Assessment of Soil-Structure Interaction Practice Based on Synthesized Results from Lotung Experiment - Earthquake Response

A. H. HADJIAN
Bechtel Corporation, Norwalk, CA USA
W. S. TSENG
International Civil Engineering Consultants, Inc., Berkeley, CA USA
Y. K. TANG, H. T. TANG, J. C. STEPP
Electric Power Research Institute, Palo Alto, CA USA

1 INTRODUCTION

In order to validate the several soil-structure interaction (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 (EPRI, 1987). The cross-section of the 1/4-scale model is shown in Fig. 1. The investigations and results reported herein relate only to the 1/4-scale model. 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, have been recorded at the site both on the surface and in down-hole arrays (Fig. 2). Table 1 gives the matrix of U.S. investigators and analysis methods used. The validation program utilized a round-robin approach.

Given the space limitations, details of the program description, site and structure characterization, the evaluation of FVT prediction results and the prediction evaluation basis will not be repeated here as these are adequately described elsewhere (Hadjian et al, 1989 and 1990). Only a summary of the conclusions from these references will be provided herein.

2 SUMMARY RESULTS FROM FVT (Hadjian et al, 1990)

Relative to the seismic problem, the FVT SSI problem has less complexity. The complexities of site response, wave scattering, and potentially strain-dependent soil properties are absent. For any analysis methodology the only significant decision for the FVT analysis relates to the stiffness and damping characterization of the foundation. The following are the main conclusions from the FVT phase of the program.

1. With adequate modeling the following codes/methods give acceptable results for FVT: SASSI, CLASSI (the industry version requires adjustments for embedment effects), SUPERALUSH (to calculate impedance functions for embedded inserts) and the frequency-independent soil-spring method (with adjustments for embedment effects, and equivalent stiffness and damping for layered sites required).

2. Geophysical methods are adequate to provide low-strain soil profile stiffness. Shear wave velocity profile based on STP data did not produce satisfactory results. Figure 3 shows the low-strain shear wave velocity profiles developed by all of the investigators for use in the FVT response

Table 1. Matrix of U.S. investigators and analysis methods used

Method

Investigator

	Soil-Spring[1]	FLUSH[2]	SUPER-ALUSH/CLASSI[3]	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.

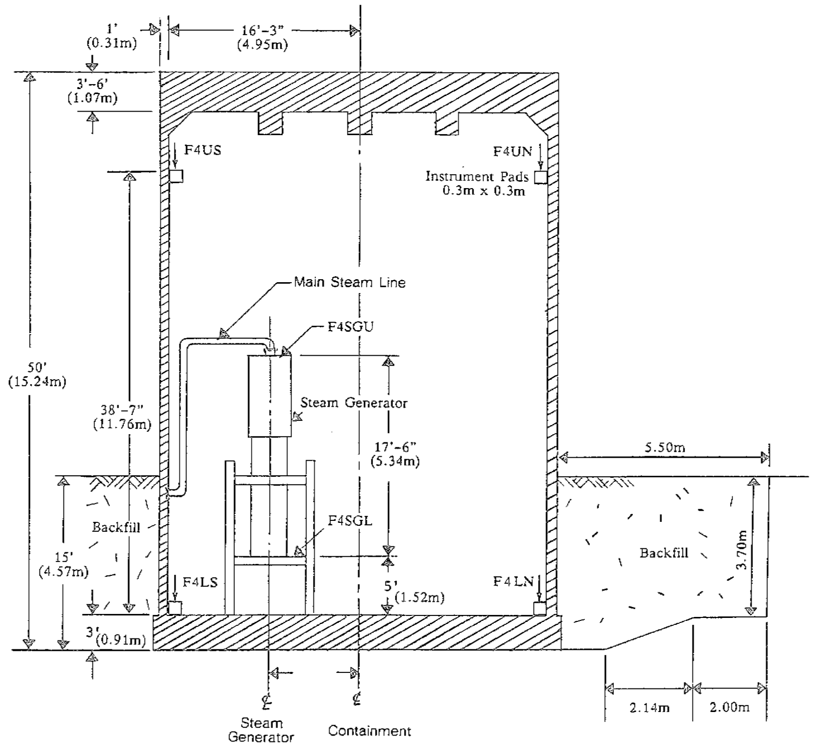
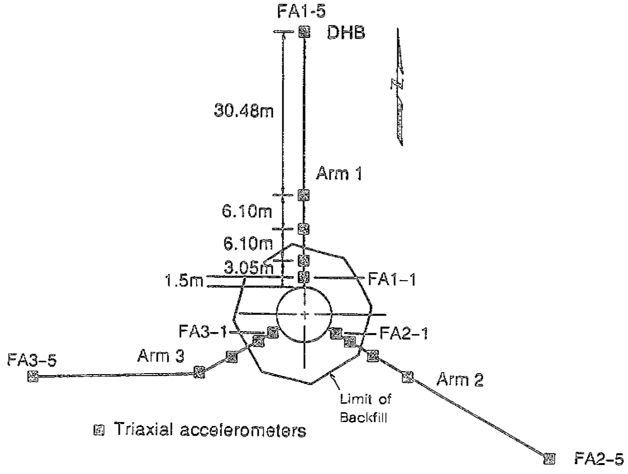
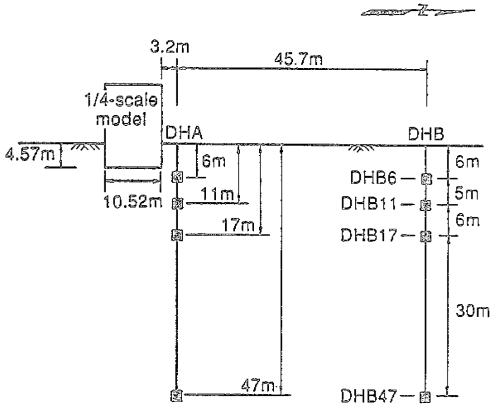


