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SOIL-STRUCTURE INTERACTION
CORRELATION OF FIELD TEST RESULTS WITH ANALYTICAL PREDICTIONS

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SUMMARY

Presented are the results of correlating the measured forced vibration and seismic responses of a 1/4-scale containment model built in Lotung, Taiwan with the corresponding predicted responses using the hybrid method of modelling and the substructure method of analysis as implemented into the HASSI-4 computer program. As demonstrated by the excellent correlations obtained, the methodologies of this program are effective and efficient in solving the three-dimensional dynamic response of a soil-structure system and its associated internal equipment.

INTRODUCTION

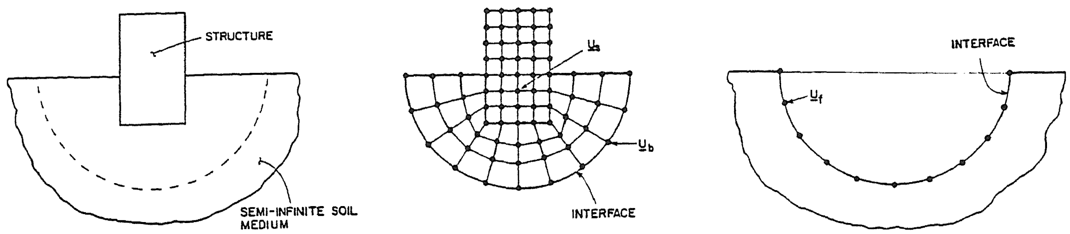
The Large Scale Seismic Test program (Ref. 1) at Lotung, Taiwan is a joint research effort sponsored by the U. S. Electric Power Research Institute (EPRI) and the Taiwan Power Company (TPC) to study the effect of soil-structure interaction on the response of a nuclear power plant containment structure. Under the test program, two nuclear power plant containment models (1/4 and 1/12 scales) were built in the seismic active area of Lotung, Taiwan at the site of the well known SMART-1 strong motion array. The two test structures and their near-field soils have been well instrumented to measure seismic responses; thus providing the necessary data base for validating various modelling and analysis methodologies used in predicting soil-structure interaction effects.

The objective of the investigation reported herein is to demonstrate the accuracy of a specific 3-D soil-structure interaction methodology, and associated computer program, through correlation of field test results with analytical predictions. This investigation is one of several such investigations carried out under a joint research program sponsored by EPRI and TPC (Ref. 2).

METHODS

The methodology used for the analytical predictions makes use of the hybrid method of modelling (Ref. 3) and the substructure method of analysis carried out in the frequency domain. The entire soil-structure system is partitioned into a near-field and a far-field by a hemispherical interface passing through the soil region, as shown in Fig. 1(a).

The near-field substructure as shown in Fig. 1(b), consisting of an embedded structure and associated equipment to be analyzed under prescribed load-



(a) SOIL-STRUCTURE SYSTEM (b) NEAR-FIELD (c) FAR-FIELD

Fig. 1 Hybrid modelling of soil-structure system

ing conditions and a finite portion of soil encompassing its base, which is modelled appropriately using finite elements. The far-field substructure as shown in Fig. 1(c), consisting of a semi-infinite half-space with surface cavity, is modelled as a continuum through the use of an impedance matrix relating the discretized cavity surface forces to their corresponding generalized nodal displacements. The hemispherical interface is chosen judiciously so that it will provide a smooth surface along which mathematical boundary conditions can be easily satisfied. Compatibility of forces and displacements between the two substructures are enforced over this interface in combining the equations of motion of the near- and far-fields. The analysis procedure was implemented into the computer program HASSI-4 suitable for dynamic analysis of the complete soil/structure system under applied harmonic forces or under three simultaneous components of earthquake motion (Ref. 4).

FIELD TESTS AND MODELLINGS

The EPRI/TPC field tests were performed under two types of excitation (1) forced vibration and (2) seismic ground motion. Initially, after excavation to allow for embedment of the 1/4-scale test structure, its basemat was constructed and tested vertically, radially, and tangentially under eccentric forced vibration over the frequency range $0 \sim 30\ Hz$ (Ref. 5). The analytical model using hybrid method is shown in Fig. 2 where the basemat was modelled as a rigid block, the sheet piles were modelled by equivalent beam elements and the soils were modelled by axisymmetric solid elements. Soil properties as shown in Table 1 were chosen after consideration of the low strain levels experienced and the effect of excavation.

