



REGULATORY GUIDE

OFFICE OF NUCLEAR REGULATORY RESEARCH

REGULATORY GUIDE 1.132

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SITE INVESTIGATIONS FOR FOUNDATIONS OF NUCLEAR POWER PLANTS

A. INTRODUCTION

This regulatory guide describes field investigations for determining the geological, engineering, and hydrogeological characteristics of a prospective plant site. It provides guidance for developing geologic information on stratigraphy, lithology, and structure of the site. The investigations recommended provide data defining the static and dynamic engineering properties of soil and rock materials at the site and their spatial distribution. Thus, the site investigations provide a basis for evaluating the safety of the site with respect to the performance of foundations and earthworks under anticipated loading conditions, including earthquakes.

In 1996, the Nuclear Regulatory Commission (NRC) issued new regulations concerning site evaluation factors and geologic and seismic siting criteria for nuclear power plants in Subpart B, "Evaluation Factors for Stationary Power Reactor Site Applications on or After January 10, 1997," of 10 CFR Part 100, "Reactor Site Criteria." In particular, 10 CFR 100.20(c), 100.21(d), and 100.23 of Part 100 establish requirements for conducting site investigations for nuclear power plants for site applications submitted after January 10, 1997.

Safety-related site characteristics are identified in detail in Regulatory Guide 1.70, "Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants." Regulatory Guide 4.7, "General Site Suitability Criteria for Nuclear Power Stations," discusses major site characteristics that affect site suitability.

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This guide was issued after consideration of comments received from the public. Comments and suggestions for improvements in these guides are encouraged at all times, and guides will be revised, as appropriate, to accommodate comments and to reflect new information or experience. Written comments may be submitted to the Rules and Directives Branch, ADM, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001.

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This regulatory guide describes methods acceptable to the NRC staff for conducting field investigations to acquire the data on geological and engineering characteristics of a site needed for a nuclear power plant site application. The guide includes recommendations for developing site-specific investigation programs and guidance for conducting subsurface investigations. The guide is being revised to incorporate newer practices and insights. A report written by the U.S. Army Corps of Engineers staff, NUREG/CR-5738, was used as a technical basis for this guide and may be consulted for details of procedures. The appendices to this guide are taken from that publication.

Laboratory tests and analyses for determining soil and rock properties are described in Regulatory Guide 1.138, "Laboratory Investigations of Soils for Engineering Analysis and Design of Nuclear Power Plants." Regulatory Guide 1.165, "Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion," defines investigations related to seismicity, faults, and vibratory ground motion. This guide does not deal with volcanologic or hydrologic investigations, except for groundwater measurements at the site. Considerations for flooding are described in Regulatory Guide 1.59, "Design Basis Floods for Nuclear Power Plants."

The information collections contained in this regulatory guide are covered by the requirements of 10 CFR Part 50, which were approved by the Office of Management and Budget, approval number 3150-0011. If a means used to impose an information collection does not display a currently valid OMB control number, the NRC may not conduct or sponsor, and a person is not required to respond to, the information collection.

B. DISCUSSION

PURPOSE

The purpose of the site investigations described in this guide is to acquire the geotechnical data needed to design nuclear power plant foundations for safety and performance. They should define the overall site geology to the degree necessary to understand subsurface conditions and to identify potential geologic hazards that may exist at the site. Local groundwater conditions must also be defined. Investigations for hazards such as fault offsets, landslides, cavernous rocks, ground subsidence, and soil liquefaction are especially important.

Investigations described here are closely related to those contained in Regulatory Guide 1.165. The main purpose of that guide is to define seismologic and related geologic aspects of the site for determining the safe shutdown earthquake ground motion (SSE), and it includes investigations over a broader area. This guide is more narrowly focused on the geologic and engineering characteristics of the specific site. Appendix D to Regulatory Guide 1.165 gives detailed instructions for investigating tectonic and nontectonic surface deformation. As these types of deformation are also part of the site engineering data, applicants are referred to that Appendix for appropriate guidance.

The aim of site investigations is to gain an understanding of the three-dimensional distribution of geological features (rocks, soils, extent of weathering, fractures, etc.) at the site, and to obtain the soil and rock properties that are needed for designing foundations for a nuclear power plant and associated critical structures. The density of data gathered varies over a plant site according to the variability of the soils and rocks and the importance assigned to structures planned for a particular location. Display and visualization of such data have traditionally been accomplished with maps and cross-sections. Given the computer resources and Geographic Information Systems (GIS) available today, it is advantageous to incorporate the data into a GIS database, which then permits plotting of appropriate maps, cross-sections, and three-dimensional displays. Employing a GIS also permits using different scales for effective viewing.

