Application of Seismic Input Motions for Deeply Embedded Structures

S.C. Wu, A. Lopez
Bechtel Power Corporation, P.O. Box 2166, Houston, Texas 77252-2166, U.S.A.

ABSTRACT

The application of seismic input motion for deeply embedded structures has been a controversial subject. The current position of the U. S. Nuclear Regulatory Commission (NRC) is that the seismic input motion whose response spectra envelop the NRC Regulatory Guide 1.60 should be applied at the foundation base level for soil-structure interaction analysis, regardless of the depth of embedment. This position is considered questionable since the motion at this lower level is strongly influenced by the soil column above.

This paper shows by comparative analyses that strict implementation of the NRC position yields unreasonable results for a deeply embedded structure. Available published recorded data and analytical results are also briefly discussed to substantiate the advocated position of reducing the input motion with depth of embedment.

1. INTRODUCTION

Presently the soil-structure interaction (SSI) seismic analysis of deeply embedded structures on layered soil may be considered to be within the state-of-the-art developmental stage. The development of rigorous solutions is hampered by the controversies on the definition of ground input motion, representation of the soil nonlinear behavior, and consideration of the structure- to-structure interaction and the three-dimensional nature of the problem.

Two methods are commonly used for the SSI analysis; namely the finite element method (FEM)[1] and the elastic half-space method (EHS)[2], which is also referred to as lumped parameter or continuum method. In the FEM of analysis, the soil is represented by two-dimensional plane strain finite element model, and the structures are modeled by three-dimensional super-elements or two-dimensional plan strain/or beam elements. In the EHS methods, three-dimensional lumped parameter models of structures are incorporated with the underlying soil represented by impedances corresponding to a set of soil springs and dampers that are treated either as frequency-independent or -dependent parameters. The relative merits of using the FEM or the EHS method for SSI analysis have been a long debated subject in the nuclear industry for the past decades.[3,4] It is considered that if the modeling techniques could be deterministically defined, such as in the idealized case of a surface structure resting on elastic half-space of uniform soil, the use of these two methods would yield similar results. However, for the case of deeply embedded structures, discrepancies between results by the two methods are acknowledged and are indeed aggravated when the NRC position on application of seismic input motion is followed.

This study is to (i) present the free-field response analysis results and the observed experimental and analytical data that justify reduction of input motion with depth of embedment, and (ii) address the effect of depth of embedment on seismic input motion in SSI analyses by controlling the input motion separately with respect to the foundation base level and the ground surface. The reactor containment building (RCB) of a nuclear power generating station which is deeply embedded is utilized in this analytical study.

2. U. S. NRC POSITION

In recognition of the complexity of the SSI issues, the NRC has adopted the interim position on SSI stated in the Standard Review Plan (SRP)[5]. The position states that (i) the seismic input motion whose response spectra envelop the NRC Regulatory Guide 1.60[6] should be applied at the foundation level (irrespective of the method of analysis and the depth of embedment), and (ii) both the FEM and EHS method should be considered in SSI analysis, and the resultant floor response spectra (FRS) should be generated based on either the envelope of results of these two methods or the results of one method with conservative design consideration of effects from use of the other method.

The NRC requirement on enveloping as stated in Item (ii) is considered to be prudent in view of the potential departures anticipated between the FEM and EHS solutions. The prescribed application of ground-surface controlled input motion at the foundation base level, however, is considered to be not a fully warranted position because it ignores the observation of reduction of ground motion with deep embedment as demonstrated by past experimental and analytical investigations. Discussion of the published recorded data and analytical results is presented in Section 4.

3. FREE-FIELD RESPONSE ANALYSIS

The artificial accelerogram (hereafter referred to as the control motion) developed so that its computed spectra envelop the NRC Regulatory Guide 1.60 design spectra[6] for a nuclear power station is used for the deconvolution analysis. The control motion has a ten (10) seconds duration and has peak acceleration of 0.05g. The analysis is performed using the site-specific soil profile of 346 ft which consists of alternating layers of stiff to hard clays and dense silts and sands. The computer code "FLUSH" is used for this analysis.