Next, the full structure, steam generator model, and associated piping were constructed and backfill was placed providing 30 percent embedment. Forced vibration tests were then carried out in the radial and tangential directions with the exciter placed on the structure's roof (Ref. 6). For the correlation study, an analytical model was chosen as shown in Fig. 3 having soil properties as shown in Table 2 which were selected consistent with the results of a geophysical survey (Ref. 7).

Since completion of construction, the entire system has experienced numerous strong earthquakes during which response measurements were recorded. Responses measured during the earthquakes of May 20, and November 14, 1986 of magnitudes 6.5 and 7.0, respectively, were used for correlation purposes. The analytical model shown in Fig. 3 was again used but the soil shear moduli and damping ratios were adjusted to be consistent with the higher soil strains experienced during the earthquakes. These adjusted soil properties are shown in Table 3.

RESULTS

Using the established analytical models shown in Figs. 2 and 3, the equiv-

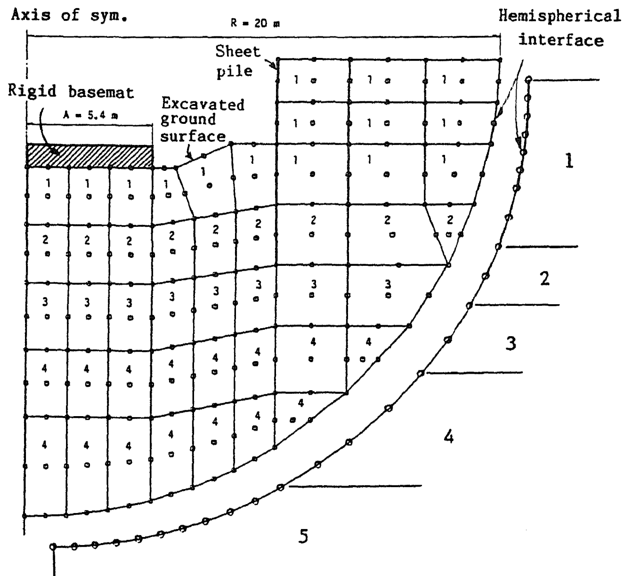


Fig. 2 Analytical model for FVT (I) analysis

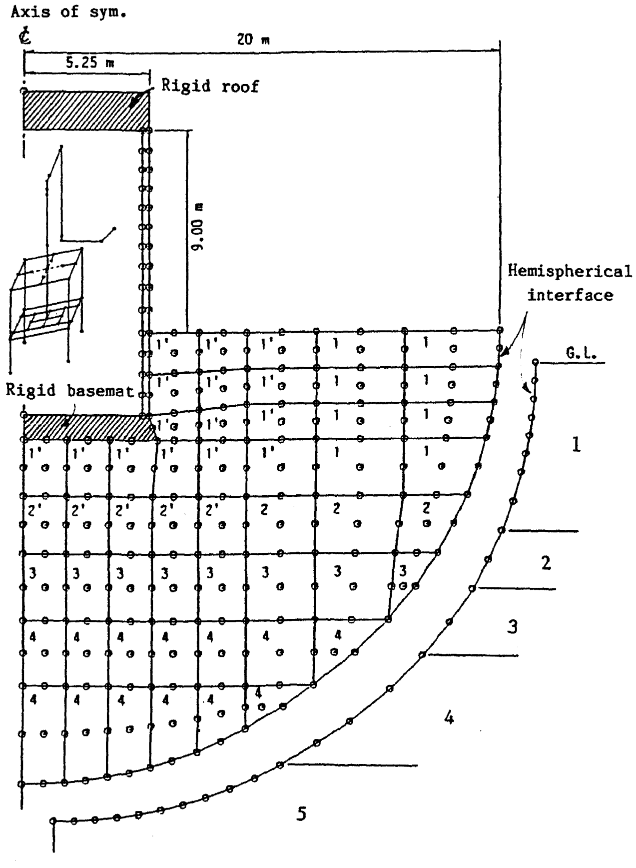


Fig. 3 Analytical model for FVT (II) and seismic analyses

Table 1 Soil properties for FVT(I) analysis

Cate-tory	Shear wave velocity C_s (m/sec)	Shear modulus G (kN/m²)	Poisson's ratio ν	Damping ratio β (%)
1	100	18000	0.44	1
2	150	40500	0.48	1
3	180	·58320	0.48	1
4	210	79380	0.48	1
5	240	103680	0.48	0

