STUDY ON DYNAMIC CROSS INTERACTION OF STRUCTURES BY EARTHQUAKE OBSERVATION AND FORCED VIBRATION TEST

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ABSTRACT： NUPEC has been carrying out experimental studies to understand basic Soil-Structure Interaction (SSI), "Model Test on Dynamic Cross-Interaction Effects of Adjacent Structures (1994-2001)". The study is currently ongoing. For this test we have constructed BWR reactor building models of 1/10 scale and performed vibration tests and earthquake observations. In this paper, we first present earthquake observation results including examples of an adjacent building effect, one of the typical SSI effects. Secondly, we present an analytical SSI model for use in simulation analyses of the vibration tests and earthquake observations. In the simulation of earthquake observations, the most important issue is the modeling of geometrical condition around the building specimens. It is found that certain modeling parameters exert a larger influence on the analytical results.

KEYWORDS：Dynamic Cross Interaction, Earthquake Observation, Forced Vibration Test, Large Scaled Model

1. INTRODUCTION

Soil-Structure-Interaction (SSI) is among the most important factors in properly evaluating a structure's earthquake response. In particular, reactor and/or turbine buildings at nuclear power plants (NPP) are generally heavy and massive, so the SSI effect plays an important role in their earthquake responses. Especially, a reactor building is generally constructed closely adjacent to other buildings like a turbine building. In such a condition, seismic response of the reactor building might be affected by the adjacent buildings. This paper calls the effect by the adjacent building Dynamic Interaction Effect (DCI).

In order to understand DCI phenomena, NUPEC has been carrying out experimental studies since 1994, "Model Test on Dynamic Cross-Interaction Effects for Nuclear Power Plant Buildings (1994-2001)" [Kitada et al. 1998]. This test consists of Field Test and Laboratory Test. In the Field Test, earthquake observation and forced vibration tests were performed on three kinds of building models with some parameters considering actual plant buildings condition and being expected to influence DCI effect.

Simulation analyses have been carried out using these earthquake observation records. In these analyses, the SSI effects were modeled based on the theoretical methodologies using soil springs postulated between the base of the buildings and surrounding soil and using input motions supposed to be applied to the models.

The soil springs were evaluated based on detailed studies of vibration test data and achieved satisfactory results. However, we are still having problems with the evaluation of the seismic input. The difficulties derive from the fact that earthquake motions display great variety in maximum acceleration, duration, envelope, and vibration frequency, depending on the properties of the seismic source, such as magnitude, focal distance, depth, directivity, etc.

In this paper, we will first present some earthquake observation results under the condition without and with embedment of the lowest story of the building model. Representative characteristics by DCI effect will be shown.

Second, we will show simulation analysis results of the earthquake observation.

2. SUMMARY OF THE TEST

2.1 OUTLINES OF THE TEST

NUPEC conducted three research projects on SSI phenomena from 1980 to 1994 to confirm the adequacy of aseismic design analyses of NPP reactor buildings. A project in particular, “Model Tests on Embedment Effect of Reactor Buildings (Embedment Test)” was conducted to evaluate the essential problems of SSI, embedment effect [Fukuoka et al. 1995], [Ohtsuka et al. 1996]. “Model Test on Dynamic Cross-Interaction Effects of Adjacent Structures (DCI Test),” succeeded to the project to resolve the DCI effect by evaluating rational modeling of soil spring and seismic input motion. In those projects, earthquake observations were carried out continuously and a large number of records have been accumulated regarding acceleration time histories for free field and building responses. The model structures were constructed on three locations (Locations A, B and D). The building conditions and the plot plan are shown in Figure 1. The Embedment Test compared two soil conditions, single building without and with embedment of the lowest story of the building model. In the DCI Test, three building conditions are planned: single building model (SB, hereafter), two identical adjacent buildings model (TIB, hereafter) and two different adjacent buildings model (TDB, hereafter). Figure 2 shows the locations of the free field, the boring points and the models. These models with embedment are shown in Photo 1. The new free field observation point was almost equidistant from each location. To discuss and analyze the observed data, we have carried out soil surveys by boring at several points around the models.

At this site, we have observed over 150 earthquake events, including 26 earthquake events whose recorded maximum acceleration in free field exceeded 10 Gal. The details of the events are shown in Table 1. Two of the events had maximum accelerations of over 100 Gal [Suzuki,et al. 1999].

2.2 EARTHQUAKE OBSERVATION RESULTS

Field tests were carried out at the test site used for the preceding test project, “Model Tests on Embedment Effect of Reactor Building,” and the two model buildings were inherited from that project.

Figure2 illustrates the model buildings used in the test. Three model conditions— SB, TIB, and TDB were employed to investigate the effect of adjacent buildings on the SSI phenomena affecting the building in question. The buildings used in this project are models of a reactor building (BWR) and a turbine building. The scale of the models was about 1/10 of the actual buildings. The space between the two different buildings (reactor building and turbine building) was determined in reference to the closest example of such buildings at an actual NPP. The space between the identical buildings was set to obtain basic data related to the dynamic interaction between the model buildings. The dimensions of the model buildings are shown in Figure 3. Earthquake observations were made to investigate the interactions between two adjacent buildings under actual earthquake conditions. The tests consisted of two series of tests without and with embedment.

Two earthquake observation data from January 1998 and November 1998, without and with embedment are shown as the examples. Figure 4 and Figure 5 show acceleration time histories and their Fourier Spectra observed at free field surface (GL-3.0m). The source locations of the two earthquakes are relatively near each other and shapes of acceleration time histories and spectra are similar each other. The earthquake observations in the free field were done at the site independently of the model buildings. The data were used to estimate the actual earthquake ground motion applied to the building models.

Table 1 shows maximum response acceleration obtained at the top of the A building models AA, BAs and DA. In the case without embedment, acceleration responses of SB and TIB are shown nearly the same level. On the other hand, in the case with embedment, acceleration responses of TIB tend to be smaller than those of single building model. The responses of TDB are relatively small because the lower half part of the basemat is embedded into bearing stratum. Figure 6 and Figure 7 show the Fourier spectra of earthquake acceleration time histories observed on the top of the SB and TIB. Dominant frequencies of 6Hz and 13Hz in horizontal and vertical without embedment, respectively, are shifted higher by the embedment. Peak amplitudes with embedment decrease due to embedded effect.

With regard to comparison between SB and TIB after embedment, horizontal peak amplitudes of TIB are apparently smaller than that of SB, which is different from the tendency before embedment. Significant change of vertical response can not be observed.

Figures 8 and 9 show the earthquake records observed at TDB, DA and DF, without and with embedment respectively. In these figures, the corresponding Fourier spectrum of the SB is also shown. Figure 8 compares the Fourier spectra of the acceleration records at TDB, without embedment. Figure 9 shows the comparison of the Fourier spectra of the earthquake records of the same kind of buildings (AA and DA) with embedment.

