U.S. NUCLEAR REGULATORY COMMISSION

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GEOLOGIC AND GEOTECHNICAL SITE CHARACTERIZATION INVESTIGATIONS FOR NUCLEAR POWER PLANTS

A. INTRODUCTION

Purpose

This regulatory guide (RG) provides guidance on field investigations for determining the geologic, geotechnical, geophysical, and hydrogeologic characteristics of a prospective site for engineering analysis and design of nuclear power plants.

Applicability

This RG applies to applicants and licensees subject to Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, "Domestic Licensing of Production and Utilization Facilities" (Ref. 1), 10 CFR Part 52, "Licenses, Certifications, and Approvals for Nuclear Power Plants" (Ref. 2), and 10 CFR Part 100, "Reactor Site Criteria" (Ref. 3).

Applicable Regulations

- 10 CFR Part 50, Appendix A, "General Design Criteria for Nuclear Power Plants," establishes minimum requirements for the principal design criteria for water-cooled nuclear power plants.
    - General Design Criterion 2, "Design Bases for Protection against Natural Phenomena," requires that structures important to safety be designed to withstand the effects of expected natural phenomena when combined with the effects of normal accident conditions without loss of capability to perform their safety function.
- 10 CFR Part 52, "Licenses, Certifications, and Approvals for Nuclear Power Plants," governs the issuance of early site permits, standard design certifications, combined licenses, standard design approvals, and manufacturing licenses for nuclear power plants.
- 10 CFR Part 100, "Reactor Site Criteria," requires the U.S. Nuclear Regulatory Commission (NRC) to consider population density; use of the site environs, including proximity to manmade hazards; and the physical characteristics of the site, including seismology, meteorology, geology, and hydrology, in determining the acceptability of a site for a nuclear power reactor.

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- 10 CFR 100 Subpart B, "Evaluation Factors for Stationary Power Reactor Site Applications on or after January 10, 1997," provides the requirements for the factors to be considered. Specific to this RG are 10 CFR 100.20(c), 100.21(d), and 100.23 that establish the requirements for conducting site investigations which include seismology, geology, meteorology, and hydrology.

Related Guidance

- NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition" (Ref. 4), provides guidance to the NRC staff in performing safety reviews under 10 CFR Part 50 and 10 CFR Part 52. Chapter 2, "Site Characteristics and Site Parameters," gives general review guidance related to site characteristics and site parameters, together with site-related design parameters and design characteristics, as applicable.

- RG 1.29, "Seismic Design Classification for Nuclear Power Plants" (Ref. 5), identifies the structures, systems, and components (SSCs) that should be designed to withstand the effects of the safe shutdown earthquake and remain functional.

- RG 1.70, "Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants: LWR Edition" (Ref. 6), and RG 1.206, "Applications for Nuclear Power Plants" (Ref. 7), provide general guidance on the types of information about the hydrologic setting and assessments of flooding hazards that a license application for a light-water reactor (LWR) power plant should include.

- RG 1.138, "Laboratory Investigations of Soils and Rocks for Engineering Analysis and Design of Nuclear Power Plants" (Ref. 8), provides guidance on sampling, storage, and laboratory investigations of the properties of soils for engineering analysis and design of nuclear power plants.

- RG1.201, "Guidelines for Categorizing Structures, Systems, and Components in Nuclear Power Plants According to Their Safety Significance" (Ref. 9), describes a risk-informed process for categorizing SSCs according to their safety significance that can remove SSCs of low safety significance from the scope of certain identified special treatment requirements.

- RG 4.7, "General Site Suitability Criteria for Nuclear Power Stations" (Ref. 10), assists applicants in the initial stage of selecting potential sites for a nuclear power station. The safety issues discussed include geological, seismic, hydrological, and meteorological characteristics of proposed sites as they relate to protecting the general public from the potential hazards of serious accidents.

Purpose of Regulatory Guides

The NRC issues RGs to describe methods that are acceptable to the staff for implementing specific parts of the agency's regulations, to explain techniques that the staff uses in evaluating specific issues or postulated events, and to describe information that the staff needs in its review of applications for permits and licenses. Regulatory guides are not NRC regulations and compliance with them is not required. Methods and solutions that differ from those set forth in RGs are acceptable if supported by a basis for the issuance or continuance of a permit or license by the Commission.

Paperwork Reduction Act

This RG provides voluntary guidance for implementing the mandatory information collections in 10 CFR Parts 50, 52, and 100 that are subject to the Paperwork Reduction Act of 1995 (44 U.S.C. 3501 et. seq.). These information collections were approved by the Office of Management and Budget (OMB), approval numbers 3150-0011, 3150-0151, and 3150-0093 respectively. Send comments regarding this information collection to the FOIA, Library, and Information Collections Branch, (T6-A10M), U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001, or by e-mail to Infocollects.Resource@nrc.gov, and to the OMB reviewer at: OMB Office of Information and Regulatory Affairs (3150-0011, 3150-0151, 3150-0093), Attn: Desk Officer for the Nuclear Regulatory Commission, 725 17th Street, NW Washington, DC 20503; e- mail: oira_submission@omb.eop.gov.

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B. DISCUSSION

Reason for Revision

This revision of the guide (Revision 3) captures updates to the U.S. Army Corps of Engineers' Engineer Manuals that provide guidance for the procedures in this RG. The manual changes are primarily modest updating of geophysical methods used for site exploration and characterization. In addition, RG 1.165, "Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion," was withdrawn in 2010 and replaced by RG 1.208, "A Performance-Based Approach to Define the Sites-Specific Earthquake Ground Motion" (Ref. 11).

Background

Site investigations are needed to define site-specific geologic, geotechnical, geophysical, and hydrogeologic characteristics to the degree necessary for understanding surface and subsurface conditions and identifying potential geologic hazards that might affect the site. Investigations for geologic hazards such as fault deformation, landslides, cavernous rocks (surface or subsurface karst), ground subsidence, soil liquefaction, and any other natural or manmade external hazards are of particular importance. The density of data collected will depend on variability of the soil and rock materials and the safety-related importance of structures planned for a particular site location. Well-conducted site investigations can save time and money by reducing problems in licensing and construction.

The site investigations described in this RG are closely related to those in RG 1.208. The main purpose of that RG is to define the site-specific, performance-based ground motion response spectrum in order to determine the safe-shutdown earthquake ground motion based on information derived from geologic, geotechnical, geophysical, and seismic investigations. Appendix C, "Investigations to Characterize Site Geology, Seismology and Geophysics," to RG 1.208 gives guidance on the appropriate information needed to identify and characterize seismic source zone parameters and assess the potential for surface fault rupture and associated deformation at the site for use in probabilistic seismic hazard analyses.

It is worthwhile to point out that good site investigations have the added benefit of saving time and money by reducing problems in licensing and construction. A case study report on geotechnical investigations by the National Research Council (Ref. 12), for example, concludes that additional geotechnical information would almost always save time and costs.

Consideration of International Standards

The International Atomic Energy Agency (IAEA) works with member states and other partners to promote the safe, secure, and peaceful use of nuclear technologies. The IAEA develops Safety Requirements and Safety Guides for protecting people and the environment from harmful effects of ionizing radiation. This system of safety fundamentals, safety requirements, safety guides, and other relevant reports reflects an international perspective on what constitutes a high level of safety. To inform its development of this RG, the NRC considered IAEA Safety Requirements and Safety Guides under the Commission's International Policy Statement (Ref. 13) and Management Directive 6.6, "Regulatory Guides" (Ref. 14).

The NRC staff considered the following IAEA safety requirements and guides in the development/update of this RG:

- IAEA Safety Standards Series No. NS-G-3.6, "Geotechnical Aspects of Site Evaluation and Foundations for Nuclear Power Plants," issued 2005 (Ref. 15)

- IAEA Specific Safety Guide No. SSG-9, "Seismic Hazards in Site Evaluation for Nuclear Installations," issued 2010 (Ref. 16)

Documents Discussed in Staff Regulatory Guidance

This RG endorses the use of one or more codes or standards developed by external organizations, and other third-party guidance documents. These codes, standards, and third-party guidance documents may contain references to other codes, standards or third party guidance documents ("secondary references"). If a secondary reference has itself been incorporated by reference into NRC regulations as a requirement, then licensees and applicants must comply with that standard as set forth in the regulation. If the secondary reference has been endorsed in a RG as an acceptable approach for meeting an NRC requirement, then the standard constitutes a method acceptable to the NRC staff for meeting that regulatory requirement as described in the specific RG. If the secondary reference has neither been incorporated by reference into NRC regulations nor endorsed in a RG, then the secondary reference is neither a legally-binding requirement nor a "generic" NRC approved acceptable approach for meeting an NRC requirement. However, licensees and applicants may consider and use the information in the secondary reference, if appropriately justified, consistent with current regulatory practice, and consistent with applicable NRC requirements.

C. STAFF REGULATORY GUIDANCE

1. General Requirements

A well-planned program of site exploration should be conducted using a phased approach that progresses from a literature search and reconnaissance investigations to detailed site investigations, construction mapping, and final as-built data compilation to provide a strong basis for site suitability determination and foundation design and construction. The actual site investigation program should be tailored to the specific conditions of the site and based on sound professional judgment. The site investigation program should be flexible and modified when needed, as the site investigation proceeds based on the provisions and criteria of the project.

Site investigations for nuclear power plants should be adequate in terms of thoroughness, suitability of methods used, quality of execution of the work, and documentation to permit an accurate determination of the geologic and geotechnical conditions that affect the design, performance, and safety of the plant. The investigations should provide information needed to perform engineering analyses and design the plant with reasonable assurance that the geologic and geotechnical conditions and associated uncertainties have been appropriately determined and considered.

This guide considers techniques available at the date of issuance. As science advances, useful procedures, standards, and equipment should be included as they are developed and accepted by the profession.

2. Types of Data to Be Acquired

2.1 Geologic Characteristics

Geologic characteristics include, but are not limited to, the following:

- Lithology and other distinguishing features of rock units at the surface and in the subsurface. Depositional and tectonic deformation features include bedding planes, faults and shear zones, joints, and foliation surfaces, the orientations of which are needed for characterization of the features.

- Nature, degree, and extent of weathering at the surface and in the shallow subsurface. Weathering-related characteristics include soil type, presence of expanding soils, and karst features that are active or relict (sinkholes and dolines, disappearing streams, caverns, and subsurface voids not detectable at the surface).

- Potential for soil liquefaction and evidence for paleoliquefaction.

- Natural hazards that include seismic events, surficial and blind faults, landslide potential, nontectonic deformation, susceptibility to erosion, sea level rise, flooding, tsunami, seiche, and storm wave action.

Appendix A to this guide lists special geologic features and conditions that might need to be investigated during site characterization, either as office-based or field studies.

2.2 Engineering Properties of Soils and Rocks

Engineering properties of soil and rock include static and dynamic properties such as density, moisture content, strength parameters, elasticity, plasticity, hydraulic conductivities, rock joint characteristics, seismic velocities, and degradation properties associated with strain. Some of these properties can be measured in situ, and those measurements, together with sample collection methods, are discussed in this guide. Determination of these and other engineering properties also requires laboratory testing, which is described in RG 1.138.

2.3 Ground Water Conditions

Ground water conditions that can impact the engineering design, performance, and durability of the foundations and structures should be determined. These conditions include ground water levels, chemical properties of ground water, thickness and extent of aquifers and confining beds, ground water flow patterns, recharge areas, discharge points and transmissivities, and storage coefficients.

2.4 Human-Induced Conditions

Existing infrastructure should be located, including dams or reservoirs that might cause a flooding hazard or induce loading effects at the site. Past or ongoing activities, such as mining, oil and gas production to include hydrofracking, and other fluid extraction or injection activities, should be assessed and documented. The presence of former or current industrial sites, underground storage tanks, abandoned well casings, buried foundations, conduits, pipes, sumps, or landfills should be identified. The potential for hazardous, toxic, or radioactive waste should also be investigated and documented.

2.5 Cultural and Environmental Considerations

Assessment for cultural resources, such as archaeological sites and artifacts, must comply with the Archaeological Resources Protection Act of 1979 and the Native American Graves Protection and Repatriation Act of 1990.

The National Historic Preservation Act (36 CFR Part 800, "Protection of Historic Properties") must be considered if the site investigation will affect historic property. Under that condition, the Section 106 review process must be followed.

Aspects of the Clean Water Act (33 U.S.C. 1344) must be taken into account. Placement of fill in wetlands is regulated at the national level, and State and local wetland protection laws may also apply. The "Corps of Engineers Wetlands Delineation Manual" (Ref. 17) gives guidance on identifying and delineating wetlands. Information on applications for Section 404 permits for modifying wetlands can be obtained from District Offices of the Army Corps of Engineers.

2.6 Related Considerations

RG 1.208 provides guidance on seismicity and related seismic data and historical records, together with guidance on determination of vibratory ground motion resulting from earthquakes. Many of the investigations listed in RG 1.208 could and should be coordinated with the site investigations described in this guide and conducted at the same time for greater efficiency. Appendix C to RG 1.208 should be used as guidance for investigating tectonic and nontectonic surface deformation.

3. Evaluation of Previously Published Information, Field Reconnaissance, and Preliminary Assessment of Site Suitability

3.1 General

Establishing the geologic characteristics and engineering properties of a site is an iterative process during which successive phases of investigation produce increasingly detailed data. Therefore, it is important to have a proper system for recording the data and gaining a three-dimensional spatial understanding of site conditions.

A geographic information system (GIS) database is an efficient way to collect and present spatial data. A well-planned database system for compiling pertinent data is important for data retrieval and analysis and is a part of the quality assurance requirements for a project (see Regulatory Position 7.2). RG 1.208 indicates that geologic, seismic, and geophysical investigations are to be performed to develop an up-to-date, site-specific, geoscience database that supports the site characterization efforts.

3.2 Evaluation of Previously Published Information

The first step in the site investigation process is to acquire and evaluate existing data related to geologic characteristics and engineering properties of the site. Information about regional geology should be considered to assist with understanding rock and soil properties of the site in the proper regional context. Reconnaissance-level investigations can start with review of published reports, data, and existing maps illustrating topography, geology, hydrology, previous land use and construction, and infrastructure. Study of aerial photographs, satellite imagery, light detection and ranging (LiDAR) surveys, and other remote sensing imagery can be used to complement this information. If available, regional strain rates measured using the Global Positioning System (GPS) (Ref. 18) should be collected to correlate with strain rates obtained from geologic data and other data sets.