Note: Unit weight $\gamma = 17.7$ kN/m³ for all soils
damping ratio $\beta = 0$ for far-field soils

Table 2 Soil properties for FVT(II) analysis

Cate-tory	Shear wave velocity C_s (m/sec)	Shear modulus G (kN/m²)	Poisson's ratio ν	Damping ratio β (%)
1	120	25920	0.44	2
1'	120	25920	0.44	5
2	150	40500	0.48	2
2'	150	40500	0.48	5
3	180	58320	0.48	2
4	210	79380	0.48	2
5	240	103680	0.48	0

Table 3 Soil properties for seismic analysis

Cate-tory	Shear wave velocity C_s (m/sec)	Shear modulus G (kN/m²)	Poisson's ratio ν	Damping ratio β (%)
1	93	15550	0.44	4
1'	71	9070	0.44	7
2	116	24300	0.48	4
2'	106	20250	0.48	7
3	161	46660	0.48	4
4	188	63500	0.48	4
5	215	83205	0.48	0

Note: In Tables 2 and 3
unit weight $\gamma = 17.7$ kN/m³ for all soils
damping ratio $\beta = 0$ for far-field soils

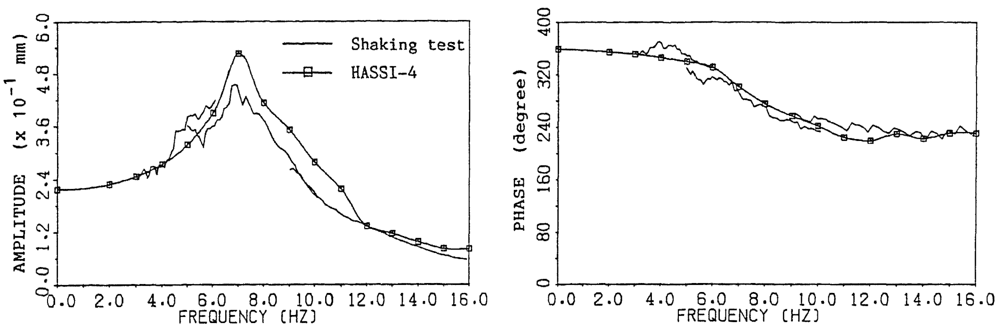


Fig. 4 Tangential displacement responses at shaker location (south edge of the basemat) in tangential test