From these results, it is clear that the dominant peak frequency in the spectra shift higher because of the embedment. Furthermore, by comparing the response of building AA, the single building structure, it is also clear that the spectra of TDB in Figures 8 and 9 contains high frequency component around and over 10Hz. This phenomenon could be considered the DCI effect of adjacent buildings.

In the following section, we present simulations of test results of TDB without embedment, emphasizing the simulation modeling. We also demonstrate the difficulty of earthquake response analysis, especially for estimating seismic input motion, even without embedment.

3. SIMULATION OF EARTHQUAKE OBSERVATIONS

In this section, we describe our simulation methodology and the earthquake responses simulation results of the model buildings. First, we show the analytical modeling procedure for earthquake response using a model consisting of the building models, surrounding soil and deep soil. The model parameters are determined by simulating the forced vibration test results. Second, we show the results of the simulated earthquake responses of the modeled buildings.

In this simulation analysis, the TDB used for the DCI tests were selected as the actual test case.

3.1 MODELING FOR SIMULATIONS

Vibration tests of the modeled buildings using an exciter were carried out to evaluate the vibrational characteristics of the building models including surrounding soil.

Furthermore, to understand the effects of embedment on the DCI among adjacent buildings, the tests were carried out with and without soil embedment.

The test model chosen for the explanation of the modeling methodology is TDB, a reactor and a turbine building (DA and DF).

Simulation analyses of forced vibration tests of the TDB without embedment were performed using a soil model obtained by the site soil survey. The results were compared quantitatively with the test results to learn how to simulate the DCI effect.

Figure 10 shows the analytical model developed for use in the simulation. Table 2 shows the characteristics of the soil model used in the final step of the simulation. The analytical model of the TDB is modeled by rigid solid elements without mass for foundations and multi-lumped mass sticks elements standing on the center of the foundations for upper structures. The foundation of the DA is embedded 1m in the soil. Therefore, both foundations and the soil in the vicinity of the buildings were modeled together in the three-dimensional FEM. The model of the soil underneath the 3D-FEM model was treated separately as horizontally layered soil. The analysis was carried out using the “three dimensional thin-layered element method.” The soil model has a viscous boundary at the bottom.

The analyses were performed in the following three steps. First, we ignored the excavated soil for modeling the SSI system. The model gave simulation earthquake responses having a lower dominant peak frequency with a larger amplitude as compared to the corresponding earthquake observation results. Therefore, in the second step, the excavated soil was introduced into the soil model to add the effect of the excavated soil the earthquake response of the buildings. As a result, the analytical model produced improved results, comparing with the tests of the reactor building model. However, the dominant peak frequency of the turbine model became higher than that of the corresponding earthquake observation result. Elastic wave exploration at the ground surface had been performed on the test location just before model construction, and a loose stratum had been discovered in the soil underneath the buildings model, softening the soil. Therefore, this relaxation of the soil was introduced to the surface of the soil model in the final step. The analytical results produced by the final model, which included the cut soil and the relaxation underneath the modeled building, agreed well with the test results for the TDB (Figs. 13(a) and (b)).

3.2 SIMULATION ANALYSIS OF EARTHQUAKE RESPONSE

Simulation analysis of the TDB for the earthquake observation records of January 1998 was performed using the analytical model of the final step described in the previous section. The input earthquake motion to be applied to the model was calculated from the free field observation data by the single-dimensional wave propagation analysis. The soil characteristics used for the analysis are shown in Table 3. Comparison between the observed and calculated free field acceleration time histories is shown in Figure 12. The calculated acceleration time histories agree well with the corresponding observed time histories. Therefore, our method of wave propagation analysis was confirmed to give satisfactory results.

Based on these results, earthquake response analyses of the model buildings were carried out by applying the calculated motion. The analyses were performed in the three steps of the model shown in the previous section. Calculated acceleration response spectra of the building response are shown in Figure 13 together with the observation results.

As it can be seen in this figure, there are some unsatisfactory points that should be imposed in the fitting between observed and calculated results around 5Hz and 10Hz. Comparing these simulation results, we attribute the unsatisfactory results primarily to the evaluation of the input motions applied to the analytical model. We are considering that the evaluation of the input motion to be applied to the model is one of big remaining problem. Particularly for the 10Hz peak, the frequency correspondent is considered directly related to the modeling of surface layer. Therefore, it is thought that the evaluation of input motion causes disagreement with the observed result around 10Hz. To understand the influence of surface layer, we are carrying out the same kind of simulation analysis for test results with embedment, in which the lowest story of the building model is connected to the surface layer through the backfill soil.

4. CONCLUDING REMARKS

NUPEC has conducted three SSI model tests in series to study the Dynamic Cross-Interaction effect. In the tests, earthquake observations and forced vibration tests had been carried out continuously. As a result, we accumulated data of 26 earthquake events whose maximum observed free field acceleration exceed 10 Gal, in which data observed in

Using these test data, NUPEC has performed simulation analyses to confirm the adequacy of current earthquake response analyses. The simulation analyses for the forced vibration tests using soil springs derived from soil surveys give results that agree reasonably well with the test results. The simulation analyses for earthquake observations also give satisfactory results. However, there still remain several problems to evaluate input motion rationally. The problematic factors include uncertainties in detailed soil structures beneath the building, vibration damping in the soil, and so on.. Some rationalization for the analytical model, particularly for the model to be used in design analyses, is required. NUPEC intends to continue its effort to develop rational modeling methodology for soil-structure interaction analysis.

ACKNOWLEDGMENT

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REFERENCES

Fukuoka A., et al.,: “Dynamic Soil-Structure Interaction of Embedded Structure”, Trans.13th SMiRT, vol.III, pp.85-90, Porto Alegre, 1995.

Kitada, Y. et al.,: “Soil-Structure Interaction Effect on An NPP Reactor Building –Activities of NUPEC; Achievements and The Current Status-”, Proc. UJNR Workshop on Soil-Structure Interaction, pp.18-1~18-14, Menlo Park, 1998.

Ohtsuka,Y., et al.,: “Experimental Studies on Embedment Effects on Dynamic Soil-Structure Interaction”, Proc.11th-WCEE, Paper No.59, Acapulco, 1996.

Suzuki,A. et al.,: “Evaluation of Seismic Input Motions and Reponses of Buildings in Nuclear Power Plants”, Proc.OECD-NEA Workshop on Engineering Characterization of Seismic Input, Session4, 1999.

