12WCEE
2000

1251

SUMMARY OF PREDICTION AND CORRELATION ANALYSES IN THE HUALIEN LARGE SCALE SEISMIC TESTS

Toshikazu HANAZATO[1], Hideaki SAITO[2], Masaaki NAKAZAWA[3], Toshio KOBAYASHI[4], Kazuhiro YOSHIDA[5] And Hiroshi TAJIMI[6]

SUMMARY

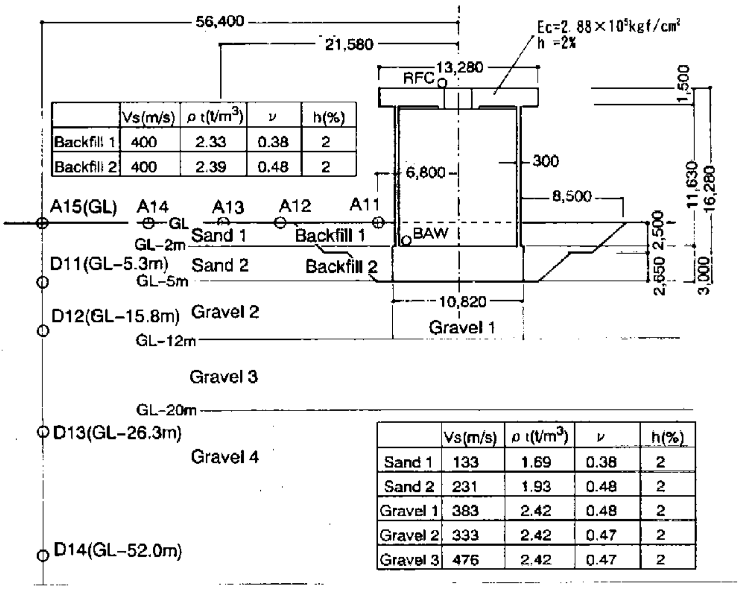
The seismic test program of a quarter-scale reinforced concrete containment model constructed in Hualien, a seismically active site in Taiwan, has been conducted for the international project (U.S., Taiwan, Korea, France and Japan) to study actual behaviors of soil-structure interaction system, as well as, to validate dynamic SSI analyses methodologies employed for seismic response prediction of nuclear power plants. At the first stage of the analytical program, both the blind prediction and the correlation analyses of the forced vibration tests before and after backfill were performed by the organizations participating in this project. At the second stage, the blind prediction and the correlation analyses of the earthquake record were subsequently carried out. The present paper summarizes these analyses results in order to validate the dynamic SSI methodologies ranging from simple soil-structure representation as Soil-spring model to more complex FEM, Lattice, SASSI, Thin layer method and Hybrid methods. For the evaluation basis, we focused on peak frequency and peak amplitude of response at roof. Statistical approach using these peak values was introduced to assess these SSI modeling techniques. The blind prediction analyses using the unified models of soils and structure after backfill showed that the peaks converged into a region with coefficients of variation of 0.06 and over 0.30 for the peak frequency and amplitude, respectively. As the prediction analyses results, whether or not soils just around the foundation were represented by finite elements had a significant effect on the numerical results. FEM and SASSI appeared to reflect a stiffer model than Soil-spring model. The correlation analyses conducted by appropriate evaluation of the soils and structure profiles resulted in a good comparison with the measurements. The validity of not only the conventional analysis methods employed in practical seismic design of commercial nuclear power plants but also the new analysis methods developed recently have been verified through the simulation analyses of the forced vibration tests and of the earthquake records.

INTRODUCTION

Evaluating dynamic soil-structure interaction effects and backfill effects are important in seismic design of nuclear power plants. Although methods of analysis for this purpose were studied by conducting the forced vibration tests and by the earthquake observations, most of these tests and observations were performed in an elastic region of low acceleration level, implying necessity for adequate verification of the analysis methods under large earthquakes. In order to study actual behaviors of soil-structure interaction, as well as, to verify the validity of various methods, the Hualien Large Scale Seismic Test program has been conducted since 1990 as the international project (U.S., Taiwan, Korea, France and Japan) [Tang,H.T.et al 1991]. In this Hualien LSST program that followed the Lotung LSST performed under the extremely soft soil conditions [Tang,H.T. et al 1987, Okamoto et al 1993a], a quarter-scale cylindrical containment model of reinforced concrete was constructed at the stiff soil site in Hualien, a seismically active region in Taiwan where high-level earthquakes