Fig. 1 Cross-section of the 1/4-scale containment model



(a) Surface Instrument Arrays



(b) Downhole Instrument Arrays

Fig. 2 Location of (a) surface accelerographs and (b) down-hole accelerographs (Tang, 1987) analyses. Due to the scatter in the field geophysical data, differences exist among the profiles. Except for the very deep strata, the differences from the middle of the range of values are less than about ±20%. The weighted (by layer thickness) maximum differences in shear wave velocity are only ±16% (about ±31% in shear modulus).

3. Low-strain soil damping does not seem to account for the total energy dissipation during SSI.

3 SEISMIC RESPONSE PREDICTION EVALUATION BASIS (Hadjian et al, 1989)

In order that the evaluation of the response predictions goes beyond a mere statement as to whether the predictions were adequate or inadequate based on a comparison of recorded and calculated response spectra, in-depth investigations of soil profile characteristics were performed and post-prediction studies, using recorded data, were conducted to develop best estimate parameters as well as to validate modeling assumptions and techniques (EPRI, 1991 and Geomatrix Consultants, 1991). The following conclusions are based on these extensive studies.

1. 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. Unlike the low-strain values the differences among the several profiles shown in Fig. 4 are 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. 5) and the decision of the analysts relative to the use of the free-field ground motions to determine the earthquake induced strain levels.

2. Shown in Fig. 5 are two sets of curves: those predicted by the investigators and those estimated from down-hole motion studies of 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. The results suggest that resonant column tests overestimate the shear modulus at the intermediate strain levels and cyclic triaxial tests overestimate soil damping.

3. Significant degradation of soil modulus occurs during moderate earthquakes. This has been established both by the study of the free-field motions and the system response transfer functions (Fig. 6). Fig. 7 is a plot of the identified system frequencies as a function of peak ground acceleration. An overall measure of this stiffness degradation can be obtained from the seismic and FVT system frequencies: i.e., $\left(\frac{2.0}{3.8}\right)^2 = 0.28$.

4. It was also determined that the significant modulus degradation is temporal and the soil stiffness is recovered as the ground motion subsides.

5. Vertical wave propagation assumption in performing SSI analyses is adequate to describe the wave field.

6. Equivalent linear analysis of soil response for SSI analyses, such as performed by the SHAKE code, provides acceptable results.