Two cases are considered, one considers definition of the control motion at the ground surface and the other at the foundation level of the RCB building (60 ft below the ground surface). Also, when the control motion is defined at the ground surface, it is scaled up so that the calculated peak acceleration at the free-field foundation level equals 0.05g.

The results of the analyses are shown in Figures 1 and 2, and clearly demonstrate that when the control motion defined at ground surface is imposed at the foundation level, the peak response at the ground surface is significantly higher than the design input motion and thus becomes unrealistic.

4. PUBLISHED RECORDED DATA AND ANALYTICAL RESULTS

The available published recorded data obtained from downhole arrays[7,8,9,10] and the Humboldt Bay Nuclear Power Plant[11] are reviewed. Data from downhole arrays show that peak accelerations decrease with depth, and typically show reductions of up to 65 percent observed at depths of 40 to 60 ft. The recorded motions at the Humboldt Bay Nuclear Power Plant also show a reduction of about 50 percent in peak acceleration from the free-field ground surface to the base of the reactor building.

The published analytical results by Professor Luco, et al[12, 13] are also reviewed. Typical results to represent the compatible motions at the foundation base level by accounting for the geometry of the excavation are obtained for the case of vertically-incident propagating waves. This produces both translational and rotational components of motion. The results show that at intermediate and high frequency ranges, the translational response at the foundation level can be reduced by as much as 50 to 75 percent of the surface motion. This is due primarily to reduction of ground motion with depth.

In summary, it is evident that the published recorded data and analytical results do support the premise that the free-field motions decrease with depth.

5. SOIL-STRUCTURE INTERACTION ANALYSIS

The following SSI methods were considered to generate the FRS of the RCB structure for the purpose of evaluating the effects of controlling the input motions at the foundation base level and at the ground surface.

5-1. Two-Step Finite Element Method (2S-FEM):

The 2S-FEM was utilized for the SSI analysis of a nuclear power generating station to account for the deep embedment and layered soil effects. The first-step analysis is to obtain the translational and rotational interaction motions at the foundation base through two-dimensional plane strain models of the structures and soil cross sections. The computed base interaction motions are then applied in the second-step analysis to three-dimensional, fixed-base lumped parameter models of the structures to obtain acceleration response and compute the FRS.

In the first-step FEM analysis the seismic input motion is based on controlled motion surface and is scaled up so that the peak acceleration at the foundation base equals 0.05g.

The 2S-FEM solution is susceptible to over-representation of the spectral response in the high frequency range corresponding to fixed-base structural frequencies and to potential under-representation of the spectral response in the soil-structure system frequency range. This is a consequence of the decoupled fixed-based structural models that artificially force the structural response to be dominated by the frequency contents which exist in the base interaction input motions.

5-2. Single-Step Finite Element Method (SS-FEM)

The SSI analysis by the SS-FEM consists of a three-dimensional structural model directly coupled to the two-dimensional finite element soil model. This model permits a single-step transient analysis devoid of decoupled structural model, and accordingly does not overemphasize the spectral response in the structural fixed-base frequency range.

Two cases are considered with respect to application of seismic input motion, one specifies the control motion at the ground surface and the other specifies the motion directly at the foundation base.

5-3. Elastic Half-Space Method (EHS):

In the EHS method of analysis the structures are represented by three-dimensional lumped parameter models considered as resting on the surface of a semi-infinite elastic medium whose properties are represented by stiffness and damping parameters defined for each of six degrees of freedom at the base. The strain-dependent stiffness and damping values are evaluated at the predominant SSI frequencies.

The input motion is applied directly at the foundation base level.

