Soil–Structure Interaction Lotung Experiment: Prediction Evaluation Basis

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INTRODUCTION

The analysis of seismic soil-structure interaction (SSI) has been a source of uncertainty in the seismic design of nuclear power plants. Over the past 15 years a variety of SSI analysis techniques and associated computer codes has evolved. In spite of the advances in the theory and analysis procedures, different techniques with different modeling assumptions and constants if not used properly could result in significantly different response predictions. Due to the lack of methodology validation, a conservative approach, based on enveloping analyses results using different techniques has often been practiced.

Recognizing the importance of validating the SSI analysis methodology to reduce the uncertainties, the Electric Power Research Institute (EPRI) in corporation with Taiwan Power Company (TPC) has recently sponsored a large scale seismic experiment (LSST). It consists of two scaled nuclear plant containment model structures in the seismic prone area of Lotung, Taiwan (Tang, H. T. et al, 1987). Both forced vibration test (FVT) data and actual earthquake induced response data have been obtained. These collected data were used for a series of round-robin blind prediction analyses by thirteen research teams worldwide using currently available SSI analysis techniques (Tang, Y. K. et al, 1987). The results of these analyses were presented in a workshop sponsored by EPRI, NRC and TPC in December 1987 (EPRI, 1987). To form a technical basis to assist the industry in performing SSI analysis with reduced uncertainties, the blind prediction results are evaluated and synthesized as a whole. This paper describes the elements included in this evaluation.

ANALYSIS METHODS

Table 1 shows the U.S. participants in and the methods used for the predictions. The objective of having Bechtel predictions using the four designated methods was to provide a matrix of comparisons. Using the same soil-structure characterization the Bechtel results provide an across methods evaluation highlighting differences only in the solution methods. On the other hand the comparison of the Bechtel results with the results from the other teams provides a basis of comparison of soil-structure characterizations within each method. A detailed comparison among the methods themselves is not performed since the objective here is not to declare a best method. The emphasis in this evaluation is on the learning from the experiment. The methods can best be compared to the actual recorded data and any possible learning elicited.

In order that the evaluation of the response predictions goes beyond a mere statement as to whether the predictions were adequate or inadequate based on a comparison of recorded and calculated response spectra, evaluation bases need to be established first. In-depth investigation of soil profile characteristics were performed and post-prediction studies using recorded data were conducted to develop best estimate parameters as well as to validate modeling assumptions and techniques.

SOIL PROFILE CHARACTERIZATION

Geotechnical conditions at the Lotung site were established during a series of field, geophysical and laboratory testing programs. Procedures used to carry out the field and laboratory testing programs conformed as closely as possible to procedures used by U.S. industry during site characterization studies for nuclear power projects.

The scope of field explorations included drilling and sampling 12 boreholes at the site to depths of 30 to 150 meters. Standard penetration tests (SPTs) were performed in general accordance with ASTM 1586, and undisturbed samples were obtained throughout the soil profile using fixed-piston sampling methods. Low-strain dynamic properties were determined in-situ by performing crosshole and uphole geophysical tests. Crosshole results were obtained along four travel paths to a maximum depth of 60 meters. Explosive procedures were used to create the seismic waves. Uphole procedures were used to obtain shear and compressional wave velocities below 60 meters.

Resonant column and cyclic triaxial tests were conducted to obtain shear modulus and material damping information at intermediate to high shearing strain amplitudes. The resonant column tests were conducted on undisturbed and reconstituted samples at multiple confining pressures. Shear modulus values and material damping ratios were obtained at shearing strains from 0.0001 to 0.01 percent. Cyclic triaxial tests were conducted on undisturbed and reconstituted samples to obtain hysteresis loops for cyclic loading. This information was used to determine secant shear modulus and material damping ratios at shearing strain amplitudes of 0.01 to 1.0 percent.

The interpretation of the field and laboratory data to generate SSI parameter values requires the development of a minimum set of guidelines. Differences exist among all of the participants as shown in Fig. 1. The weighted (by layer thickness) maximum variability in low-strain shear wave velocity is $\pm16\%$ (about $\pm32\%$ in shear modulus.) More importantly though, for the top layers (down to about 15m), very much clustered results are obtained. Figures 2 and 3 summarize the strain-dependency curves used for shear modulus and damping. For the range of strains of importance to the seismic excitation, significant variability exists. The impact of this variability is shown in Fig. 4. Unlike the low-strain values the differences among the several profiles shown is important, particularly at the top elevations - down to a depth of at least one diameter below the foundation (15m), where an average of about $\pm30\%$ difference in shear wave velocity exists (about $\pm60\%$ in shear modulus). These differences reflect the different degradation curves used (Fig. 2) and the decision of the analysts relative to the use of the free-field ground motion(s) to determine the induced strain levels.