7. Soil-wall separation was unlikely to have occurred during moderate ground shaking.

4 EVALUATION OF SEISMIC RESPONSE RESULTS

The evaluation primarily emphasized the U.S. practice in SSI analysis as shown in Table 1. The EQE/EET method, called herein the SUPERALUSH/CLASSI method, is so characterized because foundation impedances and wave

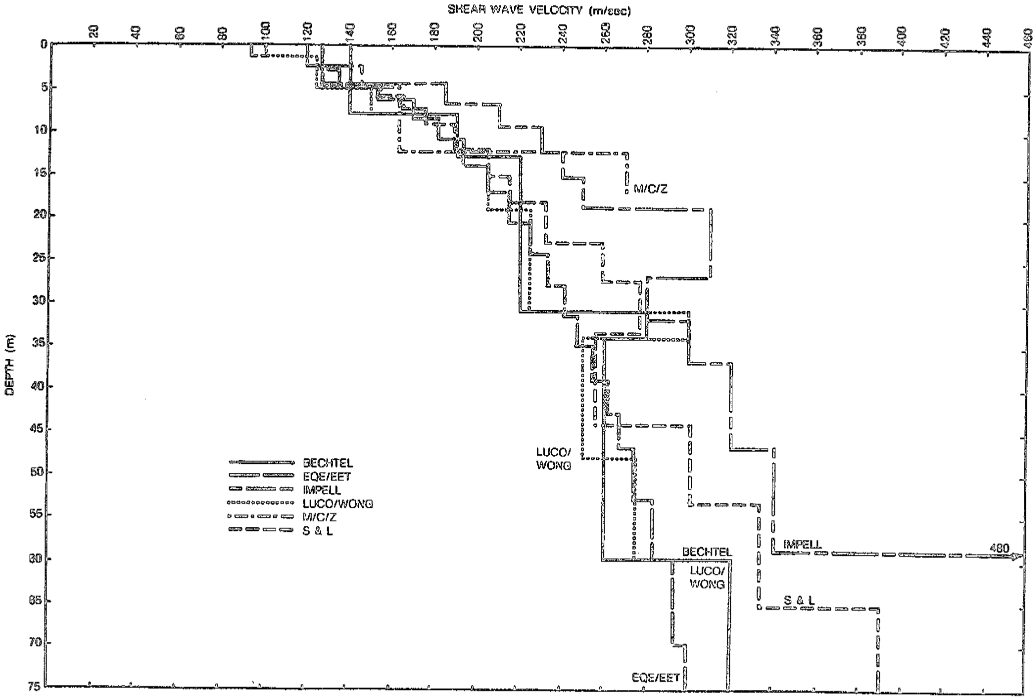


Fig. 3 Low-strain shear wave velocity profiles for model B

