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Guidelines for seismic evaluation of nuclear facilities

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ABSTRACT: Current procedures to evaluate the potential effects of soil-structure interaction (SSI) on Category I facilities for commercial nuclear plants typically make use of complex computer analyses. These newer approaches more properly treat the various aspects of the problem as compared to the simplified methods used in past years. However, their use has reduced the inherent conservatism which had been incorporated into the response analyses. This paper presents some recent experiences resulting from studies performed to address these issues to make them compatible with the newer approaches. The specific areas of concern discussed herein have to do with the specification and the location of the input control motions, the inclusion of variability in soil properties into the analyses, particularly for deep soil sites and the use of fixed base assumptions in the structural response analyses.

1 INTRODUCTION

This paper presents a summary of the results achieved in a study (Costantino and Miller, 1991) to evaluate some effects of soil-structure interaction (SSI) on the seismic response of structures. Current procedures typically include the use of complex computer analyses which more properly treat the problem than the simpler approaches used in previous years. However, it is often not clear that the use of these new approaches suitably account for significant aspects of the problem in order to arrive at reasonably safe predictions. In addition, the numerical procedures used in these methods are often extremely sensitive to the specific methods of discretization used in the various parts of the particular computer code utilized. The objective of this study has been to address some of these uncertainties. The particular areas of interest briefly summarized below are associated with the definition of the location of the control point where the input motion is specified within the free-field soil column, the criteria that should be used to determine when fixed base analyses are appropriate and SSI effects can be neglected, and descriptions of procedures to incorporate variability in soil properties into the analyses needed to more properly support the SSI evaluations of facilities.

2. LOCATION OF CONTROL MOTION

The objective of this task has been to investigate the effects of control motion location within the soil column on ground motions developed at the foundation level of the facility. The most consistent definition of the site specific ground motion can generally be determined from a statistical analysis of recorded strong motion records which are chosen from their similarity in source, path and site properties as well as magnitude, fault type and tectonic environment. However, a sufficiently large number of site specific time histories must be available to define a spectrum which is sufficiently broad-banded to encompass the uncertainties in the controlling parameters of the site. If the control motion location and time history is derived using methods which are based upon a consistent set of recorded motions, the results for both control motion location and acceleration time history (or response spectra) are compatible, no matter where the control motion is specified. Wherever the acceleration time history is defined (at either the bedrock surface, some suitable interface of the soil column or the ground surface), the soil parameters defined throughout the soil column (initial stiffness, strain degradation and hysteretic damping ratio) and the controlling parameters of the bedrock all form a compatible data set appropriate for the site. If the control motion location is to be changed, the corresponding time history is also modified so as to maintain compatibility between properties and ground motion

If strong motion records are not available, however, site specific estimates of peak ground acceleration, velocity and/or displacements must be determined from appropriate scaling relationships based on magnitude, distance and site conditions. Where only estimates of peak ground acceleration are available for a given site, then standardized response spectra such as defined in USNRC's Regulatory Guide 1.60 (RG1.60) can be used to assist in developing a time history of the control motion and location of this control motion specified within the free-field. Current guidance provided by the Standard Review Plan (SRP, 1989) indicates that the control motion should be defined to be at the ground surface for uniform sites with relatively smooth variation of properties with depth. The variation in free-field ground motion with depth is then chosen to be consistent with the properties of the soil profile. Usually, this variation of free-field motion is limited to allow no more than a 40% reduction across the frequency range of interest to provide sufficient conservatism in the design. For sites composed of one or more thin layers overlying competent material, the control point is specified at an outcrop (real or fictitious) at a location at the top of competent material. In either case, the selection of the ground motion location completely dominates the free-field motion developed at the foundation depth.

To investigate the sensitivity of the computed motions at foundation depth to the choice of the control point location and the soil property variation with depth, a large number of soil column convolution calculations were conducted, varying many of the geotechnical parameters of both the soil column and founding bedrock, and using as input an acceleration time history derived to match the broad-banded RG1.60 spectral shape anchored to a given peak acceleration. This time history was generated to have a 20 second total duration, and contains frequencies from 0.05 hz to 50 hz in increments of 0.05 hz, with frequency components combined by random phasing. This time history was input to the soil column convolution model at either the bedrock level or at the ground surface and complete iterative calculations performed to generate compatible motions in the soil column at the foundation depth. The SLAVE Code (Costantino, 1979) was used for these calculations as it has been modified to contain many of the capabilities in soil property descriptions desired for this study. The parameters varied in this study include: peak acceleration level of the input accelerogram; length of the soil column above bedrock; initial stiffness of the soils in the soil column defined by the initial low strain shear wave velocity; soil degradation model used to represent shear strain effects on the soil stiffness and hysteretic soil damping; shear wave velocity of the founding bedrock; and depth below the ground surface to the foundation level. For each parameter set considered, the compatible time history and corresponding 5% damped response spectrum was computed at the foundation depth. Spectral ratios were then computed as the spectral acceleration of the output acceleration at the foundation depth divided by the input spectral acceleration at each frequency over the entire frequency range of interest.