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, for example, concludes that additional geotechnical information would almost always save time and costs (National Research Council).

C. REGULATORY POSITION

1. GENERAL

A well-thought-out program of site exploration, progressing from literature search and reconnaissance investigations to detailed site investigation, construction mapping, and final as-built data compilation should be established to form a clear basis for the geotechnical work and foundation design. Because details of an actual site investigation program will be site dependent, such a program should be tailored to the specific conditions of the site using sound professional judgment. The program should be flexible and adjusted as the site investigation proceeds, with the advice of personnel experienced in site investigations. Also, this guide represents techniques available at the date of issuance. As the science advances, useful procedures and equipment should be included as they are developed and accepted by the profession.

Site investigations for nuclear power plants should be adequate, in terms of thoroughness, suitability of the 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 assess foundation conditions at the site and to perform engineering analysis and design with reasonable assurance that foundation conditions have been realistically estimated.

2. TYPES OF DATA TO BE ACQUIRED

2.1 Geological Conditions

Geological conditions comprise general geological conditions, the types and structure of soils and rocks at the surface and in the subsurface, the degree and extent of weathering, and petrological characteristics, such as structure, texture, and composition. The presence of potential hazards, such

as faulting, landslides, erosion, or deposition by rivers or on shorelines; caverns formed by dissolution or mining activity; ground subsidence; and soil shrinking and swelling, is also to be determined. Data to evaluate the soil liquefaction potential and the orientation and characteristics of bedding, foliations, or jointing and faulting are also needed.

2.2 Engineering Properties of Soils and Rocks

These properties include density and seismic velocities and parameters of strength, elasticity, and plasticity. Some of these properties can be measured in situ, and those measurements together with sample collection are discussed in this guide. Detailed determination of these and other engineering properties also requires laboratory testing, which is described in Regulatory Guide 1.138.

2.3 Groundwater Conditions

Only conditions at the site, such as groundwater levels, thickness of aquifers and confining beds, groundwater flow patterns, and transmissivities and storage coefficients are to be determined.

2.4 Man-Induced Conditions

The existing infrastructure is to be located, together with dams or reservoirs whose locations may cause a flooding hazard or produce loading effects at the site. Past or ongoing activities, such as mining or oil and gas production, and other fluid extraction or injection also need to be documented. The presence of former industrial sites, underground storage tanks, or landfills should be determined and the potential for hazardous, toxic, or radioactive waste investigated.

2.5 Cultural and Environmental Considerations

Cultural resources, such as archaeological sites and artifacts, must be considered to comply with the Archaeological Resources Protection Act of 1979 and the Native American Graves Protection and Repatriation Act of 1990.

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

2.6 Related Considerations

Guidance on seismicity and related seismic data and historical records is in Regulatory Guide 1.165, together with guidance on vibratory ground motion resulting from earthquakes. Although this subject is not repeated here, many of the investigations listed in that guide could and should be coordinated with the site investigations described here and conducted at the same time for greater

efficiency. Appendix D to Regulatory Guide 1.165 is to be used as guidance for investigating tectonic and nontectonic surface deformation.

3. LITERATURE SEARCH AND RECONNAISSANCE

3.1 General

Establishing the geological conditions and engineering properties of a site is an iterative process whereby successive phases of investigation lead to increasingly detailed data. Therefore, it is important to have a proper system for recording the data and gaining a three-dimensional understanding of site conditions. At the present time, a GIS is the most efficient way to record and present the data. A well-thought-out system of classifying and filing information is also important and is part of the quality assurance required for the project (see Regulatory Position 7.2). Appendix A to this guide lists some of the geologic features and conditions that may have to be considered in site investigations.

3.2 Existing Literature and Map Studies

The first step in the site investigation is to acquire existing knowledge of geological and other site conditions. An understanding of the regional geology must also be developed in order to interpret the rocks and soils of the site in their proper context. Published material and existing maps of topography, geology, hydrology, soils, etc., can reveal a wealth of information on site conditions. Study of aerial photographs and other remote sensing imagery complements this information. Regional strain rates of Global Positioning System (GPS), if available, should be collected to correlate with rates obtained from geology and other methods.

Possible sources of current and historical documentary information may include:

- 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 the State Geological Survey,
- 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 events of significance,
- Interviews with local inhabitants and professionals.

Published maps such as topographic, geologic, and soils maps can be used to obtain information on the site, to aid in the field reconnaissance, and as a basis for further work. Aerial photographs and other remote-sensing imagery are also useful and complement this information. For additional sources, see Appendix B to this guide that contains a list of potential sources for maps, imagery, and other geologic data.