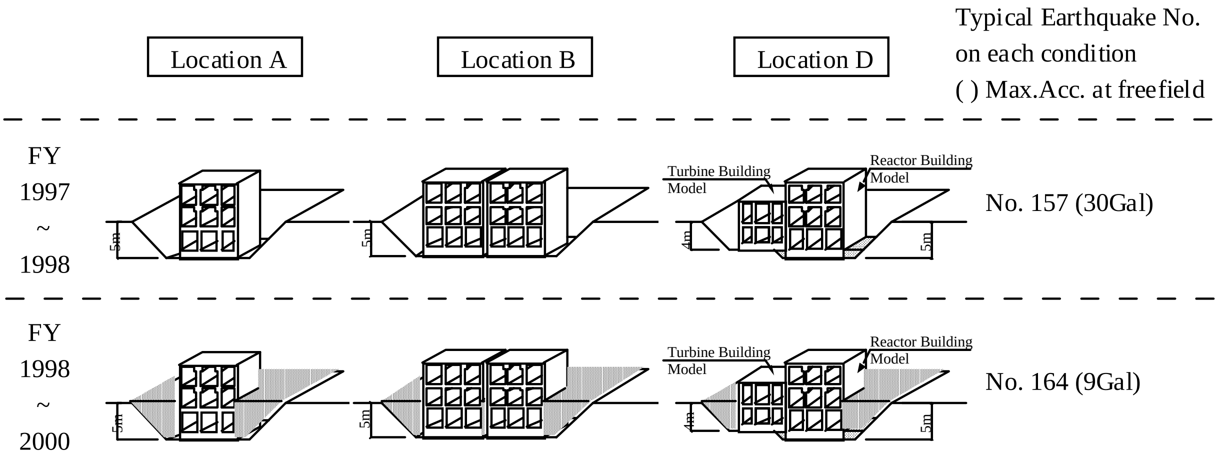


Fig. 1 Embedment Conditions of the Building Models

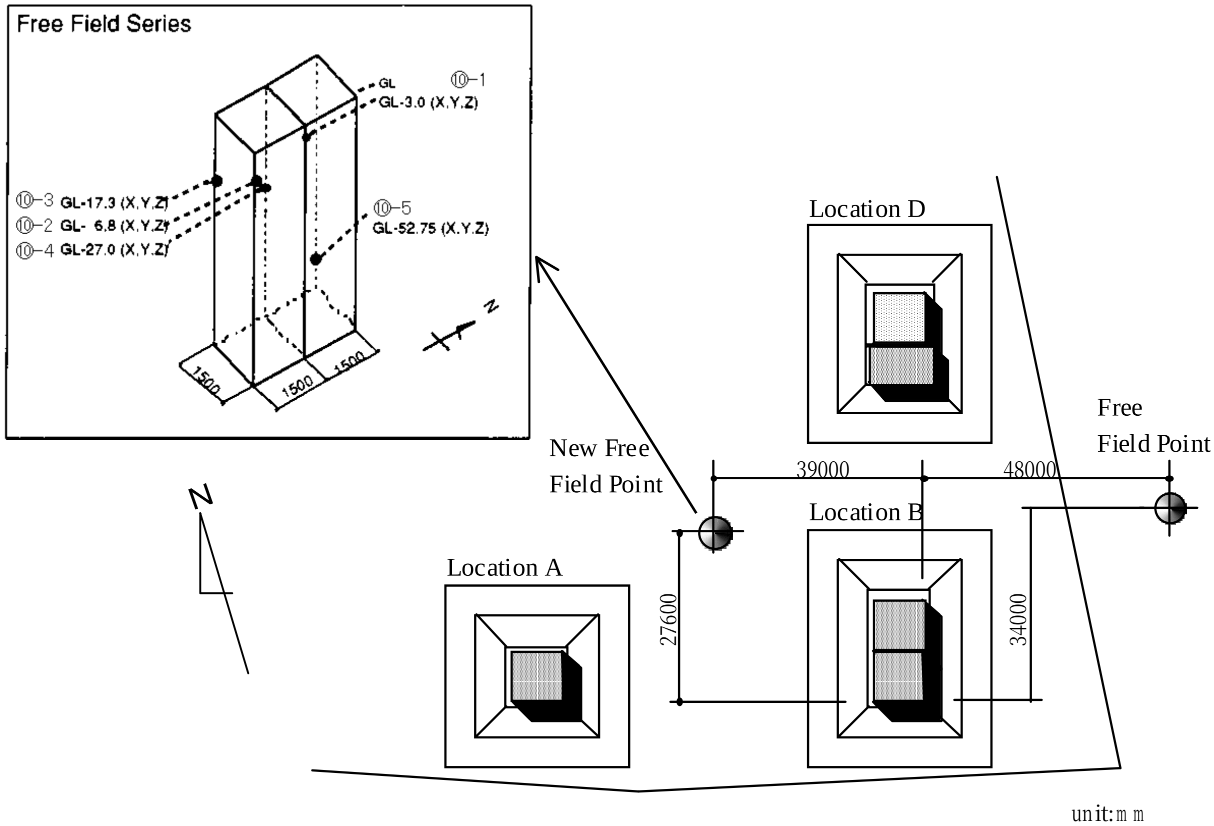


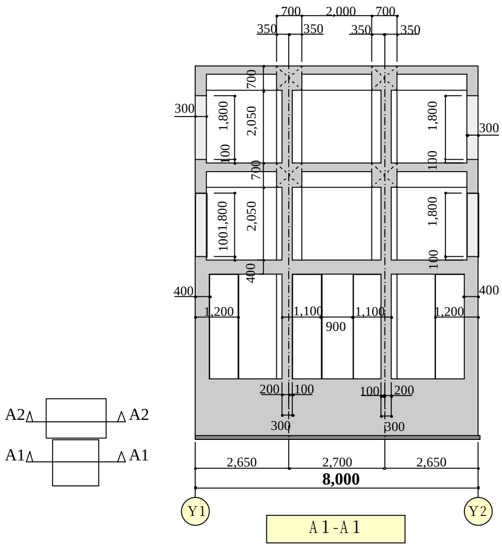
Fig. 2 Embedment Conditions of the Building Models

