both values typically increase as the rock mass becomes less weathered/fractured with depth; however, both values are highly dependent on the type of rock, amount of fracturing, etc. Rock strength (which is typically measured using unconfined triaxial compression test per ASTM guidelines) is used to evaluate bearing capacity, excavability, etc.

30.2.4 *In Situ* Testing

There are a variety of techniques that use instrumented probes or testing devices to measure soil properties and conditions in the ground, the more widely used of which are described below. In contrast to sampling that removes a sample from its *in situ* stress conditions, *in situ* testing is used to measure soil and rock properties in the ground at their existing state of stress. The various *in*

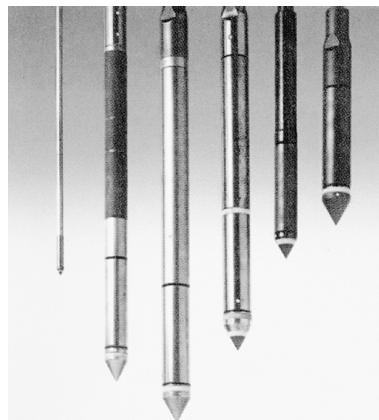


FIGURE 30.2 CPT cones.

situ tests can either be conducted in a borehole or as a continuous sounding from the ground surface. Except as noted, those techniques are not applicable to rock.

30.2.4.1 Cone Penetration Test Soundings

CPT sounding is one of the most versatile and widely used *in situ* test. The standard CPT cone consists of a 1.4-in.-diameter cone with an apex angle of 60°, although other cone sizes are available for special applications (Figure 30.2). The cone tip resistance beneath the 10-cm² cone tip and the friction along the 150 cm² friction sleeve are measured with strain gauges and recorded electronically at 1- or 2-cm intervals as the cone is advanced into the ground at a rate of about 2 cm/s. In addition to the tip and sleeve resistances, many cones also are instrumented to record pore water pressure or other parameters as the cone is advanced.

Because the CPT soundings provide continuous records of tip and sleeve resistances (and frequently pore pressure) vs. depth (Figure 30.3), they provide a continuous indicator of soil and subsurface conditions that are useful in defining soil stratification. Numerous correlations between the CPT measurements have been developed to define soil type and soil classification. In addition, empirical correlations have been published to relate the cone tip and sleeve friction resistances to engineering behavior, including undrained shear strength of clay soils and relative density and friction of granular soils.

Most land CPTs are performed as continuous soundings using large 20-ton cone trucks (Figure 30.4a), although smaller, more portable track-mounted equipment is also available. CPT soundings are commonly extended down to more than 20 to 50 m. CPT soundings also can be performed over water from a vessel using specialized equipment (Figure 30.4b) deployed by a crane or from a stern A-frame. In addition, downhole systems have been developed to conduct CPTs in boreholes during offshore site investigations. With a downhole system, CPT tests are interspersed with soil sampling to obtain CPT data to more than 100 m in depth.

30.2.4.2 In Situ Vane Shear Tests

The undrained shear strength of clay soils can be measured *in situ* using a vane shear test. This test is conducted by measuring the torque required to rotate a vane of known dimensions. The test can be conducted from the ground surface by attaching a vane blade onto a rod or downhole below the bottom of a borehole with a drop-in remote vane (Figure 30.5). The downhole vane is preferable, since the torque required to rotate the active rotating vane is not affected by the torque of the rod. The downhole vane is used both for land borings and over-water borings.

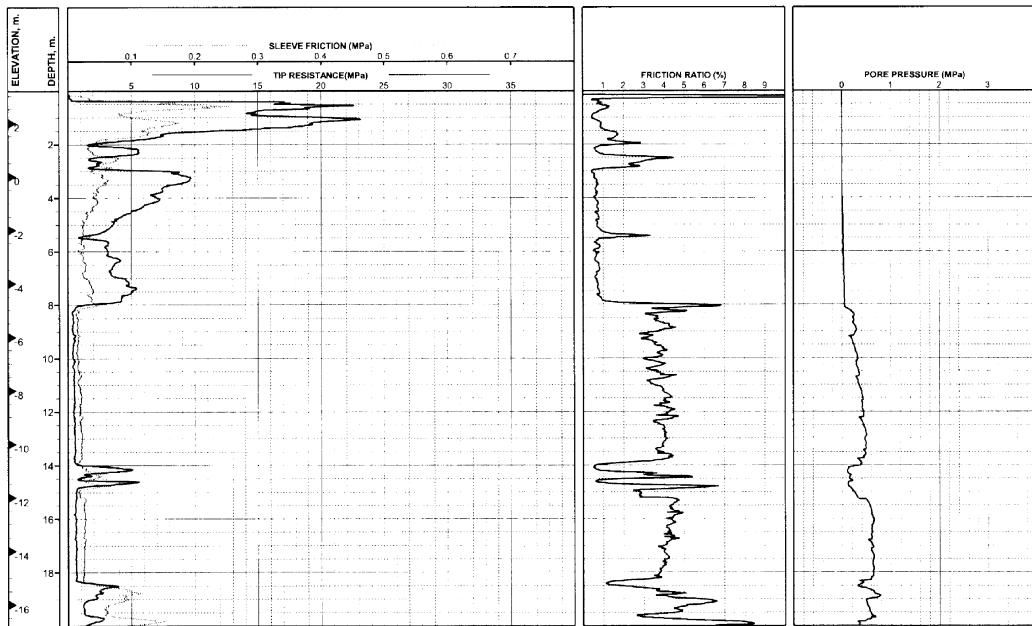


FIGURE 30.3 CPT data provide a continuous record of *in situ* conditions.

30.2.4.3 Pressure Meter and Dilatometer Tests

Pressure meter testing is used to measure the *in situ* maximum and average shear modulus of the soil or rock by inflating the pressure meter against the sidewalls of the borehole. The stresses, however, are measured in a horizontal direction, not in the vertical direction as would occur under most types of foundation loading. A test is performed by lowering the tool to the selected depth and expanding a flexible membrane through the use of hydraulic fluid. As the tool is inflated, the average displacement of the formation is measured with displacement sensors beneath the membrane, which is protected by stainless steel strips. A dilatometer is similar to a pressure meter, except that the dilatometer consists of a flat plate that is pushed into the soil below the bottom of the borehole. A dilatometer is not applicable to hard soils or rock.

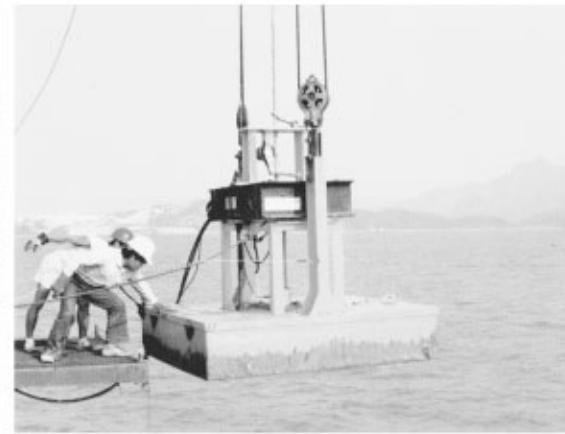
30.2.5 Downhole Geophysical Logging

Geophysical logs are run to acquire data about the formation or fluid penetrated by the borehole. Each log provides a continuous record of a measured value at a specific depth in the boring, and is therefore useful for interpolating stratigraphy between sample intervals. Most downhole geophysical logs are presented as curves on grid paper or as electronic files (Figure 30.6). Some of the more prevalent geophysical tools, which are used for geotechnical investigations, are described below.