Some of the basic aspects that should be investigated include geologic conditions, previous land uses, and existing construction and infrastructure. Plans held by utilities should be consulted to locate services such as water, gas, electric, and communication lines. The locations of power lines,

pipelines, and access routes should also be established. Mining records should be consulted for locations of abandoned adits, shafts, benches, and tailings embankments. Oil, gas, and water well records, as well as oil exploration data, can provide valuable subsurface information. Cultural resources such as historical and archaeological sites should be identified.

3.3 Field Reconnaissance

In addition to the study of published data, it is essential to perform a preliminary field reconnaissance of the site and its surrounding area. This will give a more realistic assessment of site conditions and regional geology and provide a basis for a detailed site investigation plan. Appendix A shows a list of special geologic features and conditions to be considered. In addition to the specific site, potential borrow areas, quarry sites, or water impoundment areas need to be investigated.

The team performing the reconnaissance should include, as a minimum, a geologist and a geotechnical engineer and may include other specialists such as an engineering geologist or geophysicist. An appropriate topographic or geologic map should be used during the field reconnaissance to note findings of interest. A GPS unit may be advantageous for recording locations in the field, as noted more in detail in Regulatory Position 7.1.

3.4 Site Suitability

After the reconnaissance investigations, sufficient information will be available to make a preliminary determination of site suitability and to formulate a plan for detailed site investigations. The presence of features that can cause permanent ground displacement such as fault displacement and settlement or subsidence, swelling soils and shales, or other hazards including underground cavities, landslides, or periodic flooding, may make proper engineering design difficult and usually will require extensive additional investigations. In such cases, it may be advantageous to abandon the site.

4. DETAILED SITE INVESTIGATIONS

4.1 General

Whereas the reconnaissance phase is oriented toward establishing the viability of the site, this phase is the task of acquiring all the geologic factors and engineering properties needed for design and construction of a plant, including its critical structures. The investigation should, therefore, be carried out in much greater detail, and a multidisciplinary team is needed to accomplish the varied tasks of this investigation.

Engineering properties of rocks and soils are determined through drilling and sampling, in situ testing, field geophysical measurements, and laboratory testing. This guide describes in situ testing and the field geophysical measurements, as well as drilling and sampling procedures used to

gather samples for laboratory testing. For laboratory testing procedures, refer to Regulatory Guide 1.138.

Data sufficient to clearly justify all conclusions should be presented. Site information to be developed should include, as appropriate, (1) topographic and geologic maps, (2) plot plans showing locations of major structures and exploration, (3) boring logs and logs of exploratory trenches and excavations, (4) geologic profiles showing excavation limits for structures, and (5) geophysical data such as seismic survey time-distance plots, resistivity curves, seismic reflection cross-sections, maps, profiles, borehole logs, and surveys. Using techniques of investigation and sampling other than those indicated in this guide is acceptable when it can be shown that the alternative methods yield satisfactory results.

Locations of all boreholes, in situ tests, piezometers, observation wells, 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, and suitable cross-sections, maps, and plans should be prepared to facilitate visualization of the geological information. Further details are given in Regulatory Position 7.1.

4.2 Surface Investigations

Detailed surface geological and geotechnical engineering investigations should be conducted over the site area to assess all the pertinent soil and rock characteristics. Some of the special geological features and conditions to be considered are listed in Appendix A.

The first steps in detailed site investigations are to prepare topographic maps at suitable scales to (1) plot geologic, structural, and engineering details at the site and (2) note conditions in the surrounding areas that are related, for instance, to borrow areas, quarries, or access roads. Aerial photographs and stereo pairs, together with other remote sensing imagery, may be of value for regional analysis, determination of fault and fracture patterns, and other features of interest.

Detailed mapping of topographic, hydrogeologic, and surface geologic features should be conducted, as appropriate for the particular site conditions, with scales and contour intervals suitable for site evaluation and engineering design (see also Regulatory Position 7.1). Rock outcrops, soil conditions, evidence of past landslides or soil liquefaction, faults, fracture patterns, geologic contacts, and lineaments should be identified and mapped. Details of local engineering geology and soil conditions should also be mapped and recorded, together with surface-water features such as rivers, streams, or lakes, as well as local surface drainage channels, ponds, springs, and sinks.

4.3 Subsurface Investigations

Subsurface explorations serve to expand the knowledge of the three-dimensional distribution of both geologic conditions (soils, rocks, structure) and engineering properties at the site and at borrow areas, as well as to gain further information on possible safety hazards such as underground cavities, hidden faults, or contacts. The investigations should be carried out using a variety of

appropriate methods, including borings and excavations augmented by geophysical measurements. Methods of conducting subsurface investigations are tabulated in Appendix C to this guide.