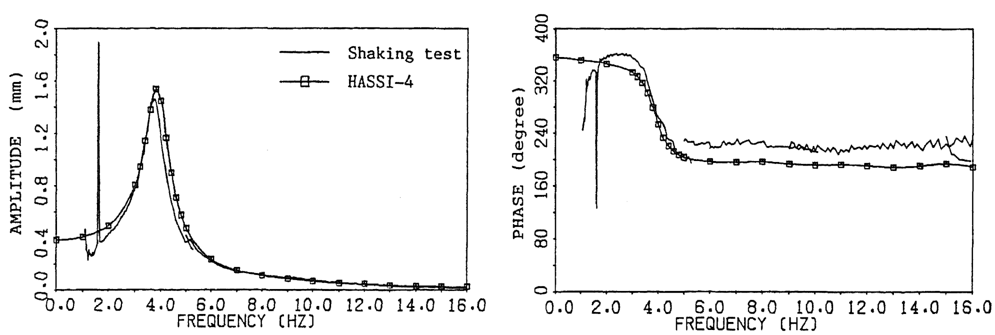
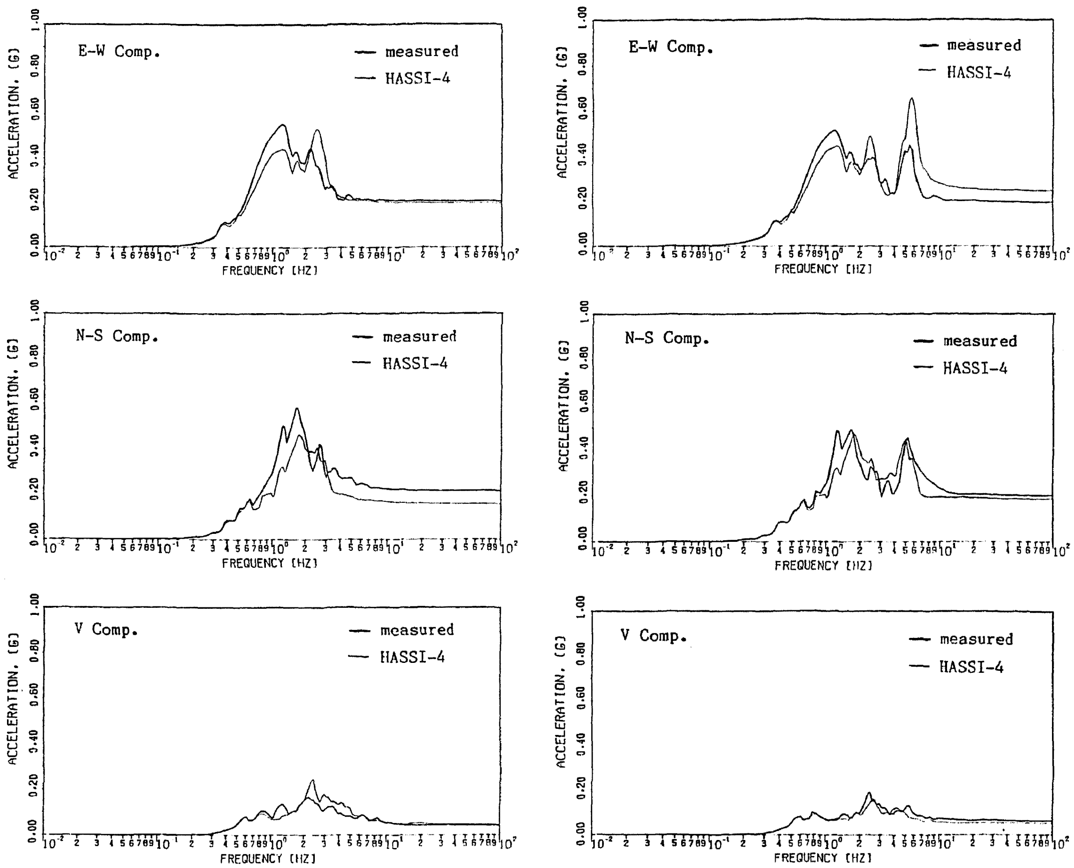


Fig. 5 Radial displacement responses at shaker location (south edge of the roof) in radial test

alent exciting loads were input to find responses under forced vibrations and under the free-field seismic ground motions recorded at a depth of 6 m and at a distance of 49 m from the structure. For the case of forced vibration of the basemat (FVT-I), the measured and predicted tangential displacement responses at the location where the tangential exciting force was applied are shown in Fig. 4 where it is seen that both the amplitude and phase angle distributions are in good agreement. The basemat responded nearly as a rigid body with its peak response occurring at a frequency of 7.0 Hz.

For the case of forced vibration of the full containment model (FVT-II), one analytical prediction using the HASSI model is shown in Fig. 5 where it can be compared with the corresponding measured field test result. Both the corresponding radial and tangential test results, show that the forced vibration response of the 1/4-scale structure is primarily rigid body rocking about a point slightly below its base. Little torsional response was experienced in the tangential test. Resonance was reached at 3.8 Hz where the system's response was magnified only about 3.6 times showing the presence of rather high total damping (material and radiation).