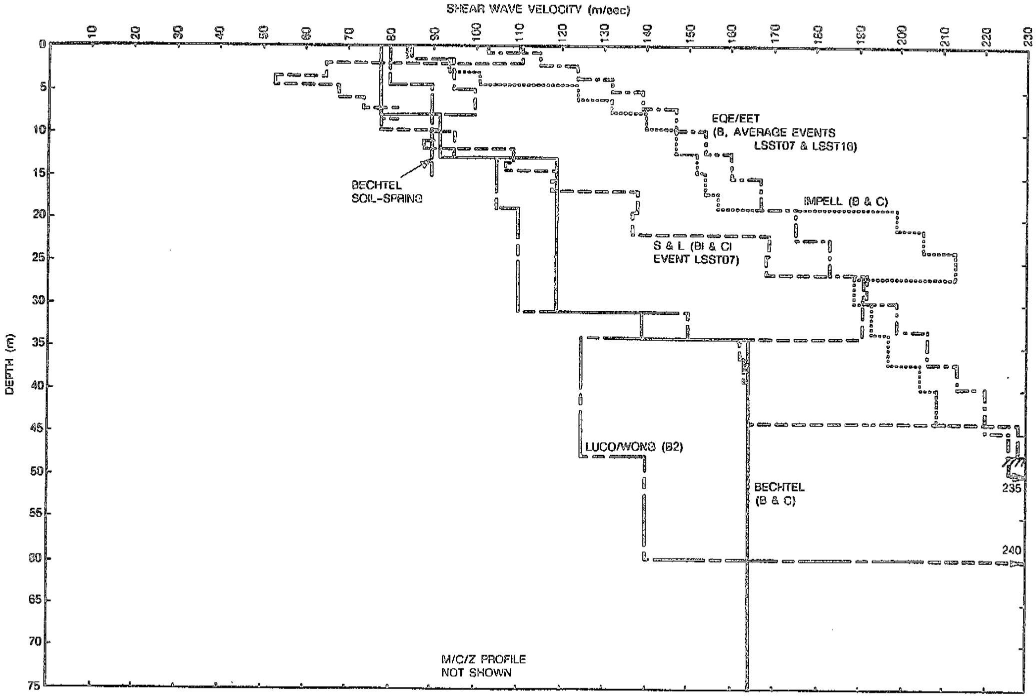


Fig. 4 Strain-dependent shear wave velocity profiles for seismic response

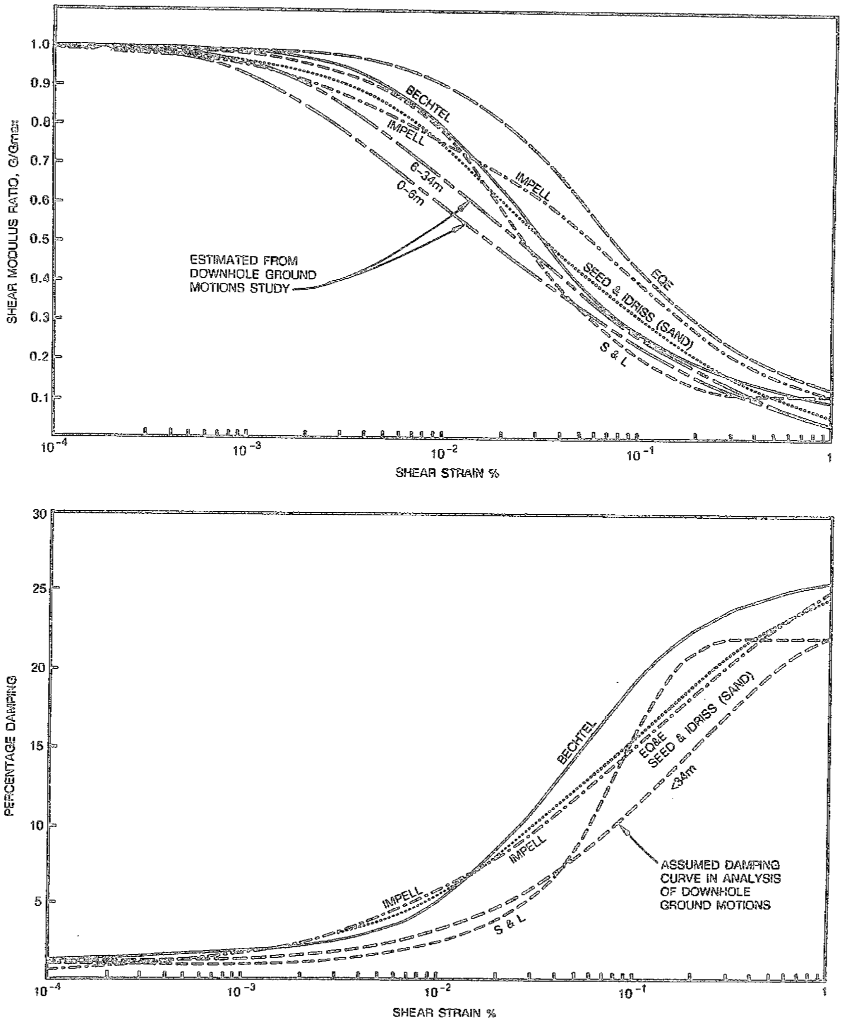


Fig. 5 Comparison of strain-dependent shear modulus and damping curves

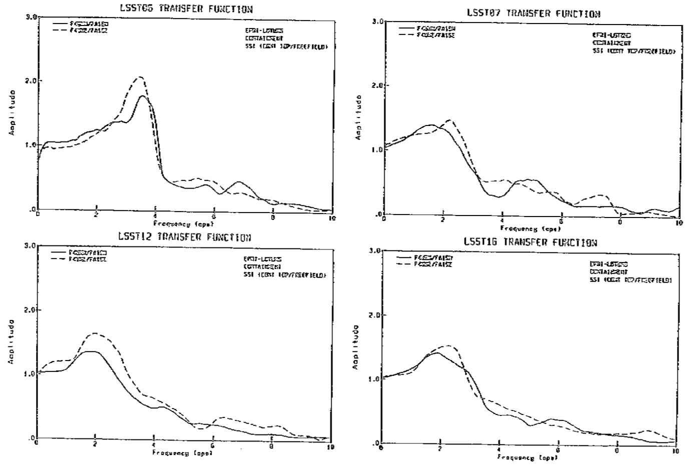


Fig. 6 Containment top SSI system response transfer function amplitudes determined from test data for four events

