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SYNOPSIS: Blind prediction analyses and subsequent correlation studies of a 1/4-scale reinforced concrete containment model constructed at Lotung, Taiwan subject to forced vibration tests and actual earthquakes are evaluated with the objective of validating soil-structure interaction (SSI) analysis methodologies commonly used in U.S. practice. The SSI methods used range from simple soil-spring representation to more complex finite-element methods and substructuring techniques. Both forced vibration test (FVT) data and actual earthquake induced response data have been obtained for use in validating selected SSI analysis methodologies. Considering that for forced vibration tests only the stiffness and damping characteristics of the foundation are required (complexities of site response, wave scattering and stiffness degradation of soils are absent), the FVT evaluation shows that acceptable frequency predictions can be obtained by most of the methods; however, soil damping as obtained from geophysical methods does not seem to account for the total energy dissipation during SSI. A number of insights have been obtained with respect to the validity of SSI analysis methodologies for earthquake response. Among these are the following: vertical wave propagation assumption in performing SSI is adequate to describe the wave field; equivalent linear analysis of soil response for SSI analysis, such as performed by the SHAKE code, provides acceptable results; a significant but non-permanent degradation of soil modulus occurs during earthquakes; the development of soil stiffness degradation and damping curves as a function of strain, based on geophysical and laboratory tests, requires improvement to reduce variability and uncertainty; backfill stiffness plays an important role in determining impedance functions and possibly input motions; scattering of ground motion due to embedment is an important element in performing SSI analysis; more than the calculational techniques, the differences in response predictions are due to the modeling of the soil-structure system.

## INTRODUCTION

This paper presents the learning from an extensive series of experimental and analytical studies that have been ongoing for several years. In order to limit the paper to some reasonable length, a large amount of detailed information had to be left out. For these details the interested reader can refer to the complete synthesis report of prediction results and correlation studies of the Lotung soil-structure interaction experiment (Hadjian et al, 1991).

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 often 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. Such an approach, even though conservative, does not reduce uncertainties, and thus, does not necessarily lend an increased confidence in the results.

In order to validate the several SSI analysis methodologies commonly used in the U.S. nuclear industry, the Electric Power Research Institute (EPRI) in cooperation with the Taiwan Power Company (TPC) conducted two scaled (1/4- and 1/12-scale) reinforced concrete containment model tests at Lotung, Taiwan (Tang, H. T. et al, 1987; Tang, Y. K. et al, 1987, EPRI, 1987). Since the completion of the facility in October 1985, forced vibration tests (FVT) were conducted and a number of earthquakes, ranging from Richter magnitude 4.5 to 7.0, has been recorded at the site both on the surface and in down-hole arrays (Fig. 1).

The validation program utilized a round-robin approach. A total of 13 participants, including industry and university groups from the United States, the Republic of China (Taiwan), Japan, and Switzerland, performed independent calculations using SSI methods ranging from simple soil-spring representations to more complex finite-element methods and substructuring techniques. The unique aspect of the program was that recorded responses were made available to the participants only after their predictions had been documented. In December 1987, the results of these investigations were presented during a two-and-a-half-day international workshop cosponsored by EPRI, NRC, and TPC (EPRI, 1989). The workshop provided a forum for discussion of the blind prediction analyses and results comparisons. More than one hundred engineers and researchers from universities, utilities, engineering firms, and governmental agencies attended the workshop.

## PROGRAM DESCRIPTION

The prediction analyses were accomplished in three phases. During Phase I, each participating investigation team developed an SSI Model B for the FVT blind prediction given identical sets of construction drawings and site geophysical and geotechnical reports. During Phase II each investigation team was furnished with the recorded FVT data for the purpose of correlation, on the basis of which a refined FVT analysis model, Model C, was developed and the prediction analysis repeated. Model A, used by the University investigation teams (Miller, Costantino and Zerva, M/C/Z, and Luco/Wong of UCSD/USC), refers to an initial SSI model based on rather limited soil data.

Subsequent to the FVT correlation phase, Phase III was initiated during which each investigation team was first furnished with the three-component accelerograms recorded during two earthquake events referred to as Events LSST07 (May 20, 1986) and LSST16 (Nov. 14, 1986). Typically earthquake response prediction Models B and C were developed. Model B was derived from the FVT prediction Model B by using strain-dependent soil properties, and Model C from the FVT correlation Model C in a similar manner. Each investigator then performed the SSI prediction analyses using the recorded surface motion at Station FA1-5 located 47m from the edge of the model as the control motion (see Fig. 1) and computed the 5% damped response spectrum at the two structure locations, i.e., F4US (roof) and F4LS (basemat), and two steam generator locations, i.e., F4SGU (top) and F4SGL (lower end) shown in Fig. 2. The soil properties in the Phase III SSI models were generally based on the soil strains induced by the recorded earthquake ground motions. Some investigators performed refined predictions after the correlation was completed, using models that were designated as Models D, E, etc.

In order to maximize the learning from the extensive prediction studies and subsequent workshop discussions described above, EPRI initiated Phase IV in which a series of post-prediction studies were performed (Geomatrix Consultants, 1991 and EPRI, 1991) dealing with the variability issue of the recorded data, the free-field ground response, the dynamic soil-structure interface pressures, and test model response parametric analyses. Simultaneously, EPRI assembled a team to conduct a comparative evaluation of the prediction results and to synthesize a collective understanding of the basic issues of soil-structure interaction. The synthesis report (Hadjian et al, 1991) was reviewed independently by a Peer Review Panel assembled by EPRI.

The evaluation primarily emphasized the U.S. practice in SSI analysis. Table 1 shows the U.S. investigators and the methods used for their predictions. The U.S. investigators include both Industry and University teams. The EQE/EET method, called herein the SUPERALUSH/CLASSI method, is so characterized because foundation impedances and wave scattering functions were computed using SUPERALUSH and the structural response calculations were performed by CLASSI. Bechtel did not include the FLUSH code in its FVT predictions since the original code does not have harmonic forcing capability. Although Sargent & Lundy (S&L) incorporated harmonic forcing capability into the FLUSH code they prefer the use of the DYNAX code for FVT predictions, and therefore, the S&L DYNAX results are included in this evaluation. Although the Bechtel and Luco/Wong predictions using the CLASSI code will be directly compared, it is important to point out an important difference between the CLASSI codes as used by Bechtel and Luco/Wong. The more current Luco/Wong version of the program considers the embedment of the structure as a rigid cylindrical (foundation) insert in the half-space and obtains the total impedance matrix and the matrix of scattering coefficients of the embedded cylinder directly. On the other hand, the Bechtel version of the code is strictly applicable to surface foundations only. In the Bechtel solution the impedance functions calculated using CLASSI for the foundation on ground surface are modified externally to account for embedment effects before proceeding with the response calculations in CLASSI. For seismic response analysis this method of accounting for embedment impedances cannot recognize scattering effects due to the vertical

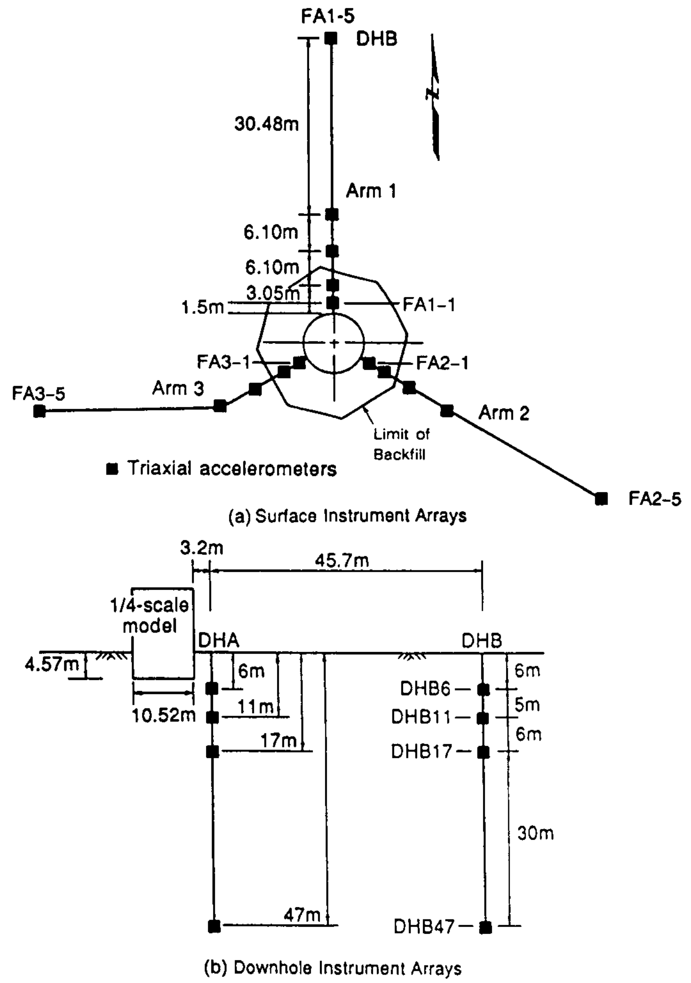



Fig. 1 Location of (a) Surface Accelerographs and (b) Down-Hole Accelerographs (Tang, 1987)

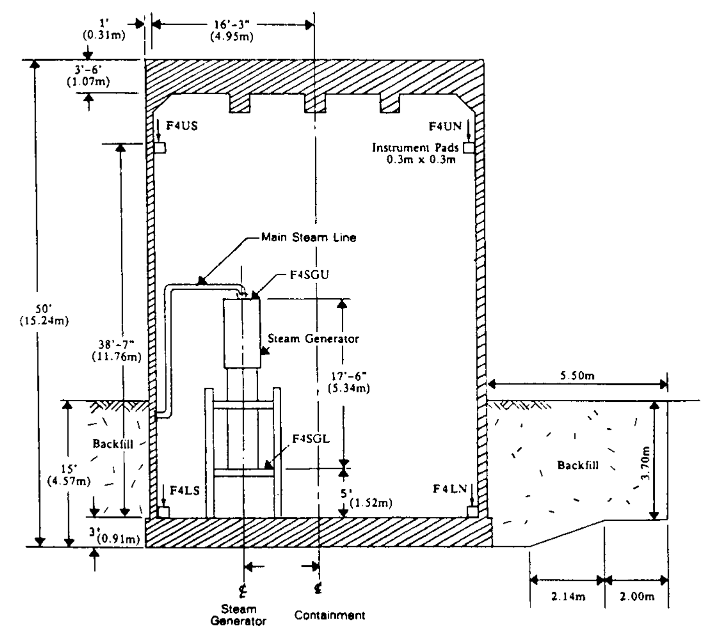



Fig. 2 Cross-Section of the 1/4-Scale Containment Model

TABLE 1. MATRIX OF U.S. INVESTIGATORS AND ANALYSIS METHODS USED

METHOD

| INVESTIGATOR | Soil-Spring[1] | FLUSH[2] | SUPER-ALUSH/[3] CLASSI | CLASSI[4] | SASSI[5] |
|---|---|---|---|---|---|
| Bechtel | X[(a)] | X | -- | X | X |
| M/C/Z * | X[(b)] | -- | -- | -- | -- |
| S&L ** | -- | DYNAX for FVT[6] X | -- | -- | -- |
| EQE/EET | -- | -- | X | -- | -- |
| Luco/Wong | -- | -- | -- | X | -- |
| Impell | -- | -- | -- | -- | X |

* Miller, Costantino and Zerva ** Sargent & Lundy

1a. F. E. Richart, Jr., J. R. Hall, Jr. and R. D. Woods, "Vibrations of Soils and Foundations", Prentice-Hall, N.J., 1970.

R. J. Aspel, "Dynamic Green's Functions for Layered Media and Applications to Boundary Value Problems", Ph.D. Thesis, University of California, San Diego, 1979.

J. A. Barneich, D. H. Johns, and R. L. McNeill, "Soil-Structure Interaction Parameters for a Seismic Design of Nuclear Power Motions", Preprint 2182, ASCE National Meeting on Water Resources Engineering, January 1974.

1b. R. V. Whitman, "Soil-Structure Interaction, Seismic Design for Nuclear Power Plants", MIT Press, 1970.

C. J. Costantino and E. Vey, "Response of Buried Cylinders Encased in Foam", Journal of Soil Mechanics, ASCE, Sept. 1969.

C. A. Miller and C. J. Costantino, "Soil-Structure Interaction Methods: SLAVE Code", NUREG/CR-1717 Vols. II and III, Brookhaven National Lab, September 1979.

2. J. Lysmer, T. Udaka, C. F. Tsai, and H. B. Seed. "FLUSH, A Computer Program for Approximate 3-D Analysis of Soil-Structure Interaction Problems." EERC Report No. 75-30, University of California, Berkeley, 1975.

3. Axisymmetric variation of FLUSH

4. J. E. Luco, "Linear Soil-Structure Interaction", Report UCRL-15272, Lawrence Livermore National Laboratory, Livermore, California, 1980.

   H. L. Wong and J. E. Luco, "The Application of Standard Finite Element Programs in the Analysis of Soil-Structure Interaction", Proc. 2nd SAP User's Conf., Univ. of Southern Calif., Los Angeles, June 1977, 11.1-11.11.

5. J. Lysmer, M. Tabatabaie, F. Tajirian, S. Vahdani and F. Ostadan, "SASSI - A System for Analysis of Soil-Structure Interaction", Report No. UCB/ GT/81-02, Geotechnical Engineering, Univ. of California, Berkeley, April 1981.

6. "DYNAX - Static and Dynamic Analysis of Axisymmetric Shells and Solids", originally written by S. Ghosh et al., modified and maintained by Sargent & Lundy as Program No. 09.7.083-7.4.

variation of input motion. Scattering of seismic waves for the horizontal variation of input motion can be considered in this approximation. Given these limitations the CLASSI version as used by Bechtel for both FVT and seismic response analysis will be referred to herein as CLASSI(Bechtel) to distinguish it from the more current authors' version, which will be referred to simply as CLASSI.

The intent of having Bechtel use all four of the designated methods to perform its predictions was to provide a matrix of comparisons. By using the same soil-structure system characterization, the Bechtel results provide an across-methods evaluation highlighting differences only in the solution methods. On the other hand, the comparison of the results from Bechtel and the other investigators for each methodology provides a basis of comparison of different soil-structure system characterizations within each method.

## SITE AND STRUCTURE CHARACTERIZATION

Geotechnical conditions at the Lotung site were established during a series of field, geophysical and laboratory testing programs. The intent of these programs was to define soil types and layering at the site, identify ground water locations, and establish dynamic soil properties necessary to conduct SSI analyses. 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. These depths correspond to from three to fifteen foundation diameters. 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. Crosshole and uphole geophysical tests were conducted to obtain shear and compressional wave velocities which could be converted to low-strain amplitude shear moduli and constrained Young's moduli. The geophysical test results are shown in Fig. 3.

Resonant column and cyclic triaxial tests were conducted in the laboratory to obtain shear modulus and material damping data at intermediate to high shearing strain amplitudes. The resonant column tests were conducted on undisturbed and reconstituted samples at multiple confining pressures. Cyclic triaxial tests were conducted on undisturbed and reconstituted samples to obtain hysteresis loops of force versus deformation due to cyclic loading. The laboratory test results are shown in Fig. 4.

Figure 5 shows the low-strain shear wave velocity profiles developed by all of the investigators for use in the FVT response analyses. Due to the scatter in the field geophysical data, differences exist among the profiles. However, the level of variability is small. Except for the very deep strata, the differences from the middle of the range of values are less than about $\pm 20\%$. The weighted (by layer thickness) maximum differences in shear wave velocity are only $\pm 16\%$ (about $\pm 31\%$ in shear modulus.)