The seismic responses of the containment structure during the May 20, and November 14, 1986 Taiwan earthquakes are shown in Figs. 6 and 7 in the form of 5% damping response spectra. Comparisons show the spectra of the measured and predicted responses to agree very well. The structure experiences primarily rocking type response under seismic excitation which has high amplification at the 2.5 Hz resonant frequency, nearly quasi-static response for those frequencies well under 2.5 Hz, and greatly filtered response for those frequencies well above 2.5 Hz. The steam generator model and associated piping experience complex response under both forced vibration and seismic excitations due to the contribu-



(a) Containment roof (b) Top of steam generator

Fig. 6 Correlation of 5% damping response spectra of May 20, 1986 earthquake

tions of numerous modes having low damping.

CONCLUSIONS

Soil-structure interaction can have considerable influence on the seismic response of a nuclear power plant containment structure and its associated equipment. Analytical modelling for prediction purposes must realistically represent all mass, stiffness, and damping (material and radiation) properties of the system in 3-D form. Through the extensive correlation studies reported herein, the capability of the HASSI-4 computer program in solving the 3-D seismic response of a complete soil-structure-equipment system has been shown to be very effective and efficient.

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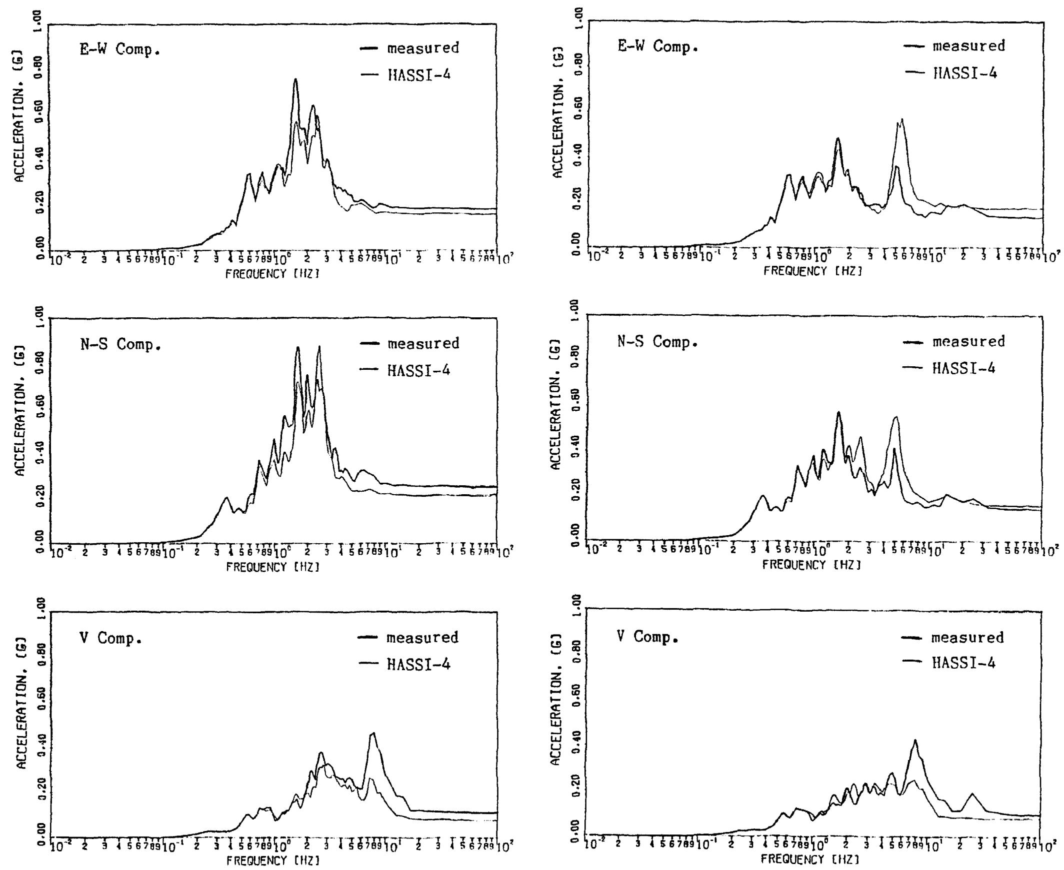

(a) Containment roof (b) Bottom of steam generator

Fig. 7 Correlation of 5% damping response spectra of November 14, 1986 earthquake

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