An example of the computed spectral ratios is shown in Fig. 1 for the particular problem of a relatively soft soil (shear wave velocity of 229 m/s) overlying a rigid bedrock. The results from calculations for three different overburden thicknesses varying from 30.5m to 152.4m are presented, with output obtained for a foundation depth of 15.2m. As may be noted, the spectral ratios convolving downward equal or exceed those convolving upward for all frequencies above about 4 hz. For this case, when the control motion is input at the bedrock level and convolved upward through the soil column, the calculated motion at the foundation level shows an amplification (spectral ratios greater than one) near the low fundamental frequency of the soil column. At higher frequencies, deamplification develops, the amount related to the peak soil strains reached in the soil layers (which are related to soil degradation and hysteretic soil damping effects as well as peak input accelerations levels). On the other hand, if the broad-banded control motion is defined at the ground surface and convolved downward, the motion computed at the foundation level shows a deamplification at the foundation level at the frequency of the shorter soil column to the foundation depth, with significant amplification at higher frequencies. The amount of this amplification is again controlled by soil shear strain effects. Similar results are shown in Fig. 2 for a stiffer soil (shear wave speed of 457 m/s) overlying bedrock. For this case, except for the case of the long soil column of 152.4m, the spectral ratios convolving upward generally exceed those convolving downward since the fundamental column frequency is higher than that of the first problem.

The general behavior noted from the large number of calculations performed can be summarized as follows.

1. For the analyses convolving downward through the soil column, the spectral ratios at the higher frequencies increase significantly with depth as greater input is needed to overcome the energy lost through propagation. Spectral ratios are about equal to or exceed unity at frequencies above about twice the soil column frequency associated with the foundation depth.

2. For soft soil sites, the spectral ratios convolving downward exceed those convolving from bedrock upward through the soil column at the higher frequency range of interest (above 4 hz at the soft site evaluated).

3. For stiffer soils, the increase in spectral ratios at the higher frequencies is not as dramatic when convolving downward since the higher initial stiffness of the soil column reduces the amount of stiffness degradation and effective hysteretic damping of the soil.

Comparison of results was also made for two different soil degradation models, the standard Seed-Idriss (1970) model typically used in such convolution studies and a model based on more recent data developed for application to deep soil sites (Coppersmith, 1991). In this latter model, both shear modulus degradation and hysteretic soil damping ratios are reduced with increased confining pressures based upon limited laboratory data as well as correlation of calculated and measured surface motions from specific events. An example of shear modulus reduction with strain from these updated soil models is shown in Fig. 3 for sandy soils. Not only is the degradation reduced for near surface soils, but the effect of soil confinement at depth is to further reduce degradation. The impact of this revised model on the computed behavior indicates that when convolving downward through the soil column, the increase in spectral ratio at higher frequencies with depth is not nearly as great as predicted from the Seed-Idriss model since not as much shear strain develops in the soil. In addition, the spectral ratios convolving upward through the soil column are less than the ratios convolving downward only for the cases of very long soil columns with low initial shear wave velocity. For all other cases, convolving upward always causes the spectral ratios to exceed those obtained from the downward convolution. It should be mentioned, however, that it is not clear that the effects of confinement on degradation of soft soils is as pronounced as indicated from the limited test data available.

Based on the relatively extensive number of calculations described above, the following recommendations are put forth for consideration.

1. For all sites, the initial shear stiffness and form of

the soil degradation model completely dominate the compatible seismic motions computed throughout the soil column. Thus, it is imperative that enough site specific geophysical and geotechnical data be made available on which to base selection of best estimate (or average) soil properties throughout the depth of the soil overburden which can then be used in convolution studies.

2. If site specific studies are performed which are based on extrapolation of strong motion records (Kimball, 1983) suitably modified by empirical and numerical evaluations relating differences from recording sites to the site being evaluated the control point time history, response spectra and location should be selected together based on the results of these site specific evaluations. The control point can be located at either the ground surface or at an outcrop (either real or fictitious) as long as all aspects of the free-field motion definition form a compatible set.

