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VALIDATION OF SOIL-STRUCTURE INTERACTION METHODS USING EARTHQUAKE DATA IN LOTUNG, TAIWAN

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SUMMARY

A large-scale seismic experiment facility was constructed in Lotung, Taiwan to collect actual seismic response data to validate soil-structure interaction (SSI) analysis techniques. Eighteen earthquakes have been recorded at the site and a method validation program sponsored by EPRI, NRC, and Taiwan Power Company has been completed. The program involves blind prediction and result evaluation of recorded responses for forced vibration tests and selected seismic events using various existing SSI methods. In this paper, the essentials of the Lotung experiment and SSI method evaluation program are described, and the results and findings are summarized.

INTRODUCTION

Seismic SSI involves the kinematic and inertial interaction of structures and their surrounding soil medium during a seismic shaking. The effects are evident, particularly on embedded, massive structures such as nuclear power plants. In the past, various seismic SSI analysis techniques have been developed and used for nuclear plant design and licensing. The methods vary from simple spring and dashpot representations (Ref. 1), to more complex finite element and substructure impedance approaches (Refs. 2, 3, 4,5). However, due to the lack of an experimental database, relatively little effort has been devoted to validate the assumptions and approximations employed in formulating these analytical techniques. To establish such a database, EPRI and Taiwan Power Company (Taipower) have undertaken a large-scale seismic experiment in Lotung, Taiwan, Republic of China (Ref. 6), where strong motion earthquakes are known to occur frequently.

THE LOTUNG LARGE-SCALE EXPERIMENT

The experiment essentially consists of two scaled concrete containment structures (one 1/4-scale and one 1/12-scale) located within the proximity of an existing strong motion array, SMART-1 (Ref. 7). Inside the 1/4-scale model, a mocked-up steam generator and a simple pipe run were installed to monitor internal component responses. A total of 130 channels of instruments were deployed to record the earthquake shaking. The instrumentation consist of in-structure, ground surface and downhole triaxial accelerometers as well as interfacial pressure transducers. To establish a well-controlled SSI database, the ground surface accelerometers consist of an array of three arms, each containing five stations; the downhole stations consist of two vertical arrays located one at near-field and one at far-field to the 1/4-scaled containment building; and the in-structure sensors are placed on top of the basemat and near the roof of the building. The locations and layout of the recording stations are shown in Figure 1.

The soil at the Lotung site mainly consists of saturated sandy-silt and silty-sand layers. Both field exploration and laboratory tests were conducted to provide site characterization information for the SSI method evaluation program.

Low-level forced vibration tests (FVT) were conducted in two stages to define dynamic characteristics of the soil-structure system. A single eccentric-mass shaker was used to generate steady-state vibratory motions in a sufficient wide frequently range (1 Hz to 30 Hz). Responses were recorded at key locations of the containment structures as well as at internal steam generator and piping models.

Since the completion of the experimental facility in October 1985, eighteen earthquakes with magnitudes from 4.5 to 7.0 have been recorded at the site. A list is provided in Table 1. Among the earthquakes, events 4, 7, 12 and 16, which occurred on January 16, May 20, July 30, and November 14 of 1986, respectively, are the most significant ones. The peak accelerations recorded at the free-field ground surface at the site are 0.25g, 0.20g, 0.18g, and 0.20g, respectively.

METHOD VALIDATION PROGRAM

With the earthquake database established, EPRI, NRC, and Taipower initiated a cooperative SSI method evaluation program. The objective of the program is to evaluate the validity of the various SSI analysis methodologies and to quantify the uncertainties and sensitivities of SSI parameters and procedures. The ultimate goal of the program is to provide a technical basis to support more realistic SSI practice and to improve nuclear plant licensing stability.

The joint international research program focused on validation of current industry practice with respect to SSI analysis. The program utilized a round-robin approach so that independent evaluation on various methods can be performed by more than one analyst. Participants from the United States included four industry groups who are the users of various SSI methods and three university groups involving original method developers. In addition, two research groups were sponsored by Taipower, and three teams participated from Japan and one from Switzerland. Table 2 provides a list of the participating groups and the SSI method they evaluated.

The approach involved simultaneous independent efforts by each participating groups to devise models, perform blind prediction calculations, compare predictions with measured records, and finally to evaluate and assess the methodology. The effort was divided into the following four major phases:

- Construct SSI model based on given structure, soil, and site information and then perform blind prediction of forced vibration test (FVT) responses.
- Compare the predictions with given FVT measurements and refine the SSI model by correlating results between test and analysis.
- With seismic control motion given at a free-field ground surface located 50m from the 1/4-scale model, perform blind prediction SSI analysis using both the original best-estimate model and the FVT refined model. All seismic SSI analyses were following common industry practice by assuming vertically propagated shear waves and by assuming compatible soil strain-dependent properties adjusted to the proper earthquake level.