Single buildings model

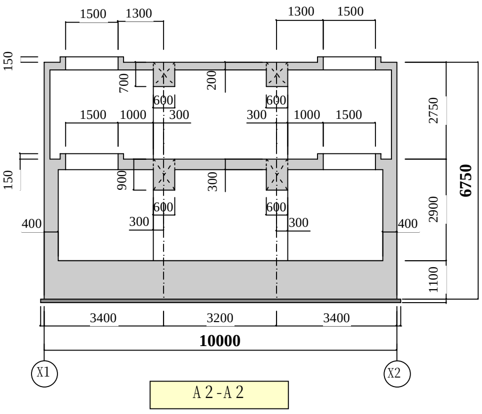
Two identical buildings model

Two different buildings model

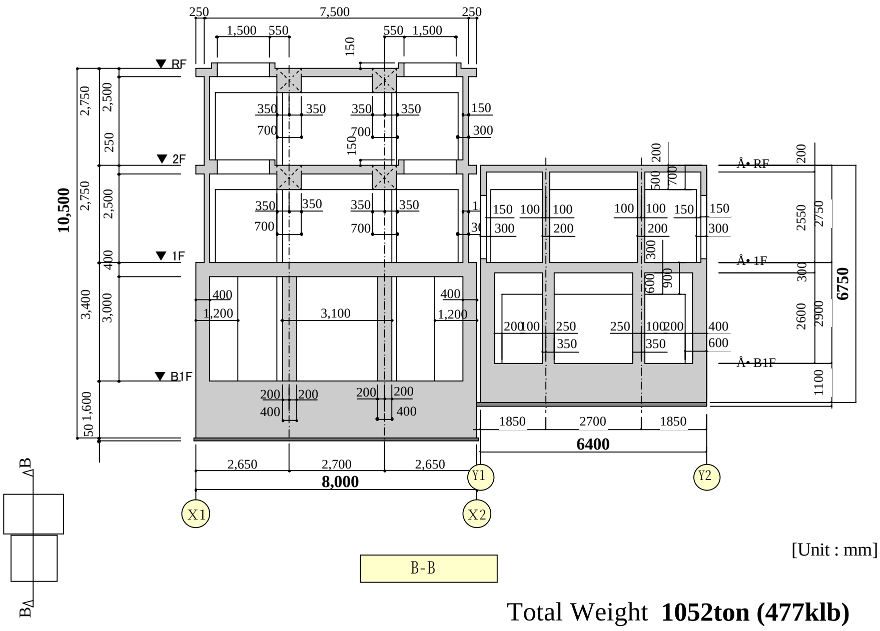
Photo 1 Building models with embedment



weight **657ton (298klb)**



weight **395ton (179klb)**

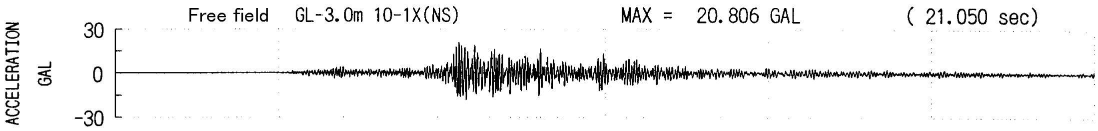


Total Weight **1052ton (477klb)**

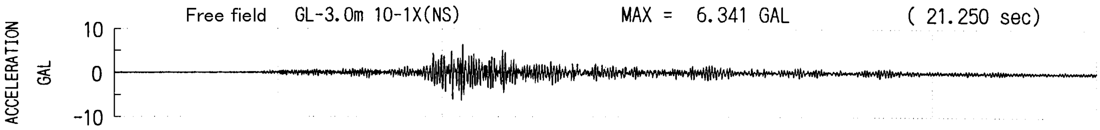
Fig.3 Dimension of the building model

Table 1 Maximum response acceleration at the top of the models

condition	Earthq.	directio	Building model		
			Single	Identical	Differen
without embed	No.157	NS	32.2	33.1	23.8
		EW	34.4	34.7	26.0
with embed	No.164	NS	7.0	6.2	5.7
		EW	9.0	6.5	5.3