- *Electrical logs (E-logs)* include resistivity, induction, and spontaneous potential (SP) logs. Resistivity and induction logs are used to determine lithology and fluid type. A resistivity log is used when the borehole is filled with a conductive fluid, while an induction log is used when the borehole is filled with a non- or low-conductivity fluid. Resistivity tools typically require an open, uncased, fluid-filled borehole. Clay formations and sands with higher salinity will have low resistivity, while sands with fresh water will have higher resistivity values. Hard rock and dry formations have the highest resistivity values. An SP log is often used in suite with a resistivity or induction log to provide further information relative to formation permeability and lithology.



(a)



(b)

FIGURE 30.4 CPT sounding methods. (a) On land; (b) over water.



FIGURE 30.5 *In situ* vane shear device.

- *Suspension (velocity) logs* are used to measure the average primary, compression wave, and shear wave velocities of a 1-m-high segment of the soil and rock column surrounding the borehole. Those velocities are determined by measuring the elapsed time between arrivals of a wave propagating upward through the soil/rock column. The suspension probe includes both a shear wave source and a compression wave source, and two biaxial receivers that detect the source waves. This technique requires an open, fluid-filled hole.
- *Natural gamma logs* measure the natural radioactive decay occurring in the formation to infer soil or rock lithology. In general, clay soils will exhibit higher gamma counts than granular soils, although decomposed granitic sands are an exception to that generality. Gamma logs can be run in any salinity fluid as well as air, and also can be run in cased boreholes.
- *Caliper logs* are used to measure the diameter of a borehole to provide insight relative to caving and swelling. An accurate determination of borehole diameter also is important for the interpretation of other downhole logs.
- *Acoustic televIEWer and digital borehole logs* are conducted in rock to image the rock surface within the borehole (Figure 30.7). These logs use sound in an uncased borehole to create an oriented image of the borehole surface. These logs are useful for determining rock layering, bedding, and fracture identification and orientation.
- *Crosshole, downhole, and uphole shear wave velocity measurements* are used to determine the primary and shear wave velocities either to determine the elastic soil properties of soil and rock or to calibrate seismic survey measurements. With the crosshole technique, the travel time is measured between a source in one borehole and a receiver in a second borehole. This technique can be used to measure directly the velocities of various strata. For downhole and uphole logs, the travel time is measured between the ground surface and a downhole source or receiver. Tests are conducted with the downhole source or receiver at different depths. These measurements should preferably be conducted in cased boreholes.

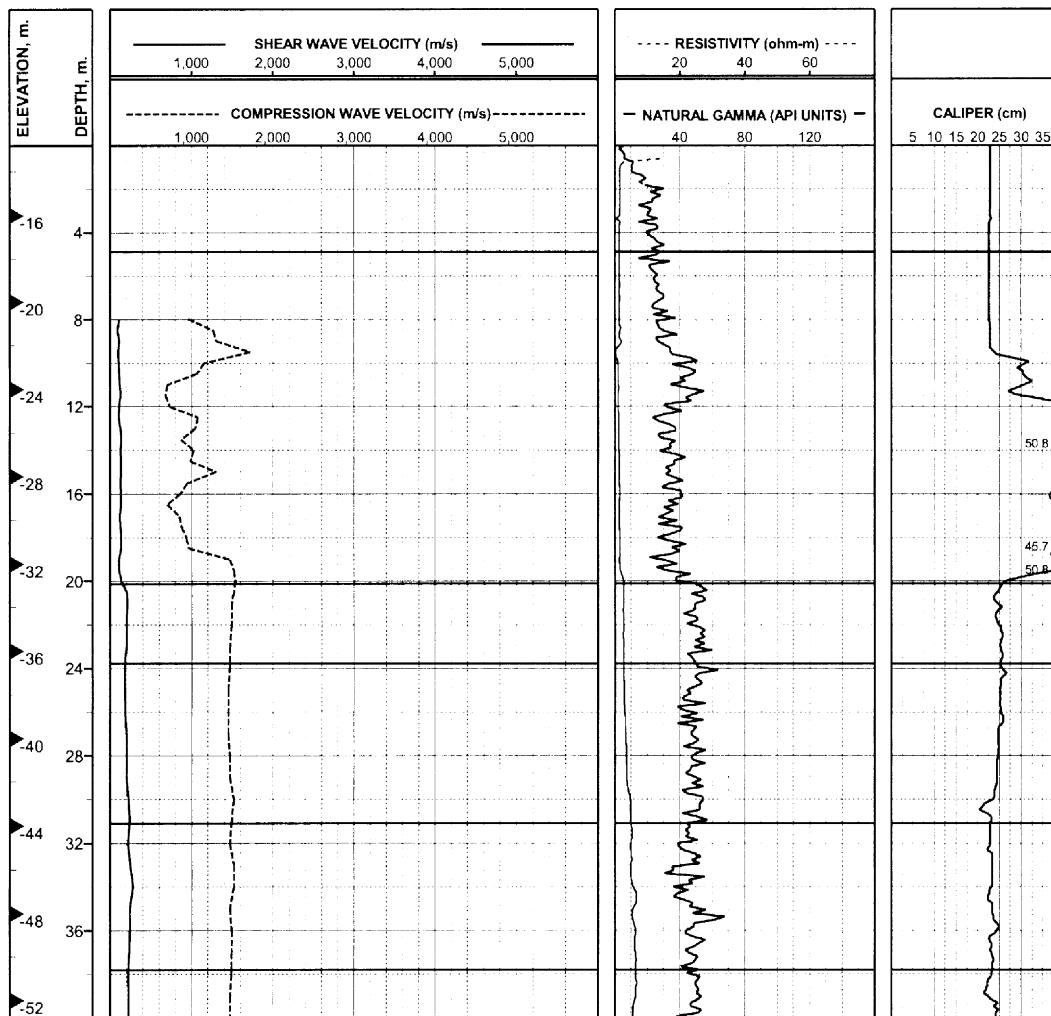


FIGURE 30.6 Example of downhole geophysical log.