- Compare prediction results with recorded earthquake response data for all models and provide engineering assessments of the modeling techniques and analysis method used.

The May 20, 1986 earthquake (event 7) was selected as the base case for SSI method evaluation. This event was selected because it produced the most complete response recordings. The damaging earthquake of November 14, 1986 (event 16), was added at later stage of the program and was analyzed by a number of participants. Event 16 has much longer strong-motion duration than the event 7. However, the dominant energy content for both earthquakes is concentrated between 1 Hz and 5 Hz.

RESULTS AND FINDINGS

Results from the round-robin method evaluation program have yielded the following major observations and findings:

Forced Vibration For the forced vibration test, twenty-six accelerometers were installed on the 1/4-scale containment structure and the internal steam generator and piping model. For each applied forcing frequency, the shaker-excited response data were reduced and provided in the form of displacement response amplitude and phase angle. In general, all blind predictions of the containment response yielded fairly good agreement with the test measurements. Differences between the analysis and measurement results were generally within 20% for both response amplitudes and system frequencies. A typical comparison is shown in Figure 2. However, the blind predictions for the steam generator and piping were poor by all four research teams whose predictions included this model. After carefully examining the response data and the structural details, all four teams independently identified that the steam generator model support had a flexible mounting at the base, while a fixed support had been assumed in the prediction. When the support flexibility was considered in a refined model, predicted and test result comparison improved significantly. Figure 3 shows a typical result comparison.

The above exercise has proved that FVT can be very useful in calibrating and confirming analytical models and in evaluating design versus as-built conditions. However, care should be exercised when applying FVT results at low strain levels to actual strong motion earthquake situations of higher strain levels.

Earthquake Analyses Most SSI models predicted conservative response of the soil-structure system. The more advanced methods with modeling capability to include soil layering, wave scattering, and embedment effects were generally in better agreement with the measured response. Simplified approaches, such as soil-spring model, tend to produce overly conservative results. Some representative result comparisons are provided in Figures 4 and 5. Figure 4 shows comparison of computed and measured peak accelerations for earthquake event 7 at various instrument locations, including downholes (DHB47, DHB6), near-field surface (FA1-1), top and bottom of containment (F4US, F4LS), and top and bottom of the steam generator (F4SGU, F4SGL). Figure 5 provides response spectrum comparisons on top of the containment from various methods.

The containment model was essentially responded in a rigid-body rocking mode during earthquake shaking. This is due to the relative softness in the foundation soil. Lotung site soil has measured shear wave velocities ranging from only 100 mps to 300 mps at the upper 60 m of soil layers. However, the analyses generally underpredicted the amplitude of the rocking motion. This suggested that the actual soil stiffness degradation during the earthquake shaking may be more profound than the model computed. Possible reasons could be due to strong soil nonlinearity, pore water pressure buildup, and foundation separation.

Deconvolution using SHAKE to estimate free-field soil responses is generally in good agreement with the measured response at shallow depth (-6m, -11m) but not at the deepest downhole (-47m). It appears that the SHAKE deconvolution may reach its limit in computing deep layer responses for such soft soil media. However, with the control motion specified at the surface, the difficulty in deconvolving to depth has little impact to the SSI analysis in predicting the response of the 1/4-scale containment structure where the bottom of the building foundation mat is located at 4.7m below grade.

One major uncertainty has been the modeling of the soil properties, even though extensive site characterization studies were carried out and the same site information data package was given to all the participants. However, due to large amount of data scattering, significant differences exist in the users depiction of boundaries of soil layers, backfill material, level of saturation at the top soil layer, and strain-compatible modulus and damping. Judgment and experience still played a significant role in soil modeling.

CONCLUDING REMARKS

The round-robin SSI method evaluation program using Lotung earthquake data provided a unique opportunity for both the industry practitioners and the method developers to assess various SSI methodologies in a systematic and independent fashion. Comparisons of numerical simulations including blind predictions with the recorded responses have proved to be a success to test the complete chain of engineering judgments, modeling assumptions, and numerical calculations involved in SSI analyses for forced vibrations and seismic excitations. More detailed evaluations and assessment will be synthesized to address the analysis procedures and method application. Ultimately, the results of the program will form the technical basis for improving SSI practice and for focusing future research needs.