[1] *Tajimi Engineering Services,Ltd., Shinjyuku-ku, Tokyo, Japan, Email: hanazato@ pub.taisei.co.jp*
[2] *Power Engineering R&D Center, Tokyo Electric Power Co., Yokohama, Japan, Fax: (45)585-8986*
[3] *Power Engineering R&D Center, Tokyo Electric Power Co., Yokohama, Japan, Fax: (45)585-8986*
[4] *Kajima Technical Research Institute, Chofu, Tokyo, Japan, Email: toshio@ katri.kajima.co.jp*
[5] *Ohsaki Research Institute Inc., Chiyoda-ku, Tokyo, Email: yoshida1@ori.shimz.co.jp*
[6] *Tajimi Engineering Services,Ltd., Shinjyuku-ku, Tokyo, Japan, Email: hanazato@ pub.taisei.co.jp*

would be anticipated to occur. Fig. 1 shows the model structure and the soil conditions at the Hualien site. Both the blind prediction and the correlation analyses were carried out by the participating organizations to validate the technical basis for dynamic SSI analysis approaches. Those analyses were conducted not only for the forced vibration tests before and after backfill but also for the earthquake records. The methodologies employed by the consortium participants ranged from practical simple approach to more complicated 3-dimensional one. The main scope of the present paper is to summarize the Hualien blind prediction and correlation analyses on the basis of statistical approach.



	Vs(m/s)	ρ t(t/m^3)	ν	h(%)
Backfill 1	400	2.33	0.38	2
Backfill 2	400	2.39	0.48	2

	Vs(m/s)	ρ t(t/m^3)	ν	h(%)
Sand 1	133	1.69	0.38	2
Sand 2	231	1.93	0.48	2
Gravel 1	383	2.42	0.48	2
Gravel 2	333	2.42	0.47	2
Gravel 3	476	2.42	0.47	2

Fig.1 The model structure and the unified soil profiles with the instrumental locations at the Hualien site

ANALYSIS METHODOLOGIES

Table 1 lists the analysis methods employed in this Hualien project. The blind analyses to predict the response before the records were not opened, as well as, the correlation analyses to fit the calculation with the records were successfully conducted by the participating organizations using a variety of analysis methods being Soil-spring model, FEM, Lattice model and SASSI used in the practical seismic design of commercial nuclear plants and new analysis methods being Thin layer method, Hybrid methods developed recently. Table 1 also indicates that the main current in SSI analyses is to deal with soils as 3-dimensional field including axisymmetric system. In the present paper, since how to represent the soils just around the foundation were considered to affect the response of the structure, the analysis methods were categorized into : 1) Soil-spring ; 2) Thin layer ; 3) FEM ; 4)Hybrid in which soils are represented by finite elements; 5) Hybrid in which soils are discretized by finite elements; and 6) SASSI. To find out the effect of the representation of soils on the numerical results, the unified soil model and the unified structural conditions were given to all the participants for conducting the blind prediction analyses. These unified models made it possible to compare the blind analysis results under the common conditions of the soils and the structure. Therefore, they revealed a significant difference in the analysis results specific to the numerical techniques.

Table 1 SSI analysis methodologies employed in the Hualien LSST program

Country	Soil-Spring	Thin layer	FEM	Hybrid	Lattice	SASSI
Japan	○	○	○	○	○	
U.S.A	○					○
Taiwan			○	○		
Korea	○			○		○
France			○			