The geophysical tests were performed in the free-field only; hence no velocity information was available during the SSI studies for the backfill material around the model. This backfill material is an angular gravelly

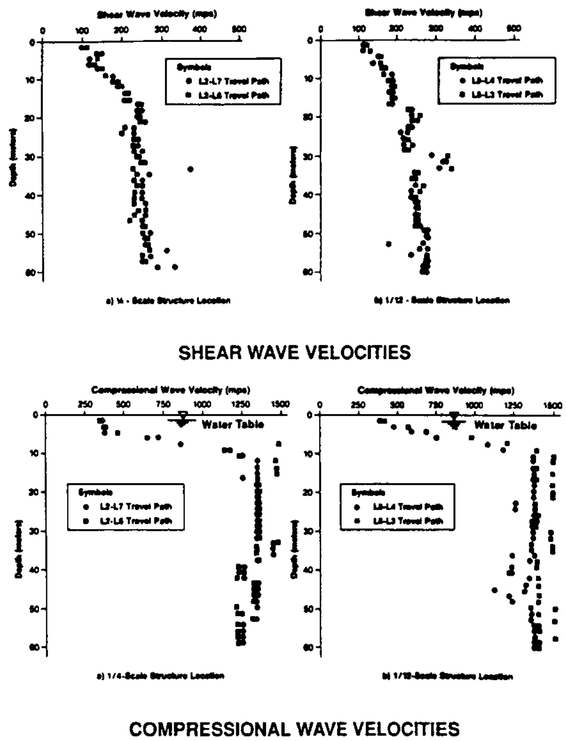



Fig. 3 Geophysical Test Data

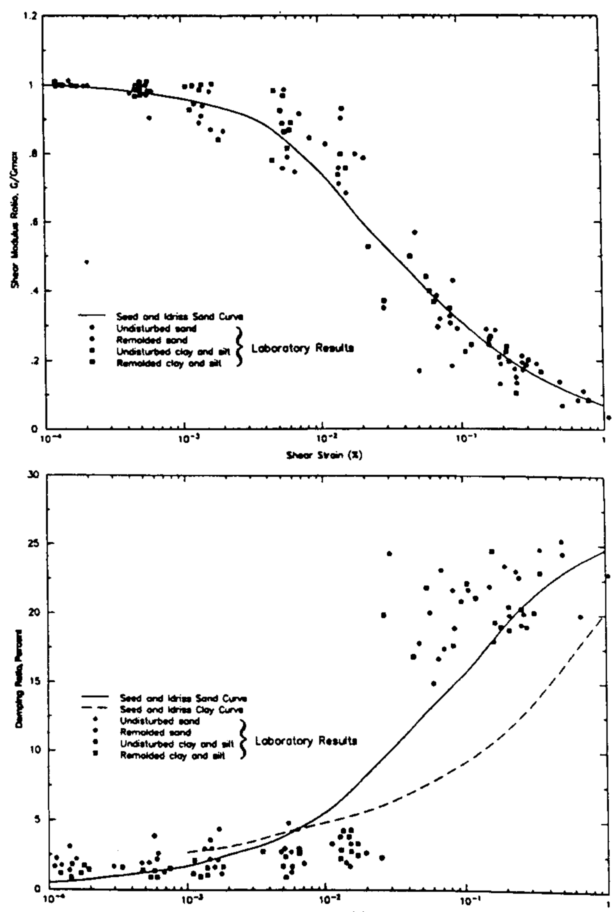



Fig. 4 Strain-Dependent Shear Modulus Ratio and Damping Ratio Data

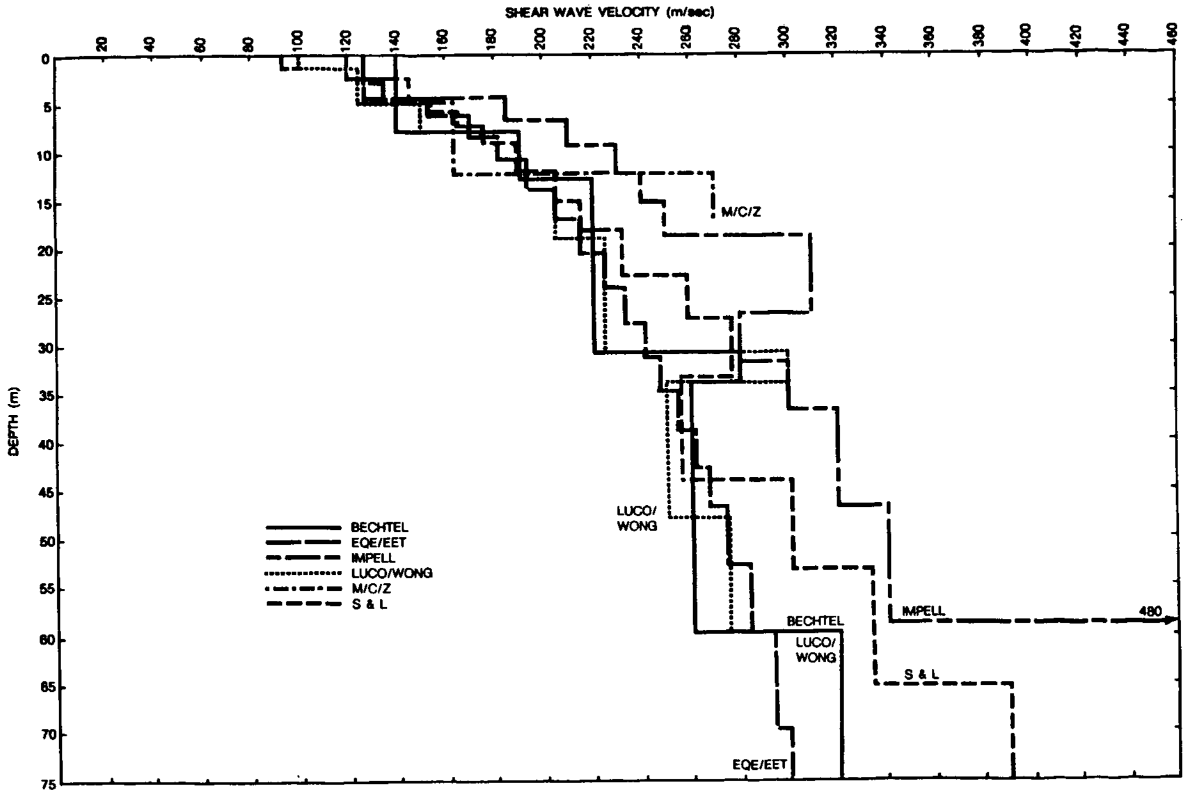



Fig. 5 Low-Strain Shear Wave Velocity Profiles for Model B

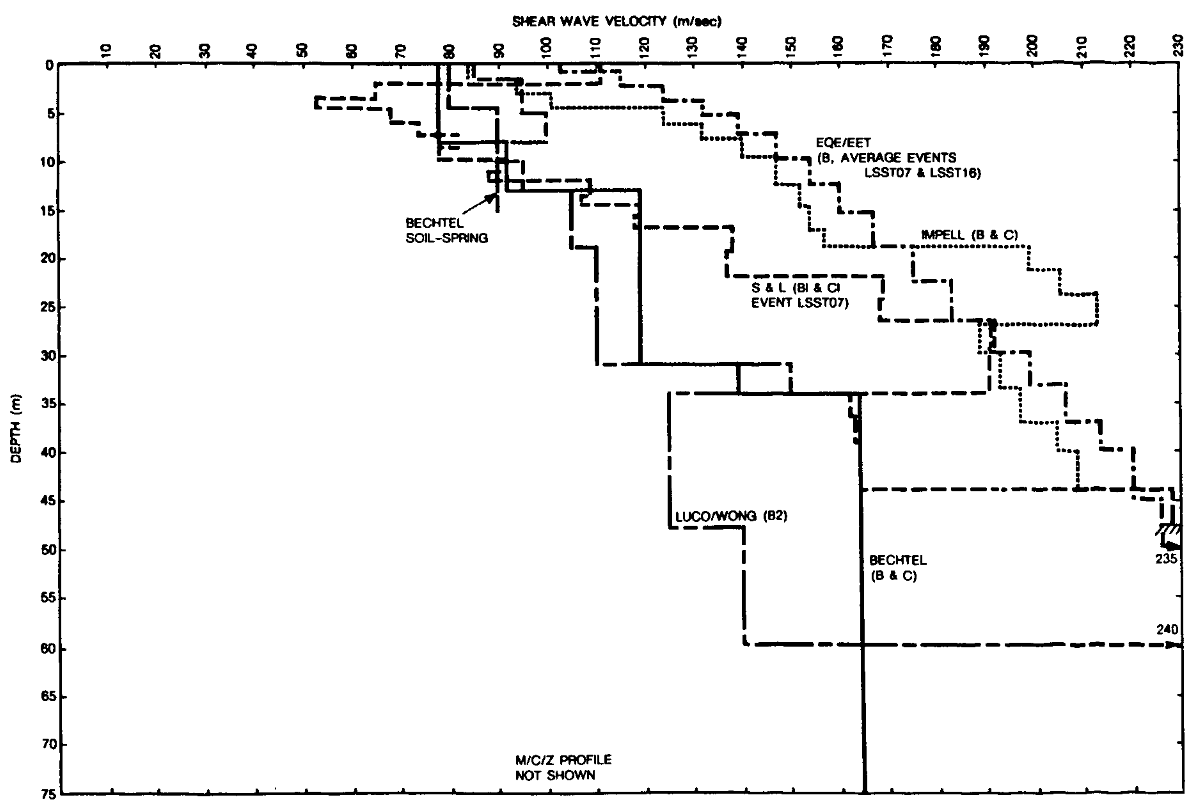



Fig. 7 Strain-Dependent Shear Wave Velocity Profiles for Seismic Response

material. Even though shear wave velocity data on the backfill material was not available at the time of the SSI investigations, backfill properties were estimated by all investigators for incorporation in their models. Following completion of the round-robin SSI studies, a series of shear wave refraction tests was conducted to define the very-near-surface dynamic properties of both the backfill and the in-situ soils. The preliminary test results suggest that the backfill and the surrounding soil may have similar shear wave velocities than expected (Ohsaki Research Institute, 1989). For deeply embedded structures the contribution of the embedment to the impedance functions is usually large. Thus, it becomes necessary that the shear modulus and damping properties of backfill materials for seismic response be determined, if not in greater precision, at least as well as the free-field soil profile.

Figure 6 summarizes the strain-dependency curves used by US investigators 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. 7. 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 ±30% difference in shear wave velocity exists (about ±60% in shear modulus). These differences reflect the different degradation curves used (Fig. 6) and the decision of the analysts relative to the use of the free-field ground motion(s) to determine the induced strain levels. Considering convenience and cost effectiveness, no one investigation team performed the analyses for both event-specific and component-specific soil properties. It is clear that guidance in this respect is needed. In a design environment a single set of strain-dependent layer properties can be used for both horizontal orthogonal excitation directions; however, for the OBE and SSE different levels of strains are expected and these strain-dependent layer properties are selected accordingly. For test correlation studies, it may sometimes become necessary to treat not only each earthquake but also each component separately, particularly when the correlation coefficient between the components of motion is small (e.g., Hadjian and Fallgren, 1989).

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 account for the effects of such potential uncertainties.

The modeling of the scaled containment structure may be evaluated on the basis of the fixed-base structural natural frequencies and associated damping values given in Table 2 (first four lines). The structural frequencies were calculated following typical engineering practice in structural modeling. Both finite element and lumped mass models have been used. The variability in the calculated horizontal fundamental frequency for FVT models is only about ±11%. For the seismic response models, the calculated frequency varies, except for one case, from 10.8 Hz to 11.9 Hz, a mere ±5% from the middle of the range. The vertical fundamental frequency, except for one case, is 33 Hz or higher. No vertical response amplification within the structure is therefore expected. These vertical frequencies vary only ±3% from the middle of the range. These are very small variations, indicating a rather uniform practice in structural modeling. The structural damping assumed in each prediction study was based on engineering judgment and/or practice. There

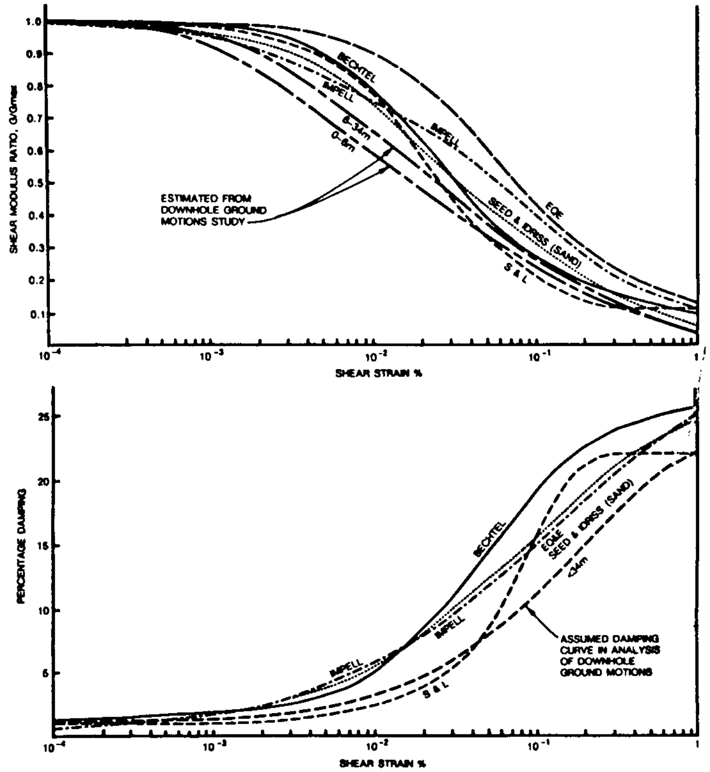



Fig. 6 Comparison of Strain-Dependent Shear Modulus and Damping Curves

is considerable scatter among the structural damping values assumed by the investigators.

## EVALUATION OF FVT PREDICTION RESULTS

Relative to the seismic problem, the forced vibration SSI problem has less complexity. For the FVT the forcing function is harmonic with known frequencies and amplitudes. The complexities of site response, wave scattering, and potentially strain-dependent soil properties are absent. Further, given that the 1/4-scale containment model is quite rigid, the only significant decision for the FVT analysis, for any analysis methodology, relates to the stiffness and damping characterization of the foundation.

The following comparative evaluations were performed:

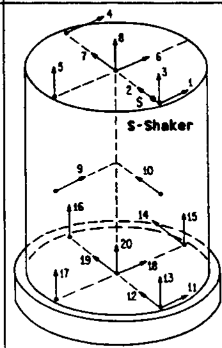
a) For each method, assumptions and results by Bechtel and the corresponding other investigator were compared.

b) The Bechtel results across all methods were compared.

c) Accounting for site characterization differences among all of the investigators, all methods were compared.

The two parameters that would directly help in assessing the assumptions made and methods used are the system frequency and peak response predictions. A match of the system frequency, with or without a match in response amplitude, would indicate that, for a relatively rigid structure, the foundation stiffness characterization and the analysis method taken together are acceptable.