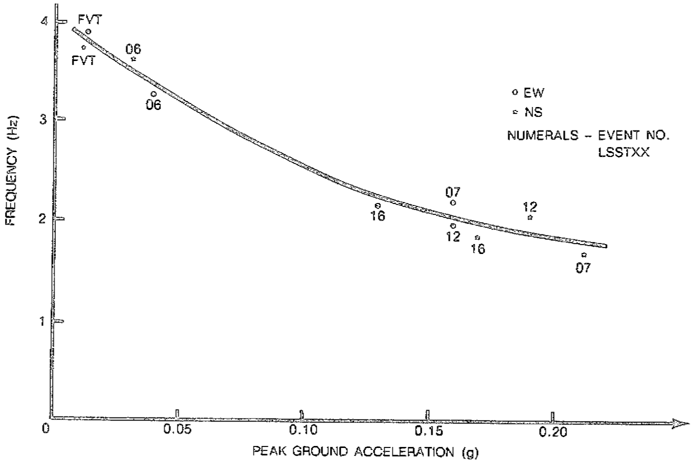


Fig. 7 Plot of containment SSI frequencies vs. peak ground accelerations

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 are 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 and obtains the total impedance matrix and the matrix of scattering coefficients directly. On the other hand, the Bechtel version of the code is strictly applicable to surface foundations. 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 variation of input motion. Given these limitations the CLASSI version as used by Bechtel is 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.

Each investigator 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 (Fig. 2) and computed the 5% damped acceleration response spectra at 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. 1. Although two events were studied in detail, event LSST07 (May 20, 1986) and event LSST16 (Nov. 14, 1986), only results from event LSST07 are presented due to space limitations. A sample of response spectra comparisons are shown in Figs. 8 through 13. The adequacy of each methodology with its basic assumptions was assessed by the closeness of the predictions to the recorded responses. Conservative results, although important from a design perspective, were not considered to be successful predictions in this evaluation.

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 was concluded 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 in this evaluation was 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 was evaluated only for the Soil-Spring method.

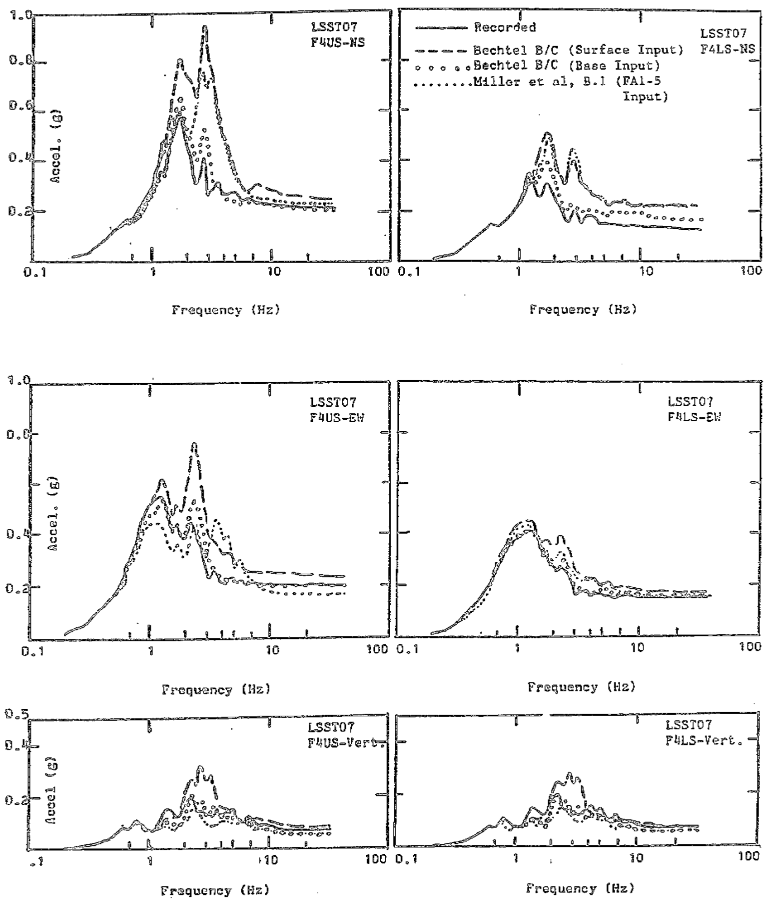


Fig. 8 Comparison of predicted and recorded response spectra for event LSST07 - Soil-Spring method