3. For sites where seismic inputs are defined from broad-banded spectra, and site specific studies are either not available or not performed, the following control motion location is recommended to achieve conservative estimates of seismic inputs at the foundation level.

a. If the site can be defined as soft, that is, have an initial shear wave velocity of 229 m/s or less with degradation properties similar to the Seed-Idriss soil model, the control point location can be placed at the ground surface for all thicknesses of the soil 30.5 meters or more and downward convolution procedures used in defining the seismic environment with depth.

b. For soft soil sites with thicknesses less than 30.5 meters thick, the control point location can be maintained at the ground surface if the fundamental frequency of the soil column falls below the frequency range of interest for the structural responses. For all other cases, the control point should be located at the bedrock outcrop at the depth of the top of competent material.

c. If soil properties indicate stiff soils with initial shear wave velocities exceeding 457 m/s, the broad-banded control motion should always be located at the bedrock outcrop for overburden thicknesses less than about 213 meters.

d. For cases of intermediate shear wave velocity, the control point should be located to produce the conservative response at the foundation level. This should be shown by the results of both upward and downward convolution studies.

3. SEISMIC RESPONSE EVALUATIONS USING FIXED BASE ASSUMPTIONS

The objective of this study was to develop criteria that can be used to determine the conditions under which SSI effects should be included in the model used to assess the seismic response of a structure. In general, the magnitude of SSI effects tends to vary inversely as the stiffness (shear wave velocity) of the media surrounding the facility. It is clear that when the surrounding media is "stiff enough", SSI effects can reasonably be neglected and the response evaluated based on a fixed base analysis; that is, the motion of the foundation of the facility is assumed to be identical to the specified free field motion.

The dynamic response of two structural models was considered in evolving criteria to be used to determine adequacy of fixed base modeling. Both models include structural "sticks" placed at the surface of an ideal elastic halfspace to represent the stiffness and mass characteristics of the structure. The first model was a simple two mass system (Fig. 4a), one representing the foundation mass, with a second mass located at the top of the structure. A circular foundation was used in the calculations to allow use of available foundation impedance SSI functions. The second structural model was a much more detailed stick used to represent a typical PWR reactor containment structure (Fig. 4b). For both structural models, computations were made using frequency independent SSI coefficients as well as frequency dependent SSI parameters..

Using the available impedance formulations, the transfer function (magnitude of response for a unit input in the free-field at a given frequency) for horizontal motion of each mass point of the structure was then computed (Costantino and Miller, 1991) for both cases of a flexible structure on the surface of a flexible elastic halfspace and a rigid halfspace (fixed base assumption). A comparison of these transfer functions was then made over a wide range of fixed base frequencies (flexible structure on the rigid halfspace) and coupled SSI frequencies (rigid structure on the flexible halfspace). The results indicate that the solution with no SSI effects (fixed base assumption) is not appropriate unless the lowest coupled SSI frequency is at least twice the structural frequency. When this criterion is not satisfied, the fixed base results do not adequately approximate the actual response. An example of these results is shown in Fig. 5 in which comparisons are made for a particular structure with a fixed base fundamental frequency of 2 hz. When the lowest coupled SSI frequency is 2 times the structural frequency, the spectral response of the upper mass point is similar to that obtained from the fixed base model.

4. SOIL CHARACTERIZATION FOR SSI EVALUATIONS

The current guidelines provided in the SRP (1989) contain general descriptions of the information required for SSI evaluations, but do not specifically describe the minimum investigation that should be undertaken to adequately support SSI evaluations. Current procedures indicate that a variation in soil properties should be incorporated into the SSI analyses by using three sets of soil properties in convolution calculations, defined in terms of the low strain soil shear modulus set at the best estimate (or average), the upper bound and the lower bound values. The upper and lower bound low strain shear moduli are defined in terms of the best estimate values by

$$\begin{aligned} G_{max\,UB} &= G_{max\,BE} * (1 + C_N) \\ G_{max\,LB} &= G_{max\,BE} / (1 + C_N) \end{aligned} \tag{1}$$

where $G_{max\ BE}$ is the best estimate low strain shear modulus and the subscripts UB and LB indicate the upper and lower bound values respectfully. The parameter C_N is the factor to be selected to ensure that the proper range of values is considered for the particular site being investigated. It is recommended in ASCE 4-86 that the parameter C_N should never be taken as less than 0.5, while it is recommended in the SRP that unless the site is well investigated, the factor C_N should be selected as 1.0, although the term "well investigated" is not further defined. Tseng and Hadjian (1991) summarize some of the experiences obtained from the Lotung experiment and have made specific recommendations based upon that experiment.