TABLE 2. SUMMARY OF FVT STRUCTURAL RESPONSE PREDICTION RESULTS

| Parameter | Soil-Spring | FLUSH | SUPERALUSH/CLASSI | CLASSI | SASSI |
|---|---|---|---|---|---|
| | Bechtel | Bechtel | Not Applicable | Bechtel | Bechtel |
| Total Weight | 614T | |   | 614T | 614T |
| Fixed Base Frequency | 10.8 Hz | | | 10.8 Hz | 10.8 Hz |
| Modal Mass | 83% | | | 83% | 83% |
| Structural Damping | 2% | | | 2% | 2% |
| B Model: | | DID NOT INVESTIGATE | | | |
| Frequency | 4.1 Hz (8% error) | | | 4.3 Hz (13% error) | 4.1 Hz (8% error) |
| Radial Response #2 | Under by 56% (full radiation) Under by 20% (half radiation) | | | Over by 25% | ± 0% |
| Tangential #1 | Under by 50% (full radiation) | | | Over by 44% | Over by 21% |
| C Model: | | | | | |
| Frequency | 3.8 Hz | | | ~ 3.8 Hz | ~ 3.8 Hz |
| Radial Response #7 | Under by 53% (full radiation) Under by 10% (half radiation) | | Response Legend | Over by 12% | Over by 10% |

| Parameter | M/C/Z | | S&L | | EQE/EET | Luco/Wong | Impell |
|---|---|---|---|---|---|---|---|
| | | | FLUSH | DYNAX | | | |
| Total Weight | 543T | | | | | 598T | |
| Fixed Base Frequency | 13.2 Hz | | N/A | N/A | 11.4 Hz | 13.6 Hz | 10.9 Hz |
| Modal Mass | | | | | 75% | 77% | |
| Structural Damping | 1% | | | | 5% | 0.5% | 1% |
| B Model: | Freq. Ind. | Freq. Dep. | | | | | |
| Frequency | 3.5 Hz | 3.2 Hz | Undefined | 5.2 Hz | 4.3 Hz (13% error) | 4.15 Hz (9% error) | 4.7 Hz (24% error) |
| Radial Response #2 | Over by 57% | Under by 13% | Sig. Under | Under by 52% | Under by 8% | Over by 6% ($B_{L2}$) | Under by 24% |
| Tangential #1 | Over by 80% | Over by 3% | | | Over by 6% | Over by 24% | Under by 12% |
| C Model: | | | | | | | |
| Frequency | | 3.8 Hz | 4.2 Hz | 3.8 Hz | 3.8 Hz | 3.79 Hz ($C_{L2}$) | 4.0 Hz (5% error) |
| Radial Response #2 | | Under by 30% | Under by 26% | Over by 15% | ±0% | Under by 3% | Under by 9% |

Recording Stations #1 and #2 are at the top edge of containment in tangential and radial directions respectively.
Recording Station #7 is at the top center of the containment.

TABLE 3. MODEL B FREQUENCY AND RESPONSE PREDICTION HIERARCHY

| Method | Investigator | System Freq. | Prediction Frequency Ratio to Test Freq. | Response Amplitude Top of Model, Edge: Radial Load Response #2 | Response Amplitude Top of Model, Edge: Tangential Load Response #1 |
|---|---|---|---|---|---|
| DYNAX | S&L | 5.2 Hz | 1.37 | Under by 52% | -- |
| SASSI | Impell | 4.7 Hz | 1.24 | Under by 24% | Under by 12% |
| CLASSI (Bechtel) | Bechtel | 4.3 Hz | 1.13 | Over by 25% | Over by 44% |
| SUPERALUSH/CLASSI | EQE/EET | 4.3 Hz | 1.13 | Under by 8% | Over by 6% |
| CLASSI | Luco/Wong($B_{L2}$) | 4.15 Hz | 1.09 | Over by 6% | Over by 24% |
| SASSI | Bechtel | 4.1 Hz | 1.08 | ±0% | Over by 21% |
| Soil-Spring | Bechtel | 4.1 Hz | 1.08 | | |
| Full Rad. Damping | | | | Under by 56% | Under by 50% |
| Half Rad. Damping | | | | Under by 20% | |
| Soil-Spring Freq. Independent | M/C/Z | 3.5 Hz | 0.92 | Over by 57% | Over by 80% |
| Soil-Spring Freq. Dependent | M/C/Z | 3.2 Hz | 0.84 | Under by 13% | Over by 3% |

However, a match of response amplitude without a corresponding match of the system frequency indicates a deficiency in the foundation characterization and/or in the methodology for determining the appropriate system damping. In harmonic response the determination of damping within the resonance range of excitation is paramount and therefore a match of response amplitudes when a corresponding frequency match has not been achieved should not be considered as an adequate prediction. This follows from the fact that critical damping ratio is a variable that depends on the system frequency.

To help focus on the basic response parameters the results from the several prediction analyses are summarized in Table 2. It is concluded that most of the methodologies used give the expected results if the models are correct, i.e., totally account for model boundaries, soil layering, soil material damping and soil-structure interface effects. Therefore, a comparison of all the results would be a statement more on the modeling by the several investigators than on the methodologies used.

The Model B system frequency predictions are rearranged and listed in Table 3 in decreasing order. CLASSI by Luco/Wong, and SASSI and Soil-Spring by Bechtel give the best frequency predictions. The relatively higher DYNAX frequency prediction by S&L is due to the very stiff embedment assumption by S&L (see Fig. 5). In general, the shear wave velocity profile derived by Impell is on the high side resulting in a significant frequency overestimate. The SUPERALUSH results can be ascribed primarily to the details of deriving the impedance functions: the finite-element model and the treatment of the soil model rigid base. The CLASSI (Bechtel) results could be due to two reasons: the approximate treatment of embedment and/or the stiffness within the embedment depth. Compared to Luco/ Wong results, Fig. 5 suggests the latter possibility to have the more dominant effect. It is to be noted that only M/C/Z underpredicted the frequency. Nevertheless, the frequency-independent results by M/C/Z are as good as the Bechtel Soil-Spring results: both are off by 8% from the test frequency.

With regard to response predictions, the discussion should be limited to only those methods that could predict the system frequency rather closely. Setting a 15% error margin (a commonly used value for broadening of floor spectra) the frequency band of interest for this evaluation becomes 3.23-4.37 Hz. This limits therefore the present discussion to six cases listed in Table 3 under Radial and Tangential Response Columns.

Overall, the Bechtel SASSI solution produced the best results followed by the CLASSI solution by Luco/Wong, SUPERALUSH/CLASSI and CLASSI(Bechtel). The reason for the differences in the two CLASSI solutions is most likely due to the relatively stiffer embedment soil characterization by Bechtel discussed above. Clearly the issue of layering as it affects both the equivalent stiffness and damping must be fully researched if the Soil-Spring method would be used for layered sites. The issue of torsional response (Tangential #1) seems to be another candidate for further study.

C Models by All Investigators

Given the B Model results it is a simple matter to change the foundation stiffness to match the test frequency and then to modify the soil damping to match the test response amplitudes. As shown in Table 4, all investigators except Impell adopted this approach, and thus, the system frequency is matched by all except Impell.

Impell, instead of scaling the soil profile properties to match the test system frequency, selected to use a different set of properties altogether. The Impell Model C soil model is based on the geophysical data and the Model B soil model on the geotechnical data. And thus, in effect, Model C should be characterized as an alternate Model B.

The issue with the response mismatch is more complex. The response results obtained by all of the investigators for Model C are listed in Table 4. Although Impell achieves a reasonably accurate response correlation it is excluded from the following discussion since the system frequency correlation is relatively poor. Therefore, except for the last two, the remaining solutions are considered to be successful based on a reasonable response calculation error band. It is to be noted that the solutions with better correlations (SUPERALUSH-EQE/EET and CLASSI-Luco/Wong) have used significantly larger soil material damping values to achieve their excellent correlations that could not be justified by the FVT induced strains. The need to increase the soil damping for the FVT induced levels of response suggests that energy dissipation occurs possibly at the interface of soil and structure, which is usually assumed to be fully bonded in analytical studies. Obviously neglecting this increase in soil damping values (SASSI and CLASSI-Bechtel and DYNAX-S&L) resulted in conservative results. The unconservative results of the Soil-Spring method as used by Bechtel with full radiation damping (the use of the elastic halfspace to represent a layered site) and the frequency-dependent Soil-Spring method used by M/C/Z are to be noted.

There is nothing here to suggest that with proper modeling the methods used by all investigators (except FLUSH and frequency-dependent Soil-Spring method) would not predict acceptable SSI results for the FVT. The computational details of impedance calculations are adequate. The issue then is the adequate modeling of the SSI problem. SASSI and CLASSI as used by Bechtel, and CLASSI (Luco/Wong), produced excellent results even for Model B. The frequency independent Soil-Spring method, with proper treatment of the equivalent stiffness and radiation damping to account for layering effects should produce improved results. Soil damping, as obtained from geophysical methods, does not seem to account for the total energy dissipation during SSI, and therefore, the fully bonded assumption of structure and soil is conservative. An investigation of soil-structure interface energy dissipation seems to be in order.

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 have 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 (Geomatrix Consultants, 1991), studies were conducted to examine the free-field ground response phenomenon using ground motion data recorded in the free-field downhole array DHB (Fig. 1). Using the effective shear-wave velocities or shear moduli derived from the Fourier spectral ratio analyses for ten earthquakes having magnitudes ranging from $M_L$4.5 to $M_L$7.0 and peak horizontal ground surface accelerations ranging from 0.03g to 0.21g, variation of normalized shear moduli ($G/G_{max}$) with effective shearing strain were derived and are shown in Fig. 8. It should be noted that shear moduli reduced substantially to as low as 20% to 30%

TABLE 4. MODEL C RESPONSE CORRELATION HIERARCHY

| Method | Investigator | Radial Response | System Frequency | Soil Material Damping |
|---|---|---|---|---|
| DYNAX | S&L | +15% | 3.8 Hz | 1% |
| CLASSI (Bechtel) | Bechtel | +12% | 3.8 Hz | 2% |
| SASSI | Bechtel | +10% | 3.8 Hz | 2% |
| SUPERALUSH/CLASSI | EQE/EET | ± 0% | 3.8 Hz | 5% |
| CLASSI | Luco/Wong ($C_{L2}$) | - 3% | 3.79 Hz | 3.3%* |
| Soil-Spring | Bechtel (Half Radiation Damping) | -10% | 3.8 Hz | - |
| Soil-Spring | M/C/Z (Frequency-Dependent) | -30% | 3.8 Hz | - |
| Soil-Spring | Bechtel (Full Radiation Damping) | -53% | 3.8 Hz | - |
| SASSI | Impell | - 9% | 4.0 Hz | 1% |

* Luco/Wong best model, $C_{L1}$, required 5.2% soil material damping.

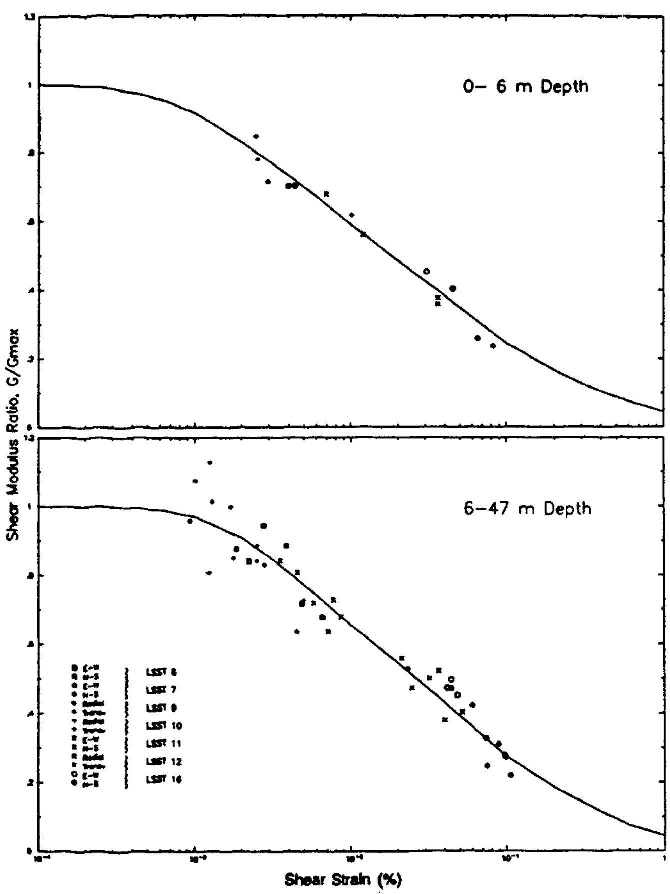


Fig. 8 Shear Modulus Reduction Curves Estimated from Recorded Downhole Ground Motions

indicating that strong nonlinear soil response occurred at the Lotung site during the strong motion events. The curves of damping ratio versus shear strain that were assumed in deriving the field $G/G_{max}$ versus shear strain curves are shown in Fig. 9. These curves are compared with the damping curves used by the SSI investigators in Fig. 6.

Comparison of the $G/G_{max}$ relationships estimated from earthquake data with the relationships estimated by the different SSI investigation teams (Fig. 6) indicates that at the larger strains associated with the strong-shaking events (LSST07, LSST12, and LSST16), the field relationships are within and toward the bottom of the range of the relationships used by the SSI investigation teams. The values of $G/G_{max}$ estimated from events LSST07, LSST12, and LSST16 are in the range of 0.55 to 0.22 for shear strains of 0.02% to 0.1%, again indicating strong nonlinear soil response. At smaller strains (approximately 0.002% to 0.02% strain), the field $G/G_{max}$ relationships are about 12 to 30 percentage points lower than the relationships estimated by the SSI investigators based on the laboratory test data. However, this smaller strain range is not significant for earthquake predictions.

Given the fact that the estimation procedure of the $G/G_{max}$ relationship using the earthquake data is the same irrespective of the range of shear strains achieved during the earthquakes and that the procedures using laboratory data are based on two distinctly different testing methods depending on shear strain levels (resonant column and cyclic triaxial tests), the differences at the smaller strains between the earthquake and laboratory results are most likely due to the reduction procedure of the resonant column test data. In a subsequent Section it will be shown, based on in-situ frequency identification, that the soil at the Lotung

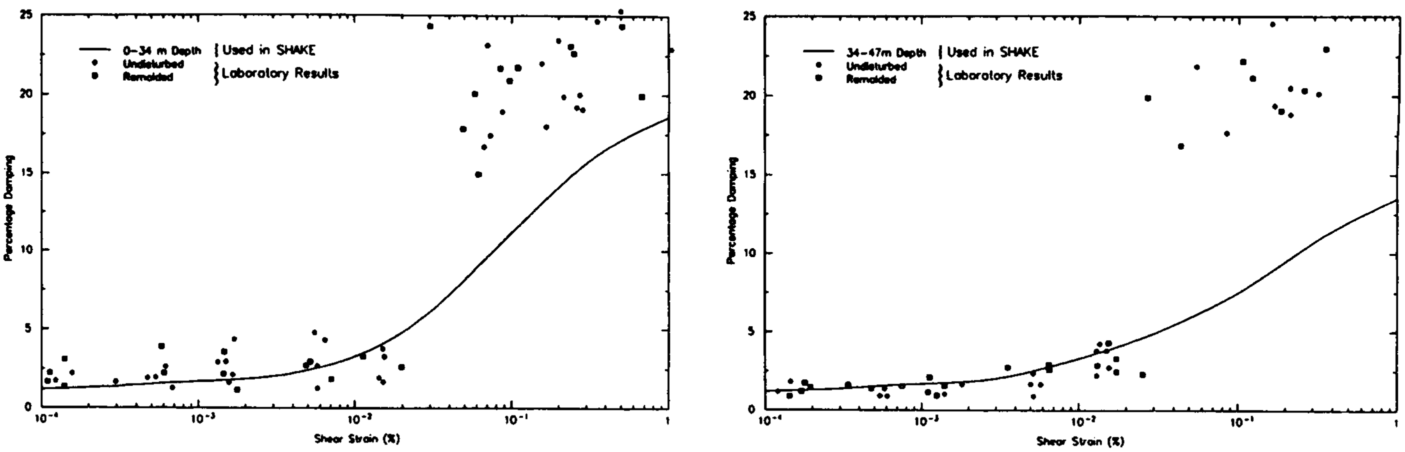



Fig. 9 Strain-Dependent Damping Ratio Curves for Sandy Soil (0-34m Depth) and Clayey Soil (34-47m Depth)

site during the events under consideration had in fact degraded significantly at the higher levels of shear strain as shown in Fig. 6. This observation strongly suggests that the similarity of the $G/G_{max}$ curves at the higher strains is reasonable and hence the soil stiffness characterization using the cyclic triaxial test data may be considered appropriate.