Possible sources of current and historical documentary information could include the following:

- geology and engineering departments of State and local universities;
- county governments, many of which have GIS data of various kinds available;
- State government agencies, such as State geological surveys;
- U.S. government agencies, such as the U.S. Geological Survey, the Bureau of Reclamation, and the U.S. Army Corps of Engineers;
- newspaper records of earthquakes, floods, landslides, and other natural events of significance;
- interviews with local inhabitants and knowledgeable professionals; and
- reputable and relevant online documents.

Appendix B to this guide lists additional potential sources for maps, imagery, and other pertinent geologic data.

For license applications for a site near an existing nuclear power plant with a similar geologic setting, documents related to the site investigation for the existing plant could provide valuable information. Plans held by utilities should be consulted to locate services such as water, gas, electric, and communication lines. Locations of power lines, pipelines, and access routes should be established. Mining records should be consulted to determine locations of abandoned adits, shafts, mining works, benches, and tailings ponds and embankments. Oil, gas, and water well records and oil and gas field exploration data can provide valuable subsurface information. Historical and archaeological sites should be identified to document locations of potential cultural resources.

3.3 Field Reconnaissance

In addition to evaluating and documenting previously published information, it is necessary to perform preliminary field reconnaissance of the site and the surrounding area. This step enables an assessment of field data related to site conditions and regional geology and establishes the basis for a detailed site investigation plan. Appendix A to this guide lists special geologic features and conditions that should be considered. In addition to site-specific conditions, areas containing potential borrow sources, quarry sites, and water impoundments should be investigated.

The team performing the reconnaissance should include, as a minimum, a geologist and a geotechnical engineer and could also include other specialists (e.g., an engineering geologist or geophysicist). Appropriate topographic and geologic maps should be used during the field reconnaissance, if available, to locate features of potential interest. A GPS unit would be advantageous for recording locations in the field, as noted in more detail in Regulatory Position 7.1.

3.4 Preliminary Assessment of Site Suitability

After completion of the field reconnaissance investigations and in conjunction with the information in the developed database, a preliminary determination of site suitability should be made to identify information gaps and potential hazards to help formulate the plan for the detailed site investigation stage. The presence of features or characteristics that could potentially result in deleterious ground displacement (e.g., fault displacement, subsurface dissolution, and settlement or subsidence), swelling soils and shales, or other natural hazards (e.g., underground cavities, landslides, or periodic flooding) could make plant design difficult and require additional extensive investigations to assess properly. For sites where such features and characteristics exist, it might be advantageous to search for a more suitable site.

4. Detailed Site Investigations

4.1 General

The detailed site investigation phase acquires all geologic and material property data needed for the engineering analyses, design, and construction of a plant, including the related critical structures. A multidisciplinary team is needed to accomplish the different tasks during this phase. Subsequent site investigations might be needed if additional data are required to supplement a gap in the knowledge associated with the geologic characteristics and subsurface material properties at the site.

The engineering properties of rock and soil can be determined through drilling and sampling, in situ testing, field geophysical measurements, and laboratory testing. This guide describes in situ testing and field geophysical measurements, as well as drilling and sampling procedures used to gather samples for laboratory testing. For guidance on laboratory testing procedures, refer to RG 1.138.

All pertinent conclusions should be presented and linked directly to the information that provides the bases for the conclusions. Site-specific information to be developed and analyzed should include, but not be limited to, the following:

(1) Topographic and geologic maps. The geologic maps should show rock types and locations of tectonic and nontectonic geologic features, as well as points where field samples were collected for laboratory analysis (e.g., for radiometric age dating and determination of material properties).

(2) Plot plans showing the locations of major anticipated engineered structures and points at which site investigation tests were conducted and data or measurements were collected.

(3) Boring logs and geologic logs of exploratory trenches and excavations.

(4) Geologic profiles illustrating subsurface geology and excavation limits for engineered structures.

(5) Geophysical information such as survey lines, seismic survey time-distance plots, resistivity curves, seismic reflection and refraction plots, seismic wave velocity profiles, surface wave dispersion plots, and borehole loggings.

Locations of all boreholes, ground water observation wells and piezometers, in situ tests, trenches, exploration pits, and geophysical measurements should be surveyed in both plan and elevation. This three-dimensional information should be entered into a GIS database. Suitable cross sections, maps, and plans should be prepared to facilitate visualization of the geologic information. Regulatory Position 7.1 gives further details.

Detailed site investigations should use applicable industrial standards for specific techniques, methods, and procedures. Regulatory Position 7.2 provides quality assurance requirements. Use of investigative and sampling techniques other than those discussed in this guide is acceptable when it can be shown that the alternative techniques yield satisfactory results.

4.2 Surface Investigations

Detailed surface geologic and geotechnical engineering investigations should be conducted over the site area to assess all pertinent soil and rock characteristics. The definition of site area, as specified in RG 1.208, is that area within a radius of 8 kilometers (5 miles) of the site. Appendix A to this guide lists some of the special geologic features and conditions to be considered.

The initial step in conducting detailed surface investigations for a site is to prepare three-dimensional topographic maps at a scale suitable for plotting the geologic features and characteristics and showing features in the surrounding area that are related, for example, to borrow areas, quarries, and access roads. Aerial photographs and stereoscopic image pairs, other remote sensing imagery (e.g., satellite imagery and LiDAR), and the results of geophysical surveys are valuable for regional analysis, determination of fault and fracture patterns, location of potential nontectonic surficial features related to possible subsurface dissolution, and other features of interest.

Depending on the site, detailed mapping of the following site characteristics and associated features should be considered during conduct of the surface investigations:

- topography (including geomorphic features, lineaments, paleo-landslides, closed depressions, river terraces, and alluvial and glacial deposits),
- hydrology (including rivers, streams, lakes, wetlands, local drainage channels, springs, and sinkholes),

- geology (including outcrops; tectonic features such as faults, shear zones, and zones exhibiting strong fracturing or alteration; nontectonic features such as surficial indicators of subsurface dissolution; rock unit contacts), and
- engineering geology (including soil conditions and soil types, chemically or physically weathered zones and horizons, and areas exhibiting material properties conducive to soil liquefaction).

All maps produced should include standard map labels such as scales, a north arrow, map projection information, title, and citation of original data or data sources.

4.3 Subsurface Investigations

Subsurface investigations expand knowledge of the three-dimensional distribution of geologic features and characteristics and geotechnical engineering properties at the site and in borrow areas. Subsurface investigations also provide information on potential natural hazards such as nontectonic underground features (e.g., dissolution cavities), hidden faults, soft zones, or geologic contacts. The investigations should use a variety of appropriate methods, including borings and excavations augmented by geophysical measurements and geophysical surveys. Appendix C to this guide tabulates methods of conducting subsurface investigations. Techniques employing different measurement approaches should be used to determine geologic conditions and geotechnical engineering properties to account for uncertainties in the data and to cross-check the conformability and reasonableness of the data obtained during site investigations. An adequate number of tests for each method should be performed to quantify the mean and variability of pertinent site parameters and geotechnical engineering properties of subsurface materials.

Locations and depths of borings, excavations, and geophysical measurements should be selected such that site-specific geology and foundation support conditions are sufficiently defined in both lateral extent and depth to permit the suitable design of all necessary excavations and engineered structures. The information acquired should also support development of geologic cross sections and subsurface profiles that contain field testing data (e.g., N-values, cone penetration test values, and seismic wave velocities) constructed through the foundations of safety-related structures and other important structures at the site.

Subsurface investigations for less critical foundations of power plants should be carried out at a spacing and depth of penetration necessary to define the geologic conditions and geotechnical engineering properties of the subsurface materials. Subsurface investigations in areas remote from plant foundations might be needed to complete the geologic description and confirm the geologic conditions of the site.

Subsurface investigations for materials to be used for backfill, improvement of subsurface conditions, or ground water control under the foundations of safety-related structures, including granular and nongranular materials, should be performed to confirm that stability and durability requirements will be met and to validate the material properties to be used for design and analysis.

Boreholes are one effective way to obtain detailed information on subsurface geologic conditions and the engineering properties of subsurface materials. Core and other samples recovered from boreholes, geophysical and borehole surveys, and other in situ borehole tests can provide important subsurface information. Test pits, trenches, and exploratory shafts can be used to complement the borehole exploration results; provide additional detailed information on rock and soil conditions, faulting, and density of in situ materials; and obtain high-quality undisturbed samples.

4.4 Borings and Exploratory Excavations

Field operations conducted at the site should be supervised by experienced personnel familiar with site operations, and systematic standards of practice should be followed. Procedures and equipment used to carry out field operations, including necessary calibrations, and all conditions encountered in various phases of the investigations should be documented. Personnel who are experienced and thoroughly familiar with sampling and testing procedures should inspect and document sampling results and transfer samples from the field to storage or laboratory facilities with a properly executed chain-of-custody record.

The complexity of geologic conditions and foundation requirements should be considered in choosing the distribution, number, and depth of borings and other excavations at the site. The investigative efforts should be greatest at the locations of safety-related structures and might vary in density and scope in other areas according to spatial and geologic relationships to the specific site. Excavation trenches across faults or shear zones might be required to determine the age of last movement on these tectonic features to better assess the potential impact of the features on site safety. At least one continuously sampled boring should be drilled for each safety-related structure, and the boring should extend to a depth sufficient for defining the geologic and hydrogeologic characteristics of the subsurface materials that will influence the stability and suitability of the safety-related structures.

NUREG/CR-5738, "Field Investigations for Foundations of Nuclear Power Plants," issued November 1999, describes procedures for borings and exploratory excavations. Appendix C to this guide reproduces a table from NUREG/CR-5738 showing widely used techniques for subsurface investigations and describing the applicability and limitations of the techniques. Appendix D to this RG contains general guidelines for spacing and depth of borings.

4.4.1 Spacing and Depth

Spacing, depth, and the number of borings for safety-related structures should be chosen and justified based on foundation requirements and the complexity of anticipated subsurface conditions. Appendix D provides general guidelines on this topic. Spacing of borings for a deeply embedded structure with smaller foundation dimensions should be reduced, and additional boreholes should be located outside the foundation footprint to obtain detailed geologic and geotechnical information about the surrounding materials. This information will provide pertinent data for the analysis of soil-structure interactions and determination of lateral earth pressures.

Uniform subsurface conditions permit the maximum spacing of borings in a regular grid for adequate definition of those conditions. Subsurface conditions can be considered uniform if the geologic characteristics and features to be defined can be correlated from one boring location to the next with relatively smooth variations in thicknesses and properties of the geologic units. An occasional anomaly or a limited number of unexpected lateral variations might occur.

If subsurface conditions are not uniform, a regular grid might not provide the most effective distribution of boreholes. Soil deposits or rock units could be encountered in which the geologic characteristics are so complex that only the major rock unit contacts are correlated. Material types and properties might also vary within major geologic units in an apparently random manner from one boring to another. The number and distribution of borings needed for such nonuniform conditions are determined by the degree of resolution needed to define geotechnical properties required for engineering design. In locations with sedimentary rock formations, it will be helpful to understand the environment of deposition for the various geologic units at the site in order to understand lateral and vertical variations within the units. The goal of the investigations is to define the thicknesses of the different subsurface materials, degree of lateral and vertical variability of the materials, and the range of geologic characteristics and geotechnical properties of the materials that underlie all major structures.

If there is evidence suggesting the presence of local adverse anomalies or discontinuities in the subsurface (e.g., cavities, sinkholes, fissures, faults, brecciated zones, lenses, or pockets of unsuitable material), then supplementary borings at a spacing small enough to detect and delineate these features are needed. At locations with limestone, dolostone, and anhydrite, the size, frequency, and depth of voids or caverns should be considered because different mechanisms or dissolution processes may exist. It is important that the supplementary borings penetrate all potentially detrimental zones or extend to depths below which presence of these zones would not influence stability of the structures. Geophysical investigations should be used together with the borings to better characterize subsurface conditions at the site.

4.4.2 Drilling Procedures

Drilling methods and procedures should be compatible with sampling requirements and the methods of sample recovery. Many of the methods are discussed in detail in U.S. Army Corps of Engineers Engineer Manual (EM) 1110-1-1804, "Geotechnical Investigations," issued 2001 (Ref. 19). The top of the borehole should be protected by a suitable surface casing where needed. Below ground surface, the borehole should be protected by drilling mud or casing, as necessary, to prevent caving and disturbance of materials to be sampled. The use of drilling mud is preferred to prevent disturbance when obtaining undisturbed samples of coarse-grained soils. However, casing may be used if proper steps are taken to prevent disturbance of the soil being sampled and to prevent upward movement of soil into the casing. After use, each borehole should be grouted in accordance with State and local codes to prevent vertical movement of ground water through the borehole.

Borehole elevation and depths into the ground should be measured to the nearest 3 centimeters (0.1 foot) and should be correlated with the elevation datum used for the site. Surveys of vertical deviation should be run in all boreholes that are used for in situ seismic tests (e.g., crosshole, downhole, compression wave-shear wave (P-S) suspension logging) and other tests where deviation potentially affects the data obtained. Boreholes with depths greater than about 30 meters (100 feet) should also be surveyed for deviation. Regulatory Position 4.5 details the information that should be presented in logs of subsurface investigations.

Except where the borehole is being preserved for future use, all boreholes and exploratory excavations should be backfilled. Many States have requirements about backfilling boreholes. Therefore, appropriate State officials should be consulted. Borings that are preserved for future use should be protected with a short section of surface casing, capped, and identified.

4.5 Sampling

Suitable samples of rock and soil should be obtained for identification and classification, mechanical analyses, and anticipated laboratory testing. The need for, number, and distribution of samples will depend on testing requirements and the variability of the field conditions. A sufficient number of samples should be collected to meet the needs of laboratory testing, especially when undisturbed samples are required. It is important to obtain good-quality undisturbed samples for cyclic load testing. In general, soil and rock samples should be collected from more than one principal boring within the foundation support zone of each safety-related structure.

Sampling of soil and rock in boreholes should include, as a minimum, recovery of samples at regular intervals and where changes in materials occur. One or more borings for each major structure should be continuously sampled. Proper sampling methods should be used to collect soil samples. Standard penetration and cone penetration tests should be used with sufficient coverage to define the soil profile and variations in soil conditions. Alternating split spoon and undisturbed samples with depth is recommended for soil samples. Color photographs of all cores should be taken soon after removal from the borehole to document the condition of subsurface materials at the time of drilling. For a deeply embedded structure, sampling intervals should be properly determined and detailed field testing should be carried out along the length of the embedded portion of the structure to obtain sufficient geologic and geotechnical information.