Regulatory Guide 1.132 presents information on the number and spacing of all soundings used to ascertain in-situ soil properties. Such soundings typically include standard borings with drive and/or press samples obtained, continuous cone penetrometers, cross-hole and uphole/downhole seismic testing, and velocity logging are taken through the upper soil mantle. All of this information can be used to generate low strain shear modulus predictions through the upper several hundred feet of the foundation soils. For deep soil sites (greater than 91.4m), the capabilities of these methods to generate appropriate information seriously degrade. For these cases, comparison with data from generic soil studies may be required to generate the low strain data required for the convolution studies.

It is recommended that plots of shear moduli with depth be made incorporating the predictions obtained from all the soundings available from the site investigations. For example, the sampler blows from the Standard Penetration Test can often be converted to equivalent shear modulus using generic data for various soil types. Cone penetrometer data can similarly be transformed to shear modulus data using standard transformation relationships. It is important, however, that the variability (uncertainty) in these conversions be included in the evaluation. Down-hole, cross-hole and velocity logging data directly generate the desired shear modulus data. From this plot, the variability in site data for any soil layer (value of the parameter C_N) can be relatively easily determined for use in the SSI studies. Based on recent experiences with deep soil sites in which such information was compiled, a value of C_N of 1.0 was found to reasonably capture the uncertainty in the data. It is recommended that this plot be required for all sites and used as a basis for the specific value of C_N chosen. It is also recommended that a minimum value of C_N of 0.5 be used in any SSI study.

For completeness of the soil model, the shear modulus degradation and hysteretic soil damping data must be defined. In many cases, the degradation models used have been based on recommendations available from older studies, such as the Seed-Idriss (1970) models. Recent evaluations using measured seismic responses at soil sites by Coppersmith (1991) and Idriss (1990) have indicated that the older formulations may be inappropriate for many sites and may indicate too much modulus degradation as well as shear damping with effective shear strain. The impact of these soil degradation models on the surface seismic response was studied for a deep soil site (Costantino, 1991), from which it was noted that the degradation models completely dominate the computed responses surface responses. It is therefore recommended that degradation models to be used in the SSI response analyses be justified for the particular site being investigated, with this justification based on comparisons with site specific laboratory data (obtained from either resonant column, torsional or cyclic triaxial tests). This is particularly appropriate to the deeper soil sites where details of the degradation models control computed responses.

5. CONCLUSIONS

Based on the numerical results obtained from a wide range of computations (Costantino and Miller, 1991), recommendations have been put forth to ensure that adequately conservative site response calculations will be performed when attempting assess the magnitude of seismic response of nuclear facilities. The results discussed in this report concern the location of the input control motion to the soil column, the requirements needed to address fixed base modeling and the recommendations associated with the degree of variability in soil properties which should be incorporated into the seismic analysis and design.

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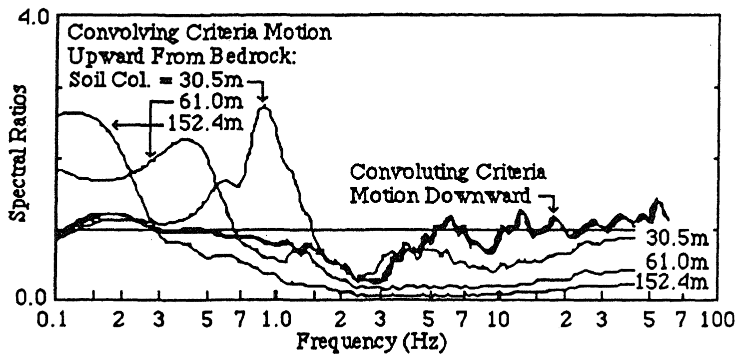


Fig. 1 Spectral Ratios at Foundation Depth for Soft Soil Site from 5% Damped Response Spectra (Parameters: 229m/sec soil shear wave velocity, rigid bedrock, Seed-Idriss 1970 1970 soil model, & 15.2m depth to foundation level)