Assuming, therefore, that the estimated field $G/G_{max}$ and damping relationships are typical of the soils at the Lotung site, the one significant difference of the curves derived from earthquake data from those curves derived from geophysical and laboratory data is the absence of a sharp discontinuity of the data in the intermediate range of shear strains. This discontinuity in the laboratory data could be interpreted as a phase change which obviously does not occur during the earthquakes considered herein even in the very soft soils at Lotung. Based on the tentative (in the sense that further evidence would be given later on) conclusion that the $G/G_{max}$ relationships and the associated damping curves of Figs. 8 and 9 reasonably represent the nonlinear behavior of the Lotung site soils, it may be suggested that the resonant column tests overestimate the shear modulus primarily at the intermediate strain levels (shear strains of 0.002% to 0.02%) and the cyclic triaxial tests overestimate the damping of soils. Supporting evidence for the latter observation is given in the following paragraph.

The argument has been often made that such drastic nonlinearity is not possible since, after the earthquake, in the absence of liquefaction, 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. Figure 10 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 Event 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 dominant 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 as a function of shear strain* and that the original stiffness was recovered <u>after</u> the shaking subsided. This is another evidence that energy dissipation in soils during earthquakes could be less than that calculated from cyclic triaxial test results.

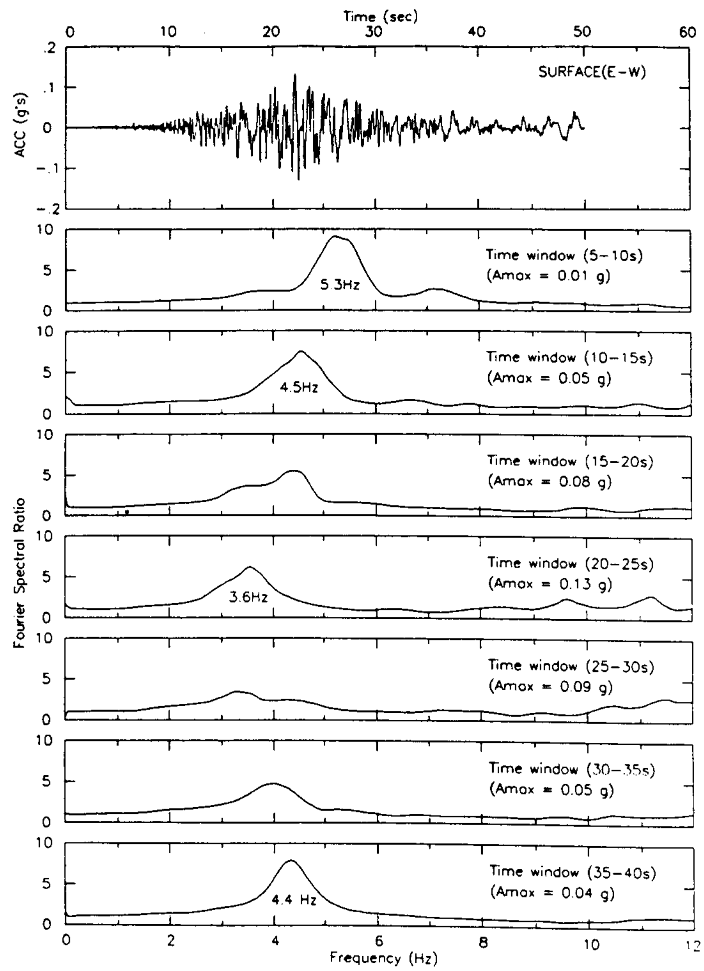



Fig. 10 Variations of Fourier Spectral Ratio with Time, LSST16 0m-6m (E-W)

* For example, the shear modulus ratio, $G/G_{max}$, was at about 0.3 during the events considered herein. From Fig. 8 this level of modulus degradation corresponds to 0.1% shear strain.

## 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 is shown in Fig. 11.

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.

## IDENTIFICATION OF SYSTEM PARAMETERS

Analyses of the recorded containment response data were performed to determine the SSI system response transfer functions and, from which, to identify the SSI system frequencies and the associated modal damping ratios. Typical containment SSI response transfer function amplitudes at the top of the containment determined from these analyses are shown in Fig. 12. The results of these analyses for four earthquake events, namely, LSST06, LSST07, LSST12, and LSST16, indicate that the SSI response of the containment was dominated by a single response mode which is the rocking response of the rigid containment on the relatively flexible soil foundation. The SSI system frequencies and the associated modal damping ratios estimated from the test response transfer function amplitude are shown in Table 5. The SSI system frequencies identified for the four events plotted

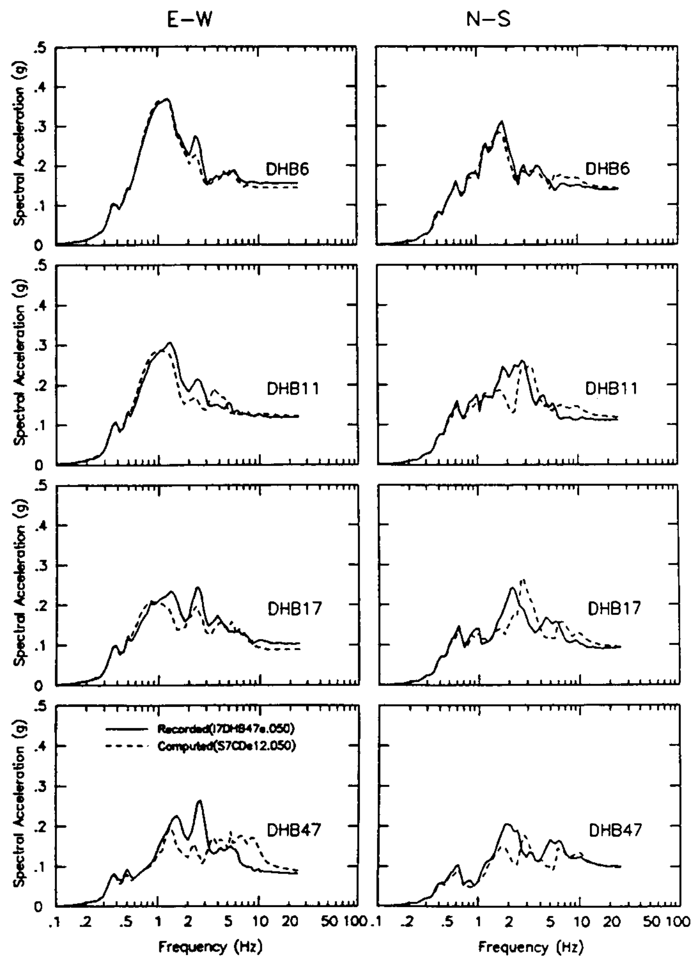



Fig. 11 Comparison of Recorded and Computed Response Spectra (5% Damping), Deconvolved with Iterated Strain-Compatible Properties, Event LSST07

TABLE 5. NATURAL FREQUENCIES AND MODAL DAMPING RATIOS OF CONTAINMENT SSI SYSTEM ESTIMATED FROM TRANSFER FUNCTION AMPLITUDES AND HALF-POWER BAND WIDTH TECHNIQUE

| Excitation | NS Direction PGA | EW Direction PGA | NS Direction Frequency (cps) | NS Direction Damping (%) | EW Direction Frequency (cps) | EW Direction Damping (%) |
|---|---|---|---|---|---|---|
| FVT | - | - | 3.8 | 10 | 3.9 | 10 |
| LSST06 | 0.03g | 0.04g | 3.6 | 13 | 3.3 | 13 |
| LSST07 | 0.21g | 0.16g | 1.7 | >25 | 2.2 | >25 |
| LSST12 | 0.19g | 0.16g | 2.1 | >25 | 2.0 | >25 |
| LSST16 | 0.17g | 0.13g | 1.9 | >25 | 2.2 | >25 |

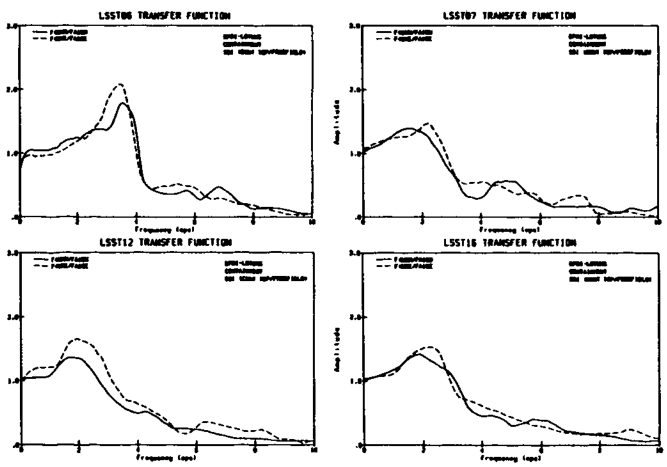



Fig. 12 Containment Top SSI System Response Transfer Function Amplitudes Determined from Test Data for Four Events

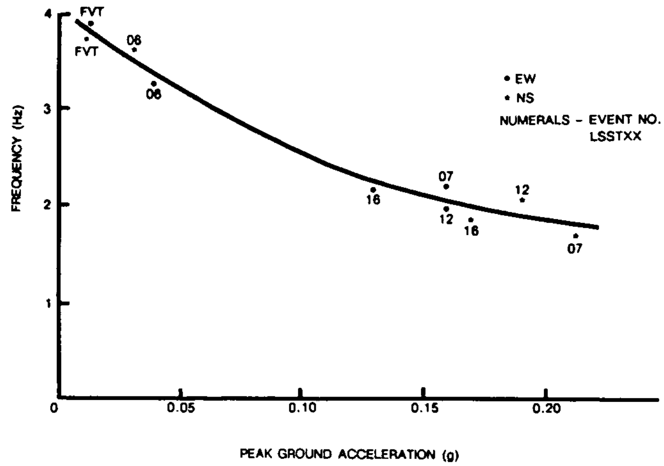



Fig. 13 Plot of Containment SSI Frequencies vs. Peak Ground Accelerations

against the maximum ground surface acceleration recorded are shown in Fig. 13. As shown in this figure, the SSI system frequency decreases as the ground acceleration increases. Since the SSI response was dominated by the rigid body rocking response, the observed change of SSI frequency with ground shaking intensity provides another field evidence that the foundation soil at the site responded nonlinearly during these earthquakes. An overall measure of this stiffness degradation can be obtained from the system frequencies of seismic and FVT responses: i.e., $\left(\frac{2.0}{3.8}\right)^2 = 0.28$.

The 2.0 Hz system frequency used above is an average of the six data points in Fig. 13 for Events LSST07, LSST12 and LSST16. An alternative method was also used to identify the NS system frequency for Event LSST07. This determination will be summarized not so much as to provide additional evidence of the severe system frequency degradation from the 3.8 Hz of the FVT, but mainly because, in the process, a certain response characteristic was identified that will be used later to estimate system frequencies for all predictions.

For the FVT the determination of a system frequency from the recorded data was simple. The soil-structure system frequency is 3.8 Hz and the modal damping value about 10%. However, for seismic events such a determination is not as straightforward. The transfer functions of Fig. 12, for example, lack a pronounced sharp spike. For a broad band input motion and a system frequency within this band, computed floor spectra are characterized by dominant peaks at the system frequency. This observation did not occur for the Lotung experiment simply because the input free-field motion is not broad banded and the system is highly damped. In support of the results given in Table 5, and possibly to refine the frequency prediction, an alternative approach to the estimation of the interaction system frequency for event LSST07 is made by utilizing the parametric prediction results reported in the Luco/Wong study based on the CLASSI Code (EPRI, 1989).

A review of the Luco/Wong predictions for event LSST07 of three submodels for each A, B and C Models shows very clearly that the second peak of the NS free-field motion at 2.8 Hz is the driving frequency in close proximity to the model system fundamental frequency. Therefore, small changes in system frequency cause large changes in the response spectral peak amplitude at this frequency as shown in the inset of Fig. 14. The inset is a plot of the calculated spectra in the vicinity of 2.8 Hz for each of the Luco/Wong models. Although the peak response at about 1.8 Hz is relatively stable for all models, the peak response at 2.8 Hz acts like a barometer: it is highly sensitive to changes in the system frequencies of the models. The 2.8 Hz peak spectral values at F4US are listed in Table 6 together with the associated frequencies of the models obtained from calculated transfer functions. Figure 14 shows the single degree-of-freedom transfer function curves for several damping values. Considering that the containment model essentially responds as a single degree-of-freedom system these curves could be used to explain this observation. Plotted on this figure are the frequencies of the Luco/Wong models. The response amplitude relationship along the 25% damped curve from models A1 through B2 is closely related to those given in Table 6. Although each

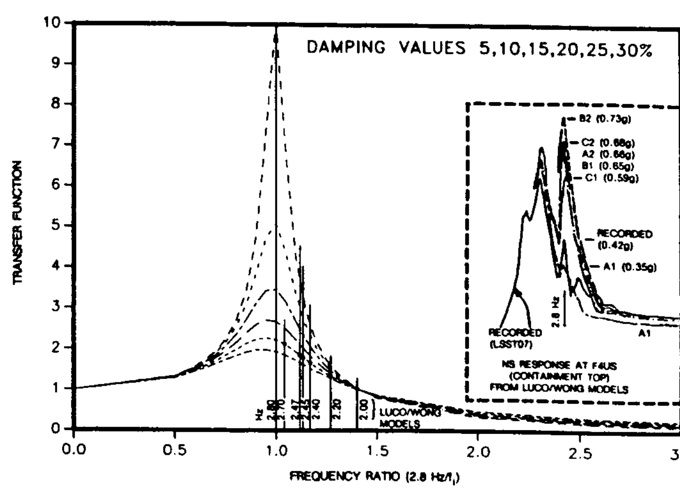



Fig. 14 Transfer Function vs. Frequency Ratio

TABLE 6. PEAK SPECTRAL ACCELERATIONS AT 2.8 HZ FOR THE NS RESPONSE AT F4US, EVENT LSST07 LUCO/WONG MODELS

| Model (Luco/Wong) | Peak Spectral Acceleration - 5% Damped (g's) | System Frequency (Hz) |
|---|---|---|
| A1 | 0.35 | 2.00 |
| In-Situ | 0.42 | 2.03 (estimated) |
| C1 | 0.59 | 2.20 |
| B1 | 0.65 | 2.40 |
| A2 | 0.66 | 2.45 |
| C2 | 0.68 | 2.47 |
| C3 | 0.70 | 2.85 |
| A3 | 0.70 | 3.20 |
| B2 | 0.73 | 2.70 |
| B3 | 0.73 | 2.95 |

of the models of Table 6 have their own system damping values, for the present purpose, the mechanics of the behavior of the peak response at 2.8 Hz is adequately explained. The recorded spectral response at F4US for 2.8 Hz frequency is 0.42g leading to the conclusion that the system frequency of the model, in-situ, is somewhere between 2.0 Hz (Model A1) and 2.2 Hz (Model C1). A closer estimation of the system frequency is possible as described below.