4.5.1 Sampling Rock

The engineering characteristics of the rock mass are related primarily to composition and geologic features of the rock units, including bedding planes, joints, fractures, orientation, position, length and spacing of any other geologic discontinuities, surface infilling, and weathering. Rock outcrops may be one of the information sources necessary for rock mass characterization, especially for structures that require relatively shallow excavations. Core samples can also provide reliable information to define the engineering characteristics of the rock mass. Suitable coring methods should be employed, and rocks should be sampled to a depth below which rock characteristics do not influence foundation performance.

Deeper borings may be needed to investigate zones critical to the evaluation of site geologic conditions. Within the depth intervals influencing foundation performance, zones of poor core recovery or low rock quality designation, zones requiring casing, and other zones where drilling difficulties are encountered should be investigated. The nature, geometry, and spacing of any discontinuities or anomalous zones should be determined by means of suitable logging or in situ observation methods, such as an in-hole camera or televiewer. Areas with evidence of significant residual stresses should be evaluated based on in situ stress or strain measurements. Dip and strike of bedding planes and joints in the near-surface region can be measured at the outcrop. However, oriented cores are needed to estimate dips and strikes at depth.

A sufficient number of samples of both intact rock and jointed rock mass should be collected for strength property testing. The parameters developed from the rock mass characterization program provide input to different rock mass classification schemes (e.g., Rock Mass Rating system, Q system, Geological Strength Index system). The quality of the rock mass, estimated using the classification schemes, may be used in empirical design methods of rock excavation.

4.5.2 Sampling Coarse-Grained Soils

For coarse-grained soils, samples should be taken at depth intervals no greater than 1.5 meters (5 feet). Beyond a depth of 15 meters (50 feet) below foundation level, the depth interval for sampling may be increased to 3 meters (10 feet). Requirements for undisturbed sampling of coarse-grained soils will depend on actual site conditions and planned laboratory testing. Experimentation with different sampling techniques may be necessary to determine the method that is best suited to local soil conditions.

Coarse-grained soils containing gravels and boulders are among the most difficult materials to sample. Obtaining good-quality samples often requires the use of trenches, pits, or other accessible excavations into the zones of interest. Standard penetration test results from these materials may be misleading and must be interpreted very carefully. When sampling of coarse soils is difficult, information that may be lost when the soil is later classified in the laboratory should be recorded in the field. This information should include observed estimates of the percentage of cobbles, boulders, and coarse material and the hardness, shape, surface coating, and degree of weathering of coarse materials.

4.5.3 Sampling Moderately Compressible or Normally Consolidated Clay or Clayey Soils

The properties of a fine-grained soil are related to the in situ structure of the soil, and undisturbed samples should be obtained. Regulatory Position 4.5.4 of this guide discusses procedures for obtaining undisturbed samples.

For compressible or normally consolidated clays, undisturbed samples should be continuous throughout the compressible strata in one or more principal borings. These samples should be obtained by means of suitable fixed-piston, thin-wall tube samplers (see Appendix F to EM 1110-1-1804 for detailed procedures) or by methods that yield samples of equivalent quality. Borings used for undisturbed sampling of soils should be at least 7.6 centimeters (3 inches) in diameter.

4.5.4 Obtaining Undisturbed Samples

In a strict sense, it is physically impossible to obtain "undisturbed" samples in borings because of the adverse effects resulting from the sampling process (e.g., unloading caused by removal from confinement) and from shipping or handling. Undisturbed samples are normally obtained using one of two general methods: push samplers or rotary samplers. These methods permit obtaining satisfactory samples for shear strength, consolidation, permeability, and density tests, provided careful measurements are made to document volume changes that occur during each step in the sampling process. Undisturbed samples can be sliced to permit detailed study of subsoil stratification, joints, fissures, failure planes, and other details. Guidance on commonly used undisturbed sampling methods can be found in relevant America Society for Testing and Materials (ASTM) standards.

Undisturbed samples of clays and silts can be obtained, as well as nearly undisturbed samples of some sands. Care is necessary in transporting any undisturbed sample, and sands and silts are particularly vulnerable to vibration disturbance. One method to prevent handling disturbance is to obtain 7.6-centimeter (3-inch) Shelby tube samples, drain them, and freeze them before transportation. The commonly used general procedure for recovering cohesionless soil is to stabilize the soil, extract the sample, and later remove (reverse) the stabilizing agent after transportation, then trim and confine the specimen in a testing device. Reversible stabilization methods include the biopolymers agar and agarose, Elmer's glue, and freezing. These stabilization methods must be durable enough to allow handling, transportation, and trimming of the samples. The methods also need to be reversible so that cohesionless soil can be restored to its in situ state before laboratory testing for evaluation of stress-stain-strength properties. Disturbance associated with these methods, such as volume changes in the soil and pore water when using chemical or biochemical solutions or by cryogenic effects, must be taken into account.

Test pits, trenches, and shafts offer the only effective access for collecting high-quality undisturbed samples and obtaining detailed information on stratification, discontinuities, or preexisting shear surfaces. Cost increases with penetration depth as the need for sidewall support arises. Samples can be obtained by hand-carving oversized blocks of soil or hand-advancing thin-walled tubes.

4.6 Borrow Materials

Exploration for borrow sources determines the location and amount of available borrow materials. Borrow area investigations should consider horizontal and vertical intervals sufficient to determine material variability and include adequate sampling of representative materials for laboratory testing. Exploration of borrow sources should be tied to performance requirements expected from the backfill. It is preferable that one source or quarry be selected as a candidate for supplying all project fill material when possible; otherwise, the number of candidate borrow sources or quarries should be minimized for optimum quality assurance and quality control. The quantity of samples required should be determined based on the type and number of tests planned. A sufficient quantity of each fill type should be collected, preferably all during the initial sampling efforts, to ensure better uniformity in soils collected and sampling methods.

4.7 Materials Unsuitable for Foundations

Boundaries of unsuitable materials should be delineated by borings and representative sampling and testing. These boundaries should be used to define the required excavation limits.

4.8 Transportation and Storage of Samples

Handling, storage, and transportation of samples are as critical for sample quality as the collection procedures used. Disturbance of samples after collection can happen in a variety of ways and transform samples from high quality to slightly disturbed to unusable. Soil samples can change dramatically because of moisture loss, moisture migration within the sample, freezing, vibration, shock, or chemical reactions.

Moisture loss might not be critical on representative samples but should be kept to a minimum. Moisture migration within a sample can cause differential residual pore pressure to equalize with time. Water can move from one layer to another, causing significant changes in the undrained strength and compressibility of the sample. Freezing of clay or silt samples can cause ice lenses to form and severely disturb the samples. Therefore, storage room temperatures for clay and silt samples should be kept above 4 degrees Celsius (C). Vibration or shock can provoke remolding and strength or density changes, especially in soft and sensitive clays, and cohesionless samples. Transportation should be carefully arranged to avoid such effects. Chemical reactions between samples and sample containers can occur during storage and induce changes that affect soil plasticity, compressibility, and shear strength. Therefore, selection of the correct sample container material is important.

Unless stabilized chemically or by freezing, cohesionless soil samples are particularly sensitive to disturbance from impact and vibration during removal from the borehole or sampler and subsequent handling. Samples should (1) be kept in the same orientation as that in which the samples were taken at all times (e.g., in a vertical position if sampled in a vertical borehole), (2) be well padded for isolation from vibration and impact, and (3) be transported with extreme care if undisturbed samples are required.

4.9 In Situ Testing

In situ testing of soil and rock materials should be conducted where necessary for definition of subsurface material properties and in situ state of stress using boreholes, excavations, test pits, and trenches that are either available or have been prepared for sampling and testing. Larger block samples for laboratory testing can also be obtained at the same locations. Appendix F to this guide shows some applicable in situ testing methods. NUREG/CR-5738 further describes the procedures.

In situ tests are often the best means to determine the engineering properties of subsurface materials and, in some cases, might be the only way to obtain meaningful results. Some materials are hard to sample and transport while keeping them representative of field conditions, because of softness, lack of cohesion, or composition. In situ testing techniques offer a valuable option for evaluating soils and rocks that cannot be sampled for laboratory analysis.

Interpretation of in situ test results in soils, clay-rich shales, and moisture-sensitive rocks requires consideration of the drainage that may occur during the test. Consolidation during soil testing makes it difficult to determine whether the results relate to unconsolidated-undrained, consolidated-undrained, consolidated-drained, or unconsolidated-drained conditions or to intermediate conditions between these limiting states. Interpretation of in situ test results requires the complete evaluation of test conditions and limitations.

Rock units commonly contain natural joints, bedding planes, or other discontinuities (e.g., faults and shear zones) that result in irregularly shaped blocks that respond as a discontinuum to various loading conditions. Individual solid blocks might have relatively high compressive and shear strengths, whereas strength along the discontinuity surfaces can be significantly lower and highly anisotropic. Commonly, little or no tensile strength exists across discontinuities. Large-scale in situ tests tend to average out effects of the complex interactions between intact rock blocks and discontinuities. In situ tests in rock are used to determine in situ stresses and deformation properties, including strength and deformation modulus of the jointed rock mass. These tests also help to determine strength and residual stresses along discontinuities in the rock mass. In situ testing performed in weak, near-surface rocks includes penetration tests, plate loading tests, pressure-meter tests, and field geophysical tests.

Table F-2 in Appendix F lists in situ tests that are useful for determining the shear strength of subsurface materials. Direct shear-strength tests in rock measure peak and residual direct shear strength as a function of normal stress on the shear plane. Direct shear strength from intact rock can be measured in the laboratory if the specimen can be cut and transported without disturbance. In situ shear tests are discussed and compared by Nicholson (1983; Ref. 20) and Bowles (1996; Ref. 21). The suggested in situ method for determining direct shear strength of rocks is described in RTH 321-80, “Suggested Method for In Situ Determination of Direct Shear Strength (ISRM),” issued 1980 (Ref. 22). Although the standard penetration test (SPT) is used extensively in investigations of soil liquefaction susceptibility, the cone penetration test (CPT) is also widely used in site investigation because (1) the CPT provides continuous penetration resistance profiles for soils and (2) CPT results are more repeatable and consistent (Ref. 23). Both Appendix C and Appendix F compare the applicability and limitations of the CPT and SPT.

4.10 Geophysical Investigations

4.10.1 General

Geophysical investigations include surface geophysical surveys and borehole logging and other testing techniques, which are important for determining subsurface engineering properties and geologic and hydrologic characteristics, features, and conditions. Data from these investigations should be used to provide more continuous, and possibly deeper, subsurface information for filling in between data derived from surface outcrops, trenches, and boreholes and correlating data from other sources.

Available geophysical and borehole logging methods are listed in Appendix E to this guide and in EM-1110-1-1802, “Geophysical Exploration for Engineering and Environmental Investigations,” issued 1995 (Ref. 24). A geophysical exploration should consider the following factors:

(1) Subsurface and surface geophysical investigations cannot be substituted for each other. Both surface and subsurface geophysical investigations should be conducted to validate and calibrate site investigation results.

(2) For subsurface material engineering properties that could have high consequences if they are not determined properly, or are deemed critical to safe performance of the facility, multiple tests using different methods are recommended to capture uncertainties.

(3) Geophysical explorations should be carried out by personnel having the necessary technical background and experience in the techniques used.

(4) Information related to acquisition of raw and processed field test data (e.g., spacing of data collection locations and instrument settings) should be recorded following applicable standards and quality assurance/quality control procedures to allow for proper interpretation of test results.

Selection of the appropriate penetration depths for geophysical investigations shall consider the need for information on site-specific stratigraphy and parameters of the materials encountered for input to analyses of site seismic response, soil-structure interaction, and foundation/structure stability. To properly determine site shear wave velocity profiles, borehole testing methods (e.g., P-S suspension logging and crosshole testing) combined with surface geophysical tests, such as seismic refraction and reflection surveys and spectral analysis of surface wave (SASW) methods (Ref. 25), should be used to cross-check and consolidate test results. Applicable ASTM and American Society of Civil Engineers standards should be used when conducting geophysical investigations.

4.10.2 Surface Geophysics

Recommended surface geophysical techniques include seismic methods (e.g., reflection, refraction, and surface wave methods), electrical methods (e.g., resistivity), electromagnetic methods (e.g., ground-penetrating radar), and potential field methods (e.g., gravity and magnetics). Surface geophysical methods can be used to (1) measure shear-wave velocity profiles, (2) determine subsurface geologic conditions such as strata layers and thickness, faults, voids, and underground objects, and (3) derive important material engineering properties (e.g., elastic moduli). The surface geophysical measurements should be correlated with borehole geophysical data and geologic logs to derive maximum benefit from the measurements.

4.10.3 Borehole Geophysics

Geophysical borehole logs are very useful for determining geologic, hydrologic, and engineering properties of subsurface materials, including correlation of lithologic units between boreholes. A suitable suite of geophysical logging methods (Ref. 23) should be used for borehole geophysics study. Appendix E to this guide lists some of the applicable geophysical logging methods, along with the geologic characteristics and engineering parameters the methods can help to determine.

Crosshole and single borehole geophysical methods can be used to obtain detailed information about subsurface materials in both horizontal and vertical directions. These methods can be used to determine site shear wave velocity profiles and derive engineering and hydrogeologic properties, such as shear modulus, porosity, and permeability. When very detailed information is needed, tomographic methods can be used to determine the geophysical properties of materials between boreholes.

Geophysical borehole logging methods include P-S suspension (Ref. 26), caliper, gamma, electrical resistivity, electromagnetic induction, fluid resistivity, temperature, flowmeter, television, acoustic televiewer, and other logs. These borehole loggings can measure in situ seismic waves; determine lithology; measure dip and strike of important structural features of the rock units; evaluate intrusion of grout into the rock mass; distinguish and analyze fractures, shear zones, soft zones, cavities, and other discontinuities; and characterize water quality and flow.

Borehole logging and crosshole shear-wave measurements are generally low-strain measurements. In rock, these measurements provide a suitable approximation of shear modulus even under high-strain conditions. In soil, the shear modulus depends strongly on strain level. Therefore, these methods are usually insufficient because nonlinear effects can occur that may lead to misinterpretation of the test results. Laboratory tests (e.g., resonant column torsional shear test) are more promising for shear modulus determination.