5-4. Comparison of FRS:

The resultant FRS computed for each case of SSI methods are shown in Figures 3 and 4. From the comparison, it is evident that for the higher frequency range above 4 cps, which corresponds to the fixed-base structural fundamental frequencies, the 2S-FEM yields very conservative results. However, at the soil-structure system frequency of about 2 cps, the EHS and SS-FEM results are higher than the 2S-FEM results. Furthermore, when the seismic input motion controlled at ground surface is imposed at the foundation base level, the spectral acceleration peaks obtained especially by the SS-FEM method are much higher than those obtained from the other cases and thus lead to excessive conservatism for the case of deeply embedded structures.

6. CONCLUSIONS AND RECOMMENDATIONS

This study reaffirms the significant reduction of ground motion with depth, and demonstrates that the structural response is overrepresented if the reduction is ignored. Application of ground-surface controlled seismic input motion at the foundation base level of deeply embedded structures amplifies excessively and unrealistically the peak spectral responses at the dominant soil-structure system frequencies.

Therefore, it is suggested that the following recommendations should be considered for incorporation into the SRP Section 3.7.2.4:

(i). The free-field design input motions whose response spectra envelop the NRC RG 1.60 broad-band design spectra should be applied at the ground surface, irrespective of the method of analysis for SSI.

(ii). A reduction of ground motion due to deep embedment should be allowed for the EHS method. The resultant translational and rotational components would be applied at the foundation base level.

(iii). Two-step FEM analyses for SSI, if performed in the time domain with decoupled models, should be discouraged since such analyses tend to overrepresent the spectral response at the higher frequencies corresponding to fixed-base structural modes.

REFERENCES

(1). Lysmer, J. , et al, "FLUSH, A Computer Program for Approximate 3D Analysis of Soil-Structure Interaction Problem", Berkeley, Univ. of California, EERC Report No. 75-30, Nov. 1975.

(2). Whitman, R. V. and Richart, F. E., "Design Procedures for Dynamically Loaded Foundation", Journal of Soil Mechanics and Foundation Division, ASCE, Vol. 93, SM 6, Nov. 1967.

(3). Seed, H. B. , et al, "Soil-Structure Interaction Analysis for Seismic Response", Journal of Geotechnical Engineering Division, ASCE, GT 5, May 1975.

(4). Hadjian, A. H., et al, " Soil-Structure Interaction- Continuum or Finite Element", Nuclear Engineering and Design 31, 1974.

(5). U. S. Nuclear Regulatory Commission, Standard Review Plan, Section 3.7.2, "Seismic System Analysis", NUREG 0800, Rev. 1, July 1981.

(6). U. S. Regulatory Guide 1.60, "Design Response Spectra for Seismic Design of Nuclear Power Plants", Rev. 1, Dec. 1973.

(7). Joyner, W. B., et al, "Analysis of Seismograms from Downhole Arrays in Sediment Near San Francisco Bay", Bulletin of the Seismological Society of America, Vol. 66, No. 3, June 1976.

(8). Johnson, L. R. and Silva W., "The Effects of Unconsolidated Sediments Upon the Ground Motion During Local Earthquake", Bulletin of the Seismological Society of America, Vol. 71, No. 1, 1981.

(9). Seed, H. B. and Lysmer, J., "The Significance of Site Response in Soil-Structure Interaction Analysis for Nuclear Facilities", Proceeding of ASCE Specialty Conference, Knoxville, Tennessee, 1980.

(10). Tanaka, T., et al, "Observation and Analysis of Underground Earthquake Motion", Proceeding of 5th World Conference on Earthquake Engineering, Rome, Italy, 1973.

(11). Valera, J. E., et al, "Soil-Structure Interaction Effects at the Humboldt Bay Power Plant in the Ferndale Earthquake of June 7, 1975", EERC Report No 77-02, Univ. of California, Berkeley, 1977.