Figure 15 shows a plot of the peak response at 2.8 Hz as a function of the system frequencies of the Luco/Wong parametric models (Table 6). Two curves are shown: one is based on the absolute peak acceleration values and the second on the ratios of the peak accelerations to the zero-period accelerations. The two curves are similar. From the curves of Fig. 15 the system frequency can be established to be at about 2 Hz for event LSST07 in the NS direction. It is not a coincidence then that Luco/Wong predict a close response to the recorded data in the horizontal direction with their $A_{H1}$ model. Figure 15a is used subsequently to estimate system frequencies given the predicted NS response spectra for event LSST07.

## 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. Fig. 16 is an example from event LSST16. 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

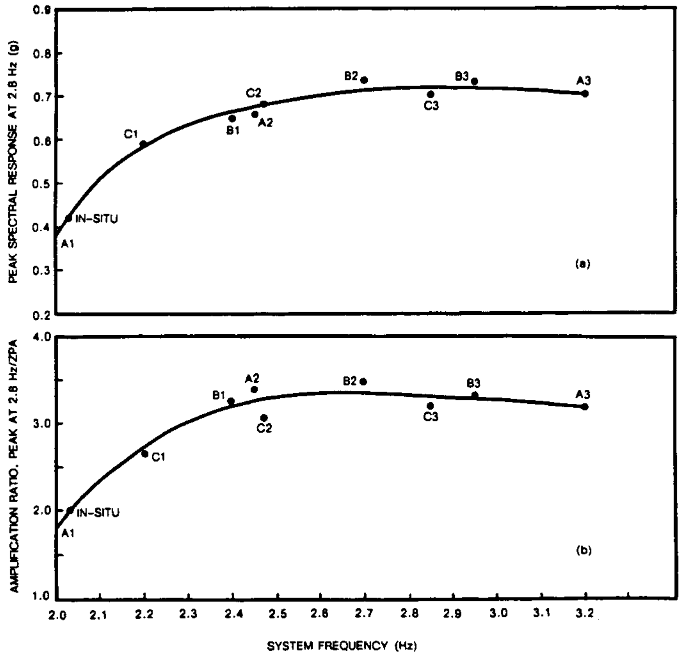



Fig. 15 Plot of Containment SSI Frequencies vs. Peak Response at 2.8 Hz of All Luco/Wong Models

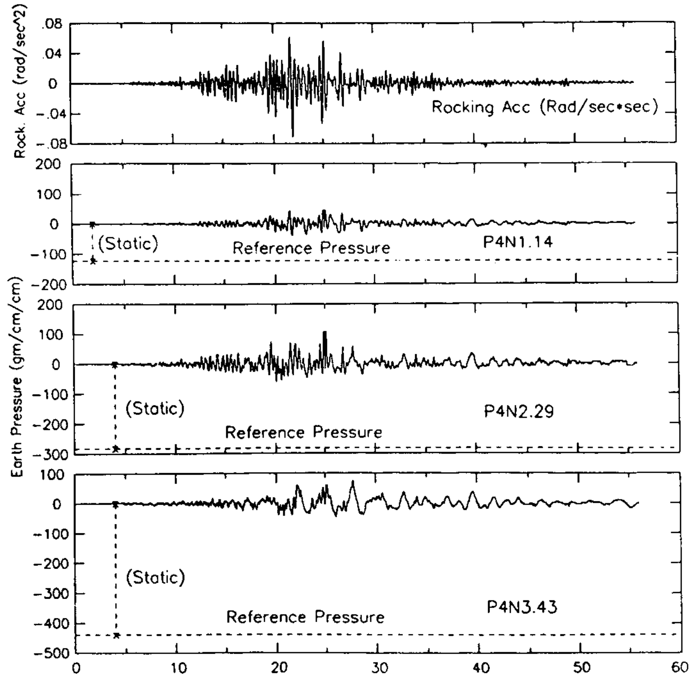



Fig. 16 Dynamic Earth Pressures for Event LSSt16

net compressive pressures at all times during the shaking, at least below the top pressure transducer located 1.14m below the ground surface. In addition, lack of truncations in the dynamic pressure time histories also substantiates this observation. Thus, it is concluded that soil-wall separation was unlikely to have occurred during Events LSST07 and LSST16 below

1.14m. However, there are uncertainties in the assessment due to the presence of the high water table at the Lotung site and the complexities of behavior at the interface of the wall and saturated soil. Even if there was no soil-wall separation, the pressure distribution in Fig. 16 indicates that there was a stiffness reduction of the backfill. Considering that the containment model rocked at its base, the data indicates that the stiffness of the backfill reduced from the bottom to the top.

Dynamic bearing pressure increments recorded during Events LSST07 and LSST16 were compared with the static average bearing pressure. The peak dynamic bearing pressures from all transducers were less than about 85% of the static average bearing pressure during the two events. It is similarly concluded that basemat uplift was unlikely to have occurred during these events.

EVALUATION OF SEISMIC RESPONSE PREDICTION RESULTS - METHOD-BY-METHOD EVALUATION

The basic approach to evaluate the seismic response results is based on the comparison of the 5% damped acceleration response spectra of the predicted and recorded responses at preselected locations on the structure. Although responses have been reported for several locations, the present evaluation will emphasize the response comparison at the top (F4US) and the base (F4LS) of the containment. Obviously all the comparison figures cannot be reproduced here. However, selected figures will be used to provide sufficient information to help in following the subsequent discussions. The adequacy of each methodology with its basic assumptions will be assessed by the closeness of the predictions to the recorded responses. Conservative results, although important from a design perspective, are not considered to be successful predictions in this evaluation. Similar to the emphasis for the FVT evaluation, an effort will be made to identify the system frequency.

In addition to the determination of the foundation impedances, seismic response computations require the determination of strain-dependent soil stiffness properties and must account, explicitly or implicitly, for the scattering effects of the embedded foundation. In this context, since all of the investigators assumed vertically propagating waves, the rocking component of the scattered input motion must also be considered in addition to the ground motion variation with depth. Based on the FVT results, it is assumed that those features of the several computer codes used in these analyses which deal with the computation of foundation impedances are adequate. Thus, the emphasis herein will be on the impact of the strain-compatible soil properties and the scattering of the free-field motions. The determination of the equivalent half-space properties will be evaluated only for the Soil-Spring method.

Soil-Spring Method

The Soil-Spring method was used by Bechtel and M/C/Z to predict the seismic response of the containment. Bechtel predicted the response to two events, LSST07 and LSST16, and M/C/Z predicted the response to only event LSST07. For the M/C/Z predictions, both frequency-independent and frequency-dependent impedances were used. The present evaluation focuses on the frequency independent results only.

The Soil-Spring Method as generally practiced in industry (ASCE, 1986) considers embedment effects only as they impact the foundation impedances. Scattering effects are ignored. In order to "bound" the problem Bechtel performed the prediction for each event using two different foundation input motions: 1) free-field ground surface motion (henceforth referred to as Surface Input motion) and 2) free-field motion in the far-field at a depth equal to the embedment depth obtained by one dimensional deconvolution (henceforth referred to as Base Input motion). In this method of analysis the associated rocking input motion of the Base Input case is ignored. As discussed for the FVT the equations used by Bechtel and M/C/Z to calculate the surface foundation impedance coefficients (Richart et al, 1970 and Whitman, 1970) are only slightly different. However, the methods of computation of the impedance coefficients for embedment effects used by M/C/Z and Bechtel are completely different and, in general, difficult to compare as was done for the surface foundation. Some results specific to the Lotung model are given in Table 7.

TABLE 7. CALCULATION OF ROCKING FREQUENCY AND ASSOCIATED CRITICAL DAMPING RATIO

| | Bechtel | M/C/Z | Ratio |
|---|---|---|---|
| Shear Modulus: | | | |
| Above 4.6m | 240 ksf | 590 ksf | 2.5 |
| Below 4.6m | 340 ksf | 980 ksf | 2.9 |
| Rocking Spring, $k_r$ | 1.84E07 k-ft/rad | 3.62E07 k-ft/rad | 2.0 |
| Rocking Damping, $C_r$ | 4.27E05 k-ft-sec | 3.09E05 k-ft-sec | 0.7 |
| Rocking Frequency, $f_r$ | 2.8 Hz | 4.0 Hz | 1.4 |
| Critical Damping, $\beta_r$ | 21% | 11% | 0.5 |

Note: Mass moment of inertia was assumed to be 58,500 k-ft-sec$^2$

The soil material damping, which is expected to be significant for seismic response, cannot be directly incorporated in the calculations of the damping coefficients based on the formulas used. On the other hand the use of an equivalent half-space to replace the layered site at Lotung without specifically taking into account the reduction of radiation damping effects tends to overpredict the radiation damping effects. Whether these two effects in general cancel each other out cannot be determined from the available results.

Once the foundation impedances are calculated the solution for the Soil-Spring method can be obtained by any structural analysis program provided the system modal damping values are appropriately synthesized. Bechtel followed this procedure to calculate the response. M/C/Z used the SLAVE and SIM Codes developed by two of the present investigators (Miller and Costantino, 1979a and b).

The most significant difference between the assumptions made by Bechtel and M/C/Z relative to the site soil stiffness is the strain-dependency of soil properties during earthquake shaking. Whereas Bechtel considered soil stiffness degradation for earthquake response analysis, M/C/Z did not. Thus, the M/C/Z predicted coupled rocking-translational system frequency is 3.8 Hz, exactly the same frequency as their C Model of the FVT response investigations. The Bechtel system frequency prediction is 2.7 Hz. Since the system frequency has been estimated to be about 2.0 Hz, the system frequency overprediction ratios are 1.9 and 1.35 for M/C/Z and Bechtel, respectively. Given the frequency content characteristics of event LSST07, M/C/Z avoided resonance conditions with the input ground motion; on the other hand, Bechtel's prediction of the system frequency placed the system in the region of the significant peak at 2.8 Hz of the free-field motion.

In order to better understand the response predictions relative to the recorded responses, the system damping should be considered. Table 7 provides the estimated system critical damping values for rocking only as 21% and 11% for the Bechtel and the M/C/Z models, respectively.

Thus, as shown in Fig. 17, despite the much smaller modal damping value used, the M/C/Z predictions are still lower than those of Bechtel (using Surface Input) at almost all frequencies for event LSST07. As discussed above, this is due to the complete avoidance of resonance conditions by M/C/Z and Bechtel's resonance condition with event LSST07.

The two Bechtel results shown in Fig. 17 are based on using the Surface Input and the Base Input motions. It is obvious that the use of the Base Input motion significantly improves the response comparison with the recorded data. The comparison with the M/C/Z results, however, should be based on the Surface Input motion results. Although there are certain similarities in the NS results, the EW results are quite different at the roof. Compared to the recorded results, the M/C/Z EW results underestimate the recorded response below about 2 Hz and overestimate it above 2 Hz. The results by M/C/Z are not helpful in resolving issues of SSI using the Soil-Spring method primarily because soil stiffness degradation was not considered. Considering the fact that the seismic in-situ system frequency is estimated to be at about 2.0 Hz the average soil shear modulus used by M/C/Z is thus overpredicted by a factor of $\left(\frac{3.8}{2.0}\right)^2 = 3.6$. The comparative evaluation of results between Bechtel and M/C/Z together with the post-prediction study results (EPRI, 1991) indicate that strain-compatible soil stiffness properties should have been used.

Figure 18 shows only Bechtel results for event LSST16. For this event also the use of Base Input motion provides significantly improved results. The computed responses for the Surface Input case for both events LSST07 and LSST16, are substantially higher than the recorded responses.

The comparison of the EW and NS results for both events at the top and base of the containment shows that the use of a uniform shear modulus for both directions has impacted the outcome. This difference for event LSST16 is more pronounced; whereas the EW prediction for the Base Input case essentially reproduces the recorded response at the top of the containment, the NS response overpredicts the response peak at 2.8 Hz. For a symmetrical structure this can only be due to the different levels of stiffness degradation in the two orthogonal

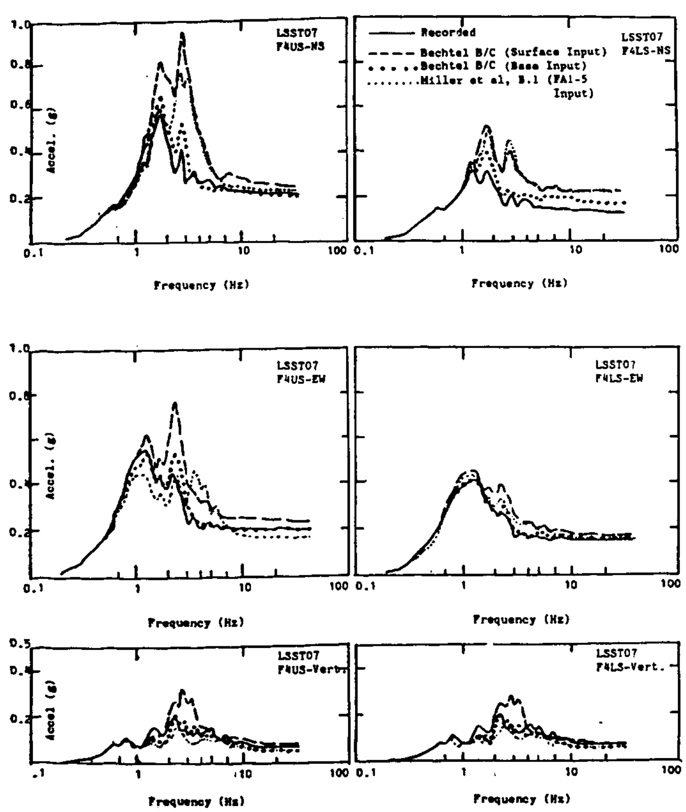



Fig. 17 Comparison of Predicted and Recorded Response Spectra for Event LSST07 - Soil-Spring Method

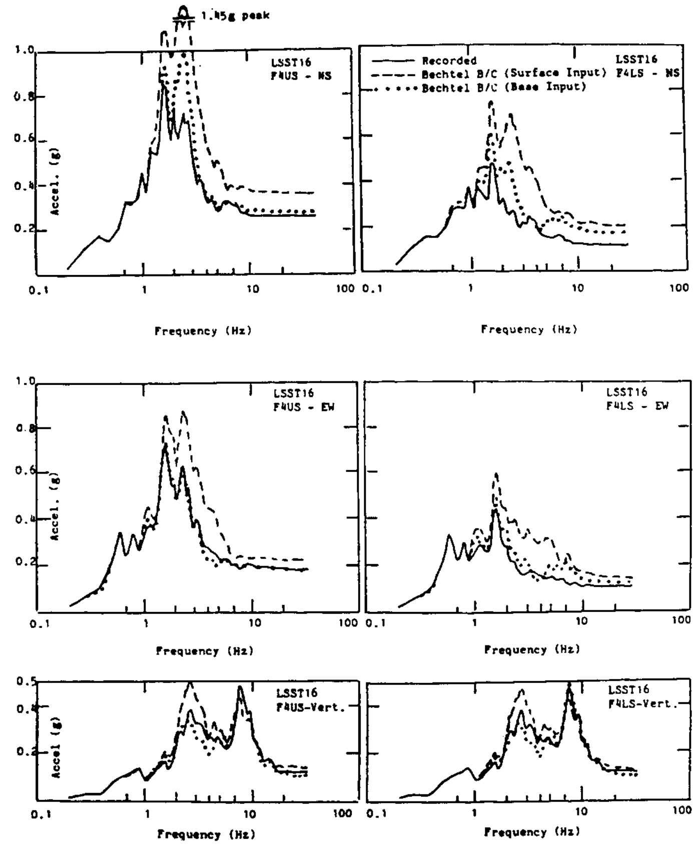



Fig. 18 Comparison of Predicted and Recorded Response Spectra for Event LSST16 - Soil-Spring Method

directions since recorded NS and EW free-field motions were used for the response analysis.

