RAS 5226

SEISMIC DESIGN

ASC -86

72-22-ISFSI Applicant Exhibit XX - Rec'd 5/2/02

NOTED JAN 2 3 1997 P. I.

ASCE STANDARD

Seismic Analysis of Safety-Related Nuclear Structures and Commentary on Standard for Seismic Analysis of Safety Related Nuclear Structures

September 1986

DOCKETED
USNRC

2003 JAN 13 AM 10: 24

OFFICE OF THE SECRETARY
RULEMAKINGS AND
ADJUDICATIONS STAFF

American Society of Civil Engineers

UCLEAR REGULATORY COMMISSION

Docket No. ______ Official Exh. No. X X

In the matter of PFS

Staff ______

Applicant ✓ IDENTIFIED ✓

ntervenor ______ RECEIVED ✓

Other ______ REJECTED ______

DATE 5-2-02 WITHDRAWN ______

Witness ______

[illegible] Amp

rock-like beneath the foundation. A rock-like foundation is defined by a shear-wave velocity of 3,500 ft/sec (1,100 m/sec) or greater at a shear strain of 10^{-3} percent or smaller when considering preloaded soil conditions due to the structure.

3.3.1.2 Spatial Variations of Free-Field Motion-- (a) Vertically propagating shear and compressional waves may be assumed for an SSI analysis provided that torsional effects due to nonvertically propagating waves are considered.

(b) Variation of amplitude and frequency content with depth may be considered for partially embedded structures. The spectral amplitude of the acceleration response spectra in the free field at the foundation depth shall be not less than ~~60% of the corresponding design response spectra at the finish grade in the free field.~~

3.3.1.3 Three-Dimensional Effects-- The three-dimensional phenomenon of radiation damping and layering effects of foundation soil shall be considered in SSI analysis.

3.3.1.4 Nonlinear Behavior of Soil-- The nonlinear behavior of soil shall be considered and may be approximated by equivalent linear material properties. Two types of nonlinear behavior may be identified: primary and secondary nonlinearities. "Primary nonlinearity" denotes nonlinear material behavior induced in the soil due to the excitation alone, i.e., ignoring structure response. "Secondary nonlinearity" denotes nonlinear material behavior induced in the soil due to structural response as a result of SSI. Primary nonlinearities shall be considered in the SSI analysis. Except for the provisions of 3.3.1.9, secondary nonlinearities including local nonlinear behavior in the vicinity of the soil-structure interface need not be considered.

3.3.1.5 Structure-to-Structure Interaction-- Structure-to-structure interaction may be generally neglected for overall structural response but shall be considered for local effects due to one structure on another, such as required in 3.5.3 for walls.

✓ **3.3.1.6 Effect of Mat and Lateral Wall Flexibility**-- The effect of mat flexibility for mat foundations and the effect of wall flexibility for embedded walls need not be considered in the SSI analysis.

3.3.1.7 Uncertainties in SSI Analysis- The uncertainties in the SSI analysis shall be considered. In lieu of a probabilistic evaluation of uncertainties, an acceptable method to account for uncertainties in SSI analysis is to vary the soil shear modulus. Soil shear modulus shall be varied between the best estimate value times (1 + C_v) and the best estimate value divided by (1 + C_v), where C_v is a factor that accounts for uncertainties in the SSI analysis and soil properties. The minimum value of C_v shall be 0.5.

(1+Cv)·G

G/(1+Cv)

3.3.1.8 Model of Structure-- (a) Structural models defined in 3.1 may be simplified for the SSI analysis. Simplified models may be used provided they adequately represent the mass and stiffness effects of the structure and adequately match the predominant frequencies, related mode shapes, and participation factors of the more detailed structure model.

(b) When a simplified model is used to generate in-structure response spectra, representative in-structure response spectra also shall be adequately matched for fixed-base conditions in both the detailed and simplified models.

3.3.1.9 Embedment Effects-- The potential for reduced lateral soil support of the structure should be considered when accounting for embedment effects. One method to comply with this requirement is to assume no connectivity between structure and lateral soil over the upper half of the embedment or 20 ft (6 m), whichever is less. However, full connection between the structure and lateral soil elements may be assumed if adjacent structures founded at a higher elevation produce a surcharge equivalent to at least 20 ft (6 m) of soil.

2 ft

?