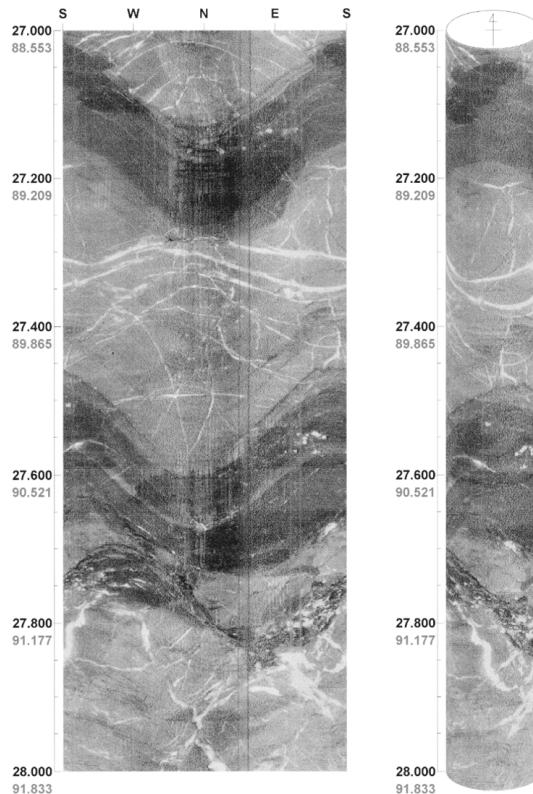
30.2.6 Test Pits and Trenches

Where near-surface conditions are variable or problematic, the results of borings and *in situ* testing can be supplemented by backhoe-excavated or hand-excavated test pits or trenches. These techniques are particularly suitable for such purposes as: (1) collecting hand-cut, block samples of sensitive soils; (2) evaluating the variability of heterogeneous soils; (3) evaluating the extent of fill or rubble, (4) determining depth to groundwater, and (5) the investigation of faulting.

30.2.7 Geophysical Survey Techniques

Noninvasive (compared with drilling methods) geophysical survey techniques are available for remote sensing of the subsurface. In contrast to drilling and *in situ* testing methods, the geophysical survey methods explore large areas rapidly and economically. When integrated with boring data, these methods often are useful for extrapolating conditions between borings (Figure 30.8). Techniques are applicable either on land or below water. Some of the land techniques also are applicable for marginal land or in the shallow marine transition zone. Geophysical survey techniques can be used individually or as a group.

Depth range: 27.000 - 28.000 m



Scale: 1/5

FIGURE 30.7 Example of digital borehole image in rock.

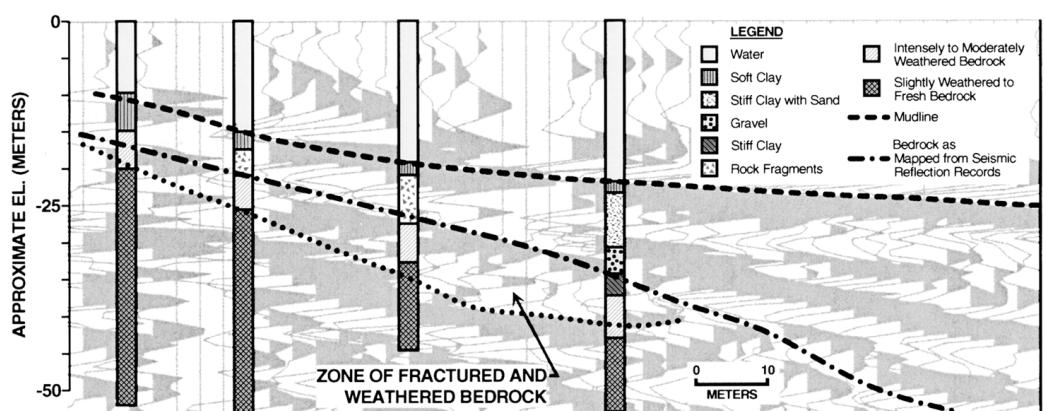


FIGURE 30.8 Example integration of seismic reflection and boring data.

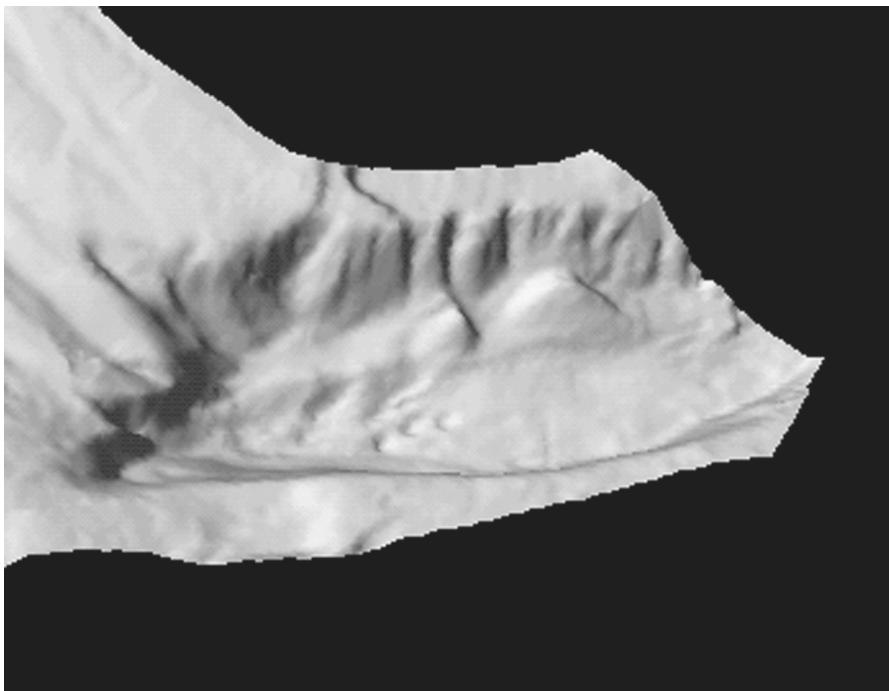


FIGURE 30.9 Multibeam image of river channel bathymetry.

30.2.7.1 Hydrographic Surveys

Hydrographic surveys provide bathymetric contour maps and/or profiles of the seafloor, lake bed, or river bottom. Water depth measurements are usually made using a high-frequency sonic pulse from a depth sounder transducer mounted on a survey vessel. The choice of depth sounder system (single-beam, multifrequency, multibeam, and swath) is dependent upon water depths, survey site conditions, and project accuracy and coverage requirements. The use and application of more-sophisticated multibeam systems (Figure 30.9) has increased dramatically within the last few years.

30.2.7.2 Side-Scan Sonar

Side-scan sonar is used to locate and identify man-made objects (shipwrecks, pipelines, cables, debris, etc.) on the seafloor and determine sediment and rock characteristics of the seafloor. The side-scan sonar provides a sonogram of the seafloor that appears similar to a continuous photographic strip (Figure 30.10). A mosaic of the seafloor can be provided by overlapping the coverage of adjacent survey lines.

30.2.7.3 Magnetometer

A magnetometer measures variations in the earth's magnetic field strength that result from metallic objects (surface or buried), variations in sediment and rock mineral content, and natural (diurnal) variations. Data are used to locate and identify buried objects for cultural, environmental, and archaeological site clearances.