Based on the above and post-prediction earthquake response parametric studies (EPRI, 1991) it is concluded that adequate and conservative response results can be obtained when the following steps are followed:

a) Equivalent uniform half-space soil properties are used. The effect of layering on both stiffness and damping must be considered. Simultaneously, though, the beneficial effects of soil material damping must be accounted for in order to minimize conservatism.

b) Published formulas for surface foundations by Richart et al (1970) or Whitman (1970) are used.

c) Stiffness and damping coefficients are adjusted for embedment effects according to, for example, Aspel (1979) and Barneich et al (1974).

d) Input motions obtained from a SHAKE deconvolution analysis at the base level of the basemat are used.

FLUSH Method

The FLUSH method was used by Bechtel and S&L to predict the seismic response of the containment to two events, LSST07 and LSST16. S&L provided results of Model C only for event LSST16.

The strain compatible shear wave velocity profiles for seismic response are compared in Fig. 7. It is to be noted that Bechtel used one soil profile for both events and S&L used two separate event-specific profiles (only event LSST07 shown). These two event-specific profiles are similar down to a depth of 22m; below this depth significant differences exist. Important differences between the Bechtel and S&L profiles occur within the top 5m depth. These differences highlight the difficulty in interpreting and specifying backfill properties both for impedance computations and for ground motion definition adjacent to the structure.

Figure 19 shows a composite redrawn comparison of results to a common scale. In general, the Bechtel results underestimate the recorded results less than S&L. It should be noted that for Model B Bechtel adjusted, according to Luco and Hadjian (1975), the foundation geometry to account for the 2D solution by FLUSH of a 3D problem. Considering also the fact that the shear wave velocity profiles down to about 10m are significantly different, not much can be learned from such a comparison. The general response underestimate, though, is a direct result of the 2D FLUSH solution (Luco and Hadjian, 1975). The same general comments apply to the Model C results for event LSST16 shown in Fig. 20, which shows a composite redrawn comparison of these results to a common scale. For this case the Bechtel and S&L results at containment bottom are quite similar. For Model C the two models are similar considering the fact that the same 3D to 2D foundation geometry adjustment has been used by both investigators and the 2m deep separation of the backfill of the S&L model has effectively nullified the very stiff backfill assumption used in Model B.

In general, for horizontal response predictions by S&L, the computed responses of the containment bottom are higher than the recorded responses beyond about 2 Hz, and the containment top computed responses are lower than the recorded response across most of the frequency spectrum. The Bechtel predictions are very much similar except that for the containment top an overprediction occurs between 2.5 and 6.0 Hz. In the vertical direction S&L and Bechtel results are similar: whereas for event LSST07 the underprediction is across the whole frequency spectrum, for event LSST16 it is confined to the range of 1-5 Hz.

Post-prediction earthquake response parametric studies (EPRI, 1990) confirms that the 2D FLUSH method of SSI analysis tends to underestimate the response, especially when viscous dampers for simulating the 3D radiation damping effect are used. Additionally, modeling improvements - finer mesh size near the containment base edge where high stresses in soils are expected, the extension of the finite element model to include the entire backfill and the inclusion of SSI-induced secondary soil strains - did not result in better response predictions.

These results support the expectation (Luco and Hadjian, 1975) that the 2D solution leads to an overly damped system. Despite model differences an overprediction of response at the base does not lead to a similar response overprediction at the top of the containment for both models. As was observed earlier, modeling changes in this analysis methodology are not sensitive for response improvements at this site and for these events. Other than these observations the results from these investigations are not very helpful in assessing the prediction capabilities of the FLUSH code.

SUPERALUSH/CLASSI Method

This Section reviews the results of the seismic response predictions by EQE/EET to both events, LSST07 and LSST16. As shown in Table 1 the combined SUPERALUSH/CLASSI method was used only by EQE/EET.

Figure 7 shows the strain-dependent shear wave velocity profile used by EQE/EET for Model B and event LSST07. Maintaining the same profile configuration, a multiplicative factor was used to obtain shear wave velocity profiles for event LSST16 and two C Models. The relatively stiffer EQE/EET soil profile follows directly from the EQE/EET shear modulus stiffness degradation curve shown in Fig. 6.

Despite the fact that Model C soil profile is relatively softer than Model B soil profile (70% of the shear modulus for event LSST07), the results shown in Fig. 21 are essentially the same for B and C Models. Judging from the peak response at 2.8 Hz in the NS direction, it can be concluded that the system frequency is overpredicted. The most notable feature of the responses shown in Fig. 21 is the fact that in the NS direction, the base slab response is overpredicted and the roof slab response is underpredicted. The overprediction at the base slab is most likely due to the poor prediction of the soil profile response (not enough reduction of motion with depth). The underprediction at the roof slab is most likely due to a combination of two effects: stiffer rocking impedance and/or inadequate scattering (underestimated rocking component of ground motion input). The same general remarks are applicable to the results of event LSST16 predictions shown in Fig. 22. The vertical response predictions for event LSST07 are underpredicted throughout the frequency spectrum and those for event LSST16 are underpredicted in the frequency range of 1.5-4.5 Hz.

A further refinement (Model D) was attempted using about 50% of the soil modulus used in Model C leading to improved comparisons with the recorded data. This significant softening of the soil leads to a better prediction of the free-field motion at downhole station DHB6, and the agreement for the roof slab response is

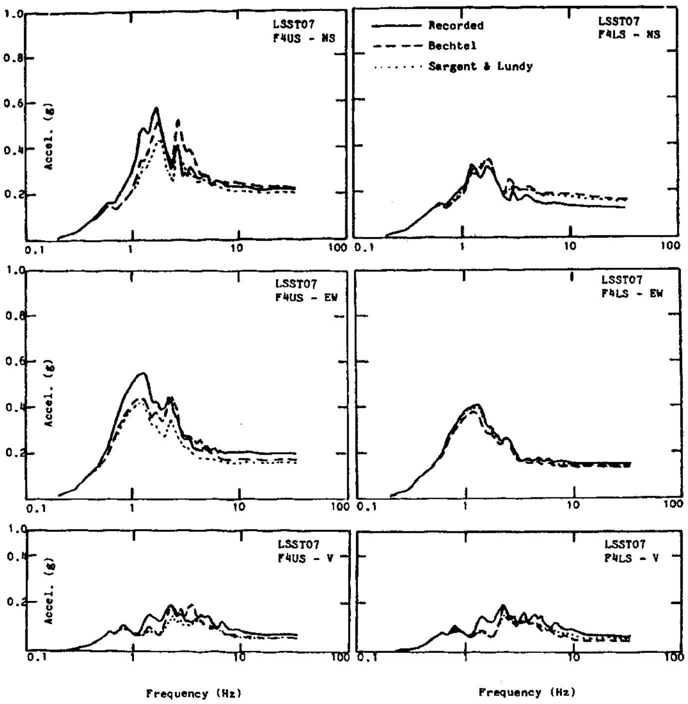



Fig. 19 Comparison of Predicted and Recorded Response Spectra for Event LSST07 - FLUSH Method

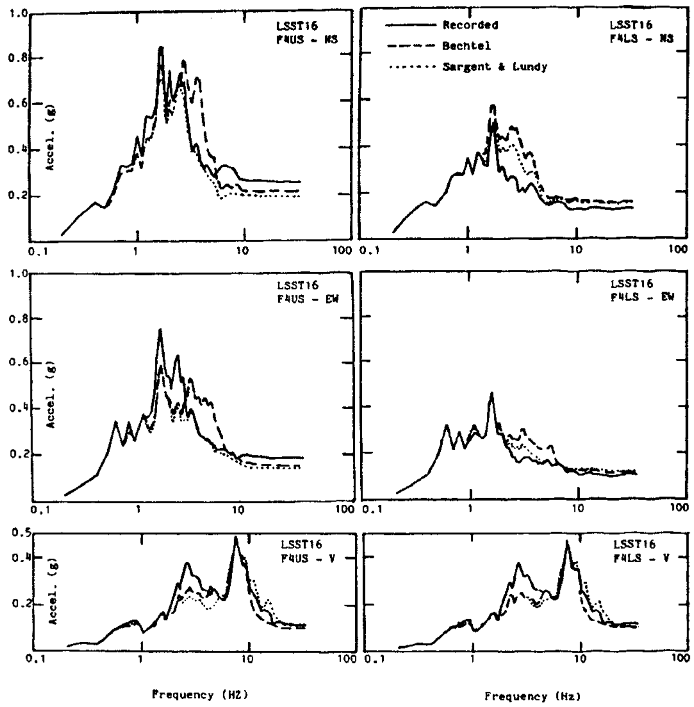



Fig. 20 Comparison of Predicted and Recorded Response Spectra for Event LSST16 - FLUSH Method

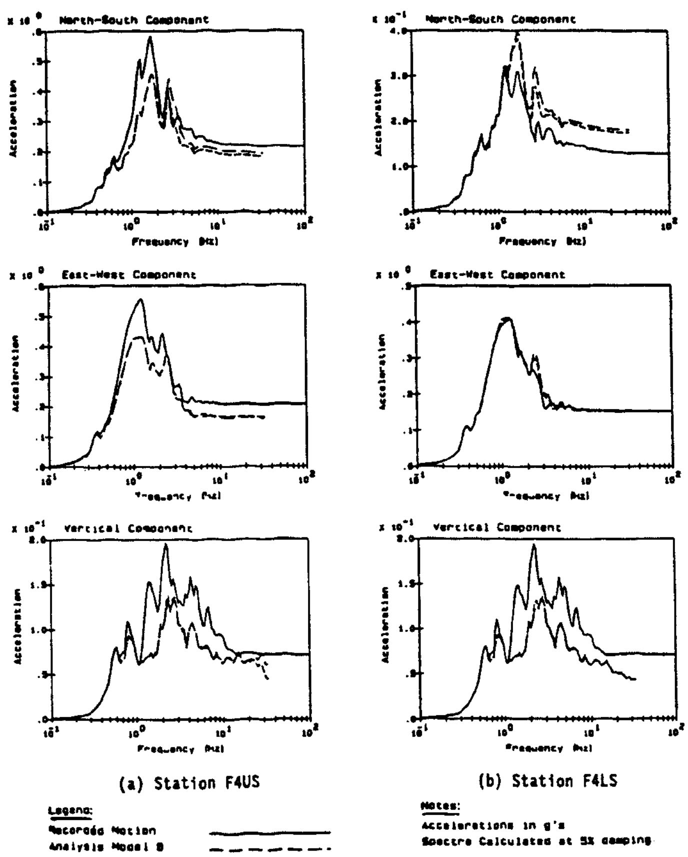



Fig. 21 Comparison of Predicted and Recorded Response Spectra for Model B, Event LSST07 - SUPERALUSH/CLASSI Method, EQE/EET

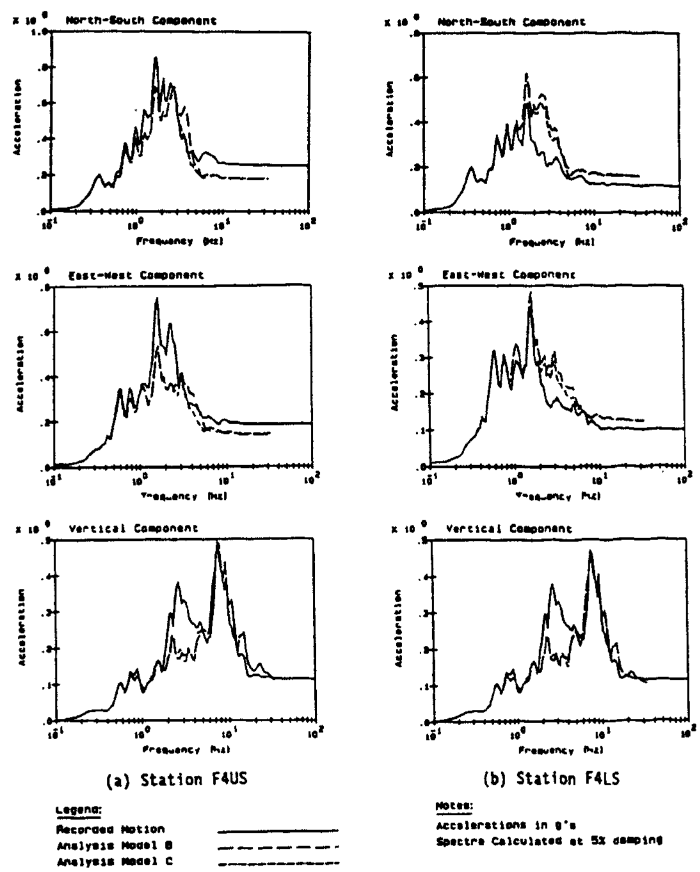



Fig. 22 Comparison of Predicted and Recorded Response Spectra for Model B, Event LSST16 - SUPERALUSH/CLASSI Method, EQE/EET

improved due to the softer rocking impedances. The predicted scattered motion, however, as measured by comparisons at the base slab is only slightly improved.

Based on the above discussions it is concluded that the substructuring methodology adopted by EQE/EET is valid provided, as always, that the appropriate soil model is used. Since the results of Model D were arrived at by a series of soil profile modifications given recorded structural responses and downhole array data, the importance of modeling of the soil profile characteristics cannot be overemphasized. Although the calculational tool should be adequate for the job, the art of performing good SSI analysis depends on the modeling of the site profile from geophysical and laboratory tests. In this respect it is important to note that the EW response, in general, is underpredicted while the NS response is overpredicted. In view of the fact that the containment model is symmetrical, further refinements in modeling of soil profiles seem to be in order.

CLASSI Method

The CLASSI method was used by Bechtel and Luco/Wong to predict the seismic response of the containment. Bechtel predicted the response to two events, LSST07 and LSST16, and Luco/Wong predicted the response to only event LSST07.

The differences between the CLASSI codes as used by Bechtel and Luco/Wong were pointed out under Program Description. And similar to the Soil-Spring method, Bechtel performed the response predictions using two different foundation input motions: Surface Input motion and Base Input motion.

The Bechtel and Luco/Wong seismic strain-compatible soil profiles are shown in Fig. 7. The Bechtel soil profile is derived directly through the use of a SHAKE analysis, and a common profile is used for Models B and C. Luco/Wong derived their strain-compatible values in a different fashion since the only information available to them when developing their models was the value of the peak ground acceleration (0.2g) of the control motion on the free-field ground surface. Using an artificial accelerogram consistent with NRC Reg. Guide 1.60 spectrum anchored to a 0.35g acceleration at a rock outcrop, Luco/Wong performed a SHAKE analysis such that a 0.20g peak acceleration was obtained on the ground surface. The resulting damping ratios were not considered realistic and were constrained to be less than 6.0% for S-waves. The shear wave velocities for Model $B_{H2}$ were obtained by reducing the Model $B_{L2}$ velocities by a factor of 0.5 for depths in the range of 8m to 60m. For depths shallower than 8m, a transition including reduction factors of 0.85, 0.75 and 0.67 in the first three layers was used. Model $C_{H2}$ was obtained from Model $C_{L2}$ in the same manner. The end result is that Luco/Wong derived two significantly different soil stiffness profiles for Models $B_{H2}$ and $C_{H2}$, henceforth referred to simply as B and C Models. For both Luco/Wong models the stiffness within the embedment depth is larger and the subfoundation stiffness, in general, smaller than Bechtel's. Based on the transfer function results by Luco/Wong, overall, Model B is about 10% stiffer than Model C. The Bechtel stiffness profile is based on an "average" of the four profiles resulting from the two orthogonal motions of events LSST07 and LSST16 using the SHAKE code. Despite these differences between Bechtel and Luco/Wong shear wave velocity profiles the predicted results for event LSST07 have certain similarities.