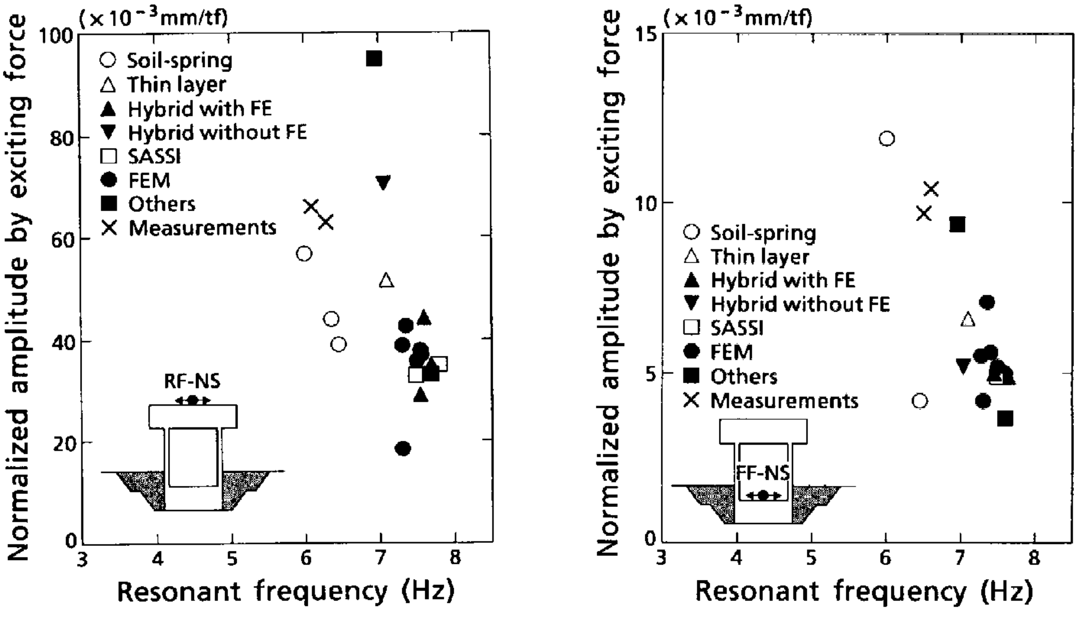
ANALYSES OF FORCED VIBRATION TESTS

Forced Vibration Tests

The Hualien 1/4-scale reinforced cylindrical concrete containment model was constructed on the gravelly soils after excavating the sandy layer of 5 meters depth, shown in Fig.1. Before starting earthquake observation, the forced vibration tests of the model structure were carried out for horizontal excitation at roof and at 1st floor, as well as, for the vertical excitation at 1st floor. These tests were executed to investigate the basic characteristics of the dynamic soil-structure interaction system under low strain level. The forced vibration tests using an excitor of 10tons were performed both before backfill and after backfill. The resonant frequency observed in the tests before backfill were 4.1Hz with the damping factor of about 4% for horizontal excitation. After backfill, the resonant frequency rose up to 6.1Hz and the damping factor increased up to 8% due to embedment effect.

Blind Prediction Analyses

A series of the geotechnical investigations, both field and laboratory ones, were carefully carried out to fully characterize the site geotechnical conditions. Based on this Hualien geotechnical investigation, the unified soil model shown in Fig.1 was proposed to conduct the blind prediction analysis [Okamoto et al. 1993b]. The design drawings of the structure with the concrete properties of $E=2.88\times10^5$ (kgf/cm^2) and h=2% were also given for the blind prediction analysis. Since the significant parameters for any of the analysis methods of the forced vibration tests were the stiffness and the damping of the soil-structure interaction system, we dealt with the peak frequency and the peak amplitude at the resonance curves. For horizontal excitation at roof and at 1st floor after backfill, Fig.2 plots the relationship between the predicted peak frequency and amplitude normalized by exciting force. Shown in Fig.2, the peak frequencies converged into about 7Hz, and at the same time, the normalized amplitudes diverged around 40(μm/tf) and 5(μm/tf) for horizontal excitation at 1st floor and 2nd floor, respectively.



a)Roof response for horizontal excitation at roof **b)Roof response for horizontal excitation at 1st floor**

Fig.2 Relationship between frequency and amplitude at resonance predicted using the unified soil and structure models, compared with the measurements

Tables 2 and 3 show the statistics of the analysis results using the unified models of soils and structure. Shown in Table 1, the coefficients of variation before backfill were evaluated to be approximately 0.04 and 0.28 for the peak frequency and the peak amplitude, respectively. On the other hand, shown in Table 3, the coefficient of variation became larger after backfill, because various techniques were applied for modeling of the backfill soils just around the foundation. Furthermore, these tables show the coefficients of variation for horizontal vibration at 1st floor are approximately equal to those for horizontal vibration at roof.