3.3.2 Subsurface Material Properties

3.3.2.1 General Requirements-- Subsurface material properties shall be determined by field and laboratory testing, supplemented as appropriate by experience, empirical relationships, and published data for similar materials. The following material properties shall be determined for use in equivalent-linear analyses: shear modulus, *G*; damping ratio, *D*, Poisson's ratio, *ν*; and total unit weight, γ.

3.3.2.2 Shear Modulus-- The shear modulus, *G*, defined as shown in Fig. 3300-1, shall be determined as a function of shear strain level.

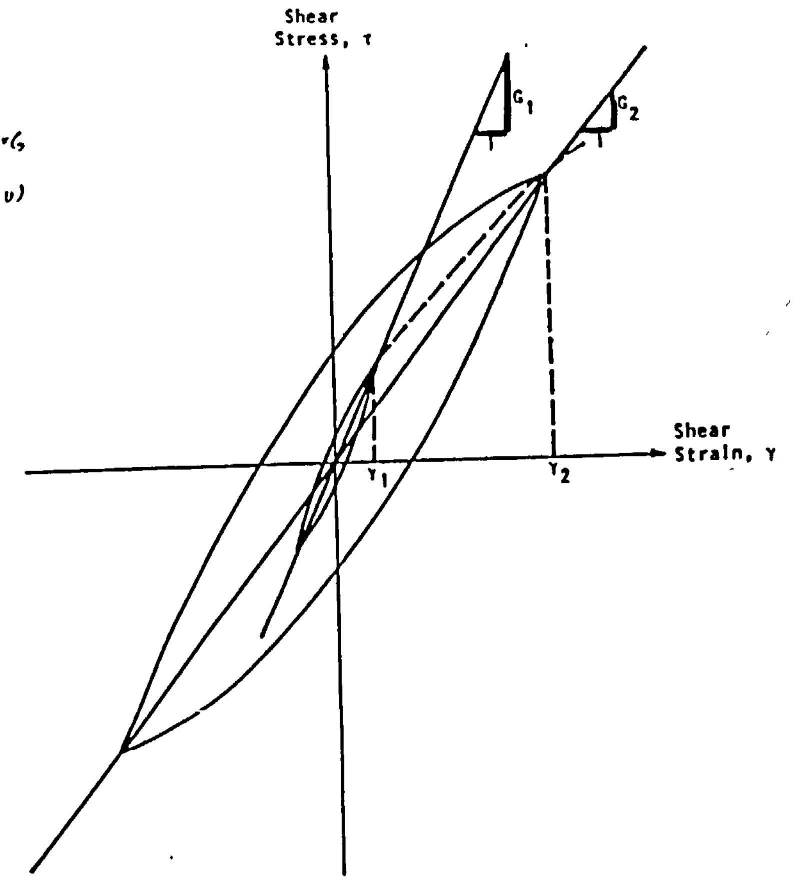

FIGURE 3300-1 DEFINITION DIAGRAM FOR SHEAR MODULUS, G

3.3.2.3 Material (Hysteretic) Damping Ratio-- (a) The material (hysteretic) damping ratio, *D*, defined as shown in Fig. 3300-2, shall be determined as a function of shear strain level.

(b) At very small strains (<10^{-4} percent), the ~~material (hysteretic) damping ratio shall not exceed~~ [illegible] critical.

3.3.2.4 Poisson's Ratio-- Poisson's ratio, *ν*, in combination with shear modulus, *G*, defines the Young's modulus of the material in accordance with the theory of elasticity. For saturated soils, the behavior of the water phase shall be considered in evaluating Young's modulus and selecting values of *ν*.

3.3.3 Direct Method

SSI analysis by the direct method shall consist of the following steps:

1. Locate the bottom and lateral boundaries of the soil-structure model.
2. Establish input motion to be applied at the boundaries.
3. Establish soil model, properties, and layer boundaries to be used for the foundation.
4. Perform SSI analyses in one or two steps, as discussed in 3.1.1.2, using structural models as discussed in 3.3.1.8.