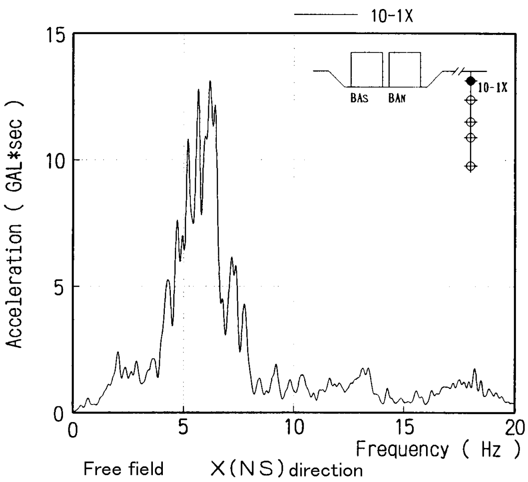


Earthquake No.157

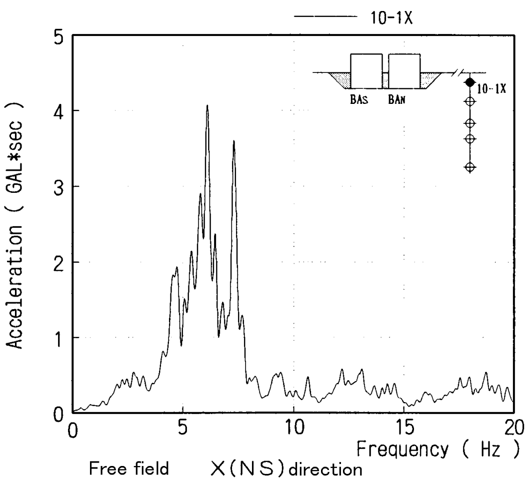


Earthquake No.164

Fig.4 Acceleration time history at Free field



Earthquake No.157



Earthquake No.164

Fig.5 Acceleration response spectra of free field records

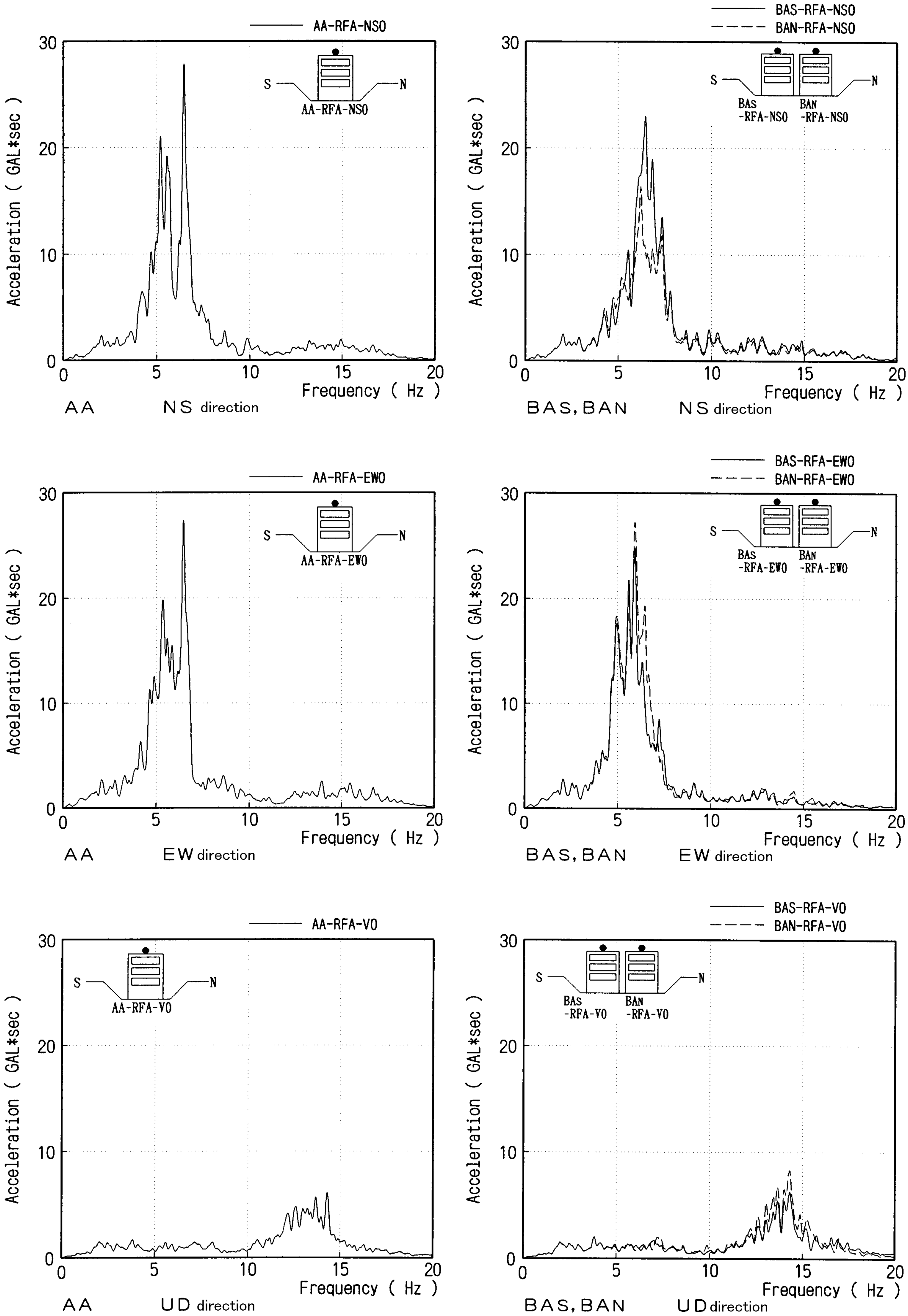


Fig.6 Comparison of Fourier spectra (Single and Two Identical Model without embedment)

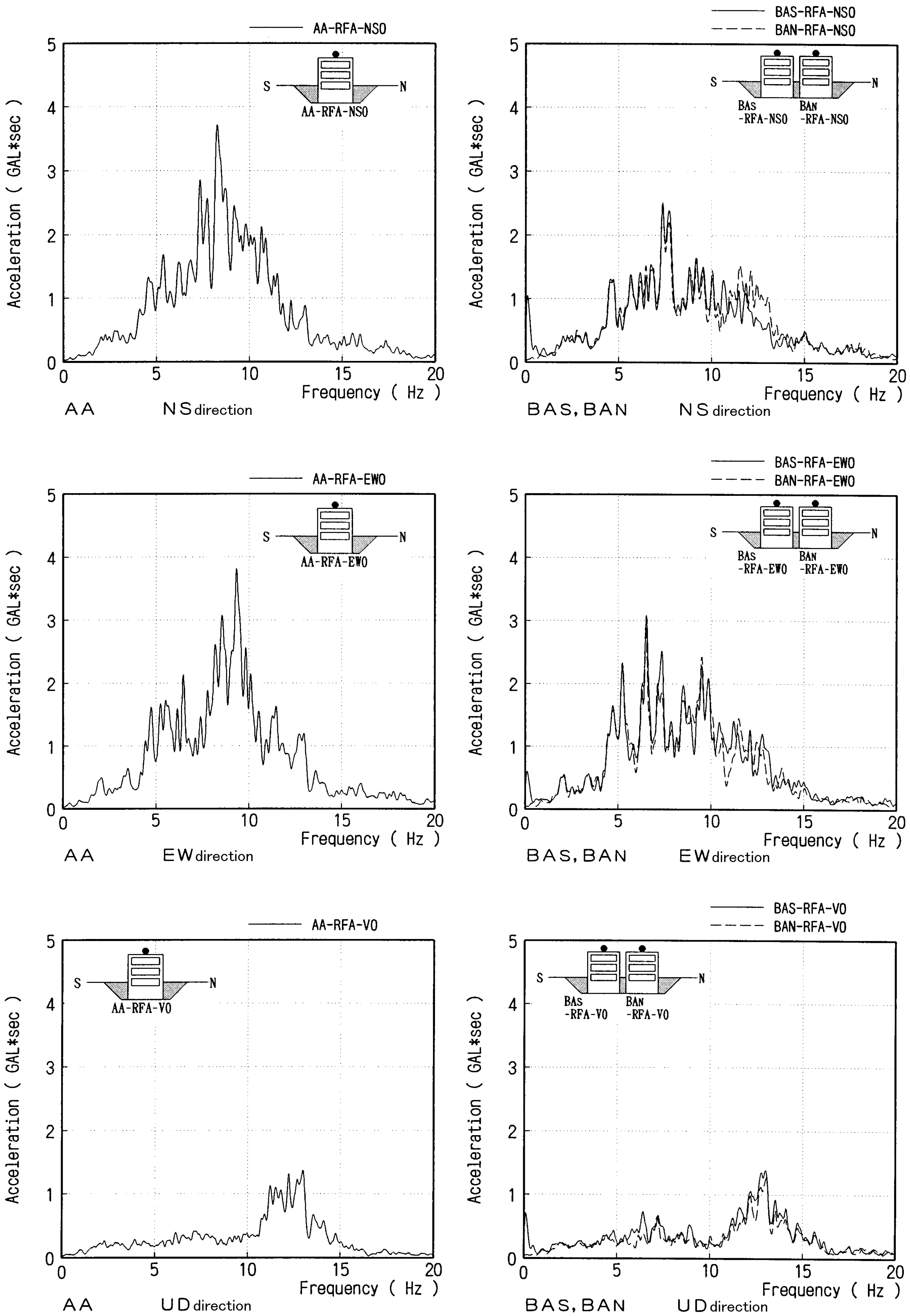


Fig.7 Comparison of Fourier spectra (Single and Two Identical Model with embedment)