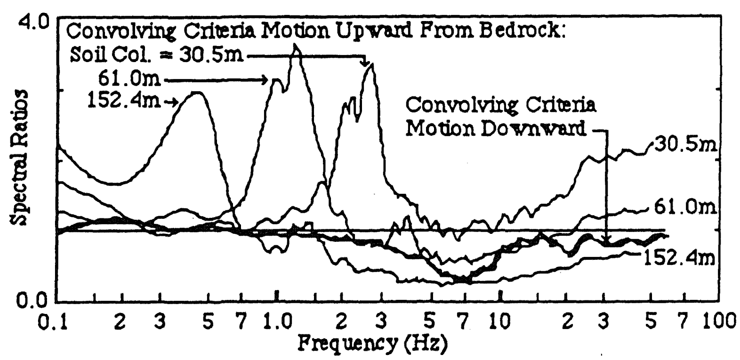


Fig. 2 Spectral Ratios at Foundation Depth for Stiff Soil Site from 5% Damped Response Spectra (Parameters: 457m/sec soil shear wave velocity, rigid bedrock, Seed-Idriss 1970 1970 soil model, & 15.2m depth to foundation level)

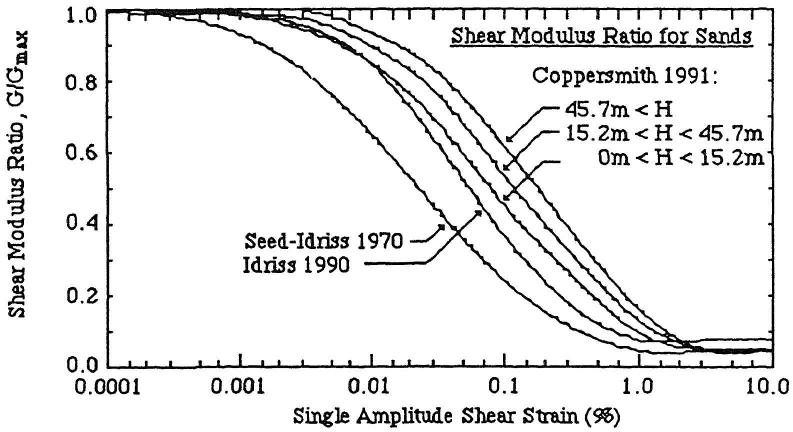
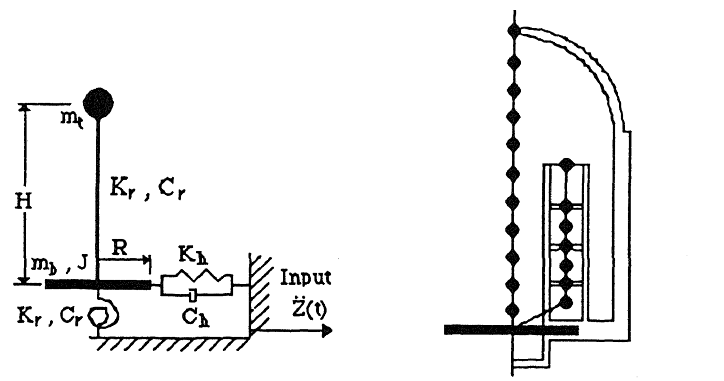


Fig. 3 Comparison of Shear Modulus Degradation Curves for Sandy Soils



(a) Simple Two Mass Structural Model (b) PWR Containment Model

Fig. 4 Stick Models Used to Assess Structural Response

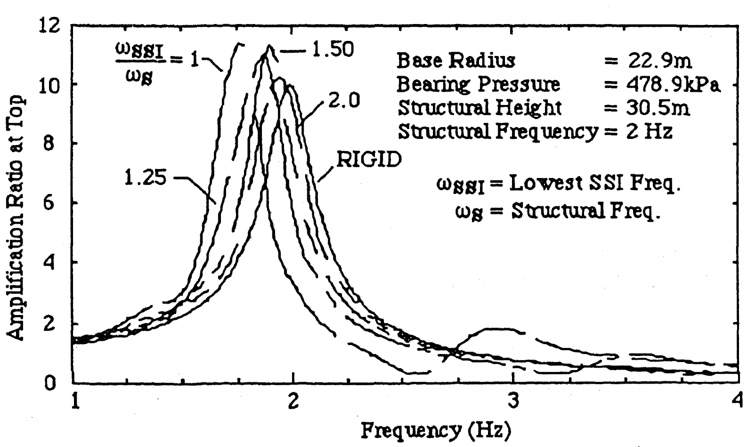


Fig. 5 Amplification at Top of Structure for Different Soil Shear Moduli