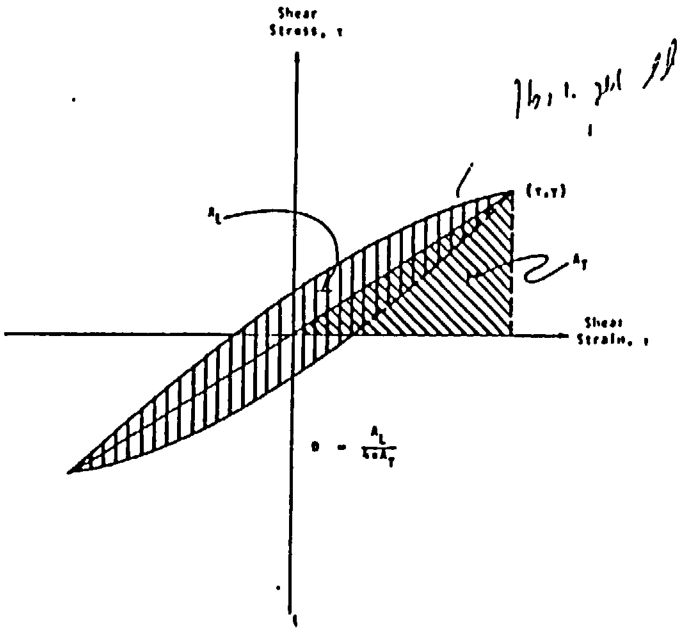

FIGURE 3300-2 DEFINITION DIAGRAM FOR HYSTERETIC DAMPING RATIO, D

3.3.3.1 Seismic Input for Model Boundaries-- (a) Boundary motion input to the soil model shall be compatible with the design earthquake specified at the finish grade in the free field.

(b) The motions shall be established as a function of the soil properties, the type of waves propagating during the earthquake, and the type of boundary assumed.

(c) The analyses to establish boundary motions shall be performed using mathematical models and procedures compatible with those used in the SSI analysis.

3.3.3.2 Lower Boundary-- The lower boundary shall be located far enough from the structure that the seismic response at points of interest is not significantly affected. The lower boundary of the model may be placed at a layer at which the shear-wave velocity equals or exceeds 3,500 ft/sec (1,100 m/sec) or at a soil layer that has a modulus 10 times or more larger than the modulus of the layer immediately below the structure foundation level. The lower boundary need not be placed more than 3 times the maximum foundation dimension below the foundation. The lower boundary may be assumed to be rigid.

3.3.3.3 Selection of Lateral Boundaries-- The location and type of lateral boundaries shall be selected so as not to significantly affect the structural response at points of interest. Elementary, viscous, or transmitting boundaries may be used.

3.3.3.4 Soil Element Size-- Soil discretization (elements or zones) shall be established to adequately reproduce static and dynamic effects. When using simple quadrilateral finite elements, at least eight horizontal discretizations over the foundation width shall be used, immediately beneath the foundation, to adequately reproduce the static stress distribution beneath the foundation. The discretization adjacent to the foundation shall be fine enough to adequately model rocking, if significant. The soil elements shall be fine enough to ensure frequency-transmitting characteristics up to a frequency of at least 25 Hz, which requires an element vertical dimension smaller than or equal to one-fifth of the smallest wavelength of interest. Larger element sizes may be used when justified.

3.3.3.5 Time Step and Frequency Increment-- (a) For solution of the SSI analysis in the time domain, the integration time step shall be selected to be small enough to ensure accuracy and stability of the solution.

(b) For solution of the SSI analysis in the frequency domain, the frequency increment shall be selected to be small enough to ensure accuracy of the solution. A quiet period shall be added to the excitation to damp out structural vibrations. The transfer functions shall be established using a sufficient number of points. ~~The cutoff frequency shall be at least 25 Hz, except a lower frequency cutoff may be used~~ when justified.

3.3.4 Impedance Method

SSI analysis by the impedance function approach shall consist of the following steps:

1. Determine the input motion to the massless rigid foundation.
2. Determine the foundation impedance functions.
3. Analyze coupled soil-structure system.

3.3.4.1 Determination of Input Motion-- The control motion defined at the free-field surface may be input to the massless rigid foundation. When the control motion is used as the input, rotational input due to embedment or wave passage effects need not be considered. Alternatively, the input motion to the massless rigid foundation may be modified from the control motion at the free-field surface to incorporate embedment or wave passage effects, provided the corresponding computed rotational inputs are also used in the analysis.

3.3.4.2 Determination of Foundation Impedance Functions

3.3.4.2.1 *Equivalent Foundation Dimensions*-- For impedance function calculations, all mat foundations may be approximated by equivalent rectangular or circular shapes. The equivalent rectangular or circular dimensions shall be computed by equating the basemat soil contact area for translational modes of excitation and by equating the contact area moment of inertia with respect to the reference axis of rotation for rotational modes of excitation. The equivalent embedment depth shall be determined by equating the volume of soil displaced by the embedded structure.