(12). Luco, J. E., "Seismic Safety Margins Research Program (phase 1), Linear Soil-Structure Interaction", Report to Lawrence Livermore Laboratory, UCRL-15272, July 1980.

(13). Day, S. M., "Finite Element Analysis of Seismic Scattering Problems", Dissertation Submitted in Partial Requirement for PhD in Earth Science, Univ. of California, San Diego, 1977.

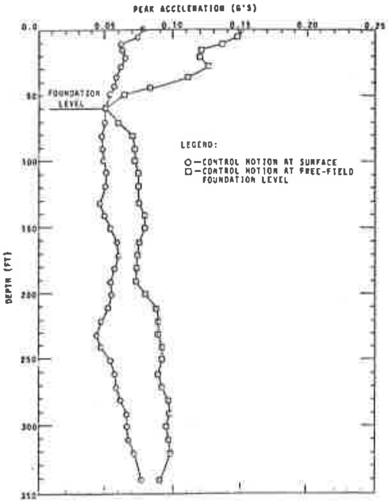

FIGURE 1: VARIATION OF PEAK ACCELERATION WITH DEPTH FOR SOUTH TEXAS PROJECT

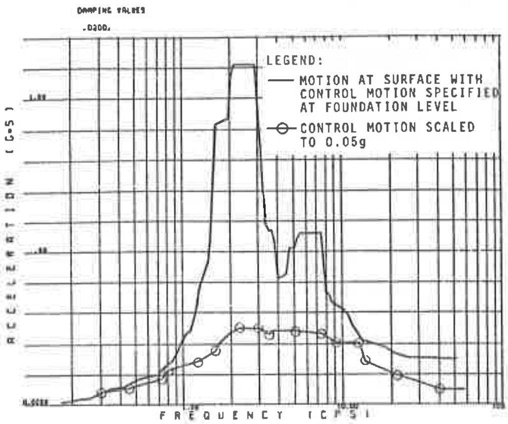

FIGURE 2: ACCELERATION RESPONSE SPECTRA AT SURFACE COMPUTED FROM ANALYSIS WITH CONTROL MOTION SPECIFIED AT FOUNDATION LEVEL

- - - - TWO-STEP FEM (INPUT @ GROUND SURFACE)

——— SINGLE-STEP FEM (INPUT @ GROUND SURFACE)

—▲—▲— SINGLE-STEP FEM (INPUT @ FDN. BASE)

—●—●— EHS (INPUT @ FDN. BASE)

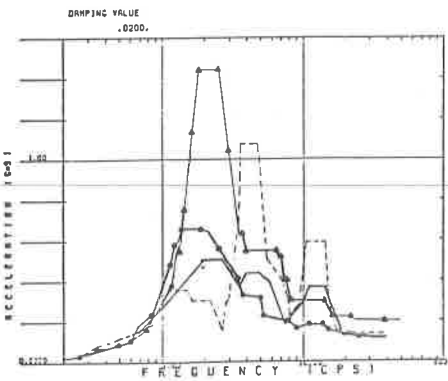

FIGURE 3: STP RCB-ACCEL. SPECTRA AT THE TOP OF CONTAINMENT SHELL, EL. 229 FT, OBE, N-S

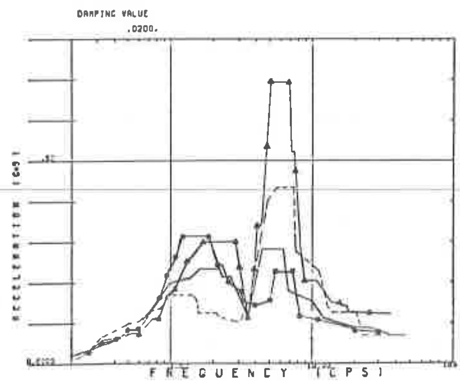

FIGURE 4: STP RCB-ACCEL. SPECTRA AT INTERNAL STRUCTURE, EL. 68 FT, OBE, N-S