30.2.7.4 High-Resolution Seismic Reflection and Subbottom Profilers

Seismic images of the subsurface beneath the seafloor can be developed by inducing sonic waves into the water column from a transducer, vibrating boomer plate, sparker, or small air or gas gun. Reflections of the sonic energy from the mudline and subsurface soils horizons are recorded to provide an image of the subsurface geologic structure and stratigraphy along the path of the survey

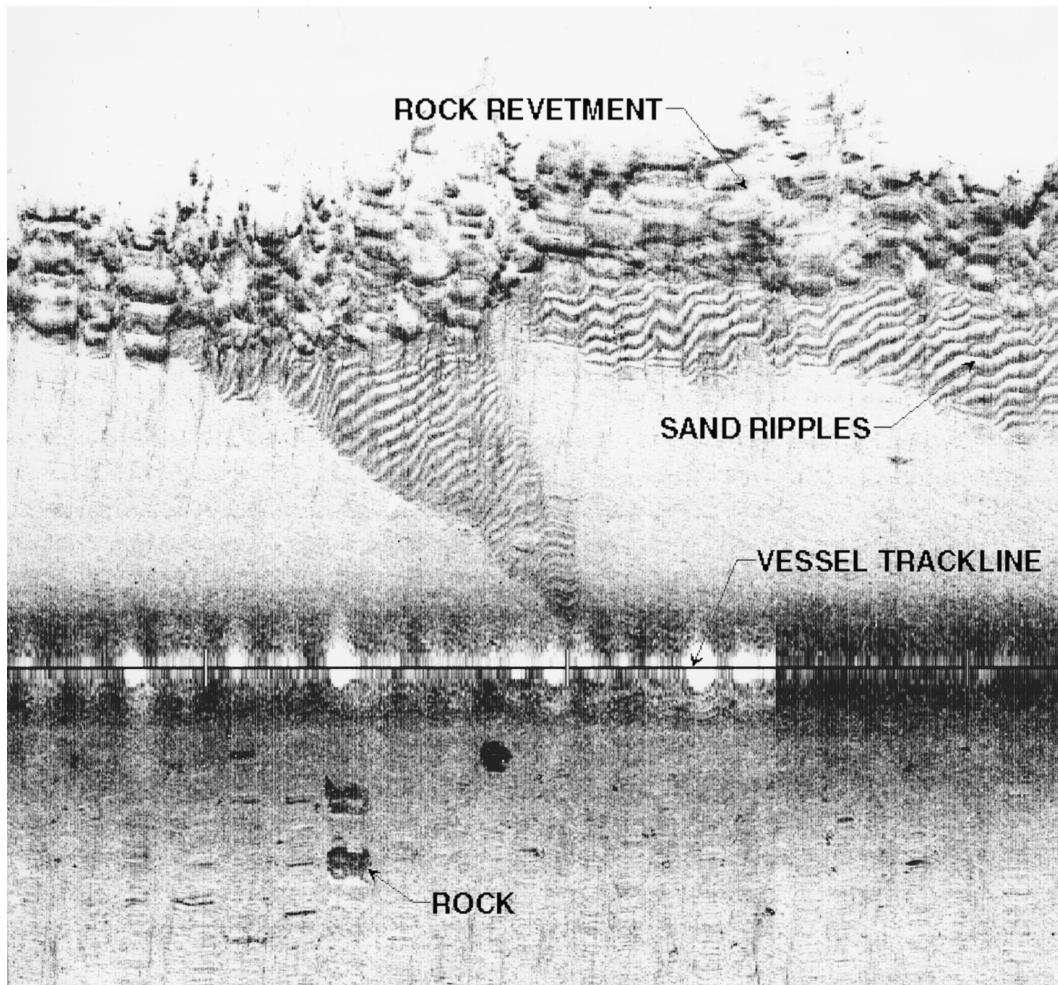


FIGURE 30.10 Side-scan sonar image of river bottom.

vessel. The effective depth of a system and resolution of subsurface horizons depend on a number of variables, including the system energy, output frequency spectrum, the nature of the seafloor, and the subsea sediments and rocks. Seismic reflection data are commonly used to determine the geologic structure (stratigraphy, depth to bedrock, folds, faults, subsea landslides, gas in sediments, seafloor seeps, etc.) and evaluate the horizon continuity between borings (Figure 30.11).

30.2.7.5 Seismic Refraction

Seismic refraction measurements are commonly used on land to estimate depth to bedrock and groundwater and to detect bedrock faulting. Measured velocities are also used for estimates of rippability and excavation characteristics. In the refraction technique, sonic energy is induced into the ground and energy refracted from subsurface soil and rock horizons is identified at a series of receivers laid out on the ground. The time-distance curves from a series of profiles are inverted to determine depths to various subsurface layers and the velocity of the layers. The data interpretation can be compromised where soft layers underlie hard layers and where the horizons are too thin to be detected by refraction arrivals at the surface. The technique also can be used in shallow water (surf zones, lakes, ponds, and river crossings) using bottom (bay) cables.