Table 2 Statistics of results of blind prediction analyses of forced vibration tests before backfill

Exciting Condition	Total number	Peak frequency		Displacement at peak*	
		Average (Hz)	Coefficient of variation	Average (μ m/tf)	Coefficient of variation
Horizontal at Roof	16	4.87	0.040	308	0.282
Horizontal at 1st Floor	11	4.83	0.036	56.6	0.269

*Normalized amplitude by force

Table 3 Statistics of results of blind prediction analyses of forced vibration tests after backfill

Exciting Condition	Total number	Peak frequency		Displacement at peak*	
		Average (Hz)	Coefficient of variation	Average (μ m/tf)	Coefficient of variation
Horizontal at Roof	18	7.22	0.067	43.3	0.382
Horizontal at 1st Floor	15	7.22	0.062	5.89	0.355

*Normalized amplitude by force

Tables 4 and 5 show significant difference in the predicted peak frequency due to analysis methodologies for horizontal excitation before and after backfill, respectively. These tables indicate that FEM and SASSI provide stiffer models for soil-spring representation. For the case after backfill, shown in Table 5, the peak frequency was predicted to be 6.3Hz and 7.4Hz for Soil-spring model and for FEM, respectively. Furthermore, the peak

Table 4 Difference in frequency predicted in blind analyses of forced vibration tests before backfill due to analysis methodologies

Methodology	FVT-1 Prediction Peak freq. of roof excitation
Soil Spring	4.7
Thin layer	4.7
Hybrid with FE	4.8
Hybrid without FE	4.7
SASSI	5.0
FEM	5.1

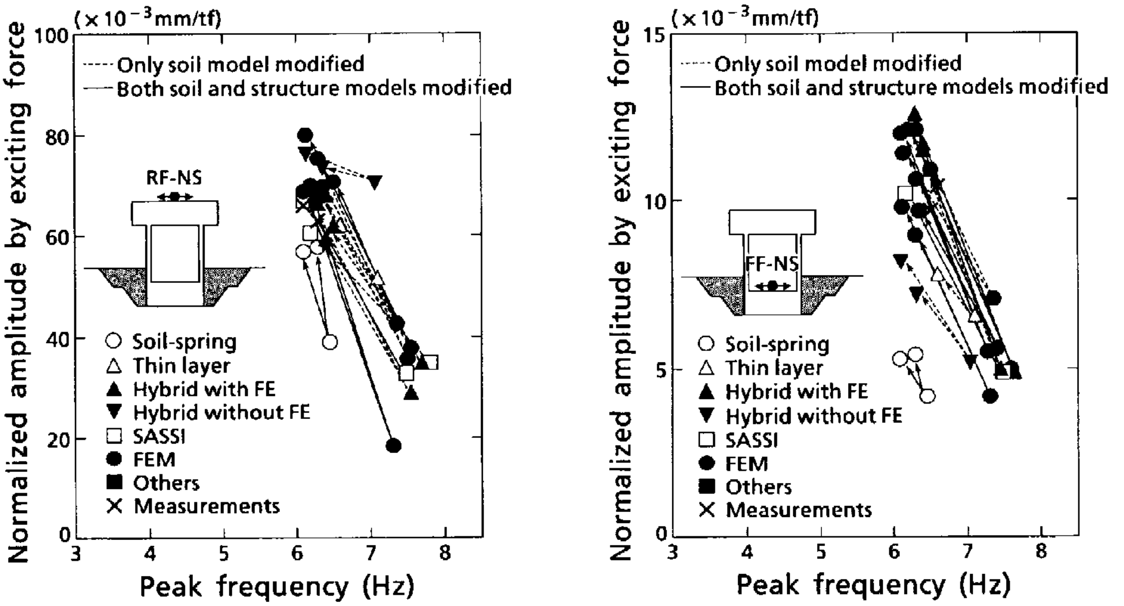
Table 5 Difference in frequency predicted in blind analyses of forced vibration tests after backfill and earthquake records due to analysis methodologies

Methodology	FVT-2 Prediction	Earthquake Prediction
	Peak freq. of roof excitation	Peak freq. of trans. func. (RF/A15)
Soil Spring	6.3	6.4
Thin layer	7.1	7.0
Hybrid with FE	7.6	7.3
Hybrid without FE	7.0	7.1
SASSI	7.6	7.4
FEM	7.4	7.4
Lattice		6.5

