APPENDIX D
SPACING AND DEPTH OF SUBSURFACE EXPLORATIONS FOR SAFETY-RELATED[1] FOUNDATIONS

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 one boring should be at the location of every safety-related structure. 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 m (33 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, Continued

STRUCTURE	SPACING OF BORINGS OR SOUNDINGS	MINIMUM DEPTH OF PENETRATION
Buildings, retaining walls, concrete dams	Principal borings: at least one boring beneath every safety-related structure. 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). In addition, a number of borings along the periphery, at corners, and other selected locations. 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, embank-ments	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 groundwater 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 groundwater 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 groundwater may influence stability.[2]

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[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, Continued

STRUCTURE	SPACING OF BORINGS OR SOUNDINGS	MINIMUM DEPTH OF PENETRATION
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]
Reservoirs, impound-ments	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 dispersion	Travel time and period of surface Rayleigh waves	Inference of shear wave velocity in near-surface materials	Rapid technique which 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.
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 m (200 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.
Electrical resistivity	Electrical resistance of a volume of material between probes	Complementary to refraction (seismic). Quarry rock, groundwater, 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.

APPENDIX E, Cont'd.

Geophysical Method	Basic Measurement	Application	Advantages	Limitations
		Surface (Continued)		
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(GPR)	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. On line 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	Velocity determination of vertical P- and/or S-waves. Identification of 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	Velocity determination of horizontal P- and/or S-waves. Elastic characteristics of sub-surface strata can be calculated.	Generally accepted as producing reliable results. Detects low-velocity zones provided borehole spacing not excessive.	Careful planning with regard to borehole spacing based upon geologic and other seismic data 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.
Borehole spontaneous potential	Natural earth potential	Correlates deposits, locates water resources, studies rock deformation, assesses permeability, and determines groundwater 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.

APPENDIX E, Cont'd.

Geophysical Method	Basic Measurement	Application	Advantages	Limitations
		Borehole (Continued)		
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 cm (16 to 64 in.)	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 (3-D) 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 1500 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.

APPENDIX E, Cont'd.

Geophysical Method	Basic Measurement	Application	Advantages	Limitations
		Borehole (Continued)		
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, chemical variation in strata affect measurement precision. Radioactive source hazard.
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, 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, 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 strata	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.

APPENDIX E, Cont'd.

Geophysical Method	Basic Measurement	Application	Advantages	Limitations
		Borehole (Continued)		
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 groundwater.
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 to 1.7 cm/s (2 - 3 ft/min).
Borehole dipmeter	Sidewall resistivity	Provides strike and dip of bedding planes. Also used for fracture detection.	Useful in determining information on the location and orientation of primary sedimentary structures 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 groundwater 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, Department of the Army, 1984)

Purpose of Test	Type of Test	Applicability to Soil	Applicability to Rock
Shear strength	Standard penetration test (SPT)	X	
	Field vane shear	X	
	Cone penetrometer test (CPT)	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	
Liquefaction susceptibility	Standard penetration	X	
	Cone penetration test (CPT)	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, Department of the Army, 1984)

	For		
Test	Soils	Rocks	Remarks
Standard penetration	X		Use as index test only for strength. Develop local correlations. Unconfined compressive strength in tsf 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 (CPT)	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, Department of the Army, 1984)

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, 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

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

Table F-4 In Situ Tests to Determine Deformation Characteristics (adapted from EM 1110-1-1804, Department of the Army, 1984)

	For		
Test	Soils	Rocks	Remarks
Geophysical refraction, Cross-hole 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 Groundwater Pressure

Instrument Type	Advantages	Limitations[1a]
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.
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 groundwater. Can be used to measure permeability.	Long time lag. 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 owing to 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.
Unbonded electrical resistance piezometer	Easy to read. Short time lag. Minimum interference to construction: level of lead wires and readout independent of level of tip. Can be used to read negative pore water pressures. No freezing problems. Provides temperature measurement. Some types suitable for dynamic measurements.	Low electrical output. Lead wire effects. Errors caused by moisture and electrical connections are possible. Need for lightning protection should be evaluated.

[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]
Bonded 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 groundwater and can be combined with inclinometer casing.	Complex installation procedure. Periodic manual readings only.

REGULATORY ANALYSIS

A separate regulatory analysis was not prepared for this regulatory guide. The regulatory analysis prepared for Draft Regulatory Guide DG-1101, "Site Investigations for Foundations of Nuclear Power Plants" (February 2001), provides the regulatory basis for this regulatory guide as well. DG-1101 was issued for public comment as the draft of this present regulatory guide. A copy of the regulatory analysis is available for inspection and copying for a fee at the U.S. Nuclear Regulatory Commission Public Document Room, 11555 Rockville Pike, Rockville, MD; the PDR's mailing address is USNRC PDR, Washington, DC 20555; telephone (301)415-4737 or 1-(800)397-4209; fax (301)415-3548; e-mail <PDR@NRC.GOV>.