4.11 Logs of Subsurface Investigations

It is important to have a complete and detailed log for every borehole. Boring logs should contain dates, locations, and depths of all borings, as well as elevations that are related to a permanent benchmark for the top and bottom of borings, boundaries of soil layers and rock units, and the level at which the water table was encountered. In addition, classification and description of soil layers and rock units, blow count values obtained from SPTs, percent recovery of rock core, quantity of core not recovered for each core interval or drill run, and rock quality designation should be noted. The factors that are needed for blow count correction, such as the type of sampler, hammer, and drill rod used in the SPT test, should also be recorded.

Results of field permeability tests and geophysical borehole logging should be included on the logs. The type of tools used to make the boring should be recorded. Notes should be provided for everything significant to the interpretation of subsurface conditions, such as drilling rate, settling or dropping of drill rods, abnormally low resistance to drilling or advance of samplers, core loss, and instability or heave of the side and bottom of boreholes. Influx of ground water, depths and amounts of water or drilling mud losses and depths at which circulation is recovered, and any other unique feature or occurrence should be recorded on the boring logs and geologic cross sections. Incomplete or abandoned borings should be described with the same care as successfully completed borings.

Logs of the walls and floor of exploratory trenches and other excavations should be presented in a graphic format that shows important components of the soil and structural features in rock units in sufficient detail to permit independent evaluation. Photomosaic panoramas can provide additional perspective and verification of trench features. Locations of all exploration efforts should be recorded in a GIS database and shown on geologic cross sections along with elevations and all pertinent data.

5. Ground Water Investigations

Knowledge of ground water conditions and the relationship of those conditions to surface water and variations associated with seasons or tides is needed for foundation analyses. Ground water levels and conditions are normally observed in boreholes at the time they are drilled. However, these observations should be supplemented by additional data from properly installed wells with piezometers that are monitored at regular intervals from time of installation at least through the construction period. Appendix G to this guide tabulates types of instruments for measuring ground water pressure and the advantages and limitations of each. ASTM D5092, “Standard Practice for Design and Installation of Groundwater Monitoring Wells” (Ref. 27) provides guidance on the design and installation of ground water monitoring wells. Types of piezometers, construction details, and sounding devices are described in EM 1110-2-1908, “Instrumentation of Embankment Dams and Levees,” issued 1995 (Ref. 28).

Ground water conditions should be observed during site investigations, and water level measurements should be taken in exploratory borings. Ground water or drilling mud level should be measured at the start of each workday for borings in progress, at the completion of drilling, and when water levels in the borings have stabilized. Ground water observation wells should be installed in as many locations as needed to adequately define the ground water environment. Pumping tests are preferred for evaluating local permeability and conductivity parameters and the level of confinement between aquifers. These parameters are input into calculations for assessing dewatering requirements for construction and operation of the plant. For major excavations where construction dewatering is required, piezometers or observation wells should be used during construction to monitor the ground water surface and pore pressures beneath the excavation and in the adjacent ground. This guide does not cover ground water monitoring during construction of plants that are designed with permanent dewatering systems.

In areas where perched ground water tables or artesian aquifer systems are expected, piezometers should be installed in each ground water element so that the piezometric level can be determined for the particular aquifer or ground water unit. Care should be taken in the design and installation of piezometers to prevent hydraulic communication between aquifers. The occurrence of artesian pressure in borings should be noted on boring logs, and the artesian heads should be measured and logged.

6. Construction Mapping

It is necessary to confirm that in situ conditions revealed in excavations for safety-related structures were accurately captured and interpreted during the preconstruction site characterization stage to ensure that information related to actual in situ conditions is properly incorporated into plant design analyses. Detailed geologic mapping should be performed for all construction excavations for safety-related structures and other excavations important for verification of subsurface conditions (e.g., cut slopes, tunnels, chambers, and water inlets and outlets). Particular attention should be given to geologic features and characteristics that might be important in assessment of the behavior of foundation materials, including tectonic and nontectonic features and lithologic variations, which might be undetected and different from what was assumed based on the results of site investigations prior to excavations. The detailed geologic mapping should be performed after the completion of excavations and before placement of backfill.

The importance of the geologic mapping is reinforced by the geologic mapping license condition normally imposed in a combined or construction license. This license condition requires a licensee to commit to performing the following associated activities: (1) conduct detailed geologic mapping of excavations for safety-related structures, (2) examine and evaluate geologic features discovered in those excavations, and (3) notify the NRC once the excavations are open for inspection by NRC staff. Changes in foundation design that result from information acquired by the detailed geologic mapping should be noted on appropriate plans and included in maps, cross sections, and the database. All pertinent newly discovered geologic features should be evaluated for their potential impact on foundation materials. This evaluation might require relative or absolute age dates on certain features and particular tectonic structures such as faults and shear zones. The maps, cross sections, and database should include any features installed to improve, modify, or control geologic conditions (e.g., reinforcing systems, permanent dewatering systems, and special treatment areas). Photographic records of foundation geologic mapping and treatments should be made and retained in the database. The GIS and other databases should be continuously updated, up to and including the construction phase, resulting in inclusion of final as-built information in the database.

Appendix A to NUREG/CR-5738 provides detailed guidance on appropriate technical procedures for geologic mapping of foundation materials. Geologic mapping of tunnels and other underground openings must be planned differently from foundation mapping. Technical procedures for mapping tunnels are outlined in Appendix B to NUREG/CR-5738 and can be modified for large chambers. The individual in charge of foundation geologic mapping should be familiar with plant design and subsurface features and characteristics based on previous site investigations. This person should consult with plant design personnel during excavation whenever differences between the actual geology and the design-basis geologic model are discovered. The same individual should be involved in all decisions about changes in plant foundation design and any additional foundation treatments that might be necessary based on actual observed conditions of the foundation materials.

7. Support Functions

7.1 Surveying, Mapping, and Development of the GIS Database

Surveying is an important function that should accompany all essential site investigation activities from reconnaissance through construction mapping. Many methods of surveying are available, from traditional triangulation or plane table work and leveling to electronic distance and GPS measurements. For mapping small areas, plane table methods may still be rapid enough. In most cases, however, GPS or differential GPS together with automated recording and computing procedures is the most suitable method. Procedures for GPS surveying can be found in EM-1110-1-1003, "NAVSTAR Global Positioning System Surveying," issued 2011 (Ref. 18). The GPS measurements and other surveyed locations should be tied to National Geodetic Survey (NGS) markers to be compatible with topographic and digital maps of various types. Survey results should have adequate precision with no more than 0.3 meter (1.0 foot) onshore and 1.5 meters (5.0 feet) offshore for plan coordinates and 3 centimeters (0.1 foot) onshore and 0.3 meter (1.0 foot) offshore for elevation. For greater accuracy, it might still be necessary to perform a certain amount of conventional leveling.

A suitable coordinate system for the site should be chosen. Three-dimensional coordinate systems include the World Geodetic System of 1984, the International Terrestrial Reference Frame, and the North American Datum of 1983 (NAD 83). Coordinates should be referred to NAD 83 to be legally recognized in most U.S. jurisdictions. Moreover, NGS provides software for converting the ellipsoid-based heights of NAD 83 to the sea-level-based heights that appear on topographic maps. NAD 83 coordinates are readily determined when measurements tie the site to an NGS marker.

All three-dimensional information should be entered into a GIS database because data of various types, in the form of tables, can be associated with a coordinate system and recalled to form the desired graphical output. Choice of a specific system is up to the applicant, but the data should be in a format that is readily readable. It is necessary to have personnel with experience in surveying and storing and displaying data in a GIS database throughout all phases of site investigation and construction in order to (1) accurately record information obtained, (2) place geologic, geotechnical, sampling, and testing information into a spatial context, and (3) permit visual display of data on maps and cross sections. Development of the GIS database is an essential activity that should be given proper emphasis and support by applicants and licensees.

7.2 Records, Sample Retention, and Quality Assurance

All data acquired during site characterization investigations should be organized into logical categories and preserved as a permanent record, at least until the power plant is licensed to operate and all matters relating to the interpretation of subsurface conditions at the site have been resolved. Much of the data will already be part of the GIS database, but other data and records, such as logs of operations, photographs, test results, and engineering evaluations and calculations, should also be preserved for further reference.

Samples and rock cores from principal borings should also be retained. Regulatory Position 4.3.3 and Chapter 7 of NUREG/CR-5738 describe procedures for handling and storing samples. The need to retain samples and cores beyond the recommended time is a matter of judgment and should be evaluated on a case-by-case basis. For example, soil samples in tubes will deteriorate with time and will not be suitable for undisturbed testing. However, they may be used as a visual record of the foundation material. Similarly, rock cores subject to slaking and rapid weathering, such as shale, will also deteriorate. Photographs of soil samples and rock cores, with field and final logs of all borings, should be preserved for a permanent record.

The site investigations should be included in the overall quality assurance program for plant design and construction according to the guidance in RG 1.28, "Quality Assurance Program Criteria (Design and Construction)" (Ref. 29), and the requirements of Appendix B, "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants," to 10 CFR Part 50. Therefore, field operations and records preservation should be conducted in accordance with quality assurance principles and procedures.

D. IMPLEMENTATION

The NRC staff may use this regulatory guide as a reference in its regulatory processes, such as licensing, inspection, or enforcement. However, the NRC staff does not intend to use the guidance in this regulatory guide to support NRC staff actions in a manner that would constitute backfitting as that term is defined in 10 CFR 50.109, "Backfitting," and as described in NRC Management Directive 8.4, "Management of Backfitting, Forward Fitting, Issue Finality, and Information Requests," (Ref. 30), nor does the NRC staff intend to use the guidance to affect the issue finality of an approval under 10 CFR Part 52, "Licenses, Certifications, and Approvals for Nuclear Power Plants." The staff also does not intend to use the guidance to support NRC staff actions in a manner that constitutes forward fitting as that term is defined and described in Management Directive 8.4. If a licensee believes that the NRC is using this regulatory guide in a manner inconsistent with the discussion in this Implementation section, then the licensee may file a backfitting or forward fitting appeal with the NRC in accordance with the process in Management Directive 8.4.

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2. *U.S. Code of Federal Regulations*, “Licenses, Certifications, and Approvals for Nuclear Power Plants,” Part 52, Chapter I, Title 10, “Energy.”

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1 Publicly available NRC published documents are available electronically through the NRC Library on the NRC’s public Web site at http://www.nrc.gov/reading-rm/doc-collections/ and through the NRC’s Agencywide Documents Access and Management System (ADAMS) at http://www.nrc.gov/reading-rm/adams.html. The documents can also be viewed online or printed for a fee in the NRC’s Public Document Room (PDR) at 11555 Rockville Pike, Rockville, MD. For problems with ADAMS, contact the PDR staff at (301) 415-4737 or (800) 397-4209; fax (301) 415-3548; or e-mail pdr.resource@nrc.gov.

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2 Copies of International Atomic Energy Agency (IAEA) documents may be obtained through their Web site: WWW.IAEA.Org/ or by writing the International Atomic Energy Agency, P.O. Box 100 Wagramer Strasse 5, A-1400 Vienna, Austria.

3 Copies of ASTM International (ASTM) standards may be purchased from ASTM, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, Pennsylvania 19428-2959; telephone (610) 832-9585. Purchase information is available through the ASTM Web site at http://www.astm.org.

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APPENDIX A

SPECIAL GEOLOGIC FEATURES AND CONDITIONS CONSIDERED IN OFFICE STUDIES AND FIELD OBSERVATIONS (adapted from EM 1110-1-1804, U.S. ARMY CORPS OF ENGINEERS, 2001)

GEOLOGIC FEATURE OR CONDITION	INFLUENCE ON PROJECT	OFFICE STUDIES	FIELD OBSERVATIONS	QUESTIONS TO ANSWER
Landslides	Stability of natural and excavated slopes	Presence or age in project area or at construction site should be determined.	Estimate areal extent (length and width) and height of slope.	Are landslides found off site in geologic formations of the same type that will be affected by project construction?
		Compute shear strength at failure. Do failure strengths decrease with age of slopes, especially for clays and clay shales?	Estimate ground slope before and after slide (may correspond to residual angle of friction).	What are probable previous and present ground water levels?
			Check highway and railway cuts and deep excavations, quarries, and steep slopes.	Do trees slope in an unnatural direction?
Faults and faulting; past seismic activity	Of decisive importance in seismic evaluations; age of the most recent fault movement may determine seismic design earthquake magnitude and may be indicative of high state of stress that could result in foundation heave or overstress in underground works.	Determine existence of known faults and fault history from available information. Check potential fault traces identified on remote sensing imagery, Google Earth, and light detection and ranging (LiDAR). Compare geologic and seismicity maps.	Verify presence of fault at site, if possible, from surface evidence. Examine and consider characteristics of geologically young alluvial deposits and river terraces in the site vicinity.	Are lineaments or possible fault traces apparent from regional aerial imagery?
		Examine existing boring logs for evidence of faulting from offset of strata and indications of breccia and shear zones.	Make field check of geologic maps, structures, cellars, chimneys, roads, fences, pipelines, known faults, caves, inclination of trees, and offset in fence lines.	
Joints and fractures	High concentration of joints indicates weakness of bedrock and high strain.	Study satellite images, aerial photos, and LiDAR and define all available lineaments and their relationship, if possible.	Investigate orientation and density of joints. Assess any cross-cutting relationships between joint sets and estimate age of jointing.	Are the joint sets related to denudation and unloading or are they tectonically formed? What is the current orientation of stress in the crust?

APPENDIX A, Cont'd.

GEOLOGIC FEATURE OR CONDITION	INFLUENCE ON PROJECT	OFFICE STUDIES	FIELD OBSERVATIONS	QUESTIONS TO ANSWER
Stress relief cracking and valley rebounding	Valley walls may have cracking parallel to valley. Valley floors may have horizontal cracking. In some clay shales, stress relief from valley erosion or glacial action may not be complete.	Review pertinent geologic literature and reports for the valley area. Check existing piezometer data for abnormally low levels in valley sides and foundation; compare with normal ground water levels outside valley.	Examine wells and piezometers in valleys to determine if levels are lower than normal ground water regime (indicates valley rebound not complete).	
Sinkholes; karst topography	Might affect stability of foundation. Major effect on location of structures and feasibility of potential site.	Consider the local geology and stratigraphy from previous publications in site vicinity. Examine topographic maps (old and recent), LiDAR, and aerial photos (old and recent) for evidence of undrained depressions and disappearing streams. Consider the location and density of caves in the vicinity. Consider alternate rock dissolution processes such as epigenic and hypogenic systems.	Locate depressions in the field and measure size depth and slopes. Differences in elevation between center and edges may be almost negligible or many feet. From local residents, attempt to date appearance of sinkhole. Consider the presence, size, and frequency of voids identified in core. Conduct field review of features identified in office studies.	Are potentially soluble rock units present, such as limestone, dolomite, gypsum, anhydrite, or halite? Are undrained depressions present that cannot be explained by glaciation? How do the water table and deeper aquifers inform understanding about cavern formation? Is surface topography rough and irregular without apparent cause?
Anhydrites or gypsum layers	Anhydrites in foundations beneath major structures may hydrate and cause expansion, upward thrust, and buckling. Gypsum may cause settlement, subsidence, collapse, or piping. Solution during life of structure may be damaging.	Determine possible existence from available geologic information and delineate possible outcrop locations.	Look for surface evidence of uplift; seek local information on existing structures. Check area carefully for caves or other evidence of solution features.	Are uplifts caused by possible anhydrite expansion or "explosion?"