frequency predicted by both SASSI and Hybrid method representing the soils just around the foundation by finite elements was 7.6Hz approximately equal to that of FEM. The peak frequency predicted using the thin layer method, 7.1Hz, fell in-between those predicted using Soil spring model and FEM. It has a significant effect on the predicted response of the soil-structure interaction system how to represent the soils just near the foundation. To clarify such effect, the stiffness ratio of the finite element representation to the soil-spring one, k_F/k_S , was estimated on the assumption that k_F/k_S was directly proportional to $(f_F/f_S)^2$, where k = stiffness ; f = peak frequency ; and the subscript S and F denote Soil-spring model and FEM, respectively. From the predicted frequencies of $f_S = 6.3Hz\ and\ f_F = 7.4Hz$ after backfill [Kobayashi et al. 1996a], the stiffness ratio k_F/k_S was estimated to be approximately 1.4. This significant ratio of 1.4 indicates that the finite element representation provides the stiffer model by 40% than Soil-spring method. For the case before backfill, the stiffness ratio k_F/k_S was estimated to be approximately 1.1 from $f_S = 4.7Hz\,and\ f_F = 5.1Hz$. Depending mainly on the representation of a displacement field of soils just near the foundation, such characteristics due to the analysis methodology appeared in the numerical results. As is well known, when soils are discretized into smaller meshes, since the displacement field defined in the finite element approximate better the field represented by exact solutions based on an elastic wave theory of a homogeneous half space, the apparent stiffness of FEM may approach that of Soil-spring model.

Post-Test Correlation Analysis

After comparing the prediction analyses with the measurements, the correlation analyses have been subsequently conducted by the participating organizations. Most of the participants carried out the correlation analyses by appropriate modification of the soil model and/or the structure model, employing the same methodologies used in their prediction study. Shown in Fig.3 for horizontal excitation, the correlation analysis results converged into a small neighborhood of the measurements. In this figure, starting and end marks of arrows denote the peaks at the resonant curves obtained from the prediction and the correlation analyses, respectively. Fig.3 also demonstrates that not only the more complex FEM and SASSI but also the simple soil-spring approach can produce the adequate frequency response by using the appropriate soil and structure models.



a)Roof response for horizontal excitation at roof **b)Roof response for horizontal excitation at 1st floor**

Fig.3 Approach of the correlation analysis results to the measurements from predictions using the unified models

ANALYSES OF EARTHQUAKE RECORDS

Earthquake Observation

Since April in 1993, the earthquakes have been observed to collect data at the Hualien site. The observation included not only the measurement of acceleration by high-density accelerometer arrangement, but also the measurement of earth pressure between base and soil. Furthermore, it included the measurement of pore water pressure and of both settlement and inclination of model structure during earthquakes. Although the records obtained so far related only to the middle- and low-level earthquakes, the blind prediction analyses using the earthquake data recorded on January 20,1994 (M=5.6, Epicentral distance=27km) was conducted by the consortium organizations [Hanazato et al. 1996b].

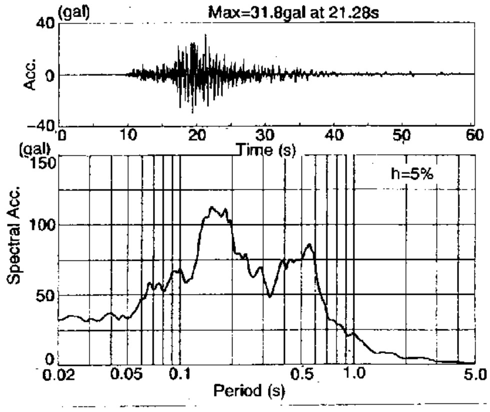


Fig.4 The control motion at A15 given for the simulation analyses (L-component)

Blind Prediction Analyses

The free field records at the ground surface (A15 in Fig.1) were given as the control motions to predict both the ground motions along the downhole array and the responses of the structure and its surrounding soils. As well as the blind analyses of the forced vibration tests, the unified models of soils and structure were given to all the participating organizations. As for the free field soil system, a good comparison of the predicted and the observed motions along the downhole array verified the validity of the deconvolution solutions employing one-dimensional elastic shear wave propagation theory (ex. SHAKE) using the unified soil properties. As for the SSI system, the participants employed the same techniques as they used in the blind analyses of the forced vibration tests, summarized in Table 1. Shown in Fig.4, since the peak acceleration of the control motion was at 30-40gals, they conducted linear response analyses using the unified models of soils and structure shown in Fig.1. In the present paper, we focussed on the response of the structure to summarize the dynamic SSI analyses results, dealing not only with the peaks of transfer functions from the roof response to the control motion but also with the peaks of response spectra at roof. As results of the prediction analyses using the unified models, Figs 5 and 6