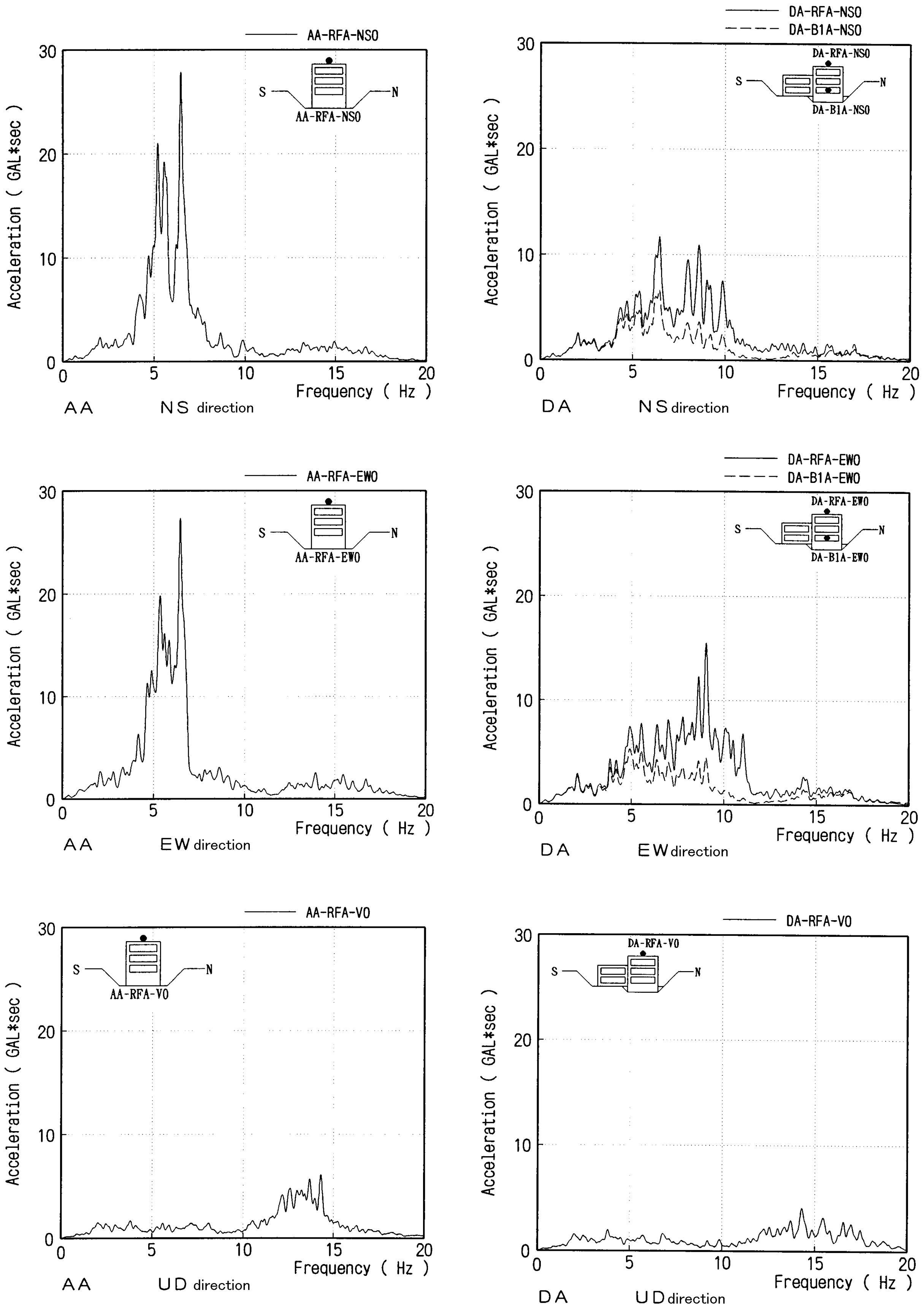


Fig.8 Comparison of Fourier spectra (Single and Two Different Model without embedment)

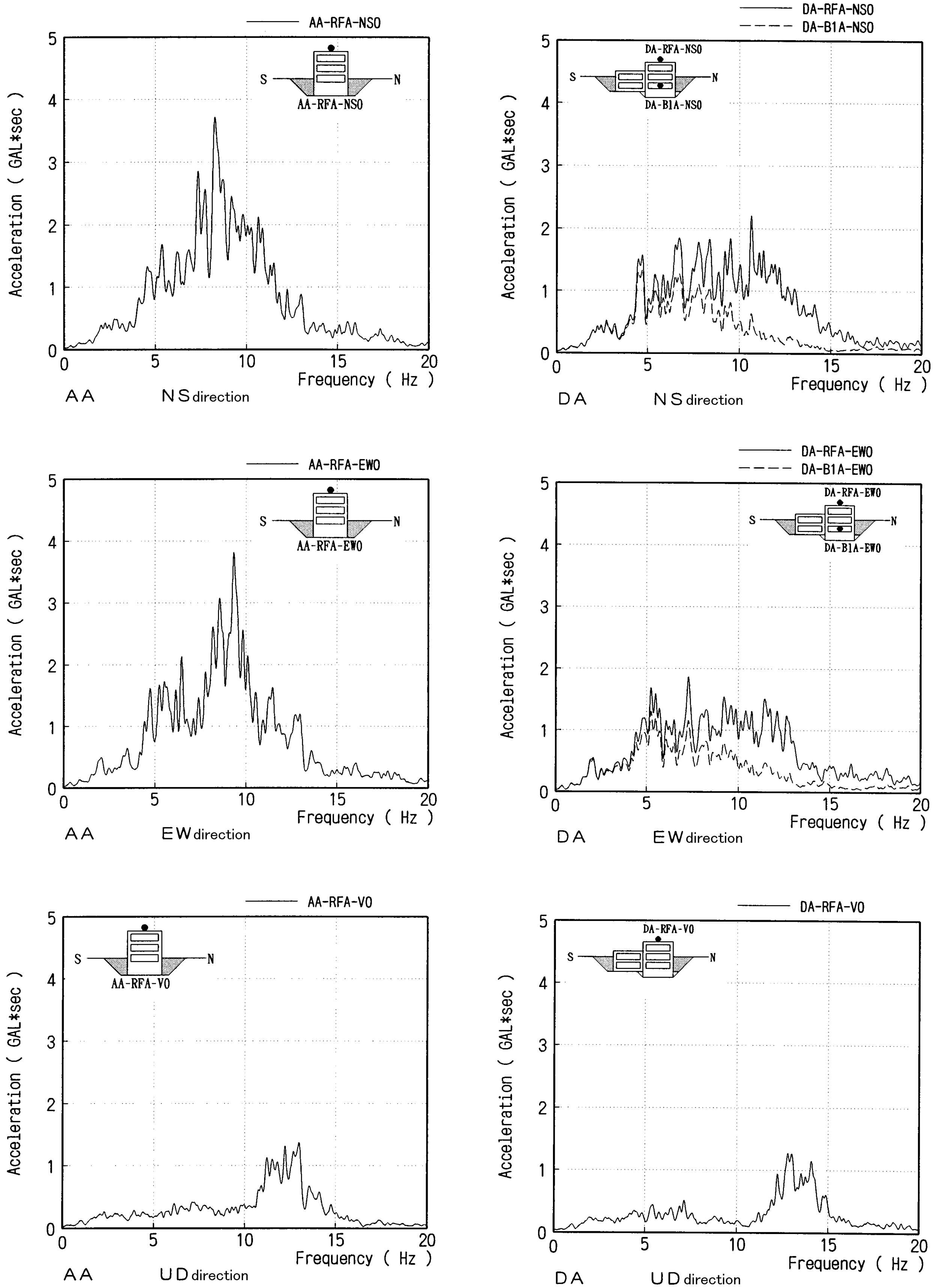
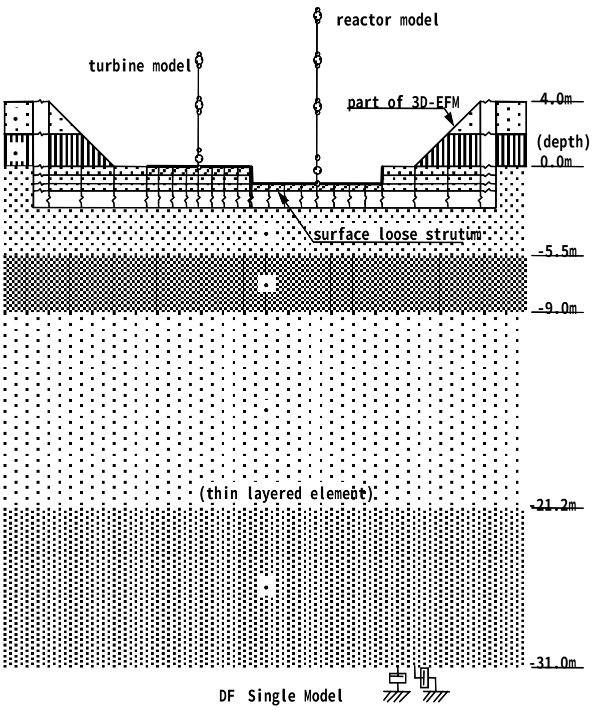