Figures 23 and 24 show a comparison of results for event LSST07. In Fig. 23 the comparison is between the C Models for the basemat with Bechtel's Base Input motion, and in Fig. 24 the comparison is between the C Models for the roof with Bechtel's Surface Input motion. These comparisons are intentionally selective in order to highlight and understand the effects due to scattering. This selection follows from the fact that for the Base Input motion case the roof response prediction by Bechtel is grossly underestimated and that for the Surface Input case the base response prediction by Bechtel is grossly overestimated. However, the results shown in Figs. 23 and 24 form an excellent set of successful predictions. These results may suggest an acceptable approximation to the consideration of scattering effects for embedded structures where this capability is not directly available in the analytical tools used for SSI calculations.

Comparing the results shown in Figs. 23 and 24, it should be noticed that at the roof the EW responses are comparable and, except for the peak at 2.8 Hz, the NS responses are also comparable. The larger overestimation of the NS responses by Luco/Wong at the 2.8 Hz is directly related to the stiffer system frequency predicted by Luco/Wong (from Fig. 15b, 2.47 Hz vs 2.12 Hz). The overestimate of the NS ZPA at the base for both Bechtel and Luco/Wong predictions is about 35%. Based on the results discussed above, it therefore can be concluded that the two solutions are quite comparable. An important corollary to this conclusion is that scattering at the Lotung site for the 1/4-scale model is simple enough a phenomenon that can be captured by the appropriate use of Surface Input and Base Input motions. More discussion on this issue is provided later on.

Although, for both Bechtel and Luco/Wong solutions the NS ZPA responses are overestimated by 35%, the EW responses almost match the recorded results. For a symmetric structure this difference between NS and EW predictions could be ascribed to the use of the same soil profile for the analysis in both NS and EW directions. This possibility becomes more credible when one considers that the differences in the predictions of the three Luco/Wong sensitivity models are relatively minor (see Fig. 23).

The basic conclusions presented above, based on event LSST07 are further substantiated by the results obtained for event LSST16.

The Bechtel vertical response results based on the Surface Input case, in general, compare better than the results from the Base Input case. Also, the vertical response results shown in Fig. 24 for both Bechtel and Luco/Wong are comparable; nevertheless, both vertical response predictions are not very successful.

Post-prediction earthquake response parametric studies (EPRI, 1991) confirm the conclusion that Surface Input motions overestimate the response of the basemat. Therefore consideration of scattering effects is important. Additionally, it has been shown that using SASSI obtained impedances and scattered input motions CLASSI(Bechtel) will produce equivalent results to SASSI. Therefore CLASSI and SASSI codes are mutually consistent and equally valid for the interaction response analysis phase of the solution.

The following observations can be made:

- o The present industry practice for determining strain-compatible stiffness soil profiles using SHAKE and shear modulus reduction curves is preferred.
- o For purposes of prediction (as against design), separate EW and NS soil profile stiffness

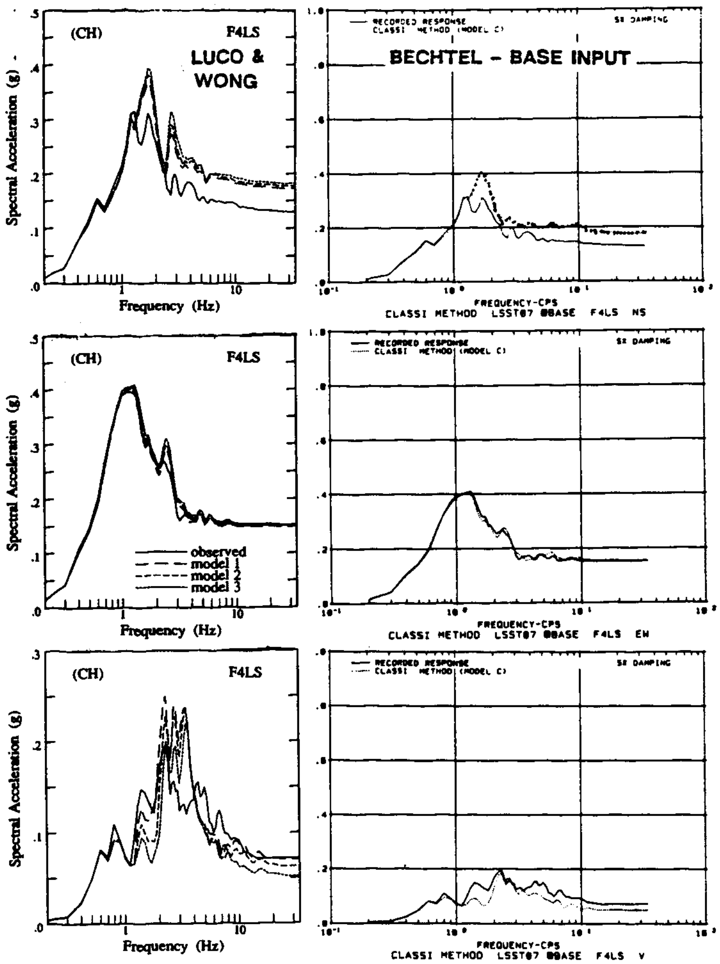



Fig. 23 Comparison of Predicted and Recorded Response Spectra for Model C, Event LSST07 - CLASSI Method

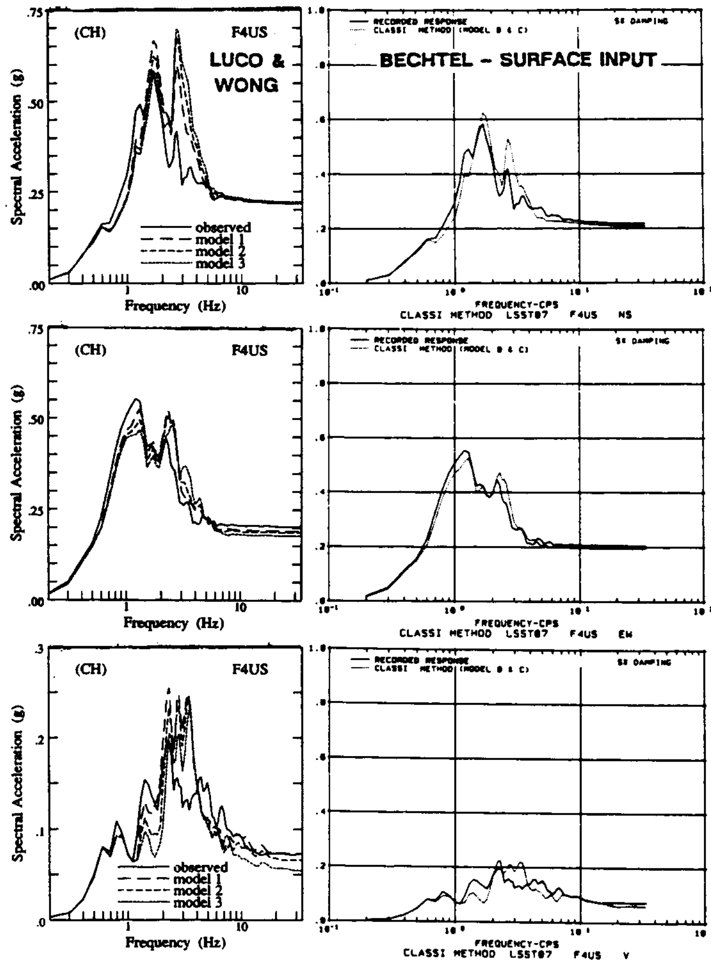



Fig. 24 Comparison of Predicted and Recorded Response Spectra for Model C, Event LSST07 - CLASSI Method

properties may have to be used, specially where important differences occur within the embedment depth and immediately below the foundation level.

- Adjusting for embedment impedances by the method used by Bechtel (Aspel, 1979 and Barneich et al, 1974) gives adequate results.
- Although physical separation of backfill and structure was not likely to have occurred, a reduction of stiffness at the backfill-structure interface seems to have occurred.
- The rigorous treatment of the scattering problem is desirable.
- Prediction of the vertical response has not been as successful as for the horizontal responses.

SASSI Method

The SASSI method was used by Bechtel and Impell to predict the seismic response of the containment to both events LSST07 and LSST16.

The only significant difference between the Bechtel and Impell solutions using SASSI is in the specification of the soil profile stiffnesses. These stiffnesses, in terms of shear wave velocity, are compared in Fig. 7. Both investigators used the same shear wave velocity profile for Models B and C, even though their soil profiles for FVT B and C Models are different. This is significant in that the effects of strain-dependency, as given by SHAKE, eliminates important differences in the starting low-strain stiffness values: the average low-strain shear modulus ratio between the Impell B and C Models is about $\left(\frac{4.7}{4.0}\right)^2 = 1.4$.

Figures 25 and 26 show a comparison of the prediction results of both Bechtel and Impell, drawn to a common scale, for Events LSST07 and LSST16, respectively. The Impell response comparisons with the recorded data are generally not as good as those of Bechtel. The more notable differences occur at the containment roof for both events.

Impell attempted a second solution (Model D) to improve their correlation. A softer soil profile to a depth of 27m was used. The results, although show, as expected, a reduction of the overestimate at the 2.8 Hz peak response, do also show an increase in the underestimates at other frequencies. A comparison of the results indicates that even Model D is not yet any better than the Bechtel Model B. Impell's parametric prediction of

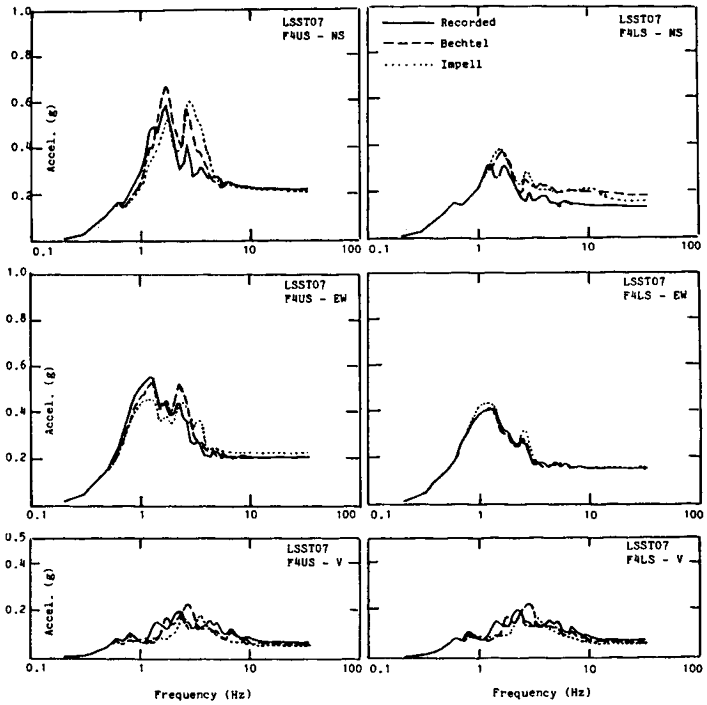



Fig. 25 Comparison of Predicted and Recorded Response Spectra for Event LSST07 - SASSI Method

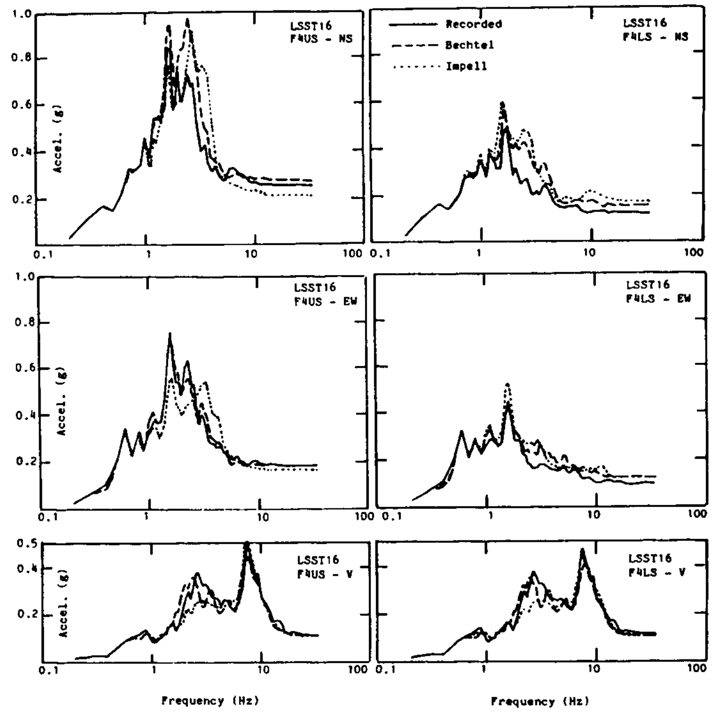



Fig. 26 Comparison of Predicted and Recorded Response Spectra for Event LSST16 - SASSI Method

Model B, which uses soil shear moduli equal to 1.5 and $\frac{1}{1.5}$ times the basic shear modulus of Model B, did not produce an adequate correlation with the recorded results either.

Post-prediction earthquake response parametric studies (EPRI, 1990) confirmed that adequate determination of strain-compatible soil stiffness profiles is very critical to the SSI response predictions of structures. Additionally, the studies showed that system damping, if not correctly specified, impacts adversely the generation of the foundation scattering input motions. And finally, SASSI method of SSI analysis can be considered valid for engineering applications.

Since the difference between the Bechtel and Impell solutions is only the determination of the shear wave velocity profile, it is concluded that the determination of the strain-compatible soil profile is very critical to the SSI response prediction of structures. And, as importantly, overall shear moduli variations are not a substitute for developing appropriate strain-compatible soil profiles. Nevertheless, based on the relative success of the Bechtel prediction results, it is concluded that the SASSI methodology is valid for seismic SSI analysis.

## EVALUATION OF SEISMIC RESPONSE PREDICTION RESULTS - ACROSS-METHODS EVALUATION

The basic strategy for the response prediction studies as described early on has proved to be sound. Because of the several variables that impact the seismic response prediction problem, the response predictions by one investigator using several methodologies but with the same soil modeling technique have contributed significantly to the understanding of seismic soil-structure interaction. This positive result is partly due to the fact that for this series of analyses the site and foundation characterization for the seismic environment has been determined relatively accurately. This latter assessment is based on the comparisons of predictions with recorded data, post-prediction estimate of the site soil shear wave velocity profile and post-prediction response parametric studies.

In this Section, the method-by-method evaluations presented above will be viewed together in order that concluding statements could be made on the relative merit of the methodologies, the identification of the important parameters that assure that adequate results would be obtained and, finally, the level of success of the site characterization as performed by the different investigators. It cannot be overemphasized that similar to any other type of engineering analysis inadequate modeling with the best of methodologies results in the wrong answers.

### Bechtel Predictions

Except for the Soil-Spring method, which requires the determination of equivalent uniform properties of the embedment layer and the sub-foundation half-space, Bechtel used the same site soil profile for the predictions with the other three methods.

The Soil-Spring profile is the more stiff in the embedment depth resulting in an overprediction of the system frequency (2.7 vs 2.0 Hz). The procedure used by Bechtel for obtaining equivalent stiffness and damping values of layered sites nevertheless needs to be improved.