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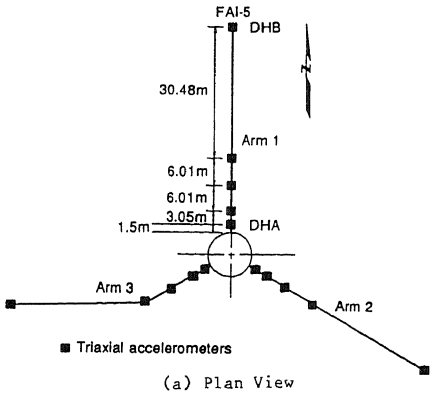
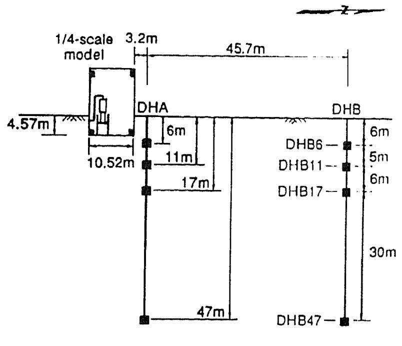
Table 1 Earthquakes Recorded by Lotung Experiment

EVENT	ORIGIN TIME	DEPTH (km)	MAG (M)	AZIM. (deg)	DELTA (km)
1	1985.09.20 15:01:24.01	3.99	6.3	106.97	45.7
2	1985.10.26 03:30:39.04	1.15	5.3	164.90	29.1
3	1985.11.07 05:25:17.31	79.00	5.5	30.46	16.9
4	1986.01.16 13:04:31.97	10.22	6.5	61.31	23.7
5	1986.03.29 07:17:14.66	10.32	4.7	159.43	8.5
6	1986.04.08 02:14:58.51	10.89	5.4	174.17	31.4
7	1986.05.20 05:25:49.58	15.82	6.5	194.53	66.2
8	1986.05.20 05:37:31.69	21.84	6.2	191.66	69.2
9	1986.07.11 18:25:26.27	1.14	4.5	146.21	5.0
10	1986.07.16 23:50:31.84	0.88	4.5	162.41	6.1
11	1986.07.17 00:03:33.51	2.01	5.0	90.10	6.0
12	1986.07.30 11:31:47.53	1.55	6.2	131.05	5.2
13	1986.07.30 11:32:	N/A	N/A	N/A	N/A
14	1986.07.30 11:38:31.70	2.28	4.9	118.75	4.7
15	1986.08.05 00:56:	N/A	N/A	N/A	N/A
16	1986.11.14 21:20:01.15	6.94	7.0	173.93	77.9
17	1986.11.14 23:04:	N/A	N/A	N/A	N/A
18	1986.11.15 00:18:	N/A	N/A	N/A	N/A

AZIM: Azimuth from 1/4-scale model center to epicenter.
DELTA: Epicenter distance from 1/4-scale model center.



(a) Plan View



(b) Elevation View

Fig. 1 Locations of Accelerometers

Table 2 Participants of SSI Method Validation Program

Sponsors	Participants	Method
• EPRI	• Bechtel	SSD,FLUSH,SASSI, CLASSI
	• Sargent & Lundy • Impell • EQE/EET	FLUSH SASSI CLASSI
• NRC	• UC Berkeley • UCSD/USC • CCNY	SASSI CLASSI SIM
• Taipower	• Eastern Intl. • Ntl.Taiwan Univ.	HASSI NEW
• TEPCO (Japan)	• Tajimi Institute • Ohsaki Institute	PETL HYBAX, AXERA
• CRIEPI (Japan)	• CRIEPI CE Lab.	RESP
• Fed. Ofc. of Energy (Switzerland)	• Basler-Hoffmann	FLUSH