The locations and depths of borings, excavations, and geophysical measurements should be chosen such that the site geology and foundation conditions are sufficiently defined in lateral extent and depth to permit designing all needed structures and excavations. The information acquired should also be such that engineering geologic cross-sections or subsurface profiles (including N-values, CPT values, etc.) can be constructed through foundations of safety-related structures and other important locations.

Subsurface explorations for less critical foundations of power plants should be carried out with spacing and depth of penetration as necessary to define the foundation geology of the site. Subsurface investigations in areas remote from plant foundations may be needed to complete the geologic description of the site and to confirm the foundation geology.

Boreholes are one of the most effective means of obtaining detailed information on geologic formations in the subsurface and their engineering properties. Cores and samples recovered, geophysical and other borehole surveys, and in situ tests all contribute to the range of information to be derived from boreholes. Excavations in the form of test pits, trenches, and exploratory shafts may be used to complement the borehole exploration; they permit acquiring more detailed and visual information on rock and soil conditions and conducting detailed fault studies, in situ density tests, and high-quality sampling.

4.3.1 Borings and Exploratory Excavations

Field operations should be supervised by experienced professional personnel at the site of operations, and systematic standards of practice should be followed. Procedures and equipment used to carry out the field operations, including necessary calibrations, should be documented, as should all conditions encountered in various phases of the investigation. Personnel that 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.

The complexity of geologic conditions and foundation requirements should be considered in choosing the actual distribution, number, and depth of borings and other excavations for a site. The investigative effort should be greatest at the locations of safety-related structures and may vary in density and scope in other areas according to their spatial and geological relations to the site. At least one continuously sampled boring should be used for each safety-related structure, and the boring should extend to a depth sufficient to define the geological and hydrogeological characteristics of the foundations.

NUREG/CR-5738 describes procedures for borings and exploratory excavations. A table from that report that shows widely used techniques for subsurface investigations and describes the applicability and limitations of these methods is reproduced in Appendix C. General guidelines for spacing and depth of borings are found in Appendix D.

4.3.1.1 Spacing. The spacing and depth of borings for safety-related structures should be chosen according to the foundation requirements and the complexity of anticipated subsurface conditions. Appendix D gives general guidelines concerning this subject. Uniform conditions permit the maximum spacing of borings in a regular grid for adequate definition of subsurface conditions. Subsurface conditions may be considered uniform if the geologic and stratigraphic features to be defined can be correlated from one boring location to the next with relatively smooth variations in thicknesses or properties of the geologic units. An occasional anomaly or a limited number of unexpected lateral variations may occur.

If site conditions are non-uniform, a regular grid may not provide the most effective borehole distribution. Soil or rock deposits may be encountered in which the deposition patterns are so complex that only the major stratigraphic boundaries are correlatable, and material types or properties may vary within major geologic units in an apparently random manner from one boring to another. The number and distribution of borings needed for these conditions are determined by the degree of resolution needed to define foundation properties. The goal is to define the thicknesses of the various material types, their degree of variability, and their range of material properties beneath the major structures.

If there is evidence suggesting the presence of local adverse anomalies or discontinuities such as cavities, sinkholes, fissures, faults, brecciation, and lenses or pockets of unsuitable material, supplementary borings at a spacing small enough to detect and delineate these features are needed. It is important that these borings penetrate all suspect zones or extend to depths below which their presence would not influence the safety of the structures. Geophysical investigations should be used to supplement the boring program.

4.3.1.2 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 EM 1110-0-1906 and *Principles of Geotechnical Engineering* (Das). The top of the hole 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 groundwater through the borehole.

Borehole elevation and depths into the borehole should be measured to the nearest 3 cm (0.1 ft) and should be correlatable to the elevation datum used for the site. Surveys of vertical deviation should be run in all boreholes that are used for crosshole seismic tests and other tests where deviation affects the use of data obtained. Boreholes with depths greater than about 30 m (100 ft) should also be surveyed for deviation. Details of information that should be presented on logs of subsurface investigations are given in Regulatory Position 4.5.

4.3.2 Sampling

Sampling of soils in boreholes should include, as a minimum, the recovery of samples at regular intervals and at changes in materials. Alternating split spoon and undisturbed samples with depth is recommended. Color photographs of all cores should be taken soon after removal from the borehole to document the condition of the soils at the time of drilling.