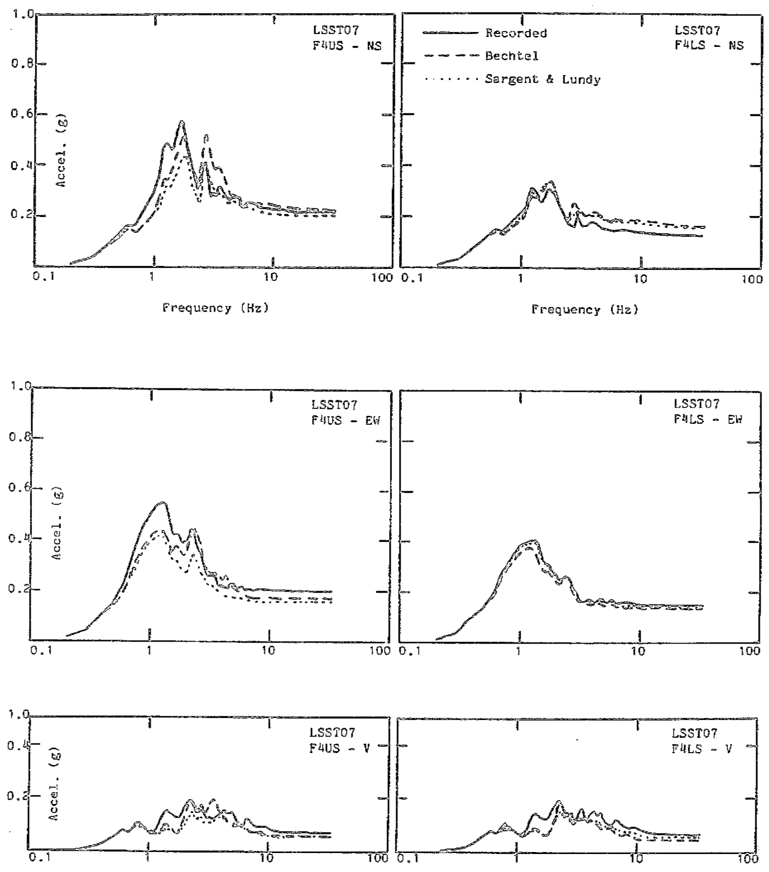
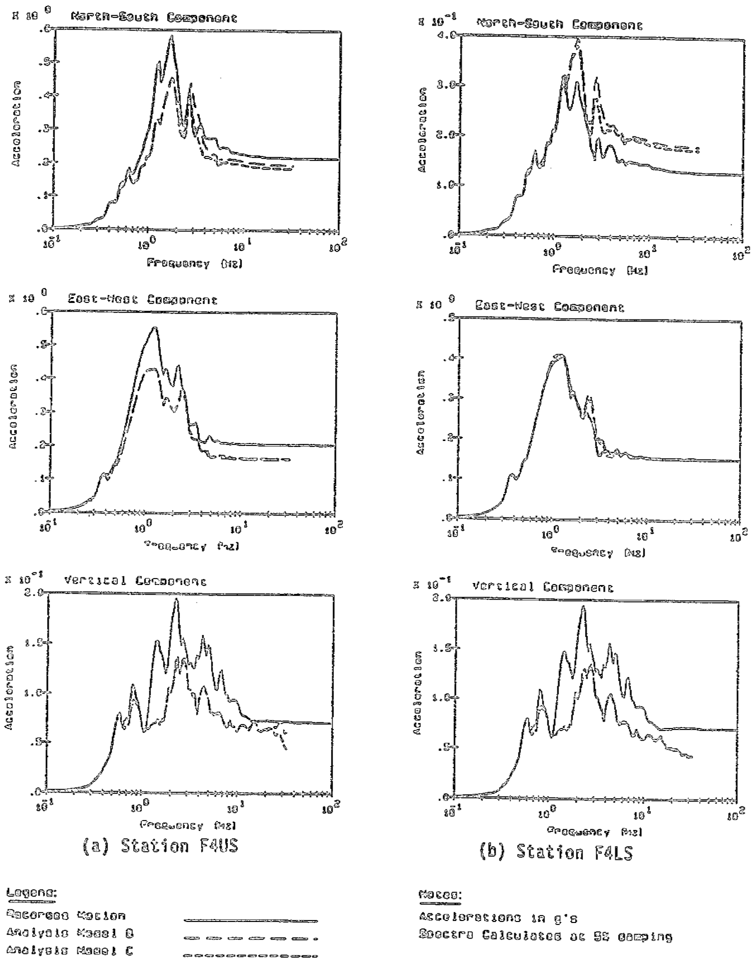