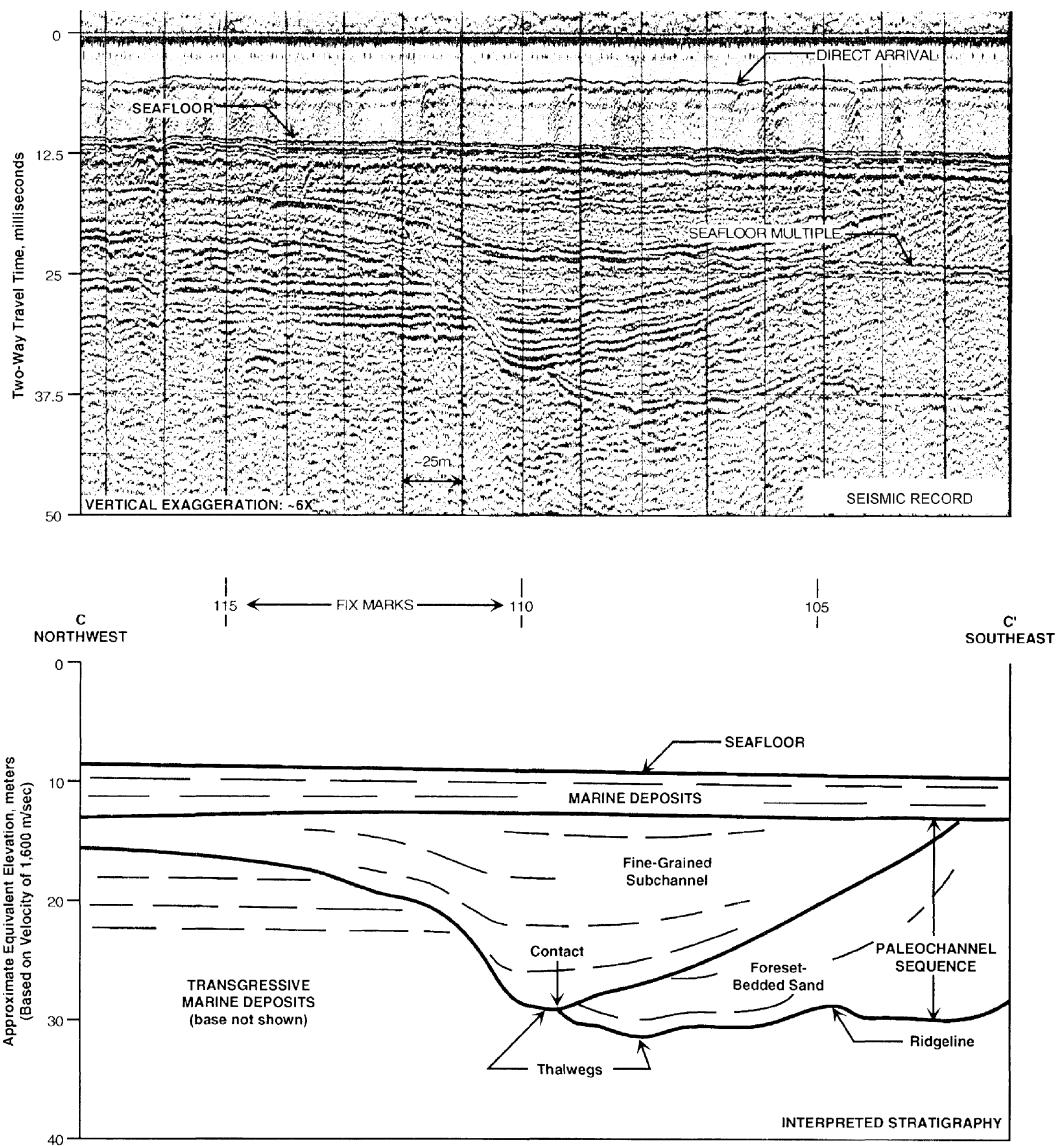


FIGURE 30.11 Interpreted stratigraphic relationships from seismic reflection data.

30.2.7.6 Ground Penetrating Radar Systems

Ground Penetrating Radar (GPR) systems measure the electromagnetic properties of the subsurface to locate buried utilities or rebar, estimate pavement thickness, interpret shallow subsurface stratigraphy, locate voids, and delineate bedrock and landslide surfaces. GPR also can be used in arctic conditions to estimate ice thickness and locate permafrost. Depths of investigation are usually limited to 50 ft or less. Where the surface soils are highly conductive, the effective depth of investigation may be limited to a few feet.

30.2.7.7 Resistivity Surveys

Resistivity surveys induce currents into the ground to locate buried objects and to investigate shallow groundwater. As electrodes are moved in specific patterns of separation, the resistivity is measured

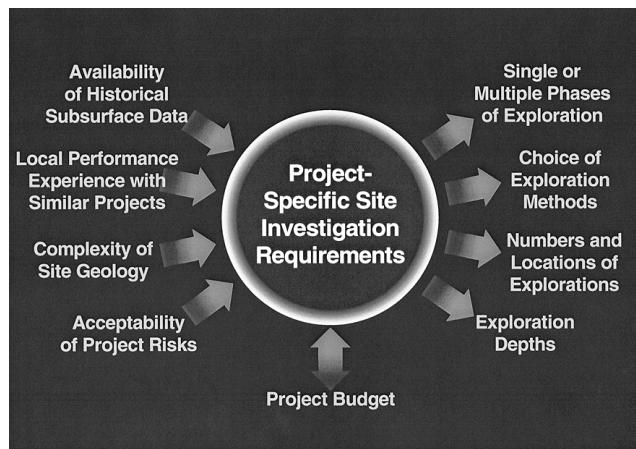


FIGURE 30.12 Key factors to consider when defining site investigation requirements.

and inverted to produce depth sections and contour maps of subsurface resistivity values. This method is used to identify and map subsurface fluids, including groundwater, surface and buried chemical plumes, and to predict corrosion potential.

30.2.8 Groundwater Measurement

Groundwater conditions have a profound effect on foundation design, construction, and performance. Thus, the measurement of groundwater depth (or depth of water when drilling over water) is one of the most fundamentally important elements of the site investigation. In addition to the measurement of the water level, the site investigation should consider and define the potential for artesian or perched groundwater. It is also important to recognize that groundwater levels may change with season, rainfall, or other temporal reasons. All groundwater and water depth measurements should document the time of measurement and, where practical, should determine variations in depth over some period of elapsed time. To determine the long-term changes in water level, it is necessary to install and monitor piezometers or monitoring wells.

30.3 Defining Site Investigation Requirements

Many factors should be considered when defining the requirements (including types, numbers, locations, and depths of explorations) for the site investigation (Figure 30.12). These factors include:

- Importance, uncertainty, or risk associated with bridge design, construction, and performance
- Geologic conditions and their potential variability
- Availability (or unavailability) of historical subsurface data
- Availability (or unavailability) of performance observations from similar nearby projects
- Investigation budget

The following factors should be considered when evaluating the project risk: (1) What are the risks? (2) How likely are the risks to be realized? (3) What are the consequences if the risks occur? Risks include:

- Certainty or uncertainty of subsurface conditions;
- Design risks (e.g., possibility that inadequate subsurface data will compromise design decisions or schedule);
- Construction risks (e.g., potential for changed conditions claims and construction delays);
- Performance risks (e.g., seismic performance).

Two additional requirements that should be considered when planning a subsurface investigation are (1) reliability of the data collected and (2) timeliness of the data generated. Unfortunately, these factors are too often ignored or underappreciated during the site investigation planning process or geotechnical consultant selection process. Because poor-quality or misleading subsurface data can lead to inappropriate selection of foundation locations, foundation types, and/or inadequate or inappropriate foundation capacities, selection of a project geotechnical consultant should be based on qualifications rather than cost. Similarly, the value of the data generated from the subsurface investigation is reduced if adequate data are not available when the design decisions, which are affected by subsurface conditions, are made. All too often, the execution of the subsurface exploration program is delayed, and major decisions relative to the general structure design and foundation locations have been cast in stone prior to the availability of the subsurface exploration results.

Frequently, the execution of the subsurface investigation is an iterative process that should be conducted in phases (i.e., desktop study, reconnaissance site investigation, detailed design-phase investigation). During each phase of site exploration, it is appropriate for data to be reviewed as they are generated so that appropriate modifications can be made as the investigation is ongoing. Appropriate adjustments in the investigation work scope can save significant expense, increase the quality and value of the investigation results, and/or reduce the potential for a remobilization of equipment to fill in missing information.

30.3.1 Choice of Exploration Methods and Consideration of Local Practice

Because many exploration techniques are suitable in some subsurface conditions, but not as suitable or economical in other conditions, the local practice for the methods of exploration vary from region to region. Therefore, the approach to the field exploration program should consider and be tailored to the local practice. Conversely, there are occasions where the requirements for a project may justify using exploration techniques that are not common in the project area. The need to use special techniques will increase with the size of the project and the uniqueness or complexity of the site conditions.

30.3.2 Exploration Depths

The depths to which subsurface exploration should be extended will depend on the structure, its size, and the subsurface conditions at the project location. The subsurface exploration for any project should extend down through unsuitable layers into materials that are competent relative to the design loads to be applied by the bridge foundations. Some of the exploration should be deep enough to verify that unsuitable materials do not exist beneath the bearing strata on which the foundations will be embedded. When the base of the foundation is underlain by layers of compressible material, the exploration should extend down through the compressible strata and into deeper strata whose compressibility will not influence foundation performance.