4.3.2.1 Sampling Rock. The engineering characteristics of rocks are related primarily to their composition, structure, bedding, jointing, fracturing, and weathering. Core samples are needed to observe and define these features. 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 the site geology. Within the depth intervals influencing foundation performance, zones of poor core recovery or low rock quality designation (RQD), 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. Areas with evidence of significant residual stresses should be evaluated on the basis of in situ stress or strain measurements. If it is necessary to determine dip and strike of bedding planes or discontinuities, oriented cores may be needed.

4.3.2.2 Sampling Coarse-Grained Soils. For coarse-grained soils, samples should be taken at depth intervals no greater than 1.5 m (5 ft). Beyond a depth of 15 m (50 ft) below foundation level, the depth interval for sampling may be increased to 3 m (10 ft). Also, one or more borings for each major structure should be continuously sampled. Requirements for undisturbed sampling of coarse-grained soils will depend on actual site conditions and planned laboratory testing. Some general guidelines for recovering undisturbed samples are given in Regulatory Position 4.3.2.4 of this guide. Experimentation with different sampling techniques may be necessary to determine the method best suited to local soil conditions.

Split spoon sampling and standard penetration tests should be used with sufficient coverage to define the soil profile and variations of soil conditions. Cone penetration tests may also be made to provide useful supplemental data if the cone test data are properly calibrated to site conditions.

Suitable samples should be obtained for soil identification and classification, mechanical analyses, and anticipated laboratory testing. For cyclic loading tests, it is important to obtain good quality undisturbed samples for testing. The need for, number, and distribution of samples will depend on testing requirements and the variability of the soil conditions. In general, however, samples should be included from at least one principal boring at the location of each safety-related structure. Samples should be obtained at regular intervals in depth and when changes in materials occur. Criteria for sampling are given in Regulatory Position 4.3.2.

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.

4.3.2.3 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. Procedures for obtaining undisturbed samples are discussed in Regulatory Position 4.3.2.4 of this guide.

For compressible or normally consolidated clays, undisturbed samples should be continuous throughout the compressible strata in one or more principal borings for each major structure. These samples should be obtained by means of suitable fixed piston, thin-wall tube samplers (see EM 1110-1-1906 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 cm (3 in.) in diameter.

4.3.2.4 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 itself (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.

Push sampling involves pushing a thin-walled tube, using the hydraulic system of the drill rig, then enlarging the diameter of the sampled interval by some “clean out” method before beginning to sample again. Commonly used systems for push samples include the Hvorslev fixed-position sampler and the Osterberg hydraulic piston sampler. Rotary samplers are considered slightly more disruptive to soil structure and involve a double tube arrangement similar to a rock coring operation, except that the inner barrel shoe is adjustable and generally extends beyond the front of the rotating outer bit. This reduces the disturbance caused to the sample from the drill fluid and bit rotation. Commonly used rotational samplers include the Denison barrel and the Pitcher Sampler.

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; sands and silts are particularly vulnerable to vibration disturbance. One method to prevent handling disturbance is to obtain 7.6 cm (3 in.) Shelby tube samples, drain them, and freeze them before transportation. There are no standard or generally accepted methods for undisturbed sampling of cohesionless soils. Such soils can be recovered by in situ freezing, followed by sampling with a rotary core barrel. For any freezing method, disturbance by cryogenic effects must be taken into account.

Chemical stabilization or impregnation can also be used as an option to sample and preserve the natural structure of cohesionless granular material. Agar has been used with positive results as

an impregnation material for undisturbed sampling of sands below the water table as an alternative to freezing. Chemical impregnation can be used either in situ before sampling or after sampling to avoid further disturbance in transporting and handling the samples. This alternative to freezing is less expensive and produces samples that are easier to manage after collection. Removal of the impregnating material may be accomplished once the sample is in the laboratory.

Test pits, trenches, and shafts offer the only effective access to collect high quality block samples and to obtain detailed information on stratification, discontinuities, or preexisting shear surfaces in the ground. Cost increases with depth as the need for side wall support arises. Samples can be obtained by means of hand-carving oversized blocks of soil or hand-advancing of thin-walled tubes.

4.3.2.5 Borrow Materials. Exploration of borrow sources serves to determine the location and amount of available borrow materials. Borrow area investigations should use horizontal and vertical intervals sufficient to determine material variability and should include adequate sampling of representative materials for laboratory testing.

4.3.2.6 Materials Unsuitable for Foundations. Boundaries of unsuitable materials should be delineated by means of borings and representative sampling and testing. These boundaries should be used to define the required excavation limits.