APPENDIX A, Cont'd.

GEOLOGIC FEATURE OR CONDITION	INFLUENCE ON PROJECT	OFFICE STUDIES	FIELD OBSERVATIONS	QUESTIONS TO ANSWER
Caves	Extent may affect project feasibility or cost. Can provide evidence about faulting that may relate to seismic design. Can result from unrecorded mining activity in the area.	See studies suggested for karst.	Observe cave walls carefully for evidence of faults and recent faulting. Estimate age of any broken stalactites or stalagmites from column rings.	Are any stalactites or stalagmites broken from apparent ground displacement or shaking?
Erosion resistance	Determines need for total or partial channel slope protection.	Locate contacts of potentially erosive strata along drainage channels.	Note stability of channels and degree of erosion and stability of banks.	Are channels stable or have they shifted frequently? Are banks stable or easily eroded? Is there extensive bank sliding?
Internal erosion	Affects stability of foundations and dam abutments. Gravelly sands or sands with deficiency of intermediate particle sizes may be unstable and develop piping when subject to seepage flow.	Locate possible outcrop areas of sorted alluvial materials or terrace deposits.	Examine seepage outcrop areas of slopes and riverbanks for piping.	
Area subsidence	Area subsidence endangers long-term stability and performance of project.	Locate areas of high ground water withdrawal, oil and gas fields, and subsurface mineral extraction (coal, solution mining, etc.) areas.	Check project area for new wells or new mining activity.	Are there any plans for new or increased recovery of subsurface water or mineral resources?
Collapsing soils	Determines need for removal of shallow foundation materials that would collapse upon wetting	Determine how deposits were formed during geologic time and any collapse problems in area.	Examine surface deposits for voids along eroded channels, especially in steep valleys eroded in fine-grained sedimentary formations.	Were materials deposited by mud flows?

APPENDIX A, Cont'd.

GEOLOGIC FEATURE OR CONDITION	INFLUENCE ON PROJECT	OFFICE STUDIES	FIELD OBSERVATIONS	QUESTIONS TO ANSWER
Locally lowered ground water	May cause minor to large local and area settlements and result in flooding near rivers or open water and differential settlement of structures.	Determine if heavy pumping from wells has occurred in project area; contact city and State agencies and U.S. Geological Survey.	Obtain ground water levels in wells from owners and information on withdrawal rates and any planned increases. Observe condition of structures. Contact local water plant operators.	
Abnormally low pore water pressures (lower than anticipated from ground water levels)	May indicate effective stresses are still increasing and may cause future slope instability in valley sites.	Compare normal ground water levels with piezometric levels if data are available.		Is a possible cause from past reduction in vertical stresses (e.g., deep glacial valley or canal excavations such as the Panama Canal in clay shales where pore water pressures were reduced by stress relief)?
In situ shear strength from natural slopes	Provides early indication of stability of excavated slopes or abutment, and natural slopes around reservoir area.	Locate potential slide areas. Existing slope failures should be analyzed to determine minimum in situ shear strengths.	Estimate slope angles and heights, especially at river bends where undercutting erosion occurs. Determine if flat slopes are associated with mature slide or slump topography or with erosion features.	Are existing slopes consistently flat, indicating residual strengths have been developed?
Swelling soils and shales	Highly preconsolidated clays and clay shales may swell greatly in excavations or upon increase in moisture content.	Determine potential problem and location of possible preconsolidated strata from available information.	Examine roadways founded on geologic formations similar to those at site. Check condition of buildings and effects of rainfall and watering.	Do seasonal ground water and rainfall or watering of shrubs or trees cause heave or settlement?
Varved clays	Pervious layers may cause more rapid settlement than anticipated. May appear to be unstable because of uncontrolled seepage flow through pervious layers between overconsolidated clay layers or may have weak clay layers. May be unstable in excavations unless well points are used to control ground water.	Determine areas of possible varved clay deposits associated with prehistoric lakes. Determine settlement behavior of structures in the area.	Check natural slopes and cuts for varved clays; check settlement behavior of structures.	

APPENDIX A, Cont'd.

GEOLOGIC FEATURE OR CONDITION	INFLUENCE ON PROJECT	OFFICE STUDIES	FIELD OBSERVATIONS	QUESTIONS TO ANSWER
Dispersive clays	Is a major factor in selecting soils for embankment dams and levees.	Check with Soil Conservation Service and other agencies regarding behavior of existing small dams.	Look for peculiar erosional features, such as vertical or horizontal cavities in slopes or unusual erosion in cut slopes. Perform "crumb" test.	
Riverbank and other liquefaction areas	Has a major effect on riverbank stability and on foundation stability in seismic areas.	Locate potential areas of loose fine-grained alluvial or terrace sand, most likely along riverbanks where loose sands are present and erosion is occurring.	Check riverbanks for scallop-shaped failure with narrow neck (may be visible during low water). If present, determine shape, depth, average slope, and slope of adjacent sections. Liquefaction in wooded areas may leave trees inclined at erratic angles. Look for evidence of sand boils in seismic areas.	
Filled areas	Relatively recent filled areas would cause large settlements. Such fill areas may be overgrown and not detected from surface or even subsurface evidence.	Check old topo maps, if available, for depressions or gullies not shown on more recent topo maps.		Obtain local history of site from area residents.
Local overconsolidation from previous site usage	Local areas of a site may have been overconsolidated from past heavy loadings of lumber or material storage piles.			Obtain local history from residents of area.

APPENDIX B

SOURCES OF GEOLOGIC INFORMATION (adapted from EM 1110-1-1804, U.S. ARMY CORPS OF ENGINEERS, 2001)

AGENCY	TYPE OF INFORMATION	DESCRIPTION	REMARKS
U.S. Geological Survey (USGS)	Topographic maps	U.S. 7.5-minute series 1:24,000 (supersedes 1:31,680); Puerto Rico 7.5-minute series 1:20,000 (supersedes 1:30,000); Virgin Island 1:24,000 series. U.S. 15-minute series 1:62,500 (1:63,360 for Alaska) U.S. 1:100,000-scale series (quadrangle, county, or regional format) U.S. 1:50,000-scale county map series U.S. 1:250,000-scale series Digital elevation models are available for entire U.S. at 1:250,000, and for certain areas at 1:100,000 and 1:24,000 scales Digital line graphs are available for some areas at 1:24,000 and 1:65,000, 1:100,000 for— • hydrography • transportation • U.S. Publication Survey • boundaries • hypsography	Orthophotoquad monocolor and color infrared maps also produced in 7.5-minute and 15-minute series. New index of maps for each State started in 1976. Status of current mapping from USGS regional offices and in monthly USGS bulletin, "New Publications of the U.S. Geological Survey." Topographic and geological information from the USGS can be accessed through the Earth Science Information Center (ESIC) (1-800-USAMAPS).
USGS	Geology maps and reports	1:24,000 (1:20,000 Puerto Rico), 1:62,500, 1:100,00, and 1:250,000 quadrangle series includes surficial bedrock and standard (surface and bedrock) maps with major landslide areas shown on later editions 1:500,000 and 1:2,500,000	New index of geologic maps for each State started in 1976. List of geologic maps and reports for each State published periodically.
USGS	Miscellaneous maps and reports	Landslide susceptibility rating, swelling soils, engineering geology, water resources, and ground water.	Miscellaneous Investigation Series and Miscellaneous Field Studies Series, maps and reports, not well cataloged; many included as open file reports.
USGS	Special maps	1:7,500,000 and 1:1,000,000: Limestone Resources, Solution Mining Subsidence, Quaternary Dating Applications, Lithologic Map of U.S., Quaternary Geologic Maps.	

APPENDIX B, Cont'd.

AGENCY	TYPE OF INFORMATION	DESCRIPTION	REMARKS
USGS	Hydrologic maps	Hydrologic Investigations Atlases with a principal map scale of 1:24,000; includes water availability, flood areas, surface drainage precipitation and climate, geology, availability of ground and surface water, water quality and use, and streamflow characteristics	Some maps show ground water contours and location of wells.
USGS	Earthquake hazard	Seismic maps of each State (started in 1978 with Maine); field studies of fault zones; relocation of epicenters in eastern United States; hazards in the Mississippi Valley area; analyses of strong motion data; state-of-the-art workshops	Operates National Strong-Motion Network. National Earthquake Information Service publishes monthly listing of epicenters worldwide. Information is available through ESIC (1-800-USAMAPS).
USGS	Mineral resources	Bedrock and surface geologic mapping; engineering geologic investigations; map of U.S. power-generating plants (location of built, under construction, planned, and type); 7.5-minute quadrangle geologic maps and reports on surface effects of subsidence into underground mine openings of eastern Powder River Basin, Wyoming	
USGS	Bibliography	"Bibliography of North American Geology" (USGS 1973)	USGS professional paper
American Geological Institute Geological Society of America	Bibliography	American Geological Institute print counterpart.	
		"Bibliography and Index of Geology" to "Geo Ref" digital index (USGS 1973)	1969 to present, 12 monthly issues plus yearly cumulative index
		"Decade of North American Geology" series	
National Oceanic and Atmospheric Administration (NOAA)	Earthquake hazards	National Geophysical Data Center in Colorado has extensive earthquake hazard information (303-497-6419)	
National Aeronautics and Space Administration (NASA)	Remote sensing data	Landsat, Skylab imagery	
NOAA	Remote sensing data		
Space Imaging Earth Observation Satellite (EOSAT)	Remote sensing data	Multiband satellite imagery with meter resolution	

APPENDIX B, Cont'd.

AGENCY	TYPE OF INFORMATION	DESCRIPTION	REMARKS
U.S. Fish and Wildlife Service	Wetlands	The National Wetlands Inventory maps at 1:24,000 for most of the contiguous United States	Available as maps or mylar overlays
USGS	Flood-prone area maps	1:24,000 series maps outlining floodplain areas not included in Corps of Engineers reports or protected by levees	Stage 2 of 1966 89th Congress House Document 465
U.S. Army Engineer Waterways Experiment Station (USAEWES)	Earthquake hazard	"State-of-the-Art for Assessing Earthquake Hazards in the United States," Miscellaneous Paper S-73-1	Series of 19 reports, 1973 to present
International Union of Geological Sciences	Worldwide mapping	Commission for the Geological Map of the World publishes periodic reports on worldwide mapping in "Geological Newsletter"	
Natural Resources Conservation Service	Soil survey reports	1:15,840 or 1:20,000 maps of soil information on photomosaic background for each country. Recent reports include engineering test data for soils mapped, depth to water and bedrock, soil profiles grain-size distribution, engineering interpretation, and special features. Recent aerial photo coverage of many areas. Soils maps at 1:7,500,000, 1:250,000, and 1:12,000 scale are available in digital format for some areas.	Reports since 1957 contain engineering uses of soils mapped, parent materials, geologic origin, climate, physiographic setting, and profiles.
Federal Emergency Management Agency	Earthquake hazard	National Earthquake Hazards Reduction Program, "Recommended Provisions for Seismic Regulations for New Buildings and Older Structures," issued 1997, includes seismic maps.	
State Geologic Agencies	Geologic maps and reports	State and county geologic maps; mineral resource maps; special maps such as for swelling soils; bulletins and monographs; well logs; water resources, ground water studies	List of maps and reports published annually, unpublished information by direct coordination with State geologist
Defense Mapping Agency (DMA)	Topographic maps	Standard scales of 1:12,500, 1:50,000, 1:250,000, and 1:1,000,000 foreign and worldwide coverage, including photomaps	Index of available maps from DMA
American Association of Petroleum Geologists	Geological highway map series	Scale approximately 1 inch to 30 miles shows surface geology and includes generalized time and rock unit columns, physiographic map, tectonic map, geologic history summary, and sections	Published as 12 regional maps, including Alaska and Hawaii
Tennessee Valley Authority (TVA)	Topographic maps, geologic maps and reports	Standard 7.5-minute TVA-USGS topographic maps, project pool maps, large-scale topographic maps of reservoirs, geologic maps and reports in connection with construction projects	Coordinate with TVA for available specific information.
U.S. Department of Interior, Bureau of Reclamation	Geologic maps and reports	Maps and reports prepared during project planning and design studies	Reports on completed projects can be obtained by interlibrary loan or from USAEWES.

APPENDIX B, Cont'd.

AGENCY	TYPE OF INFORMATION	DESCRIPTION	REMARKS
Agricultural Stabilization and Conservation Services Aerial Photography Field Office (APFO)	Aerial photographs	The APFO offers aerial photographs across the United States, typically a series of photographs taken at different times, as available for a given site.	Information is available at 801-975-3503.
USGS Earth Resources Observation Systems (EROS) Center (EDC)	Aerial photographic coverage	The EDC houses the nation's largest collection of space- and aircraft-acquired imagery.	Information is available at 605-594-6151 or 1-800-USAMAPS.
Satellite Pour l'Observation de la Terre (SPOT)	Remote sensing imagery	High-resolution multispectral imagery produced by France's SPOT satellite imager is available for purchase.	The contact number for SPOT images is 800-275-7768.
Google Earth	Combination of satellite imagery, aerial photography, and geographic information	Maps the Earth by the superimposition of images obtained from satellite imagery, aerial photography, and geographic information system (GIS) onto a three-dimensional globe. Resolution varies from 15 meters to 15 centimeters.	Available online.