Overall, the Bechtel predictions using SASSI are the best for both events LSST07 and LSST16 as shown in Figs. 25 and 26, respectively. In an absolute sense the SASSI predictions should be considered to be very good, the EW predictions being better than the NS predictions. These differences between EW and NS results persist throughout; the possible reasons for this occurrence were elaborated above. Nevertheless, given an acceptable soil characterization it should be concluded that the SASSI methodology is valid for performing SSI analyses of embedded structures.

Despite the fact that scattering effects are treated in a simplified fashion, (Base Input motion for basemat response and Surface Input motion for roof response), the CLASSI(Bechtel) results shown in Figs. 23 and 24 are equally acceptable; nevertheless, for event LSST16, an underprediction, particularly in the vertical direction, is to be noted. The generalization though of using Surface Input and Base Input motions to account for scattering effects cannot be made at this time.

Although the Surface Input motion case gives conservative results not only at the basemat but also at the top of the containment, the Soil-Spring method with Base Input motion has produced acceptable results. The important issue for this methodology is the determination of the equivalent soil stiffness and damping characteristics of both the embedment layer and the sub-foundation half-space. Considering the simplicity of the Soil-Spring method, additional cases should be studied to gain confidence in the adequacy of this solution technique.

The least satisfactory results were obtained by the FLUSH method (Figs. 19 and 20). Given the same soil characterization for all of the methods used, this situation can be ascribed only to the inherent limitations of the FLUSH 2D methodology for solving 3D problems. Other analytical evaluations have also shown that there are inherent difficulties in using this approach for 3D structures (Luco and Hadjian, 1975) and in modeling the infinite half-space (Hadjian et al, 1986).

All Predictions

Considering all the predictions together is a more complex task, since, in addition to the basic computational methodology, important differences in the characterization of the site soil profile and foundation input motion must be considered. Thus, whereas the Bechtel SASSI results are satisfactory, the Impell SASSI results, even including their Model D results, are less satisfactory than the Bechtel Model B results. The superimposed results in Figs. 25 and 26 clearly show that at the top of the containment the Impell results, for all three directions, are not satisfactory. The reason for the unsatisfactory results by Impell is most likely due to the modeling of the soil profile rather than the SASSI method.

Overall, the best predictions have been obtained by Bechtel using the SASSI method. Obviously the CLASSI version used by Luco/Wong is more appropriate to solve the embedment problem than the Bechtel version of CLASSI. However, allowing for Bechtel's approximate treatment of the embedment impedances and the simple treatment of the scattering problem, it is concluded that the CLASSI(Bechtel) selected results for event LSST07 are slightly better than those of CLASSI by Luco/Wong (Figs. 23 and 24) validating in part the approximate treatments of the embedment effect and the scattering problem. The EQE/EET Model D results are comparable to those by CLASSI(Bechtel). It is likely that the CLASSI(Bechtel) limitations may become important for other sites and prototypical structures. However, the Luco/Wong version of CLASSI should produce adequate results given adequate models (e.g., Luco/Wong $A_{H1}$ model).

Following similar comparisons of all the figures (Hadjian et al, 1991) it is possible to establish a ranking of predictions that would indicate reasonably accurately the assessment of the results from all of the investigators. It is likely that a different ranking could be judged to be more appropriate, where adjacently ranked solutions could be switched by other evaluators; however, it is unlikely that a complete rearrangement of the ranking of the fourteen solutions could result from two different evaluations. One such ranking of predictions starting with the best results is shown in Table 8. The prediction and post-prediction results shown in Table 8 can be divided into two distinct groups: the better and comparable solutions are listed as Solutions 1 through 7, and the less successful results, as Solutions 8 through 14.

Considering that significant improvements in the predictions were made by improved modeling (SUPERALUSH/CLASSI from 8th to 3rd position) with the same methodology, the combined modeling/methodology ranking of Table 8 could be broken down into its constituent parts. This has been done and the results are shown in Table 9. Based on the present study results, it would be difficult to distinguish between the first three methodologies of Table 9a. It is concluded that given the appropriate model, all three methodologies would produce very similar valid results. However, both CLASSI(Bechtel) and Soil-Spring methods should be used cautiously within their

TABLE 8. RANKING OF SOLUTIONS

| Solutions No. | Method | Investigator | Model | Comments |
|---|---|---|---|---|
| 1 | SASSI | Bechtel | B/C | |
| 2 | CLASSI | Luco/Wong | $A_{H1}$ | |
| 3 | SUPERALUSH/CLASSI | EQE/EET | D | Post-Prediction |
| 4 | CLASSI(Bechtel) | Bechtel | B/C | Input Motion Comb. |
| 5 | CLASSI | Luco/Wong | B or C | |
| 6 | Soil-Spring | Bechtel | B/C | Base Input Motion |
| 7 | SASSI | Impell | D | Post-Prediction |
| 8 | SUPERALUSH/CLASSI | EQE/EET | B | |
| 9 | SASSI | Impell | B | |
| 10 | FLUSH | Bechtel | B/C | |
| 11 | FLUSH | S&L | C1 | Post-Prediction |
| 12 | FLUSH | S&L | B | |
| 13 | Soil-Spring | Bechtel | B/C | Surface Input Motion |
| 14 | Soil-Spring | M/C/Z | B1 or C | |

TABLE 9. BREAKDOWN OF TABLE 8 INTO METHODOLOGY AND MODELING RANKINGS

| (a) METHODOLOGY | (b) MODELING |
|---|---|
| CLASSI, SASSI, SUPERALUSH/CLASSI | Bechtel - Models B and C<br>Luco/Wong - Model $A_{H1}$ (CLASSI)<br>EQE/EET - Model D (SUPERALUSH/CLASSI) |
| CLASSI (Bechtel) - Combination of results using simplified scattering | Luco/Wong - Models B or C (CLASSI)<br>Impell - Model D (SASSI) |
| Soil-Spring (Base Input Motion with appropriate consideration of layering effects) | EQE/EET - Model B (SUPERALUSH/CLASSI)<br>Bechtel - Models B/C (FLUSH)<br>Impell - Models B and C (SASSI) |
| FLUSH | S&L - Model C1 (FLUSH)<br>S&L - Model B (FLUSH)<br>M/C/Z - Models B1 or C (Soil-Spring) |

known limitations. The use of FLUSH should be limited to essentially 2D problems with attention given to the effect of the model bottom boundary for deeply embedded structures (Hadjian et al, 1986) and to discontinue the use of viscous dampers for simulating 3D radiation damping effects. On the contrary, steps should be taken to reduce the effective damping.

Based on the rankings of Tables 8 and 9a, it is possible to deduce a modeling ranking as shown in Table 9b. Or alternatively, given the two rankings of Table 9, the combined ranking of Table 8 could be derived. Table 9b will be used to identify those modeling details that have contributed to producing acceptable or unacceptable results.

The first three models were discussed at length above. From Table 6 it is clear that the Luco/Wong results for C2 and B2 Models tend to deteriorate from that of $A_{H1}$ simply due to the increased stiffness modeling of the soil profiles, resulting in system frequencies of 2.47 Hz and 2.70 Hz for Models C2 and B2, respectively.

Impell Model D soil profile is an improvement on Model B/C. For Model D a softer soil profile, down to a depth of 27m, was used. Softening of the Model B/C profile for Model D was not sufficient to obtain adequate comparisons with recorded data. Figure 6 clearly shows why Impell obtained a stiffer soil profile for seismic analysis.

Post-prediction, EQE/EET reduced the stiffness modulus of its initial Model B soil profile by about 50% leading to the successful prediction using Model D. This soil modulus reduction was achieved by using the Seed & Idriss curves. As shown in Fig. 6 the original EQE/EET shear modulus degradation curve was the most inappropriate when compared to the post-prediction curves.

Throughout this evaluation, the difficulties associated with obtaining adequate 2D models for 3D problems for use with the FLUSH method have been highlighted. So it is not surprising that in Table 9 the S&L Models C1 (post-prediction) and B follow the other models. Although, in general, the Bechtel FLUSH results are better than those of S&L, they also underestimate the response relative to the recorded data. The differences between S&L and Bechtel results are to be expected from the shear wave velocity profiles of Fig. 6.

And finally, the modeling of M/C/Z was unacceptable simply because no degradation of shear modulus was incorporated considering seismic-induced strains. As discussed before, significant shear modulus reduction occurred for both events LSST07 and LSST16.

## CONCLUSIONS

A spectrum of prediction and correlation results were obtained during the round-robin prediction studies. Additionally, post-prediction studies were performed to resolve questions that arose during the evaluation of the results. In the previous Sections all of these results were reviewed, compared, and evaluated in an attempt to better understand the SSI response behavior of the Lotung model, evaluate the capabilities and limitations of the several SSI analysis methods that are commonly used by the US nuclear industry, and, finally, to recommend improvements in the use of these methods.

The Lotung experiment is relatively simple and thus is an excellent test for the purpose of validating SSI analysis methods and modeling techniques: the 1/4-scale containment model structure is rigid, and hence a significant complexity of structural response, possibly associated with nonlinear concrete cracking, has been avoided; the foundation material is very soft, thus assuring of significant soil-structure interaction and providing an opportunity to study severe nonlinear soil response during moderate earthquakes; the combination of the model structure geometry, embedment, and site soil properties caused the structure to respond primarily in the rocking mode, thus, significant coupling of translational and rocking interaction was not present to complicate the evaluation process; and finally, the system frequency during the earthquakes selected for the study, even though lower than originally expected, was still within the range of frequencies with adequate seismic energy.

On the assumption that the foundation can be appropriately modeled, it would be difficult to distinguish between the computational capabilities of the SASSI, CLASSI and SUPERALUSH/CLASSI methods of analysis. Given the appropriate model, all three methodologies would produce very similar valid results. However, both CLASSI (Bechtel) and Soil-Spring methods should be used cautiously within their known limitations. The use of FLUSH should be limited to essentially 2D problems.

More than the computational methods, the differences in the response results reported herein are due to the modeling of the soil-structure system and the characterization of the input motions.

The low-strain shear wave velocity characterization based on geophysical data has proved to be adequate for the FVT. The shear wave velocity profile based on SPT data, as initially used by Impell, did not produce satisfactory results.

Even though piezometric readings indicate that the water table is essentially at the ground surface, P-wave measurements indicate complete saturation at about 10m depth. There exists a uniform transition zone from $V_p$ = 1500 mps at 10m depth to $V_p$ = 300 mps at the ground surface. It is not clear whether this transition zone was considered by all investigators for their vertical response calculations.

The SHAKE program was invariably used to estimate the strain-compatible soil properties for seismic response. Both blind-prediction and post-prediction studies indicate that deconvolution analysis using equivalent linear methods with strain-compatible soil properties to represent nonlinear soil behavior and assuming vertically propagating plane waves are satisfactory in capturing the main features of ground motion variation within the shallow depth range that was important to SSI. Deconvolution analyses using SHAKE and the field-estimated shear modulus degradation curve produced excellent results down to 47m depth. Therefore, with appropriate modeling, ground motion variations with depth could be obtained, eliminating the need to artificially limit the amount of ground motion reduction with depth. By restricting the reduction of ground motion with depth, certain structures could be penalized depending on the soil profile properties and the depth of embedment. The soil profile modeling uncertainty is a separate issue and should be addressed directly as discussed below.

Small differences in the initial low-strain shear modulus values did not impact the end results. This follows from the fact that several of the successful predictions that had two distinct soil-profiles for Models B and C used in the FVT analysis used only one common soil profile for both Models B and C in the seismic response analysis.

Severe stiffness degradation occurred during the Lotung earthquakes within the site soil profile. Based on the FVT and Seismic Response system frequency results, the overall stiffness degradation ratio is $\left(\frac{2.0}{3.8}\right)^2 = 0.28$. The G/Gmax ratio at about 0.1% strain obtained from the stiffness degradation curves generated by the investigators ranges from 0.21 to 0.44. These variabilities should be considered as upperbound. Even then, reduction of this variability is desirable. Although the cyclic triaxial data shows significant scatter and the shear modulus degradation and damping curves used by the investigators show a large variability, these levels of severe degradation are now believable to occur at soft sites even during moderate shaking. Parametric studies using the FLUSH code suggest that secondary local nonlinearities due to SSI response were comparatively not significant.

The post-prediction free-field ground response studies clearly indicate that the field-estimated shear modulus, G/Gmax, versus shear strain curve has different characteristics than those that are commonly used in practice. In the range of strains from about 2 x $10^{-3}$% to 2x$10^{-2}$% the field-estimated G/Gmax curve is appreciably lower from all of the other curves used by the investigators, suggesting that resonant column tests tend to overestimate shear modulus. The character of the curve deduced from the field data is such that the normalized shear modulus, G/Gmax, is almost inversely proportional to the logarithm of the shear strain.

The same level of variability exists in the damping versus strain curves used by the investigators. Although the damping curve used in the ground response studies has not been directly derived from the recorded earthquake data, it, together with the field-estimated shear modulus degradation curve, form a consistent set. The fact that, in general, the field-estimated damping curve in the higher ranges of strain falls significantly below the cyclic triaxial test results is consistent with the observation that the cyclic triaxial tests tend to produce higher damping values possibly due to excessive friction or compliance of the loading system.

The above two results, that resonant column tests overestimate the shear modulus at the intermediate strain levels and cyclic triaxial tests overestimate soil damping, strongly suggest that the interpretation of laboratory tests to predict in-situ soil properties needs to be re-evaluated. It should be noted that in one case overall variations of shear moduli by 1.5 and $\frac{1}{1.5}$ times the basic shear modulus did not produce adequate correlations with the recorded results.

The evidence exists that soil stiffness properties below about one diameter the foundation do not seem to be of significance to the SSI rocking response analysis. Since the structure responded primarily in the rocking mode and the vertical response predictions were inferior to the horizontal response predictions, the above observation must be used with caution for other modes of response. Analytical extrapolation studies could be used in order that a more definitive conclusion is reached relative to all modes of response.

The five Industry Group investigators made three different decisions relative to the development of strain-compatible shear wave velocity profiles for SSI analysis. No one investigation team performed the analysis for both event-specific and component-specific soil properties. Obviously a common approach is lacking in the treatment of orthogonal responses (NS and EW in these studies). The successful response predictions that used a single shear wave velocity profile for both directions of excitation show how this has impacted the predictions: the EW comparisons of the predictions with the recorded data are, in general, better than the NS comparisons. Moreover, the response reductions (relative to the free-field motions) at the base of the test model are measurably larger in the NS direction than in the EW direction. For a symmetric structure these results could only occur if the stiffness degradation and damping values are different in the two orthogonal directions, given the fact that recorded ground motions at stations FA1-5 and FA2-5 have been judged to have similar characteristics. For test correlation studies, it may sometimes become necessary to treat each earthquake and each component separately, particularly when the correlation coefficient between the components of motion is small.

A most notable result from the post-prediction ground motion studies is the determination that the stiffness degradation of soils during earthquakes has a transient character. Even though drastic stiffness degradation occurred <u>during</u> the earthquake as a function of shear strain, the original stiffness was recovered soon after the shaking subsided. The fact that the nonlinear behavior did not lead to permanent deformations (the test model stayed plumb) further suggests that energy dissipation in soils during earthquakes is less than that calculated from cyclic triaxial test results where permanent deformations of samples occur.

Although shear wave velocity data on the backfill material was not available at the time of the SSI investigations, backfill properties were estimated by all investigators for incorporation in their models. For deeply embedded structures the effect of the embedment (impedance function and foundation input motion) on the SSI response is usually important. Thus, it is necessary that the shear modulus and damping properties of backfill materials for seismic response be determined to within the same precision as the free-field soil profile.

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