4.3.3 Transportation and Storage of Samples

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

Moisture loss may not be critical on representative samples, but it is preferable that it be kept to a minimum. Moisture migration within a sample causes differential residual pore pressures to equalize with time. Water can move from one formation 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. Storage room temperatures for these kinds of samples should be kept above 4°C. Vibration or shock can provoke remolding and strength or density changes, especially in soft and sensitive clays or cohesionless samples. Transportation arrangements to avoid these effects need to be carefully designed. Chemical reactions between samples and their containers can occur during storage and can induce changes that affect soil plasticity, compressibility, or shear strength. Therefore, the correct selection of sample container material is important.

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

4.3.4 In Situ Testing

In situ testing of soil and rock materials should be conducted where necessary for definition of foundation properties, using boreholes, excavations, test pits, and trenches that are either available or have been prepared for the purpose of sampling and testing. Larger block samples for laboratory testing can also be obtained in such locations. Some of the applicable in situ testing methods are shown in Appendix F. For further description of procedures see NUREG/CR-5738.

In situ tests are often the best means to determine the engineering properties of subsurface materials and, in some cases, may 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 techniques offer an option for evaluating soils and rocks that cannot be sampled for laboratory analysis.

Interpretation of in situ test results in soils, clay 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, unconsolidated-drained conditions, or to intermediate conditions between these limiting states. Interpretation of in situ test results requires complete evaluation of the test conditions and limitations.

Rock formations are generally separated by natural joints and/or bedding planes, resulting in a system of irregularly shaped blocks that respond as a discontinuum to various loading conditions. Individual blocks have relatively high strengths, whereas the strength along discontinuities is reduced and highly anisotropic. Commonly, little or no tensile strength exists across discontinuities. Large-scale in situ tests tend to average out the effect of complex interactions. In situ tests in rock are used to determine in situ stresses and deformation properties, including the shear strength of the jointed rock mass. They also help to measure strength and residual stresses along discontinuities or weak seams in the rock mass. In situ testing performed in weak, near-surface rocks include penetration tests, plate loading tests, pressure-meter tests, and field geophysical techniques.

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 in Nicholson and in Bowles. The suggested in situ method for determining direct shear strength of rocks is described in RTH 321-80. Although the standard penetration test (SPT) was used extensively in investigation of soil susceptibility, the usage of the cone penetration test (CPT) has increased significantly in recent years because CPT provides continuous penetration resistance profiles for soils and CPT results are more repeatable and consistent (Youd et al.). In both Appendix C and Appendix F, the applicability and limitations of the CPT and SPT are compared in parallel.

4.4 Geophysical Investigations

4.4.1 General

Geophysical methods include surface geophysics, borehole logging, and cross-borehole measurements. In all cases, these methods are a means of exploring the subsurface. Geophysical measurements should be used to fill in information between surface outcrops, trenches, and boreholes. Such measurements permit acquiring more continuous, and sometimes deeper, subsurface coverage, including data on geological and hydrogeological conditions and certain engineering properties of materials. They are of particular value in tying together information from various sources.

Available geophysical and borehole logging methods are listed in Appendix E to this guide and in EM-1110-1-1802. For boreholes that are deeper than 30 m (100 ft) or are used for crosshole measurements, borehole deviation should be measured. Geophysical measurements, borehole logging, and interpretation of geophysical measurements should be carried out by personnel that have the necessary background and experience in these techniques. Parameters of acquisition (spacings, instrument settings, etc.) and processing should be recorded to allow for proper interpretation of results.

At soil sites or rock sites with substantial weathering, crosshole shear wave measurements should be conducted in boreholes deep enough to allow determining the site amplification for seismic waves. These boreholes should also be sampled and logged as appropriate, including acoustic logging. Other geophysical measurements, such as seismic refraction and reflection and microseismic monitoring, may also be used for site amplification calculations.

4.4.2 Surface Geophysics

Recommended surface geophysical methods include seismic refraction and reflection surveys, as well as surface electromagnetic or electrical resistivity surveys. Other methods such as gravity, magnetics, and ground penetrating radar may also be used as appropriate. Spectral analysis of surface waves may be used to measure shear-wave velocity profiles. The method permits deriving elastic moduli and soil layer thicknesses (Gucunski and Woods, Stokoe and Nazarian, and Stokoe et al.). The surface geophysical measurements should be correlated with borehole geophysical and geological logs to derive maximum benefit from the measurements.

4.4.3 Borehole Geophysics

Boreholes should be logged with a suitable suite of geophysical logging methods. Borehole logs are useful for determining lithological, hydrological, and engineering properties of subsurface horizons. They are also very useful for the correlation of stratigraphic horizons between boreholes. Some of the applicable methods are shown in Appendix E to this guide, together with the engineering parameters they help to determine.