APPENDIX C

METHODS OF SUBSURFACE EXPLORATION

METHOD	PROCEDURE	APPLICABILITY	LIMITATIONS
1. Methods of Access for Sampling, Test, or Observation			
Pits, trenches, shafts, tunnels	Excavation is made by hand, large auger, or digging machinery.	Visual observation, photography, disturbed and undisturbed sampling, in situ testing of soil and rock.	Depth of unprotected excavations is limited by ground water or safety considerations. May need dewatering.
Auger boring	Boring is advanced by hand auger or power auger.	Recovery of remolded samples and determining ground water levels. Access for undisturbed sampling of cohesive soils.	Will not penetrate bounders or most rock.
Hollow-stem auger boring	Boring is advanced by means of continuous-flight helix auger with hollow-center stem.	Access to undisturbed or representative sampling through hollow stem with thin-wall tube sampler, core barrel, or split-barrel sampler.	Should not be used with coarse-grained soils. Not suitable for undisturbed sampling in loose sand or silt. Not recommended below the ground water table in cohesionless soils.
Wash boring	Boring is advanced by chopping with light bit and by jetting with upward deflected jet.	Cleaning out and advancing hole in soil between sample intervals.	Suitable for use with sampling operations in soil only if done with low water velocities and with upward deflected jet.
Rotary drilling	Boring is advanced by rotating drilling bit; cuttings removed by circulating drilling fluid.	Boring in soil or rock.	Drilling mud should be used in coarse-grained soils. Bottom discharge bits are not suitable for use with undisturbed sampling in soil unless combined with protruding core barrel, as in Denison sampler, or with upward deflected jets.
Percussion drilling	Boring is advanced by air-operated impact hammer.	Detection of voids and zones of weakness in rock by changes in drill rate or resistance. Access for in situ testing or logging.	Not suitable for use in soils.
Sonic drilling	Boring is advanced by vibrating entire drill string that strongly reduces friction on the drill string and drill bit due to liquefaction, inertia effects, and a temporary reduction of porosity of the soil.	Drilling for coarse alluvial deposit that consists of significant amount of gravel and cobble.	While sonic drill usually can produce continuous samples and with good recovery, the samples retrieved from the plastic sampling tubes are highly disturbed and broken up.
Cable drilling	Boring is advanced by repeated dropping of heavy big; removal of cuttings by bailing	Advancing hole in soil or rock. Access for sampling, in situ testing, or logging in rock. Penetration of hard layers, gravel, or boulders in auger borings.	Causes severe disturbance in soils; not suitable for use with undisturbed sampling methods.
Continuous sampling or displacement boring	Boring is advanced by repeated pushing of sampler, or closed sampler is pushed to desired depth and sample is taken.	Recovery of representative samples of cohesive soils and undisturbed samples in some cohesive soils.	Effects of advance and withdrawal of sampler result in disturbed sections at top and bottom of sample. In some soils, entire sample may be disturbed. Best suited for use in cohesive soils. Continuous sampling in cohesionless soils may be made by successive reaming and clearing of hole between sampling.

APPENDIX C, Cont'd.

METHOD	PROCEDURE	APPLICABILITY	LIMITATIONS
2. Methods of Sampling Soil or Rock			
Hand cut or cylindrical sample	Sample is cut by hand from soil exposed in excavation.	Highest quality samples in all soils and in soft rock.	Requires accessible excavation and dewatering if below water table. Extreme care is required in sampling cohesionless soils.
Fixed-piston sampler	Thin-walled tube is pushed into soil with fixed piston in contact with top of sample during push.	Undisturbed samples in cohesive soils, silts, and sands above or below the water table.	Some types do not have a positive means to prevent piston movement.
Hydraulic piston sampler (Osterberg Sampler)	Thin-walled tube is pushed into soil by hydraulic pressure. Fixed piston is in contact with top of sample during push.	Undisturbed samples in cohesive soils, silts, and sands above or below the water table.	Not possible to determine amount of sampler penetration during push. Does not have vacuum breaker in piston.
Free-piston sampler	Thin-walled tube is pushed into soil. Piston rests on top of soil sample during push.	Undisturbed samples in stiff, cohesive soils. Representative samples in soft to medium cohesive soils and silts.	May not be suitable for sampling in cohesionless soils. Free piston provides no control of specific recovery ratio.
Open drive sampler	Thin-walled open tube is pushed into soil.	Undisturbed samples in stiff, cohesive soils. Representative samples in soft to medium cohesive soils and silts.	Small diameter of tubes may not be suitable for sampling in cohesionless soils or for undisturbed sampling in uncased boreholes. No control of specific recovery ratio.
Swedish Foil Sampler	Sample tube is pushed into soil, while stainless steel strips unrolling from spools envelop sample. Piston, fixed by chain from surface, maintains contact with top of sample.	Continuous undisturbed samples up to 20 meters (66 feet) long in very soft to soft clays.	Small sampler diameter increases sample disturbance. Not suitable for soils containing gravels, sand layers, or shells, which may rupture foils and damage samples. Difficulty may be encountered in alternating hard and soft layers, with squeezing of soft layers and reduction in thickness. Requires experienced operator.
Pitcher sampler	Thin-walled tube is pushed into soil by spring above sampler, while outer core bit reams hole. Cuttings are removed by circulating drilling fluid.	Undisturbed samples in stiff, hard, brittle, cohesive soils and sands with cementation, and in soft rock. Effective in sampling alternating hard and soft layers. Representative samples in soft-to-medium cohesive soils and silts. Disturbed samples may be obtained in cohesionless materials with variable success.	Frequently ineffective in cohesionless soils.
Split-barrel or split-spoon sampler	Split-barrel tube is driven into soil by blows of falling ram. Sampling is carried out in conjunction with Standard Penetration Test.	Representative samples in soils other than coarse-grained soils.	Samples are disturbed and not suitable for tests of physical properties.
Auger sampling	Auger drill used to advance hole is withdrawn at intervals for recovery of soil samples from auger flights.	Determine boundaries of soil layers and obtain samples of soil classification.	Samples are not suitable for physical property or density tests. Large errors in locating strata boundaries may occur without close attention to details of procedure. In some soils, particle breakdown by auger or sorting effects may result in errors in determining gradation.

APPENDIX C, Cont'd.

METHOD	PROCEDURE	APPLICABILITY	LIMITATIONS
Rotary core barrel	Hole is advanced by core bit while core sample is retained within core barrel or within stationary inner tube. Cuttings removed by drilling fluid.	Core samples in competent rock and hard soils with single tube core barrel. Core samples in poor or broken rock may be obtainable with double tube core barrel with bottom discharge bit.	Because recovery is poorest in zones of weakness, samples generally fail to yield positive information on soft seams, joints, or other defects in rocks.
Denison sampler	Hole is advanced and reamed by core drill while sample is retained in nonrotating inner core barrel with core catcher. Cuttings removed by circulating drilling fluid.	Undisturbed samples in stiff-to-hard cohesive soil, sand with cementation, and soft rocks. Disturbed sample may be obtained in cohesionless materials with variable success.	Not suitable for undisturbed sampling in loose, cohesionless soils or soft, cohesive soils. Difficulties may be experienced in sampling alternating hard and soft layers.
Shot core boring (Calyx)	Boring is advanced by rotating single core barrel, which cuts by grinding with chilled steel shot fed with circulating wash water. Used shot and coarser cuttings are deposited in an annular cup, or calyx, above the core barrel.	Large-diameter cores and accessible boreholes in rock.	Cannot be used in drilling at large angles to the vertical. Often ineffective in securing small diameter cores.
Oriented integral sampling	Reinforcing rod is grouted into small diameter hole, then overcored to obtain an annular core sample.	Core samples in rock with preservation of joints and other zones of weakness.	Samples are not well suited to tests of physical properties.
Wash sampling or cuttings sampling	Cuttings are recovered from wash water or drilling fluid.	Samples useful in conjunction with other data for identification of major strata.	Sample quality is not adequate for site investigations for nuclear facilities.
Submersible vibratory (Vibracore) sampler	Core tube is driven into soil by vibrator.	Continuous representative samples in unconsolidated marine sediments.	Because of high area ratio and effects of vibration, samples may be disturbed.
Underwater piston corer	Core tube attached to drop weight is driven into soil by gravity after a free fall of controlled height.	Representative samples in unconsolidated marine sediments.	Samples may be seriously disturbed. Cable-supported piston remains in contact with soil surface during drive.
Gravity corer	Open core tube attached to drop weight is driven into soil by gravity after free fall.	Representative samples at shallow depth in unconsolidated marine sediments.	No control of specific recovery ratio. Samples are disturbed.

APPENDIX C, Cont'd.

METHOD	PROCEDURE	APPLICABILITY	LIMITATIONS
3. Methods of In Situ Testing of Soil and Rock			
Standard Penetration Test (SPT)	Split-barrel sampler is driven into soil by blows of free-falling weight. Blow count for each 15 centimeters (6 inches) of penetration is recorded.	Blow count may be used as an index of consistency or density of soil. May be used for detection of changes in consistency or density in clays or sands. May be used with empirical relationships to estimate relative density of clean sand.	Extremely unreliable in silts, silty sands, or soils containing gravel. In sands below water table, positive head must be maintained in borehole. Determination of relative density in sands requires site-specific correlation or highly conservative use of published correlations. Results are sensitive to details of apparatus and procedure. The technique should not be applied to soils containing large amounts of cobbles.
Cone Penetration Test/Seismic Cone Penetration Test (SCPT)	Instrument steel cone is pushed continuously into the ground and measures resistance to penetration, skin friction, and other properties depending on devices incorporated in the cone. SCPT consists of a receiver to conduct downhole seismic test.	Detection of changes in consistency, strength, and density in soils ranging from clays to finer gravel. Used to estimate static undrained shear strength of clays, liquefaction potential of cohesionless soils, and, if so instrumented, changes in pore water pressure in saturated soils. SCPT can measure compression wave velocity and shear wave velocity in soils. Experimental cone penetrometers are under development to detect various contaminants.	Does not acquire soil samples unless use modified tools. Penetration depth may be limited due to push rig capacity in stiff soils, and the technique should not be applied to soils containing large amounts of cobbles.
Field vane shear test	Four-bladed vane is pushed into undisturbed soil, then rotated to cause shear failure on cylindrical surface. Torsional resistance versus angular deflection is recorded.	Used to estimate in situ undrained shear strength and sensitivity of clays.	Not suitable for use in silts, sands, or soils containing appreciable amounts of gravel or shells. May yield unconservative estimates of shear strength in fissured clay soils or where strength is strain-rate dependent.
Drive point penetrometer	Expandable steel cone is driven into soil by falling weight. Blow count versus penetration is recorded.	Detection of gross changes in consistency or relative density. May be used in some coarse-grained soils.	Provides no quantitative information on soil properties.
Plate bearing test (soil)	Steel loading plate is placed on horizontal surface and is statically loaded, usually by hydraulic jack. Settlement versus time is recorded for each load increment.	Estimation of strength and moduli of soil. May be used at ground surface, in excavations, or in boreholes.	Results can be extrapolated to loaded areas larger than bearing plate only if properties of soil are uniform laterally and with depth.
Plate bearing test or Plate jacking test (rock)	Bearing pad on rock surface is statically loaded by hydraulic jack. Deflection versus load is recorded.	Estimation of elastic moduli of rock masses. May be used at ground surface, in excavations, in tunnels, or in boreholes.	Results can be extrapolated to loaded areas larger than bearing pad only if rock properties are uniform over volume of interest, and if diameter of bearing pad is larger than average spacing of joints or other discontinuities.
Pressure meter test (Dilatometer test)	Uniform radial pressure is applied hydraulically over a length of borehole several times its diameter. Change in diameter versus pressure is recorded.	Estimation of elastic moduli of rocks and estimation of shear strengths and compressibility of soils by empirical relationships.	Test results represent properties only of materials in vicinity of borehole. Results may be misleading in testing materials whose properties may be anisotropic.

APPENDIX C, Cont'd.

METHOD	PROCEDURE	APPLICABILITY	LIMITATIONS
Field pumping test	Water is pumped from or into an aquifer at constant rate through penetrating well. Change in piezometric level is measured at well and at one or more observation wells. Pumping pressures and flow rates are recorded. Packers may be used for pump-in pressure tests.	Estimation of in situ permeability of soils and rock mass.	Apparent permeability may be greatly influenced by local features. Effective permeability of rock is dependent primarily on frequency and distribution of joints. Test result in rock is representative only to the extent that the borehole intersects a sufficient number of joints to be representative of the joint system of the rock mass.
Borehole field permeability test	Water is added to an open-ended pipe casing sunk to desired depth. With constant head tests, constant rate of gravity flow into hole and casing pipe are measured. Variations include applied pressure tests and falling head tests.	Rough approximation of in situ permeability of soils and rock mass.	Pipe casing must be carefully cleaned out just to the bottom of the casing. Clear water must be used or tests may be grossly misleading. Measurement of local permeability only.
Direct shear test	Block of in situ rock is isolated to permit shearing along a preselected surface. Normal and shearing loads are applied by jacking. Loads and displacements are recorded.	Measurement of shearing resistance of rock mass in situ.	Tests are costly. Usually, variability of rock mass requires a sufficient number of tests to provide statistical control.
Pressure tunnel test	Hydraulic pressure is applied to sealed-off length of circular tunnel, and diametral deformations are measured.	Determination of elastic constants of the rock mass in situ.	Volume of rock tested is dependent on tunnel diameter. Cracking caused by tensile hoop stresses may affect apparent stiffness of rock.
Radial jacking test	Radial pressure is applied to a length of circular tunnel by flat jacks. Diametral deformations are measured.	Same as pressure tunnel test.	Same as pressure tunnel test.
Borehole jack test	Load is applied to wall of borehole by two diametrically opposed jacks. Deformations and pressures are recorded.	Determination of elastic modulus of rock in situ. Capable of applying greater pressure than dilatometers.	Apparent stiffness may be affected by development of tension cracks.
Borehole deformation meter	Device for measuring diameters is placed in borehole, and hole is overcored to relieve stresses on annular rock core with deformation meter. Diameters (usually 3) are measured before and after overcoring. Rock modulus is measured by laboratory tests on core; in situ stresses are computed by elastic theory.	Measurement of absolute stresses in situ.	Stress field is affected by borehole. Analysis subject to limitations of elastic theory. Two boreholes at different orientations are required for determination of complete stress field. Questionable results in rocks with strongly time-dependent properties.

APPENDIX C, Cont'd.