Fig.9 Comparison of Fourier spectra (Single and Two Different Model with embedment)



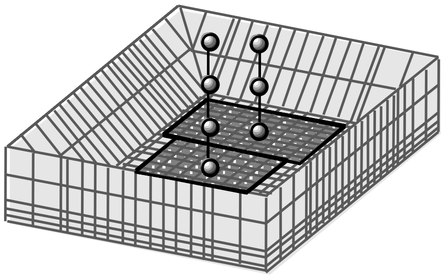
(a) Whole model

Table 2 Characteristics of soil model

Layer No.	depth (m)	thickness of layer (m)	Vs (m/sec)	Poisson's ratio	density (t/m)	damping factor h(%)
•	4.0～2.0	2.0	165.0	0.20	1.64	5.0
•	2.0～0.0	2.0	250.0	0.25	1.83	5.0
•	0.0～5.5	5.5	255.0	0.445	1.70	5.0
•	5.5～9.0	3.5	510.0	0.450	2.05	2.0
•	9.0～21.2	12.2	1110.0	0.400	2.15	2.0
•	21.2～31.0	9.8	2010.0	0.360	2.25	2.0
31.0～	semi-inginite soil (Layer• No.)					

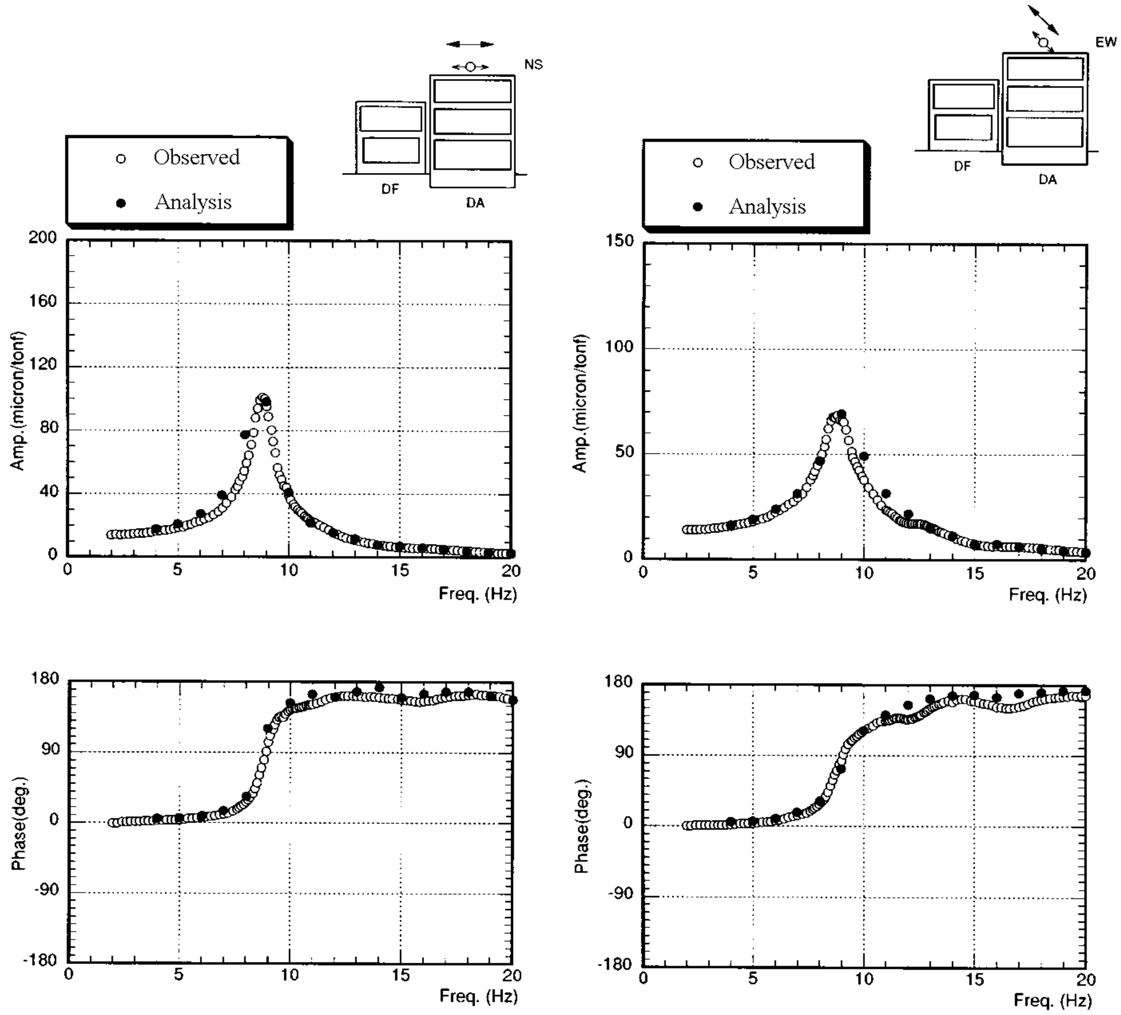
note) Damping factor was calculated from Q Value. (Q=Vs/15, h=1/2Q)

: surface loose stratum(t=0.5):Vs150m/sec, ν=0.2
ρ=1.70 t /m ,h=5%



(b) Portion of the building and vicinity of the building

Fig.10 Analysis model of Two different buildings model (without embedment)