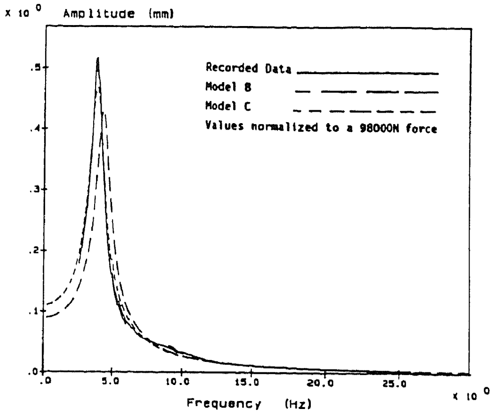


Fig. 2 Comparison of FVT Response at Top of Containment Model

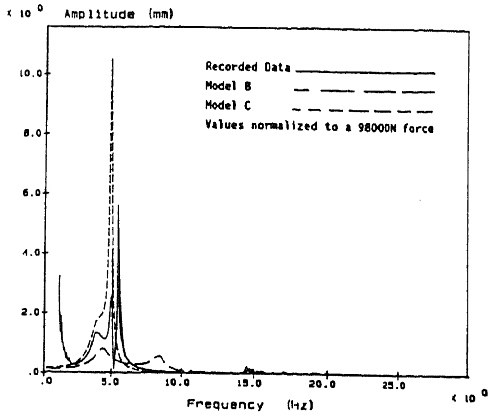


Fig. 3 Comparison of FVT Response at Top of the Steam Generator Model

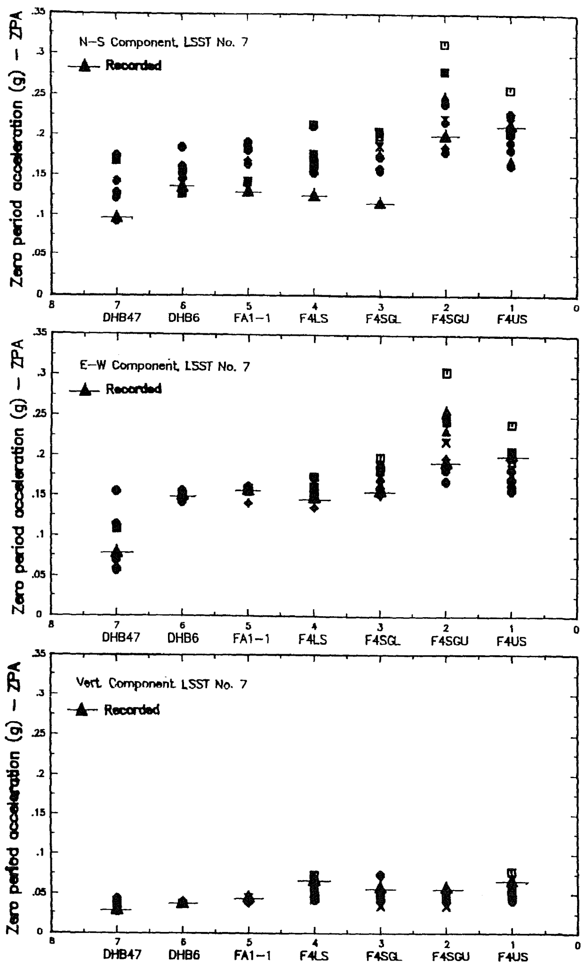


Fig. 4: Comparison of Predicted and Recorded Peak Accelerations for Earthquake Event 7

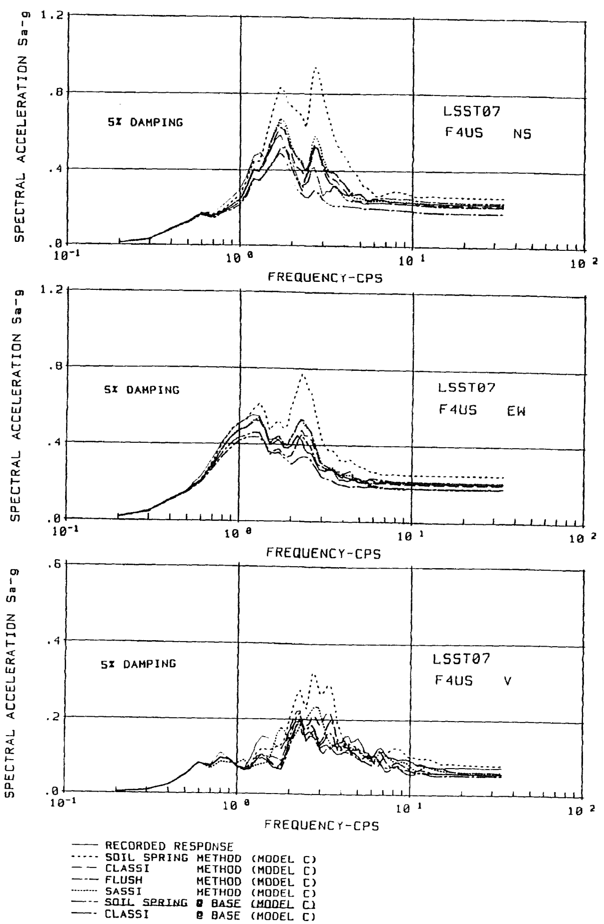


Fig. 5: Comparison of Response Spectra at Top of Containment for Earthquake Event 7