METHOD	PROCEDURE	APPLICABILITY	LIMITATIONS
Inclusion stressmeter	Rigid stress-indicating device (stressmeter) is placed in borehole, and the hole is overcored to relieve stresses on annular core with stress meter. In situ stresses are computed by elastic theory.	Measurement of absolute stresses in situ. Does not require accurate knowledge of rock modulus.	Same as above.
Borehole strain gauge	Strain gauge is cemented to bottom of borehole, and gauge is overcored to relieve stresses on core containing strain gauge. Stresses are computed from resulting strains and from modulus obtained by laboratory tests on core.	Measurement of one component of normal stress in situ. Does not require knowledge of rock modulus.	Stress field affected by excavation or tunnel used. Interpretation of test results subject to assumption that loading and unloading moduli are equal. Questionable results in rock with strongly time-dependent properties.
Hydraulic fracturing test	Fluid is pumped into sealed-off portion of borehole with pressure increasing until fracture occurs.	Estimation of minor principal stress.	Affected by anisotropy of tensile strength in rock.
Crosshole seismic test	Seismic signal is transmitted from source in one borehole to receiver(s) in other borehole(s), and transit time is recorded.	In situ measurement of compression wave velocity and shear wave velocity in soils and rocks.	Requires deviation survey of boreholes to eliminate errors due to deviation of holes from vertical. Refraction of signal through adjacent high-velocity beds must be considered.
Uphole/downhole seismic test	Seismic signal is transmitted between borehole and ground surface, and transit time is recorded.	In situ measurement of compression wave velocity and shear wave velocity in soils and rocks.	Apparent velocity obtained is time average for all strata between source and receiver.
P-S-suspension log	A 7-meter probe contains a source and two receivers spaced 1 meter apart, suspended by a cable. The source generates a pressure wave in the borehole fluid. The pressure wave is converted to seismic waves (P and S) at the borehole wall, and the P and S waves are then converted back to pressure waves in the fluid and received by the geophones. The transit time over the gauge length is recorded as the difference in arrival times at the receivers.	Measurement of shear and compression wave velocities for soil and rock continuously along the borehole.	Results represent only the material immediately adjacent to the borehole.
Three-dimensional velocity log	Logging tool contains transmitting and receiving transducer separated by fixed gauge length. Signal is transmitted through rock adjacent to borehole, and wave train at receiver is recorded.	Measurement of compression wave and shear wave velocities in rock. Detection of void spaces, open fractures, and zones of weakness.	Results represent only the material immediately adjacent to the borehole. Can be obtained only in uncased, fluid-filled borehole. Correction required for variation in hole size. Use is limited to materials with P-wave velocity greater than that of borehole fluid.

APPENDIX C, Cont'd.

METHOD	PROCEDURE	APPLICABILITY	LIMITATIONS
Electrical resistivity log	Apparent electrical resistivity of soil or rock in neighborhood of borehole is measured by in-hole logging tool containing one of a wide variety of electrode configurations.	Appropriate combination of resistivity logs can be used to estimate porosity and degree of water saturation in rocks. In soils, may be used as qualitative indication of changes in void ratio or water content for correlation of strata between boreholes and for location of strata boundaries.	Can be obtained only in uncased boreholes. Hole must be fluid filled, or electrodes must be pressed against borehole. Apparent resistivity values are strongly affected by changes in hole diameter, strata thickness, resistivity contrast between adjacent strata, resistivity of drilling fluid, etc.
Neutron log	Neutrons are emitted into rock or soil around borehole by a neutron source in the logging tool. A detector, isolated from the source, responds to either slow neutrons or secondary gamma rays. Response of detector is recorded.	Correlation of strata between boreholes and location of strata boundaries. Provides an approximation to water content and can be run in cased or uncased, fluid-filled, or empty boreholes.	Because of very strong borehole effects, results are generally not of sufficient accuracy for quantitative engineering uses.
Gamma-gamma log (density log)	Gamma rays are emitted into rock around the borehole by a source in the logging tool, and a detector isolated from the source responds to back-scattered gamma rays. Response of detector is recorded.	Estimation of bulk density in rock, qualitative indication of changes of density in soils. May be run in empty or fluid-filled holes.	Effects of borehole size and density of drilling fluid must be accounted for. Presently not suitable for qualitative estimate of density in soils other than those of rock-like character. Cannot be used in cased boreholes.
Borehole cameras	Film-type or television camera in a suitable protective container is used for observation of walls of borehole.	Detection and mapping of joints, seams, cavities, or other visually observable features in rock. Can be used in empty uncased holes or in boreholes filled with clear water.	Results are affected by any condition that impairs visibility.
Borehole televiewer	A rotating acoustic signal illuminates the borehole wall, and reflected signals are recorded.	Detection and mapping of joints, seams, cavities, or other observable features in rock. Can be used in mud-filled boreholes.	Transparency of borehole fluid is not essential.

APPENDIX D

SPACING AND DEPTH OF SUBSURFACE EXPLORATIONS FOR FOUNDATIONS OF SAFETY-RELATED[1] ENGINEERED STRUCTURES

STRUCTURE	SPACING OF BORINGS[2] OR SOUNDINGS	MINIMUM DEPTH OF PENETRATION
General	For favorable, uniform geologic conditions, where continuity of subsurface strata is found, the recommended spacing is as indicated for the type of structure. At least three borings should be at locations within the footprint of every safety-related structure, unless other reliable information is available in the immediate vicinity or otherwise justifiable. Where variable conditions are found, spacing should be smaller, as needed, to obtain a clear picture of soil or rock properties and their variability. Where cavities or other discontinuities of engineering significance may occur, the normal exploratory work should be supplemented by borings or soundings at a spacing small enough to detect such features.	The depth of borings should be determined on the basis of the type of structure and geologic conditions. All borings should be extended to a depth sufficient to define the site geology and to sample all materials that may swell during excavation, may consolidate subsequent to construction, may be unstable under earthquake loading, or whose physical properties would affect foundation behavior or stability. Where soils are very thick, the maximum required depth for engineering purposes, denoted d_{max}, may be taken as the depth at which the change in the vertical stress during or after construction for the combined foundation loading is less than 10% of the effective in situ overburden stress. It may be necessary to include in the investigation program several borings to establish the soil model for soil-structure interaction studies. These borings may be required to penetrate depths greater than those required for general engineering purposes. Borings should be deep enough to define and evaluate the potential for deep stability problems at the site. Generally, all borings should extend at least 10 meters (m) (33 feet (ft)) below the lowest part of the foundation. If competent rock is encountered at lesser depths than those given, borings should penetrate to the greatest depth where discontinuities or zones of weakness or alteration can affect foundations and should penetrate at least 6 m (20 ft) into sound rock. For weathered shale or soft rock, depths should be as for soils.

[1] As determined by the final locations of safety-related structures and facilities.

[2] Includes shafts or other accessible excavations that meet depth requirements.

APPENDIX D, Cont'd.

STRUCTURE	SPACING OF BORINGS[2] OR SOUNDINGS	MINIMUM DEPTH OF PENETRATION
Buildings, retaining walls, concrete dams	Principal borings: one boring at the center of safety-related structures and additional borings along the periphery, at corners, and other selected locations. For larger, heavier structures, such as the containment and auxiliary buildings, at least one boring per 900 m^2 (10,000 ft^2) (approximately 30 m (100 ft) spacing). One boring per 30 m (100 ft) for essentially linear structures.	At least one-fourth of the principal borings and a minimum of one boring per structure to penetrate into sound rock or to a depth equal to d_{max}. Others to a depth below foundation elevation equal to the width of structure or to a depth equal to the width of the structure or to a depth equal to the foundation depth below the original ground surface, whichever is greater.[3]
Earth dams, dikes, levees, embankments	Principal borings: one per 30 m (100 ft) along axis of structure and at critical locations perpendicular to the axis to establish geological sections with ground water conditions for analysis.[2]	Principal borings: one per 60 m (200 ft) to d_{max}. Others should penetrate all strata whose properties would affect the performance of the foundation. For water-impounding structures, to sufficient depth to define all aquifers and zones of underseepage that could affect the performance of structures.[2]
Deep cuts,[4] canals	Principal borings: one per 60 m (200 ft) along the alignment and at critical locations perpendicular to the alignment to establish geologic sections with ground water conditions for analysis.[2]	Principal borings: one per 60 m (200 ft) to penetrate into sound rock or to d_{max}. Others to a depth below the bottom elevation of excavation equal to the depth of cut or to below the lowest potential failure zone of the slope.[2] Borings should penetrate pervious strata below which ground water may influence stability.[2]
Pipelines	Principal borings: This may vary depending on how well site conditions are understood from other plant site borings. For variable conditions, one per 30 m (100 ft) for buried pipelines; at least one boring for each footing for pipelines above ground.	Principal borings: for buried pipelines, one of every three to penetrate sound rock or to d_{max}. Others to 5 times the pipe diameters below the elevation. For pipelines above ground, depths as for foundation structures.[2]
Tunnels	Principal borings: one per 30 m (100 ft)[2]; may vary for rock tunnels, depending on rock type and characteristics and planned exploratory shafts or adits.	Principal borings: one per 60 m (200 ft) to penetrate into sound rock or to d_{max}. Others to 5 times the tunnel diameter below the invert elevation.[2,3]

3 Also supplementary borings or soundings that are design dependent or necessary to define anomalies, critical conditions, etc.

4 Includes temporary cuts that would affect ultimate site safety.

APPENDIX D, Cont'd.

STRUCTURE	SPACING OF BORINGS[2] OR SOUNDINGS	MINIMUM DEPTH OF PENETRATION
Reservoirs, impoundments	Principal borings: In addition to borings at the locations of dams or dikes, a number of borings should be used to investigate geologic conditions of the reservoir basin. The number and spacing of borings should vary, with the largest concentration near control structures and the coverage decreasing with distance upstream.	Principal borings: at least one-fourth to penetrate that portion of the saturation zone that may influence seepage conditions or stability. Others to a depth of 7.5 m (25 ft) below reservoir bottom elevation.[2]

Sounding = An exploratory penetration below the ground surface used to measure or observe an in situ property of subsurface materials, usually without recovery of samples or cuttings.

Principal boring = A borehole used as a primary source of subsurface information. It is used to explore and sample all soil or rock strata penetrated to define the site geology and the properties of subsurface materials. Not included are borings from which no samples are taken, borings used to investigate specific or limited intervals, or borings so close to others that information obtained represents essentially a single location.

APPENDIX E

APPLICATIONS OF SELECTED GEOPHYSICAL METHODS FOR DETERMINATION OF ENGINEERING PARAMETERS

GEOPHYSICAL METHOD	BASIC MEASUREMENT	APPLICATION	ADVANTAGES	LIMITATIONS
Surface				
Refraction (seismic)	Travel time of compressional waves through subsurface layers	Velocity determination of compression wave through subsurface. Depths to contrasting interfaces and geologic correlation of horizontal layers.	Rapid, accurate, and relatively economical technique. Interpretation theory generally straightforward and equipment readily available.	In saturated soils, the compression wave velocity reflects mostly wave velocities in the water and thus is not indicative of soil properties.
Reflection (seismic)	Travel time of compressional waves reflected from subsurface layers	Mapping of selected reflector horizons. Depth determinations, fault detection, discontinuities, and other anomalous features.	Rapid, thorough coverage of given site area. Data displays highly effective.	In saturated soils, the compression wave velocity reflects mostly wave velocities in the water and thus is not indicative of soil properties.
Rayleigh wave (surface wave) dispersion	Travel time and period of surface Rayleigh waves	Inference of shear wave velocity in near-surface materials.	Rapid technique that uses conventional refraction seismographs.	Coupling of energy to the ground may be inefficient, restricting extent of survey coverage. Data resolution and penetration capability are frequency dependent; sediment layer thickness and/or depth interpretations must be considered approximate. The data interpretation model needs to be verified and validated.
Vibratory (seismic)	Travel time or wavelength of surface Rayleigh waves	Inference of shear wave velocity in near-surface materials.	Controlled vibratory source allows selection of frequency, hence wavelength and depth of penetration [up to 60 meters (m) (200 feet (ft)]. Detects low-velocity zones underlying strata of higher velocity. Accepted method.	Coupling of energy to the ground may be inefficient, restricting extent of survey coverage. Data resolution and penetration capability are frequency dependent; sediment layer thickness and/or depth interpretations must be considered approximate.
Reflection profiling (seismic-acoustic)	Travel times of compressional waves through water and subsurface materials and amplitude of reflected signal	Mapping of various lithologic horizons; detection of faults, buried stream channels, and salt domes, location of buried man-made objects; and depth determination of bedrock or other reflecting horizons.	Surveys of large areas at minimal time and cost; continuity of recorded data allows direct correlation of lithologic and geologic changes; correlative drilling and coring can be kept to a minimum.	Data resolution and penetration capability is frequency dependent; sediment layer thickness and/or depth to reflection horizons must be considered approximate unless true velocities are known; some bottom conditions (e.g., organic sediments) prevent penetration; water depth should be at least 5 to 6 m (15 to 20 ft) for proper system operation.

APPENDIX E, Cont'd.

GEOPHYSICAL METHOD	BASIC MEASUREMENT	APPLICATION	ADVANTAGES	LIMITATIONS
Surface (Continued)				
Electrical resistivity	Electrical resistance of a volume of material between probes	Complementary to refraction (seismic). Quarry rock, ground water, and sand and gravel prospecting. River bottom studies and cavity detection.	Economical nondestructive technique. Can detect large bodies of "soft" materials.	Lateral changes in calculated resistance often interpreted incorrectly as depth related; hence, for this and other reasons, depth determinations can be grossly in error. Should be used in conjunction with other methods, i.e., seismic.
Acoustic (resonance)	Amplitude of acoustically coupled sound waves originating in an air-filled cavity	Traces (on ground surface) lateral extent of cavities.	Rapid and reliable method. Interpretation relatively straightforward. Equipment readily available.	Must have access to some cavity opening. Still in experimental stage; limits not fully established.
Ground-penetrating radar	Travel time and amplitude of a reflected electromagnetic wave	Rapidly profiles layering conditions. Stratification, dip, water table, and presence of many types of anomalies can be determined.	Very rapid method for shallow site investigations. Online digital data processing can yield "on site" look. Variable density display highly effective.	Transmitted signal rapidly attenuated by water. Severely limits depth of penetration. Multiple reflections can complicate data interpretation. Generally performs poorly in clay-rich sediments.
Gravity	Variations in gravitational field	Detects anticlinal structures, buried ridges, salt domes, faults, and cavities.	Provided extreme care is exercised in establishing gravitational references, reasonably accurate results can be obtained.	Requires specialized personnel. Anything having mass can influence data (buildings, automobiles, etc.). Data reduction and interpretation are complex. Topography and strata density influence data.
Magnetic	Variations of earth's magnetic field	Determines presence and location of magnetic or ferrous materials in the subsurface. Locates ore bodies.	Minute quantities of magnetic materials are detectable.	Only useful for locating magnetic materials. Interpretation highly specialized. Calibration on site extremely critical. Presence of any ferrous objects near the magnetometer influences data.
Uphole/downhole (seismic)	Vertical travel time of compressional and/or shear waves	Determines velocity of vertical P- and/or S-waves. Identifies low-velocity zones.	Rapid technique useful to define low- velocity strata. Interpretation straightforward.	Care must be exercised to prevent undesirable influence of grouting or casing.
Crosshole (seismic)	Horizontal travel time of compressional and/or shear waves	Determines velocity of horizontal P- and/or S-waves. Elastic characteristics of subsurface strata can be calculated.	Generally accepted as producing reliable results. Detects low-velocity zones provided borehole spacing is not excessive.	Careful planning with regard to borehole spacing based upon geologic and other seismic data is an absolute necessity. Snell's law of refraction must be applied to establish zoning. A borehole deviation survey must be run. Requires highly experienced personnel. Repeatable source required.