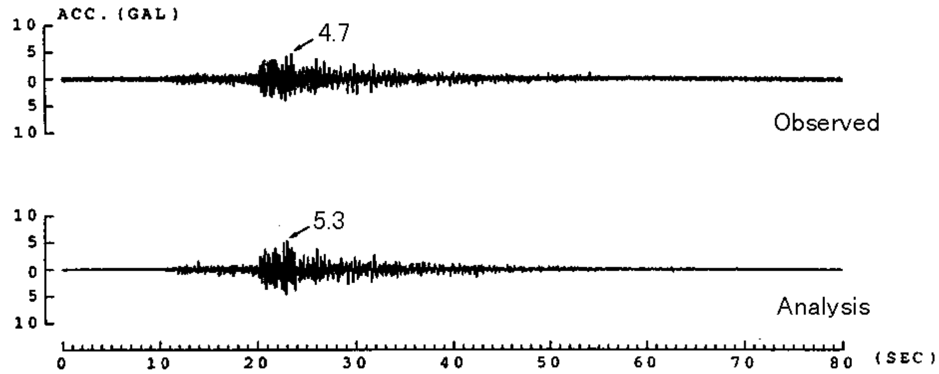


NS direction EW direction

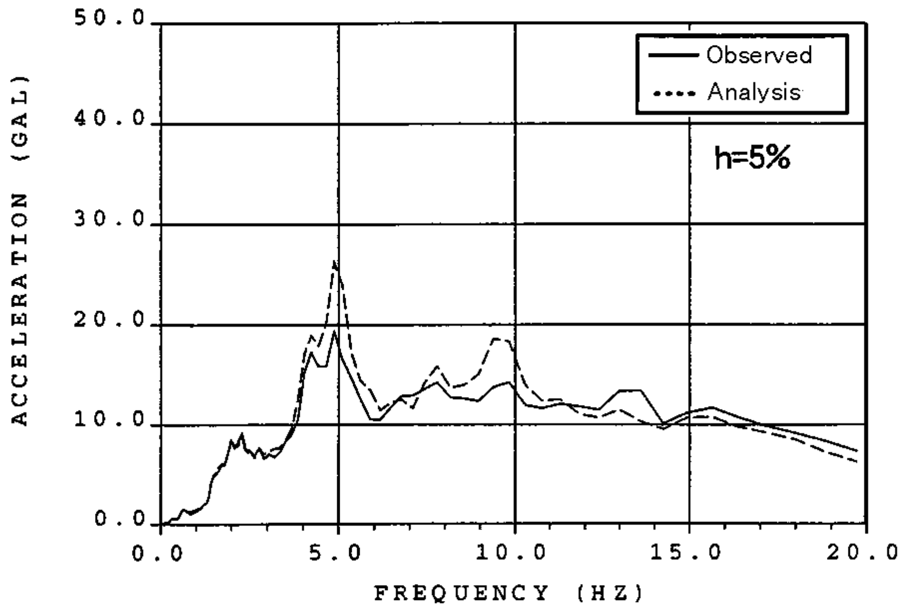
Fig.11 Comparison of resonance curves between observed results and analysis results

Table 3 Soil Characteristics of the New Free Field

	Layer No.	Results of soil survey				One dimensional wave propagation model	
		G (t/m³)	Vs (m/s)	h (%)	Thickness (m)	Vs (m/s)	h (%)
⑩-1	1	1.57	140	5.4	3.0	140	10
⑩-2	2	1.70	210	3.6	3.8	250	
	3-1	1.78	430	3.6	5.0	420	
⑩-3	3-2	1.78	430	1.7	5.5	530	
⑩-4	4	2.11	1200	0.6	9.7	1210	
⑩-5	5	2.26	1590	0.5	26.0	1620	



Acceleration time history (NS)



Acceleration response spectra (NS)

Fig.12 Comparison between analysis and observation of free field response (Earthquake No.157, Observation point ⑩-4, GL-27.0m)

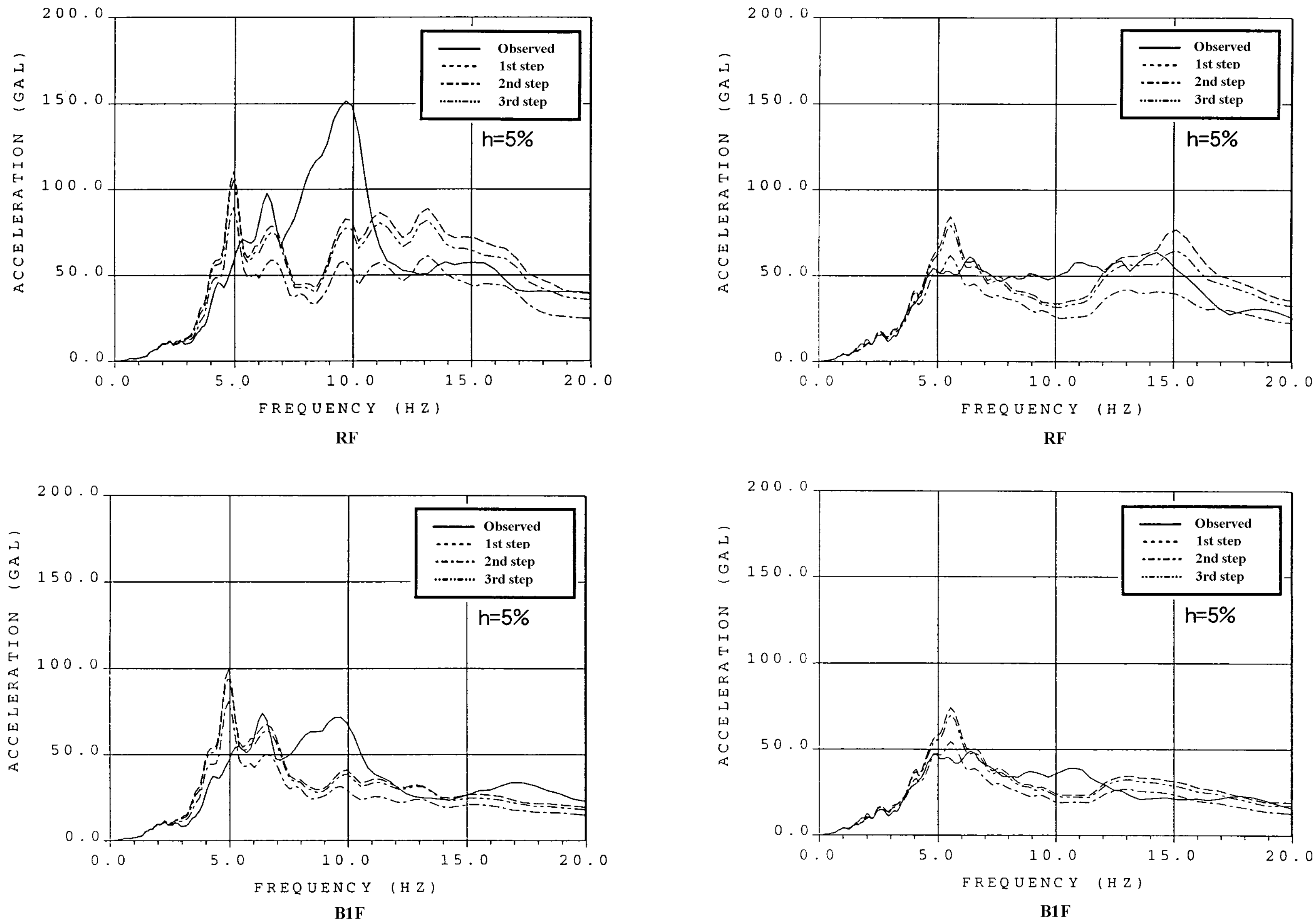


Fig.13 Comparison of response spectra of Two different buildings model between analysis and observation