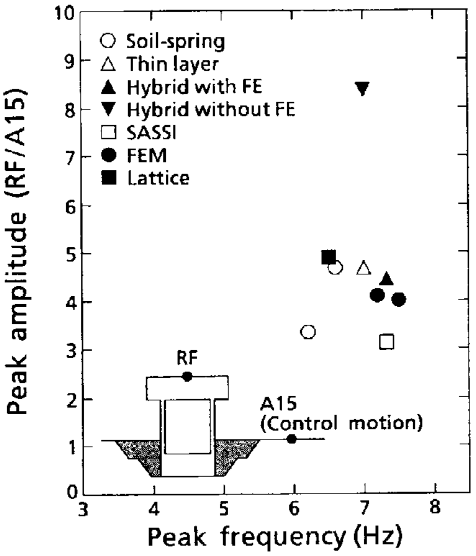


Fig.5 Relationship between frequency and amplitude at peaks of predicted transfer function (RF/A15)

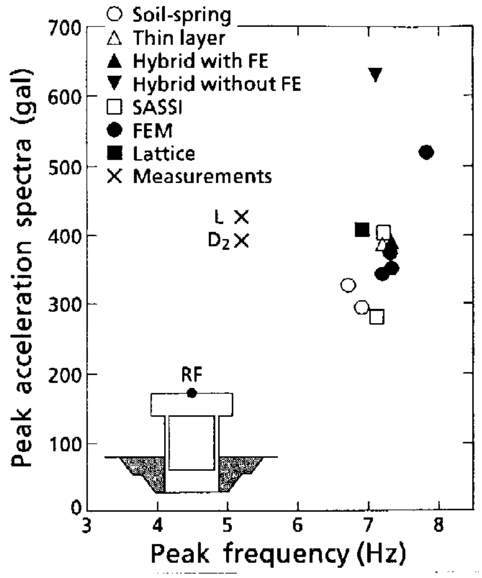


Fig.6 Relationship between frequency and amplitude at peaks of predicted response spectra (RF,h=5%)

plot the relationship between frequency and amplitude at the peak of the transfer function and the response spectra at roof, respectively. Shown in Figs. 5 and 6, the peaks converged into about 7Hz in frequency. At the same time, the peaks diverged around 4.0 and 350Gals in amplification and spectral acceleration, respectively. Table 6 shows the statistics of the analysis results of the earthquake prediction using the unified models. Shown in this table, the coefficient of variation of the peak frequency and the peak amplification at the transfer function were evaluated to be approximately 0.06 and 0.32, respectively. It should be pointed out that these statistical values were well compared with those obtained from the forced vibration tests after backfill shown in Table 3, because each participant employed the same analysis methodology in this earthquake prediction study as used in the analysis of the forced vibration tests. In table 5 showing difference in the predicted peak frequencies due to the analysis methodologies, the same relationship between the methodologies and the peak frequency was found out as that obtained from analyses results of the forced vibration tests after backfill. As was mentioned in 3.2 for the forced vibration tests, FEM, SASSI and Hybrid method representing the soils around the foundation by finite elements provided stiffer model than Soil-spring model.

Table 6 Statistics of earthquake blind prediction analysis results using the unified models

Response characteristics at roof	Total number	Frequency		Amplitude	
		Average (Hz)	Coefficient of variation	Average	Coefficient of variation
Peak of transfer func. (RF/A15)	9	6.97	0.060	4.62	0.316
Peak of response spectra (h=5%)	12	7.17	0.037	393gal	0.238

Correlation Analyses

In Figs 5 and 6, since there showed some discrepancy in frequency and in amplitude between the prediction using the unified models and the observation, the correlation analyses were subsequently carried out by employing the same methodologies that they used in the prediction analyses and by appropriately modifying the

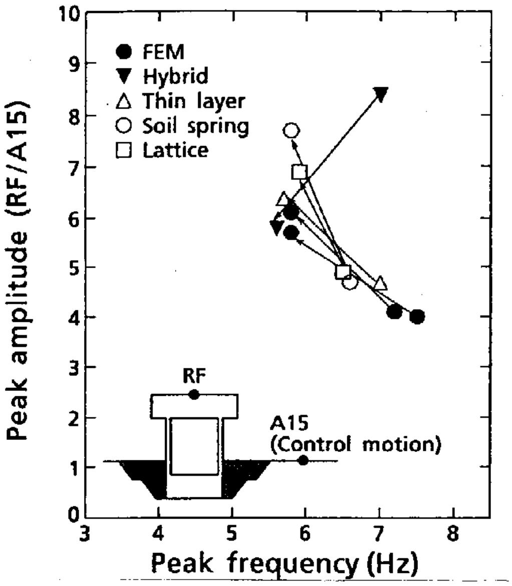


Fig.7 Convergence of the correlation analysis results from the predictions shown in Fig.5 ; Peaks of transfer function (RF/A15)