Crosshole geophysical measurements may be used to obtain detailed information on the region between two boreholes and to derive engineering and hydrogeologic properties, such as shear modulus, porosity, and permeability. Measurements of shear- and compressional-wave velocities are most common, but electrical resistivity and electromagnetic methods may also be employed. When

very detailed information is desired, tomographic methods may be used that can provide a detailed picture of geophysical properties between boreholes.

Acoustic borehole logging and crosshole shear-wave measurements generally are low strain measurements. In rock, they provide a suitable approximation of shear modulus even under higher strain conditions. In soil, on the other hand, the modulus depends strongly on the strain level. However, so-called high strain shear-wave methods (crosshole) in soil are usually ineffective, because nonlinear effects may occur. Other in situ and laboratory tests are more promising for such measurements.

4.5 Logs of Subsurface Investigations

Boring logs should contain the date when the boring was made, the location of the boring, the depths of borings, and the elevations with respect to a permanent benchmark. The logs should also include the elevations of the top and bottom of borings and the elevations of the boundaries of soil or rock strata, as well as the level at which the water table was encountered. In addition, the classification and description of soil and rock layers, 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 (RQD) should be noted.

Results of field permeability tests and geophysical borehole logging should also be included on logs. The type of tools used in making the boring should be recorded. If the tools were changed, the depth at which the change was made and the reason for the change should be noted. Notes should be provided of everything significant to the interpretation of subsurface conditions, such as incidents of settling or dropping of drill rods, abnormally low resistance to drilling or advance of samplers, core losses, or instability or heave of the side and bottom of boreholes. Influx of groundwater, depths and amounts of water or drilling mud losses, together with depths at which circulation is recovered, and any other special feature or occurrence should be recorded on boring logs and geological cross sections.

Incomplete or abandoned borings should be described with the same care as successfully completed borings. Logs of exploratory trenches and other excavations should be presented in a graphic format in which important components of the soil matrix and structural features in rock are shown in sufficient detail to permit independent evaluation. The location of all explorations should be recorded in the GIS and shown on geologic cross-sections, together with elevations and important data.

5. GROUNDWATER INVESTIGATIONS

Knowledge of groundwater conditions, their relationship to surface waters, and variations associated with seasons or tides is needed for foundation analyses. Groundwater conditions are normally observed in borings at the time they are made. However, such data should be supplemented by groundwater observations in properly installed wells or piezometers that are read at regular intervals from the time of their installation at least through the construction period.

Appendix G to this guide lists types of instruments for measuring groundwater pressure and their advantages and limitations. ASTM D 5092-95 provides guidance on the design and installation of groundwater monitoring wells. Types of piezometers, construction details, and sounding devices are described in EM 1110-2-1908.

Groundwater conditions should be observed during the course of the site investigation, and measurements should be made of the water level in exploratory borings. The groundwater or drilling mud level should be measured at the start of each workday for borings in progress, at the completion of drilling, and when the water levels in the borings have stabilized. In addition to the normal borehole groundwater measurements, piezometers or wells should be installed in as many locations as needed to adequately define the groundwater environment. Pumping tests are a preferred method for evaluating local permeability characteristics and 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 groundwater surface and pore pressures beneath the excavation and in the adjacent ground. This guide does not cover groundwater monitoring during construction of plants that are designed with permanent dewatering systems.

When the possibility of perched groundwater tables or artesian pressures is indicated by borings or other evidence, piezometers should be installed such that each piezometric level can be measured independently. 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 essential to verify during construction that in situ conditions have been realistically estimated during analysis and design. Excavations made during construction provide opportunities for obtaining additional geologic and geotechnical data. All construction excavations for safety-related structures and other excavations important to the verification of subsurface conditions should be geologically mapped and logged in detail. This work is usually performed after the excavation has been cleaned to grade and just before the placement of concrete or backfill, to permit recording of geologic details in the foundation. Particular attention should be given to the identification of features that may be important to foundation behavior but were undetected in the investigation program. Changes in foundation design should be noted on the appropriate plans, and newly discovered geologic features should be surveyed and entered into maps, cross-sections, and the database.

Features requiring excavation, such as structure foundations, cut slopes, tunnels, chambers, water inlets and outlets, should be mapped and investigated for geologic details that may be different from assumptions based on the pre-construction investigations. This work is usually performed after the excavation has been cleaned to grade and just before the placement of concrete or backfill. These maps should be prepared to show any feature installed to improve, modify, or control geologic conditions. Some examples are rock reinforcing systems, permanent dewatering systems, and special

treatment areas. All features found or installed should be surveyed and entered into maps, cross-sections, and the database. Photographic or videographic records (or both) of foundation mapping and treatment should be made. Generally, the GIS and other databases should be continuously updated, up to and including the construction phase, resulting in as-built information.