For lightly loaded structures, it may be adequate to terminate the exploration when rock is encountered, provided that the regional geology indicates that unsuitable strata do not underlie the rock surface. For heavily-loaded foundations or foundations bearing on rock, it is appropriate to verify that the explorations indeed have encountered rock and not a boulder. It is similarly appropriate to extend at least some of the explorations through the weathered rock into sound or fresh rock.

30.3.3 Numbers of Explorations

The basic intent of the site investigation is to determine the subsurface stratigraphy and its variations, and to define the representative soil (or rock) properties of the strata together with their lateral and vertical variations. The locations and spacing of explorations should be adequate to provide a reasonably accurate definition of the subsurface conditions, and should disclose the presence of any important irregularities in the subsurface conditions. Thus, the numbers of explorations will depend on both the project size and the geologic and depositional variability of the site location. When subsurface conditions are complex and variable, a greater number of more closely spaced explorations are

warranted. Conversely, when subsurface conditions are relatively uniform, fewer and more widely spaced explorations may be adequate.

30.3.4 The Risk of Inadequate Site Characterization

When developing a site exploration program, it is often tempting to minimize the number of explorations or defer the use of specialized techniques due to their expense. The approach of minimizing the investment in site characterization is fraught with risk. Costs saved by the execution of an inadequate site investigation, whether in terms of the numbers of explorations or the exclusion of applicable site investigation techniques, rarely reduce the project cost. Conversely, the cost saved by an inadequate investigation frequently increases the cost of construction by many times the savings achieved during the site investigation.

30.4 Development of Laboratory Testing Program

30.4.1 Purpose of Testing Program

Laboratory tests are performed on samples for the following purposes:

- Classify soil samples;
- Evaluate basic index soil properties that are useful in evaluating the engineering properties of the soil samples;
- Measure the strength, compressibility, and hydraulic properties of the soils;
- Evaluate the suitability of on-site or borrow soils for use as fill;
- Define dynamic parameters for site response and soil–structure interaction analyses during earthquakes;
- Identify unusual subsurface conditions (e.g., presence of corrosive conditions, carbonate soils, expansive soils, or potentially liquefiable soils).

The extent of laboratory testing is generally defined by the risks associated with the project.

Soil classification, index property, and fill suitability tests generally can be performed on disturbed samples, whereas tests to determine engineering properties of the soils should preferably be performed on relatively undisturbed, intact specimen. The quality of the data obtained from the latter series of tests is significantly dependent on the magnitude of sample disturbance either during sampling or during subsequent processing and transportation.

30.4.2 Types and Uses of Tests

30.4.2.1 Soil Classification and Index Testing

Soil classification and index properties tests are generally performed for even low-risk projects. Engineering parameters often can be estimated from the available *in situ* data and basic index tests using published correlations. Site-specific correlations of these basic values may allow the results of a few relatively expensive advanced tests to be extrapolated. Index tests and their uses include the following:

- Unit weight and water content tests to evaluate the natural unit weight and water content.
- Atterberg (liquid and plastic) limit tests on cohesive soils for classification and correlation studies. Significant insight relative to strength and compressibility properties can be inferred from the natural water content and Atterberg limit test results.
- Sieve and hydrometer tests to define the grain size distribution of coarse- and fine-grained soils, respectively. Grain size data also are used for both classification and correlation studies.

Other index tests include tests for specific gravity, maximum and minimum density, expansion index, and sand equivalent.

30.4.2.2 Shear Strength Tests

Most bridge design projects require characterization of the undrained shear strength of cohesive soils and the drained strength of cohesionless soils. Strength determinations are necessary to evaluate the bearing capacity of foundations and to estimate the loads imposed on earth-retaining structures.

Undrained shear strength of cohesive soils can be estimated (often in the field) with calibrated tools such as a torvane, pocket penetrometer, fall cone, or miniature vane shear device. More definitive strength measurements are obtained in a laboratory by subjecting samples to triaxial compression (TX), direct simple shear (DSS), or torsional shear (TS) tests. Triaxial shear tests (including unconsolidated-undrained, UU, tests and consolidated-undrained, CU, tests) are the most common type of strength test. In this type of test, the sample is subject to stresses that mimic *in situ* states of stress prior to being tested to failure in compression or shear. Large and more high risk projects often warrant the performance of CU or DSS tests where samples are tested along stress paths which model the *in situ* conditions. In contrast, only less-sophisticated UU tests may be warranted for less important projects.

Drained strength parameters of cohesionless soils are generally measured in either relatively simple direct shear (DS) tests or in more-sophisticated consolidated-drained (CD) triaxial tests. In general, few laboratory strength tests are performed on *in situ* specimens of cohesionless soil because of the relative difficulty in obtaining undisturbed specimens.

30.4.2.3 Compaction Tests

Compaction tests are performed to evaluate the moisture–density relationship of potential fill material. Once the relationship has been evaluated and the minimum level of compaction of fill material to be used has been determined, strength tests may be performed on compacted specimens to evaluate design parameters for the project.

30.4.2.4 Subgrade Modulus

R-value and CBR tests are performed to determine subgrade modulus and evaluate the pavement support characteristics of the *in situ* or fill soils.

30.4.2.5 Consolidation Tests

Consolidation tests are commonly performed to (1) evaluate the compressibility of soil samples for the calculation of foundation settlement; (2) investigate the stress history of the soils at the boring locations to calculate settlement as well as to select stress paths to perform most advanced strength tests; (3) evaluate elastic properties from measured bulk modulus values; and (4) evaluate the time rate of settlement. Consolidation test procedures also can be modified to evaluate if foundation soils are susceptible to collapse or expansion, and to measure expansion pressures under various levels of confinement. Consolidation tests include incremental consolidation tests (which are performed at a number of discrete loads) and constant rate of strain (CRS) tests where load levels are constantly increased or decreased. CRS tests can generally be performed relatively quickly and provide a continuous stress–strain curve, but require more-sophisticated equipment.

30.4.2.6 Permeability Tests

In general, constant-head permeability tests are performed on relatively permeable cohesionless soils, while falling-head permeability tests are performed on relatively impermeable cohesive soils. Estimates of the permeability of cohesive soils also can be obtained from consolidation test data.

30.4.2.7 Dynamic Tests

A number of tests are possible to evaluate the behavior of soils under dynamic loads such as wave or earthquake loads. Dynamic tests generally are strength tests with the sample subjected to some sort of cyclic loading. Tests can be performed to evaluate variations of strength, modulus, and damping, with variations in rate and magnitude of cyclic stresses or strains. Small strain parameters for earthquake loading cases can be evaluated from resonant column tests.

For earthquake loading conditions, dynamic test data are often used to evaluate site response and soil-structure interaction. Cyclic testing also can provide insight into the behavior of potentially liquefiable soils, especially those which are not easily evaluated by empirical *in situ* test-based procedures.