Fig. 9 Comparison of predicted and recorded response spectra for event LSST07 - FLUSH method


(a) Station F4US

(b) Station F4LS

Fig. 10 Comparison of predicted and recorded response spectra for model B, event LSST07 - SUPERALUSH/CLASSI method

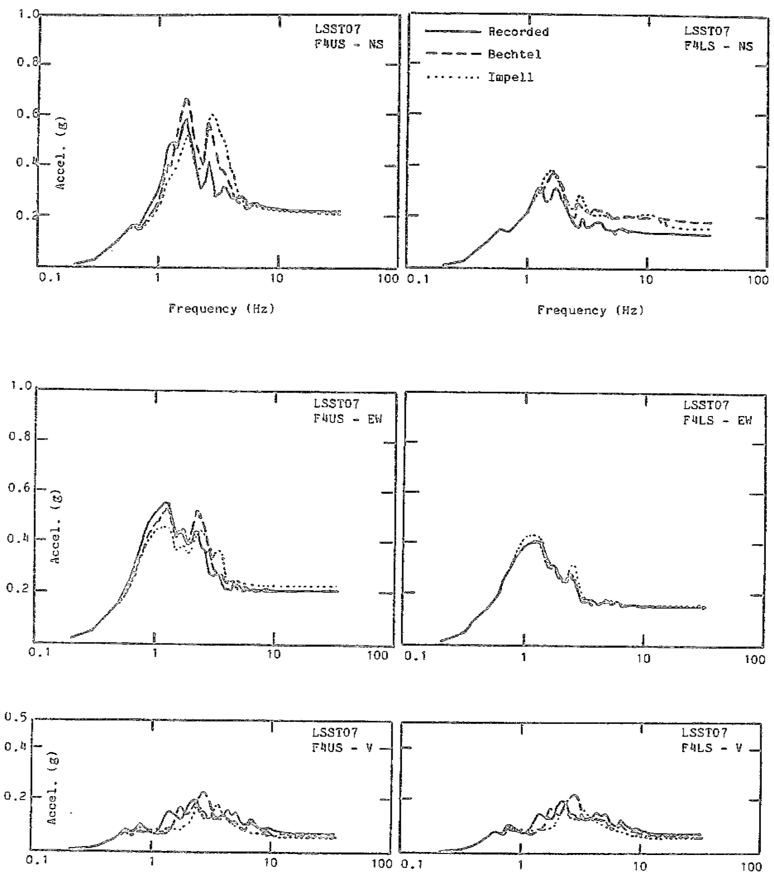


Fig. 11 Comparison of predicted and recorded response spectra for event LSST07 - SASSI method