Appendix A to NUREG/CR-5738 provides detailed guidance on technical procedures for mapping foundations. Mapping of tunnels and other underground openings must be planned differently from foundation mapping. Design requirements for support of openings may require installation of support before an adequate cleanup can be made for mapping purposes. Consequently, mapping should be performed as the heading or opening is advanced and during the installation of support features, which necessitates a well-trained geologist, engineering geologist, or geotechnical engineer at the excavation site. Specifications should be included in construction plans for periodic cleaning of exposed surfaces and to allow a reasonable length of time for mapping. Technical procedures for mapping tunnels are outlined in Appendix B to NUREG/CR-5738 and can be modified for large chambers.

The person in charge of foundation mapping should be familiar with the design and should consult with design personnel during excavation work whenever differences between the actual geology and the design base geological model are found. The same person should be involved in all decisions concerning changes in foundation design or additional foundation treatment that may be necessary based on observed conditions.

The previous requirement for a two-step licensing procedure for nuclear power plants, involving first a construction permit (CP), and then an operating license (OL), has been modified to allow for an alternative procedure. Requirements for applying for a combined license for a nuclear power facility are contained in Subpart C of 10 CFR Part 52. The combined licensing procedure may result in the award of a license before the start of construction. However, the need for construction mapping applies equally under the combined license procedure. In the past, previously unknown faults were often discovered in site excavations for nuclear power plants, demonstrating the importance of mapping such features while the excavations' walls and bases are exposed and the importance of assessing their potential to generate offsets or ground motion. Documents supporting the combined license application (Safety Analysis Reports) should, therefore, include plans to geologically map all excavations. Applicants must meet the requirements of 10 CFR 50.9 regarding notification to the NRC of information concerning a regulated activity with significant implications for public health and safety or common defense and security.

7. SUPPORT FUNCTIONS

7.1 Surveying/Mapping/GIS

Surveying is an important function that should accompany all essential site investigation activities from reconnaissance through construction mapping. There are many methods of surveying available today, from traditional triangulation or plane table work together with leveling to electronic distance and GPS measurements. For mapping small areas, plane table methods may still be among

the fastest. In most cases, however, GPS or DGPS (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. The GPS measurements and other surveyed locations should be tied to National Geodetic Survey (NGS) markers in order to be compatible with topographic maps and digital maps of various kinds. The vertical component of GPS measurements is the least accurate component, but it is being improved with more accurate satellite orbits and other corrections. For greater accuracy, it may 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 (WGS 84), the International Terrestrial Reference Frame (ITRF), 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. One of the advantages of a GIS is that data of various kinds, in the form of tables, can be associated with a coordinate system and then recalled to form graphical output of a desired type. The choice of the particular system used is up to the applicant. However, the data should be in a format that is readily readable.

In order to record the information gathered during site investigations, to place geological, geotechnical, and sampling/testing information into a spatial context, and to permit visual display in maps and cross sections, it is necessary to have a staff available that is experienced in surveying and in storing and displaying data in a GIS throughout all phases of site investigation and construction. These are essential activities that should be given proper emphasis and support by applicants.

7.2 Database/Sample Repository/Quality Assurance

All data acquired during the site investigation should be organized into suitable 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 core 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 what the foundation material is like. Similarly, cores of rock subject to slaking and rapid weathering such as shale will also deteriorate. It is recommended that photographs of soil samples and rock cores, together with field and final logs of all borings, 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 Regulatory Guide 1.28 and the requirements of Appendix B to 10 CFR Part 50. Field operations and records preservation should, therefore, be conducted in accordance with quality assurance principles and procedures.

D. IMPLEMENTATION

The purpose of this section is to provide guidance to applicants regarding the NRC staff's plans for using this regulatory guide.

Except when an applicant proposes an acceptable alternative method for complying with the specified portions of the NRC's regulations, the methods described in this guide reflecting public comments will be used in the evaluation of applications for site approval of commercial nuclear power reactors submitted after January 10, 1997.

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¹ ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, phone (610)832-9500.

² Copies are available at current rates from the U.S. Government Printing Office, P.O. Box 37082, Washington, DC 20402-9328 (telephone (202)512-1800); or from the National Technical Information Service by writing NTIS at 5285 Port Royal Road, Springfield, VA 22161; <<http://www.ntis.gov/ordernow>>; telephone (703)487-4650. Copies are available for inspection or copying for a fee from the NRC Public Document Room at 11555 Rockville Pike, Rockville, MD; the PDR's mailing address is USNRC PDR, Washington, DC 20555; telephone (301)415-4737 or (800)397-4209; fax (301)415-3548; email is PDR@NRC.GOV.

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