APPENDIX E, Cont'd.

GEOPHYSICAL METHOD	BASIC MEASUREMENT	APPLICATION	ADVANTAGES	LIMITATIONS
Borehole spontaneous potential	Natural earth potential	Correlates deposits, locates water resources, studies rock deformation, assesses permeability, and determines ground water salinity.	Widely used, economical tool. Particularly useful in the identification of highly porous strata (sand, etc.).	Log must be run in a fluid-filled, uncased boring. Not all influences on potentials are known.
Single-point resistivity	Strata electrical resistance adjacent to a single electrode	In conjunction with spontaneous potential, correlates strata and locates porous materials.	Widely used, economical tool. Log obtained simultaneous with spontaneous potential.	Strata resistivity difficult to obtain. Log must be run in a fluid-filled, uncased boring. Influenced by drill fluid.
Long and short-normal resistivity	Near-hole electrical resistance	Measures resistivity within a radius of 40 to 165 centimeters (16 to 64 inches).	Widely used, economical tool.	Influenced by drill fluid invasion. Log must be run in a fluid-filled, uncased boring.
Lateral resistivity	Far-hole electrical resistance	Measures resistivity within a radius of 6 m (20 ft).	Less drill fluid invasion influence.	Log must be run in a fluid-filled, uncased boring. Investigation radius limited in low-moisture strata.
Induction resistivity	Far-hole electrical resistance	Measures resistivity in air- or oil-filled holes.	Log can be run in a nonconductive casing.	Large, heavy tool.
Borehole imagery (acoustic)	Sonic image of borehole wall	Detects cavities, joints, fractures in borehole wall. Determines attitude (strike and dip) of structures.	Useful in examining casing interior. Graphic display of images. Fluid clarity immaterial.	Highly experienced operator required. Slow log to obtain. Probe awkward and delicate.
Continuous sonic (three-dimensional) velocity	Time of arrival of P- and S-waves in high-velocity materials	Determines velocity of P- and S-waves in near vicinity of borehole. Potentially useful for cavity and fracture detection. Modulus determinations. Sometimes S-wave velocities are inferred from P-wave velocity.	Widely used method. Rapid and relatively economical. Variable density display generally impressive. Discontinuities in strata detectable.	Shear wave velocity definition questionable in unconsolidated materials and soft sedimentary rocks. Only P-wave velocities greater than 1,500 meters per second (m/s) (5,000 ft/s) can be determined.
Natural gamma radiation	Natural radioactivity	Lithology, correlation of strata, may be used to infer permeability. Locates clay strata and radioactive minerals.	Widely used, technically simple to operate and interpret.	Borehole effects, slow logging speed, cannot directly identify fluid, rock type, or porosity. Assumes clay minerals contain potassium-40 isotope.
Gamma-gamma density	Electron density	Determines rock density of subsurface strata.	Widely used. Can be applied to quantitative analyses of engineering properties. Can provide porosity.	Borehole effects, calibration, source intensity, and chemical variation in strata affect measurement precision. Radioactive source hazard.

APPENDIX E, Cont'd.

GEOPHYSICAL METHOD	BASIC MEASUREMENT	APPLICATION	ADVANTAGES	LIMITATIONS
Borehole (Continued)				
Neutron porosity	Hydrogen content	Moisture content (above water table), total porosity (below water table).	Continuous measurement of porosity. Useful in hydrology and engineering property determinations. Widely used.	Borehole effects, calibration, source intensity, and bound water all affect measurement precision. Radioactive source hazard.
Neutron activation	Neutron capture	Concentration of selected radioactive materials in strata.	Detects elements such as U, Na, Mn. Used to determine oil-water contact (oil industry) and in prospecting for minerals (Al, Cu).	Source intensity and presence of two or more elements having similar radiation energy affect data.
Borehole magnetic	Nuclear precession	Deposition, sequence, and age of strata.	Distinguishes ages of lithologically identical units.	Earth field reversal intervals under study. Still subject of research.
Mechanical caliper	Diameter of borehole	Measures borehole diameter.	Useful in a wet or dry hole.	Must be recalibrated for each run. Averages 3 diameters.
Acoustic caliper	Sonic ranging	Measures borehole diameter.	Large range. Useful with highly irregular shapes.	Requires fluid-filled hole and accurate positioning.
Temperature	Temperature	Measures temperature of fluids and borehole sidewalls. Detects zones of inflow or fluid loss.	Rapid, economical, and generally accurate.	None of importance.
Fluid resistivity	Fluid electrical resistance	Water-quality determinations and auxiliary log for rock resistivity.	Economical tool.	Borehole fluid must be same as ground water.
Tracers	Direction of fluid flow	Determines direction of fluid flow.	Economical.	Environmental considerations often preclude use of radioactive tracers.
Flowmeter	Fluid velocity and quantity	Determines velocity of subsurface fluid flow and, in most cases, quantity of flow.	Interpretation is simple.	Impeller flowmeters usually cannot measure flows less than 1–1.7 centimeters per second (2–3 ft/minute).
Borehole dipmeter	Sidewall resistivity	Provides strike and dip of bedding planes. Also used for fracture detection.	Useful in determining information on location and orientation of bedding planes and fractures over a wide variety of hole conditions.	Expensive log to make. Computer analysis of information needed for maximum benefit.
Downhole flow meter	Flow across the borehole	Determines the rate and direction of ground water flow.	A reliable, cost effective method to determine lateral foundation leakage under concrete structures.	Assumes flow not influenced by emplacement of borehole.

APPENDIX F

IN SITU TESTING METHODS

Table F-1 In Situ Tests for Rock and Soil
(adapted from EM 1110-1-1804, U.S. Army Corps of Engineers, 2001)

PURPOSE OF TEST	TYPE OF TEST	APPLICABILITY TO	
		SOIL	ROCK
Shear strength	Standard penetration test	X	
	Field vane shear	X	
	Cone penetrometer test	X	
	Direct shear	X	
	Plate bearing or jacking	X	X[a]
	Borehole direct shear[b]	X	
	Pressuremeter[b]		X
	Uniaxial compressive[b]		X
	Borehole jacking[b]		X
Bearing capacity	Plate bearing	X	X[a]
	Standard penetration	X	
Stress conditions	Hydraulic fracturing	X	X
	Pressuremeter	X	X[a]
	Overcoring		X
	Flatjack		X
	Uniaxial (tunnel) jacking	X	X
	Borehole jacking[b]		X
	Chamber (gallery) pressure[b]		X
Mass deformability	Geophysical (refraction)	X	X
	Pressuremeter or dilatometer	X	X[a]
	Plate bearing	X	X
	Standard penetration	X	
	Uniaxial (tunnel) jacking	X	X
	Borehole jacking[b]		X
	Chamber (gallery) pressure[b]		X
Relative density	Standard penetration	X	
	In situ sampling	X	
	Cone[b] penetration	X	
Liquefaction susceptibility	Standard penetration	X	
	Cone penetration test	X	
	Shear wave velocity (v_s)	X	

a. Primarily for clay shales, badly decomposed, or moderately soft rocks, and rock with soft seams.
b. Less frequently used.

APPENDIX F, Cont'd.

Table F-2 In Situ Tests to Determine Shear Strength (adapted from EM 1110-1-1804, U.S. Army Corps of Engineers, 2001)

TEST	FOR		REMARKS
	SOILS	ROCKS	
Standard penetration	X		Use as index test only for strength. Develop local correlations. Unconfined compressive strength in tons/square foot) is often 1/6 to 1/8 of N-value.
Direct shear	X	X	Expensive. Use when representative undisturbed samples cannot be obtained.
Field vane shear	X		Use strength reduction factor.
Plate bearing	X	X	Evaluate consolidation effects that may occur during test.
Uniaxial compression		X	Primarily for weak rock. Expensive since several sizes of specimens must be tested.
Cone penetration test	X		Consolidated undrained strength of clays. Requires estimate of bearing factor, N_c.

Table F-3 In Situ Tests to Determine Stress Conditions (adapted from EM 1110-1-1804, U.S. Army Corps of Engineers, 2001)

TEST	SOILS	ROCKS	REMARKS
Hydraulic fracturing	X		Only for normally consolidated or slightly consolidated soils
Hydraulic fracturing		X	Stress measurements in deep holes for tunnels
Vane shear	X		Only for recently compacted clays, silts and fine sands (see Blight, 1974,[1] for details and limitations)
Overcoring techniques		X	Usually limited to shallow depth in rock
Flatjacks	X		
Uniaxial (tunnel) jacking	X	X	May be useful for measuring lateral stresses in clay shales and rocks, also in soils
Pressuremeter (Menard)	X		

[1] Blight, G.E., "Indirect Determination of in situ Stress Ratios in Particulate Materials," *Proceedings of a Specialty Conference, Subsurface Explorations for Underground Excavation and Heavy Construction,* American Society of Civil Engineers, New York, 1974.

APPENDIX F, Cont'd.

Table F-4 In Situ Tests to Determine Deformation Characteristics (adapted from EM 1110-1-1804, U.S. Army Corps of Engineers, 2001)

TEST	FOR		REMARKS
	SOILS	ROCKS	
Geophysical refraction, crosshole and downhole	X	X	For determining dynamic Young's Modulus, E, at the small strain induced by test procedure. Test values for E must be reduced to values corresponding to strain levels induced by structure or seismic loads.
Pressuremeter	X	X	Consider test as possibly useful but not fully evaluated. For soils and soft rocks, shales, etc.
Chamber test	X	X	
Uniaxial (tunnel) jacking	X	X	
Flatjacking		X	
Borehole jack or dilatometer		X	
Plate bearing		X	
Plate bearing	X		
Standard penetration	X		Used in empirical correlations to estimate settlement of footings; a number of relationships are published in the literature to relate penetration test blow counts to settlement potential.

APPENDIX G

INSTRUMENTS FOR MEASURING GROUND WATER PRESSURE

INSTRUMENT TYPE	ADVANTAGES	LIMITATIONS[a]
Observation well	Can be installed by drillers without participation of geotechnical personnel.	Provides undesirable vertical connection between strata and is therefore often misleading; should rarely be used. Should not be confused with monitoring well.
Open standpipe piezometer	Reliable. Long, successful performance record. Self-de-airing if inside diameter of standpipe is adequate. Integrity of seal can be checked after installation. Can be converted to diaphragm piezometer. Can be used for sampling ground water. Can be used to measure permeability.	Slow response to changes in piezometric head. Subject to damage by construction equipment and by vertical compression of soil around standpipe. Extension of standpipe through embankment fill interrupts construction and causes inferior compaction. Porous filter can plug from repeated water inflow and outflow. Push-in versions subject to several potential errors.
Twin-tube hydraulic piezometer	Inaccessible components have no moving parts. Reliable. Long, successful performance record. When installed in fill, integrity can be checked after installation. Piezometer cavity can be flushed. Can be used to measure permeability.	Application generally limited to long-term monitoring of pore water pressure in embankment dams. Elaborate terminal arrangements needed. Tubing must not be significantly above minimum piezometric elevation. Periodic flushing may be required. Attention to many details is necessary.
Pneumatic piezometer	Short time lag. Calibrated part of system accessible. Minimum interference to construction: level of tubes and readout independent of level of tip. No freezing problems.	Attention must be paid to many details when making selection. Push-in versions subject to several potential errors.
Vibrating wire piezometer	Easy to read. Short time lag. Minimum interference to construction: level of lead wires and readout independent of level of tip. Lead wire effects minimal. Can be used to read negative pore water pressures. No freezing problems.	Special manufacturing techniques required to minimize zero drift. Need for lightning protection should be evaluated. Push-in version subject to several potential errors.

a. Diaphragm piezometer readings indicate the head above the piezometer, and the elevation of the piezometer must be measured or estimated if piezometric elevation is required. All diaphragm piezometers, except those provided with a vent to the atmosphere, are sensitive to barometric pressure changes.

APPENDIX G, Cont'd.

INSTRUMENT TYPE	ADVANTAGES	LIMITATIONS[a]
Electrical resistance piezometer	Easy to read. Short time lag. Minimum interference to construction: level of lead wires and readout independent of level of tip. Suitable for dynamic measurements. Can be used to read negative pore water pressures. No freezing problems.	Low electrical output. Lead wire effects. Errors caused by moisture, temperature, and electrical connections are possible. Long-term stability uncertain. Need for lightning protection should be evaluated. Push-in version subject to several potential errors.
Multipoint piezometer, with packers	Provides detailed pressure-depth measurements. Can be installed in horizontal or upward boreholes. Other advantages depend on type of piezometer: See above in table.	Limited number of measurement points. Other limitations depend on type of piezometer: See above in table.
Multipoint piezometer, surrounded with grout	Provides detailed pressure-depth measurements. Simple installation procedure. Other advantages depend on type of piezometer: See above in table.	Limited number of measurement points. Applicable only in uniform clay of known properties. Difficult to ensure in-place grout of known properties. Other limitations depend on type of piezometer: See above in table.
Multipoint push-in piezometer	Provides detailed pressure-depth measurements. Simple installation procedure. Other advantages depend on type of piezometer: See above in table.	Limited number of measurement points. Subject to several potential errors. Other limitations depend on type of piezometer: See above in table.
Multipoint piezometer, with movable probe	Provides detailed pressure-depth measurements. Unlimited number of measurement points. Allows determination of permeability. Calibrated part of system accessible. Great depth capability. Westbay Instruments system can be used for sampling ground water and can be combined with inclinometer casing.	Complex installation procedure. Periodic manual readings only.