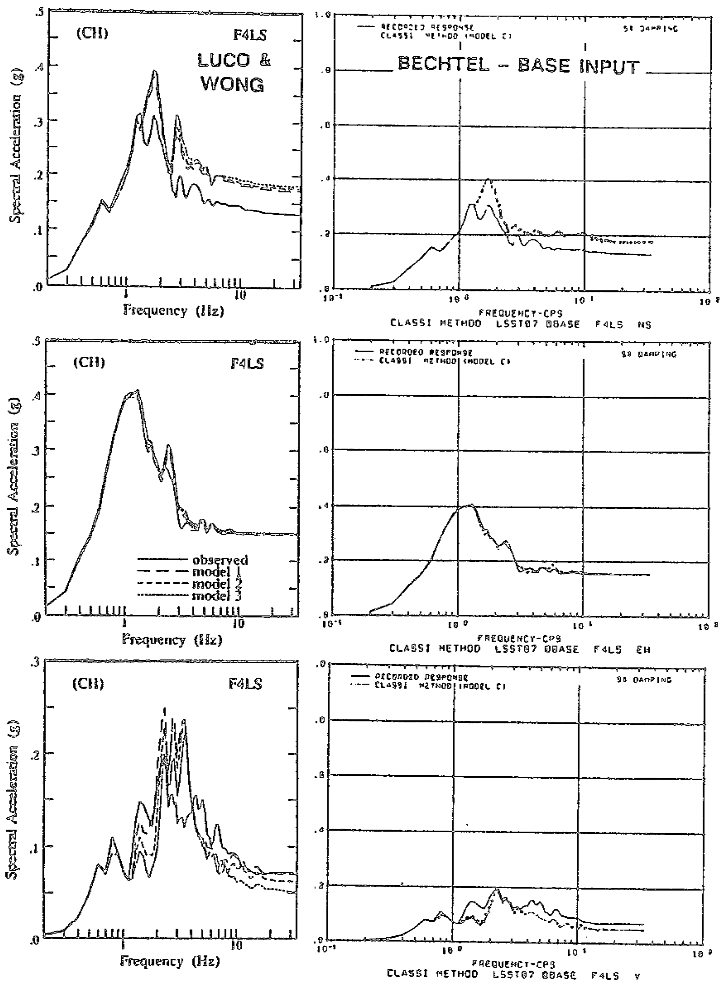


Fig. 12 Comparison of predicted and recorded response spectra for model C, event LSST07 - CLASSI method

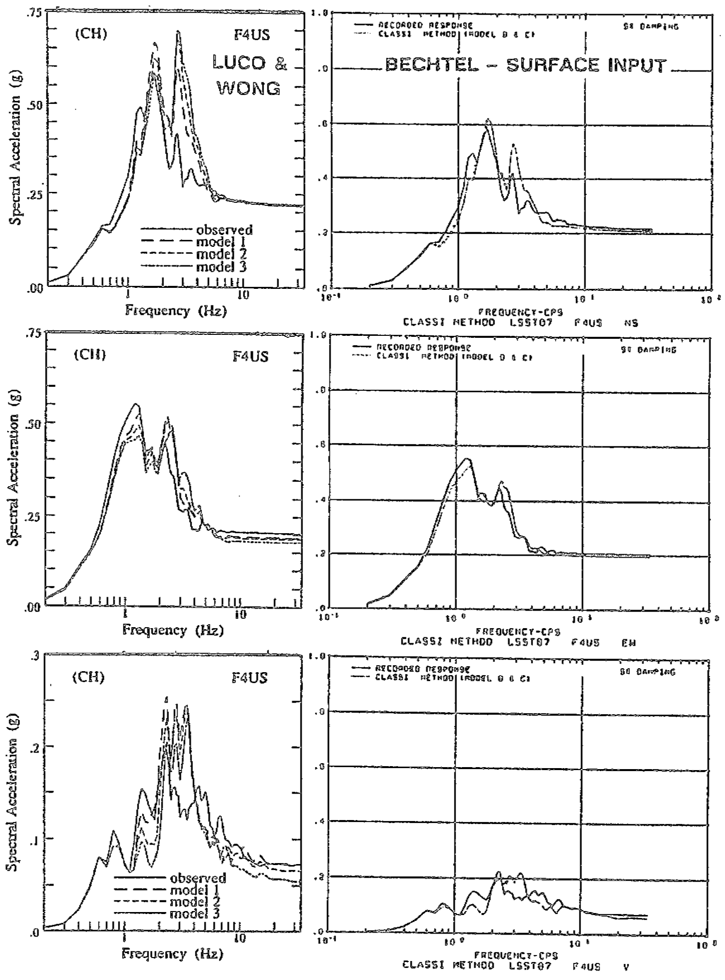


Fig. 13 Comparison of predicted and recorded response spectra for model C, event LSST07 - CLASSI method

The results from a spectrum of prediction, correlation and post-prediction studies 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, and, finally, to recommend improvements in the use of these methods. Based on the strategy of Table 1, first a method-by-method evaluation was performed followed by an across-methods evaluation. These were then 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 adequate results and, finally, the level of success of the site characterization.

Space does not allow to go into any discussion of the comparisons and the evaluations. The interested reader should refer to Hadjian et al (1991a and b). Based on detailed comparisons of all the results a ranking of predictions starting with the best results is shown in Table 2. 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. The prediction and post-prediction results shown in Table 2 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 2 could be broken down into its constituent parts. This has been done and the results are shown in Table 3. Based on the present study results, it would be difficult to distinguish between the first three methodologies of Table 3a. 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. Based on the rankings of Tables 2 and 3a, it is possible to deduce a modeling ranking as shown in Table 3b. Or alternatively, given the two rankings of Table 3, the combined ranking of Table 2 could be derived. The modeling details that have contributed to producing acceptable or unacceptable results have been identified. However, without presenting the supporting evidence, it is impossible to explain the root causes. These have been elicited and presented in the above-mentioned references.

Table 2. 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 3. Breakdown of Table 3 into methodology and modeling rankings

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

5 CONCLUSIONS

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 SSI 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 seismic response results obtained are due to the modeling of the soil-structure system and the characterization of the input motions. 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.

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