3.3.4.2.2 *Uniform Soil Sites*-- When the soil below the foundation basemat is relatively uniform to a depth equal to the largest foundation dimension, frequency-independent soil spring and dashpot constants, as shown in Table 3300-1 for circular foundations and Table 3300-2 for rectangular foundations, may be used. Frequency-dependent impedance functions for a viscoelastic half-space using the integral equation formulation may also be used.

3.3.4.2.3 *Layered Soil Sites*-- Where the soil deposit can be approximated by a number of horizontal layers of uniform soil, or where the uniform soil deposit is underlain by bedrock at a depth less than the largest equivalent foundation dimensions, frequency-dependent impedance functions shall be developed. An integral equation formulation is acceptable for computing the impedance functions. The use of finite-element or finite-difference formulations is also acceptable.

3.3.4.2.4 *Embedded Foundations*-- (a) ~~For shallow embedments (depth-to-equivalent-radius ratio less than 0.3), the effect of embedment may be neglected in obtaining the~~ impedance functions, provided the soil profile and properties below the ~~basemat~~ elevation are used for the impedance calculations.

(b) When the effect of embedment is considered, a simplified formulation may be used that assumes that the soil reactions at the base of the foundation are equal to those of a foundation placed on the soil surface assumed at the foundation elevation and uses lateral soil reactions calculated independently using soil properties of the side soil. More accurate formulations using integral equations, finite-element methods, finite-difference methods, or a combination of these methods may also be used.

3.3.4.3 Analysis of Coupled Soil-Structure System-- (a) The coupled soil-structure system shall include the structure, or its modal representation, and the soil spring and dashpots anchored at the foundation level. The dynamic characteristics of the soil shall be defined by impedance functions computed in accordance with 3.3.4.2. The coupled soil-structure dependent. Foundation impedances depend on the soil configuration and material behavior, the frequency of the excitation, and the geometry of the foundation.

- Analysis of the coupled soil-structure system by solving the appropriate equations of motion.

The impedance-function approach is limited to linear or equivalent linear analysis, since it is based on the principle of superposition. It is typically applied to general, three-dimensional environments.

3.3.1.1 Fixed-Base Analysis-- A fixed-base condition may be assumed for soil-structure systems when the site soil conditions behave in a rock-like manner to reduce computational efforts. However, SSI analysis may always be performed.

3.3.1.2 Spatial Variations of Free-Field Motion-- The earthquake ground motion at the site is a function of the location and source mechanism of the earthquake, the transmission path, and the local site conditions. Describing the free-field ground motion entails specifying the point at which the motion is applied (the control point), the amplitude and frequency characteristics of the motion, and the spatial variations of the motion. In terms of SSI, the variation of motion over the depth and width of the foundation is the key factor. For surface foundations, the variation of motion on the surface of the soil is important; for embedded foundations, the variation of motion over both the embedment depth and the foundation width should be known. Specification of the control motion is discussed in Section 2 of the standard. Spatial variation of the free-field ground motion is discussed here.

To perform SSI analysis by either the direct method or the impedance-function approach, an assumption as to the wave-propagation characteristics of this ground motion must be made (3.3-1). The direct method requires a compatible seismic excitation on the boundaries of the model. The impedance-function approach requires determination of the motions of a massless foundation bonded to the soil. It is common to assume a horizontally stratified soil and vertically propagating trains of waves. In this case, vertically propagating shear waves produce only horizontal translations, and vertically propagating dilatational waves produce only vertical motions in the free-field soil deposit. This assumption reduces the free-field wave-propagation problem to one dimension.

In general, the pattern of wave propagation due to an earthquake is extremely complex and very uncertain. The assumption of trains of waves incident to the soil deposit free surface at angles other than vertical produces effects which can increase or decrease the structural response depending on the specific situation. Consider a massless foundation bonded to the free surface of a soil deposit for illustrative purposes. Vertically propagating shear and dilatational waves will produce only a resultant horizontal and vertical motion, respectively, of the foundation. Trains of waves incident to the surface at varying angles will produce a coupling of horizontal and torsional motion and vertical and rocking motion. The resultant effect may be a net increase or decrease in foundation motion depending on the site specificity, assumed wave trains, the foundation characteristics, and the frequency range of interest.