30.4.2.8 Corrosion Tests

Corrosion tests are performed to evaluate potential impacts on steel or concrete structures due to chemical attack. Tests to evaluate corrosion potential include resistivity, pH, sulfate content, and chloride content.

30.5 Data Presentation and Site Characterization

30.5.1 Site Characterization Report

The site characterization report should contain a presentation of the site data and an interpretation and analysis of the foundation conditions at the project site. The site characterization report should:

- Present the factual data generated during the site investigation;
- Describe the procedures and equipment used to obtain the factual data;
- Describe the subsurface stratigraphic relationships at the project site;
- Define the soil and rock properties that are relevant to the planning, design, construction, and performance of the project structures;
- Formulate the solutions to the design and construction of the project.

The site data presented in the site characterization report may be developed from the current and/or past field investigations at or near the project site, as-built documents, maintenance records, and construction notes. When historic data are included or summarized, the original sources of the data should be cited.

30.5.2 Factual Data Presentation

The project report should include the accurate and appropriate documentation of the factual data collected and generated during the site investigation and testing program(s). The presentation and organization of the factual data, by necessity, will depend upon the size and complexity of the project and the types and extent of the subsurface data. Regardless of the project size or extent of exploration, all reports should include an accurate plan of exploration that includes appropriate graphical portrayal of surface features and ground surface elevation in the project area.

The boring log (Figure 30.13) is one of the most fundamental components of the data documentation. Although many styles of presentation are used, there are several basic elements that generally should be included on a boring log. Those typical components include:

- Documentation of location and ground surface elevation;
- Documentation of sampling and coring depths, types, and lengths — e.g., sample type, blow count (for driven samples), and sample length for soil samples; core run, recovery, and RQD for rock cores — as well as *in situ* test depths and lengths;
- Depths and elevations of groundwater and/or seepage encountered;
- Graphical representation of soil and rock lithology;
- Description of soil and rock types, characteristics, consistency/density, or hardness;
- Tabular or graphical representation of test data.

In addition to the boring logs, the factual data should include tabulated summaries of test types, depths, and results together with the appropriate graphical output of the tests conducted.

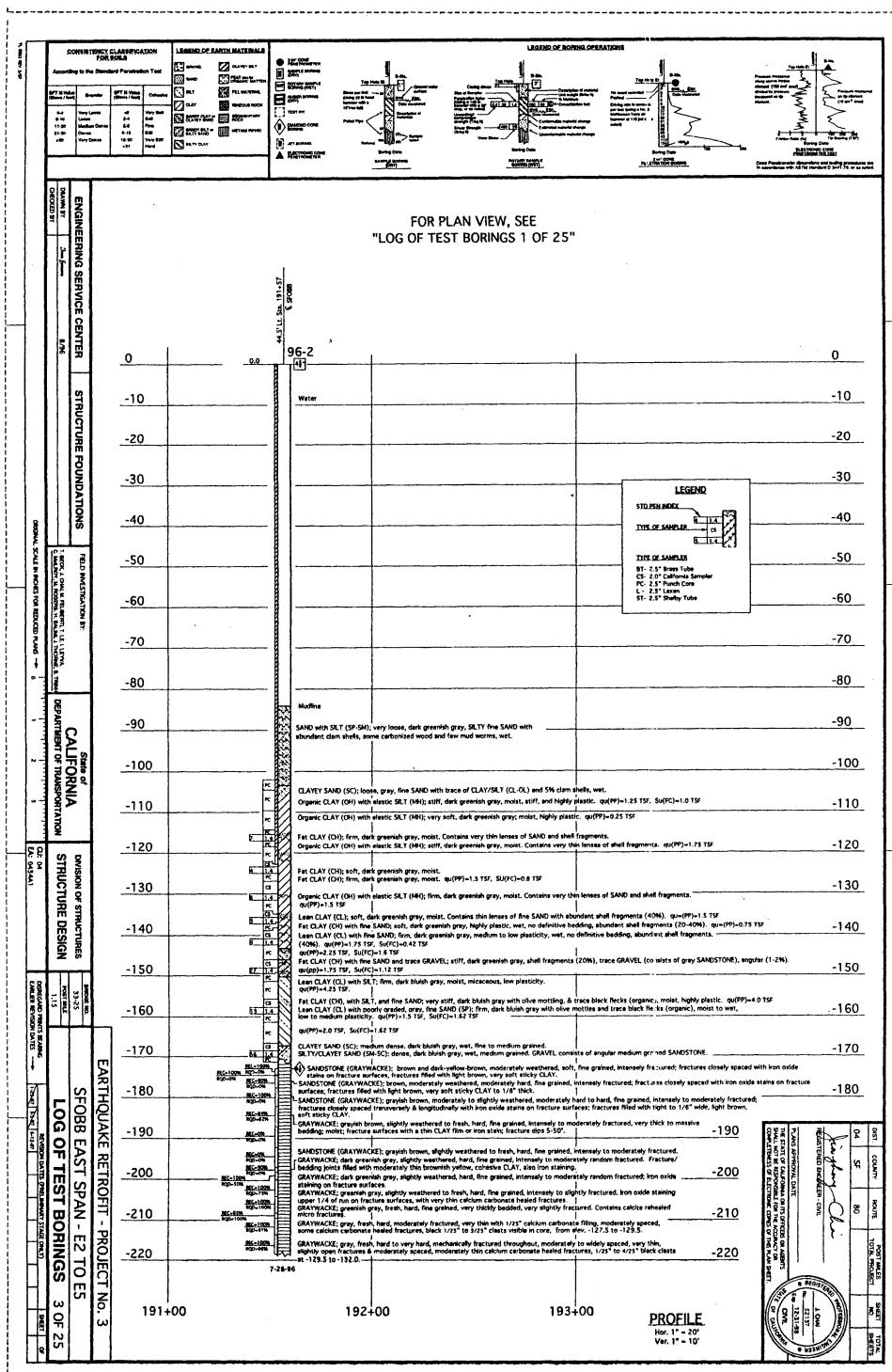


FIGURE 30.13 Typical log of test boring sheet for Caltrans project.

30.5.3 Description of Subsurface Conditions and Stratigraphy

A sound geologic interpretation of the exploration and testing data are required for any project to assess the subsurface conditions. The description of the subsurface conditions should provide users of the report with an understanding of the conditions, their possible variability, and the significance of the conditions relative to the project. The information should be presented in a useful format and terminology appropriate for the users, who usually will include design engineers and contractors who are not earth science professionals.

To achieve those objectives, the site characterization report should include descriptions of

1. Site topography and/or bathymetry,
2. Site geology,
3. Subsurface stratigraphy and stratigraphic relationships,
4. Continuity or lack of continuity of the various subsurface strata,
5. Groundwater depths and conditions, and
6. Assessment of the documented and possible undocumented variability of the subsurface conditions.

Information relative to the subsurface conditions is usually provided in text, cross sections, and maps. Subsurface cross sections, or profiles, are commonly used to illustrate the stratigraphic sequence, subsurface strata and their relationships, geologic structure, and other subsurface features across a site. The cross section can range from simple line drawings to complex illustrations that include boring logs and plotted test data ([Figure 30.14](#)).