In summary, there is inherent variability in the computation of strain-dependent soil properties attributed to the sources of uncertainty discussed above. In a typical seismic SSI analysis of nuclear plant structures, therefore, it is necessary to vary the computed soil properties by a sufficient margin to account for the effects of such potential uncertainties.

FREE-FIELD GROUND RESPONSE EVALUATION

Despite the fact that cyclic triaxial tests have always shown drastic reductions of shear moduli such drastic reductions during earthquakes has been a controversial issue in soil-structure interaction analyses. However, because of the lack of field evidence, the issue has continued to exist. As part of the post-prediction correlation studies, studies were conducted to examine the free-field ground response phenomenon using ground motion data recorded in the free-field downhole array DHB. Using the effective shear-wave velocities or shear moduli derived from the Fourier spectral ratio analyses for ten earthquakes having magnitudes ranging from $M_L4.5$ to $M_L7.0$ and peak horizontal ground surface accelerations ranging from 0.03g to 0.21g, variation of normalized shear moduli (G/G_{max}) with effective shearing strain were derived and are shown in Fig. 5. It should be noted that shear moduli reduced substantially to as low as 20 to 30% indicating that strong nonlinear soil response occurred at the Lotung site during strong motion events.

The argument has been often made that such drastic nonlinearity is not possible since, after the earthquake, most all structures stand plumb. An evaluation of several records using 5 sec time windows in the recorded ground motions clearly shows that the nonlinear response phenomenon has a temporal character. Fig. 6 is an example of this type of evaluation. It shows the Fourier spectral ratio between the surface and 6m depth of the EW records of LSST16. The softening of the soil profile from 5.3 Hz to 3.6 Hz and its stiffness recovery back to 4.4 Hz is to be noted. At about the same level of ground shaking (as measured by the peak ground acceleration of about 0.05g), the soil frequency is about the same for time-windows 10-15s and 35-40s. It is concluded that drastic stiffness degradation occurred <u>during</u> the earthquake and that the original stiffness was recovered <u>after</u> the shaking subsided.

REASONABLENESS OF DECONVOLUTION ANALYSES

Deconvolution analyses assuming vertically propagating waves are generally used in industry practice to assess variations of ground motion with depth for purposes of evaluating wave scattering effects on foundation input motions for embedded structures. As part of the post-prediction studies an extensive series of deconvolution analyses using computer program SHAKE were performed at the Lotung site to assess the reasonableness of using deconvolution analyses in estimating variations of earthquake ground motion with depth. Nonlinear soil behavior was approximated by the equivalent linear techniques implemented in SHAKE. The motions recorded at the ground surface were used as input motions, and motions were calculated at depths of 6m, 11m, 17m, and 47m. Both the response spectra (5% damping) and the acceleration time histories of the computed motions were compared with those of the recorded motions at corresponding depths. An example for Event LSST07 (May 20, 1986 earthquake) is shown in Fig. 7.

These and similar results indicate that deconvolution analyses using equivalent linear methods and assuming vertically propagating shear waves captured the main features of variations of ground motion with depth, particularly in the shallow depth range that was important to SSI.

DYNAMIC SOIL-STRUCTURE INTERACTION PRESSURES

Dynamic lateral earth pressure increments were recorded at pressure transducers, installed around the embedded containment wall and underneath the basemat, during Events LSST07 and LSST16. The recorded data were studied to confirm whether there is any soil-wall separation during earthquake strong motion excitations. The data indicate that the dynamic pressure increments oscillate on top of the static earth pressures. Decreases in earth pressure due to unloading in terms of percentages of the static earth pressure are higher near the ground surface and decrease with increasing depth. However, the dynamic pressure increments during unloading are smaller than the static earth pressure indicating that the wall was subjected to net compressive pressures at all times during the shaking. In addition, lack of truncations in the dynamic pressure time histories also substantiates this observation. Thus, it is concluded that