Refs. 3.3-4, -6, and -17 contain specific examples quantifying the effect of nonvertically incident seismic waves on in-structure response. These results span the range of increases and decreases in response. For realistic angles of incidence, the one quantity which requires consideration is the induced torsional response due to nonvertically incident waves. For design purposes, an accidental eccentricity of 5% of the structure's plan dimension accounts for this phenomenon. It is the judgment of the Committee that vertically propagating waves may be assumed for design when an accidental eccentricity is included.

For the direct method, a consistent seismic motion on the boundaries of the model must be known, assumed, or computed corresponding to the design ground motion specified at the control point. For the common assumption of vertically propagating trains of waves, a one-dimensional iterative linear wave-propagation analysis may be performed. Variations in soil material properties with strain level may be treated in an equivalent linear sense, i.e., iterate on the linear material properties to converge on a measure of the strain level over the duration of the excitation. The analysis may be either convolution or deconvolution. In the former, an excitation is specified along the boundary of the model, and the computed motion on the free-surface of the soil deposit is compared with the design specification. This is a trial-and-error process if a specified surface motion is to be matched. In the latter case, the free-surface motion is deconvolved to determine the boundary motion. In either case, the computed motions within the soil deposit exhibit amplifications and reductions in frequency content dependent on the location in the deposit and the assumed soil model.

A comparison of the design ground response spectra with the computed in-soil response spectra at the foundation depth in the free field should be made. The reduction of the in-soil response spectra at the foundation depth should be limited for design purposes to 60% of the corresponding design ground response spectra at all frequencies. When soil properties are varied in accordance with 3.3.1.7, the 60% limitation may be satisfied using the envelope of the three spectra corresponding to the three soil properties. This limitation reflects engineering judgment to account for the uncertainties in the assumptions leading to the reduction, e.g., assumed wave types, angles of incidence, soil material behavior, etc. The recording and analysis of earthquake motions at depth will assist in reducing these uncertainties in the future.

3.3.1.3 Three-Dimensional Effects-- SSI is a three-dimensional phenomenon—the soil and structure exhibit three-dimensional dynamic characteristics. The structure's supporting medium (soil or rock) is infinite in extent in two horizontal directions and the vertical direction. The dynamic behavior of this three-dimensional medium should be adequately represented in the analysis. For example, radiation damping, the geometric dispersion of energy away from the structure, is an important three-dimensional phenomenon to be included in the analysis. If two-dimensional, plane strain, approximations are made, special consideration should be given to the three-dimensional effects. In general, for deep soil sites, the plane strain approximation to the three-dimensional dynamic behavior cannot adequately represent both the stiffness and damping characteristics. The nonuniform character of the soil in the neighborhood of the site should also be considered.

Structures of a nuclear power plant facility exhibit three-dimensional dynamic behavior. Coupling between horizontal translations and torsional rotations exist even in structures nearly axisymmetric such as typical reactor buildings. This coupling should be treated in the analysis and design.

3.3.1.4 Nonlinear Behavior of Soil-- The constitutive behavior of soil with varying strain levels is clearly nonlinear as described in 3.3.2. For discussion purposes, this nonlinear behavior can be separated into two parts: Primary and secondary nonlinearities. The term "primary nonlinearity" denotes the nonlinear material behavior induced in the soil due to the excitation alone, i.e., ignoring structure response. The term "secondary nonlinearity" denotes the nonlinear material behavior induced in the soil due to the structural response as a result of SSI. The nonlinear behavior of soil should be taken into account for the SSI analysis. However, to perform rigorous nonlinear analysis of a typical nuclear power plant structure would require a fully three-dimensional model and an appropriate set of constitutive equations for soil. This is currently beyond the state of the art for design. Nonlinear soil behavior may be treated by:

- Using equivalent linear soil material properties typically determined from an iterative linear analysis of the free-field soil deposit. This accounts for the primary nonlinearity.
- Performing an iterative linear analysis of the coupled soil-structure system. This accounts for the primary and secondary nonlinearities.

Either technique is acceptable for structural response determination.

In view of the large uncertainties in describing the material behavior of soil and the SSI phenomenon, engineering judgment dictates consideration of a range of material properties for design.

3.3.1.5 Structure-to-Structure Interaction-- Structure-to-structure interaction