Maps are commonly used to illustrate and define the subsurface conditions at a site. The maps can include topographic and bathymetric contour maps, maps of the structural contours of a stratigraphic surface, groundwater depth or elevation maps, isopach thickness maps of an individual stratum (or sequence of strata), and interpreted maps of geologic features (e.g., faulting, bedrock outcrops, etc.). The locations of explorations should generally be included on the interpretive maps.

The interpretive report also should describe data relative to the depths and elevations of groundwater and/or seepage encountered in the field. The potential types of groundwater surface(s) and possible seasonal fluctuation of groundwater should be described. The description of the subsurface conditions also should discuss how the groundwater conditions can affect construction.

30.5.4 Definition of Soil Properties

Soil properties generally should be interpreted in terms of stratigraphic units or geologic deposits. The interpretation of representative soil properties for design should consider lateral and vertical variability of the different soil deposits. Representative soil properties should consider the potential for possible *in situ* variations that have not been disclosed by the exploration program and laboratory testing. For large or variable sites, it should be recognized that global averages of a particular soil property may not appropriately represent the representative value at all locations. For that condition, use of average soil properties may lead to unconservative design.

Soil properties and design recommendations are usually presented with a combination of narrative text, graphs, and data presented in tabular and/or bulleted list format. It is often convenient and helpful to reference generalized subsurface profiles and boring logs in those discussions. The narrative descriptions should include such factors as depth range, general consistency or density, plasticity or grain size, occurrence of groundwater, occurrence of layers or seams, degree of weathering, and structure. For each stratigraphic unit, ranges of typical measured field and laboratory data (e.g., strength, index parameters, and blow counts) should be described.

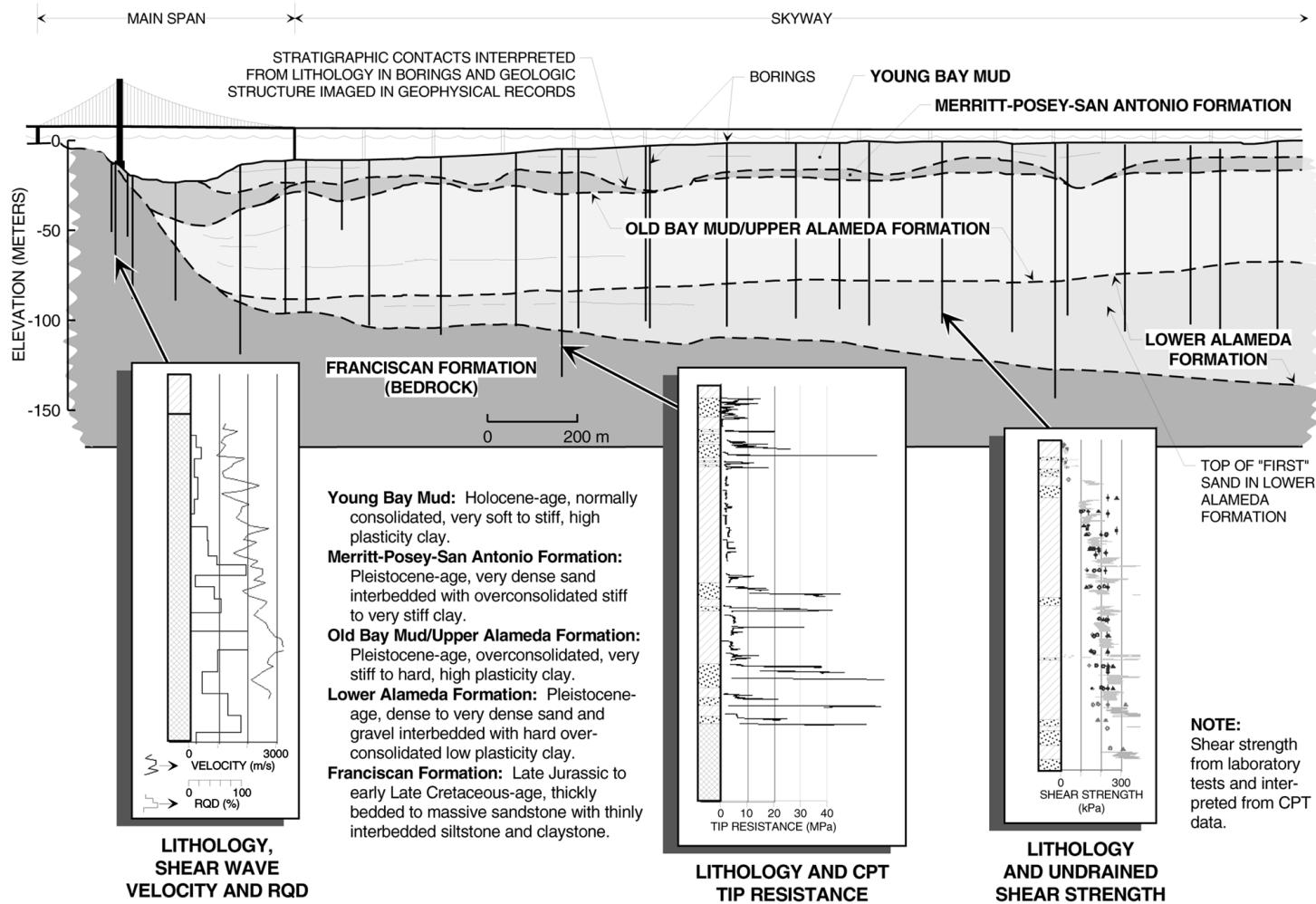


FIGURE 30.14 Subsurface cross section for San Francisco–Oakland Bay Bridge East Span alignment.

30.5.5 Geotechnical Recommendations

The site characterization report should provide solutions to the geotechnical issues and contain geotechnical recommendations that are complete, concise, and definitive. The recommended foundation and geotechnical systems should be cost-effective, performance-proven, and constructible. Where appropriate, alternative foundation types should be discussed and evaluated. When construction problems are anticipated, solutions to these problems should be described.

In addition to the standard consideration of axial and lateral foundation capacity, load-deflection characteristics, settlement, slope stability, and earth pressures, there are a number of subsurface conditions that can affect foundation design and performance:

- Liquefaction susceptibility of loose, granular soils;
- Expansive or collapsible soils;
- Mica-rich and carbonate soils;
- Corrosive soils;
- Permafrost or frozen soils;
- Perched or artesian groundwater.

When any of those conditions are present, they should be described and evaluated.

30.5.6 Application of Computerized Databases

Computerized databases provide the opportunity to compile, organize, integrate, and analyze geotechnical data efficiently. All collected data are thereby stored, in a standard format, in a central accessible location. Use of a computerized database has a number of advantages. Use of automated interactive routines allows the efficient production of boring logs, cross sections, maps, and parameter plots. Large volumes of data from multiple sources can be integrated and queried to evaluate or show trends and variability. New data from subsequent phases of study can be easily and rapidly incorporated into the existing database to update and revise the geologic model of the site.