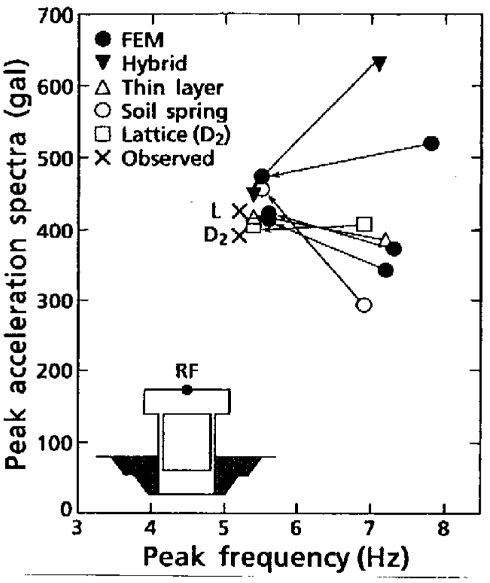


Fig.8 Approach of the correlation analysis results from the predictions shown in Fig.6 to the observations ; Peaks of acceleration response spectra (RF,h=5%)

soil and structure models. As results of the correlation analyses, Figs.7 and 8 show the peaks of the transfer function and the response spectra, respectively. In these figures, arrows are drawn from prediction analyses using the unified models to correlation ones. Fig.8 presents a good correlation between the analyses using the modified soils and structure models and the observation.

CONCLUDING REMARKS

As results of the blind prediction analyses using the unified models of soils and structure, the coefficients of variation were estimated to be about 0.06 for the peak frequency and over 0.30 for the peak amplitude at the resonance curves in the forced vibration tests after backfill. These coefficients were evaluated to be approximately equal to those at the transfer function during the earthquake from the response at roof to the control motion defined at the ground surface. The coefficients of variation of the peak values obtained from the blind prediction analyses before backfill were significantly smaller than those after backfill, because the effect of the modeling of the backfilled side soils was neglected. .

Whether or not the soils just around the foundation were represented by finite elements showed a significant effect on the predicted frequency responses of the SSI system. FEM and SASSI appeared to provide a stiffer model than Soil-spring model.

As results of the correlation analyses conducted by evaluating appropriate models of the soil and the structure, the methodologies ranging from those used practically in seismic design of nuclear power plants to more advanced ones developed recently were well compared with the measurements. This verification demonstrates that those methodologies can simulate well dynamic behaviors of ddynamic soil-structure interaction system during both forced vibration tests and earthquakes. In order to observe a high-level earthquake motions at the site, the duration of the Hualien earthquake observation is extended.

ACKNOWLEDGEMENTS

The Consortium of Hualien LSST Program consists of EPRI, NRC, Taipower, CRIEPI, CEA, Edf, Framatome, KEPCO, and TEPCO. The writers acknowledge the great effort of Dr. H.T.Tang, EPRI, who is Chairmen of this international consortium.

REFERENCES

Kobayashi, T., Yamaya,H., Kitamura E. and Sugawara,T.(1996a), “ System identification of the Hualien LSST model structure”, *11WCEE*, Disk 1 of 4, Paper No. 67

Hanazato,T., Kishi,Y., Sakai,Y. and Tajimi,H. (1996b), “Earthquake blind prediction analysis using ring exciting thin layer method in the international project of Hualien large scale seismic test”, *11WCEE*, Disk 2 of 4, Paper No.1008

Okamoto, T. et al (1993a), “Distribution of ground rigidity in Hualien project of large scale seismic test”, *Transactions of SMiRT13*, Vol.III, pp97-101

Okamoto,T. et al (1993b), “Ground model for seismic response analysis in Hualien project of large scale seismic test”, Transactions of SmiRT13, VolIII,pp1102-108

Tang.H.T. et al (1987), A large-scale soil-structure interaction experiment : Part I Design and construction”, *Transactions of SMiRT9*, Vol.K1,pp177-182

Tang,H.T. et al (1991), ”The Hualien Large-Scale Seismic Test for Soil-Structure Interaction Research”, *Transactions of SMiRT11*, Vol.K1, pp69-74