Forced Vibration Test on Large Scale Model on Hard Rock Site
(Embedment Effect Test on Soil-Structure Interaction)

Tomoyuki INUKAI, Tamio IMAZAWA
Takenaka Corporation, Tokyo, Japan
Masanori IZUMI
Tohoku University, Sendai, Japan
Masashi YAMAMOTO
Nuclear Power Engineering Center, Tokyo, Japan

1 INTRODUCTION

The effects of dynamic soil-structure interaction play an important role on the behavior of reactor buildings during earthquakes. One of them is the embedment effects that are as follows; "increase of soil spring constant", "increase of radiational damping" and "variation of effective input motion". In order to investigate the embedment effects, a series of forced vibration tests were carried out. This series used a large scale test model constructed on an actual hard rock site. Simulational analyses of the test results were carried out employing two models. One was the sway-rocking model and the other was the axisymmetric FEM model. This paper describes the test results and the analytical results.

2 CONDITION OF FORCED VIBRATION TEST

2.1 Test model and site conditions

The tests were carried out under condition of different embedment depths, non-embedment case and full-embedment case referred as to Test D1 and D2 respectively as shown in Figure 1. The large-scale test model is a RC structure with shear walls in NS direction and a 8x8 m square foundation as shown in Figure 2. The total weight of the model is approximately 920ton and the height is 10m. This test model was designed in consideration of the vibration characteristics, which are non-dimensional frequency and mode shape at the first resonant frequency, of the PWR-type reactor buildings constructed in Japan.

The test model was constructed on an actual hard rock site excavated 5m below the surface. The shear wave velocity (Vs) of the supporting ground is about 1000m/s. The structure of the ground is almost uniform. In the backfilling work, the thickness of each layer for once was 15cm and the target shear wave velocity was about 130m/s (125-135m/s).

2.2 Test method

The harmonic force was generated by the exciter installed at the center of the top floor or the center of the base mat floor, referred as to RF- or BF-excitation respectively. The excitation moment was properly set within 60-400 kg･cm so that the backfill soil and the surrounding ground were in linear range. The steady-state responses to harmonic excitation, the amplitude and the phase lag, were measured. The measurement was made on the displacement of the test model and the ground surface and the acceleration in the backfill soil and the surrounding ground.

3 TEST RESULTS

3.1 Response of test model

Table 1 shows the vibration characteristics of the test model at the natural frequencies under the condition of different embedment depths. The values were obtained from the horizontal components of the resonance curves at the top floor. Figure 3 shows the comparison of D1 and D2 on the resonance curves at the center of the base bottom. For the embedment effects exerted upon the vibration behaviors of the test model supported on the hard rock site, the followings can be clarified:

1) Due to the embedment effect, the response of the test model to a unit force at the resonance frequencies decrease to a large extent in both NS and EW direction.
2) In the embedded case the radiational damping effect is added from the side of the test model so that the damping factor increases.
3) Since the impedance ratio between the backfill soil (Vs=130m/s) and the supporting ground (Vs=1000m/s) is considerably high, the dynamic characteristics of the soil-structure interaction system is controlled by the supporting ground property.
4) Due to the high impedance ratio, the change of the natural frequency caused by the embedment effect is small. The change of the displacement contribution ratio at RF is small too.
5) In the every test case, the ratio of the elastic diformation of the super-structure in the displacement at RF is high. And the change of the ratio caused by the embedment effect is very small.

3.2 Dynamic ground impedance

Figure 4 shows the comparison of the dynamic soil impedance between D1 and D2. This figure is made in the case of the NS-direction excitation at RF. From this, the followings are clarified:

1) In the low frequency range, due to the binding effect of the backfill soil the real part of the impedance, which indicates the stiffness, increases.
2) In the frequency which is higher than the natural frequency of the soil-structure system. there are a few frequency range where the real part of the impedance obtained from D2 results becomes rather small compared with the non-embedment case.
3) The imaginary part of the impedance, which indicates the radiational damping effect, increases due to the embedment effect. This tendency is outstanding in the sway component.

4 METHOD OF SIMULATIONAL ANALYSIS

The simulational analyses of the forced vibration test were worked out using two analytical models. One is the sway-rocking model(S-R model) employing the frequency-dependent impedances determined by the three-dimensional wave propagation theory in layered half-space. The other is the axisymmetric FEM model (FEM model) that is equipped with transmitting boundaries and also viscous boundaries to account for the three-dimensional effects as shown in Figure 5. Table 2 shows the soil property of the FEM model estimated by the elastic wave survey results. The soil impedance of the S-R model is evaluated for the half-space below the bottom of the test model . And the Vs of the surface layer, which has a thickness of 0.5m, is 450m/s. Table 3 shows the properties of the test model as the flexual-vibration system which has two degrees of freedom per mass.

5 ANALYTICAL RESULTS

The simulation analyses were carried out on the non-embedment case, namely Test D1. The comparison of the test and analytical results on the soil impedances is shown in Figure 6. Figures 7 to 9 show the comparison of the test and analytical results on the resonance curves at the center of the base bottom and in the surrounding ground respectively. Some remarks obtained from this study are as follows:

1) As regards the soil impedance, the analytical results obtained from the S-R model and the FEM model correspond well to the test results.
2) As regards the resonance curve at the center of the base bottom, the analytical results correspond well to the test results near the first resonance frequencies in both NS and EW directions.
3) On the response of the surrounding ground, the results obtained from the FEM model correspond relatively well to the test results.

6 CONCLUSIONS

The concluding remarks obtained from the experimental and analytical studies are as follows:

1) Due to the embedment effect, namely increase of the radiational damping, the resonance amplitude of the test model decreases.
2) In this test, the impedance ratio between the backfill soil and the surrounding ground is high so that the binding effect of the backfill soil, increase of soil spring constant, is small. And the change of the natural frequency caused by the embedment effect is small.
3) Two analytical models, the S-R model and the axisymmetric FEM model, were used in the simulation of the non-embedment case. These models are verified to be valid for evaluating the dynamic behaviors of the soil-structure interaction system.

ACKNOWLEDGEMENT

This work was carried out as the entrusted project sponsored by the Ministry of International Trade and Industry in Japan. This work was supported by "Sub-committee of Model Tests on Embedment Effect on Reactor Building" under "Committee of Seismic Verification Test" of Nuclear Power Engineering Center. The authors wish to express their gratitude for the co-operation and valuable suggestions given by the members of committee.

REFERENCES

Izumi, M. et al., "Model Tests on Embedment Effect on Reactor Building - Field Test (Part 8-12)", Summaries of Annual Meeting AIJ, 1990, Vol.B, 1385-1394, (in Japanease)

Inukai, T. et al., "Experimental Studies on an Embedded Soil - Structure Interaction in a Case of Hard Supporting Ground", 2nd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, 1991, (Submitting)

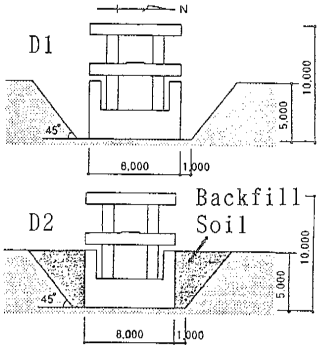


Fig. 1 D-Test Models

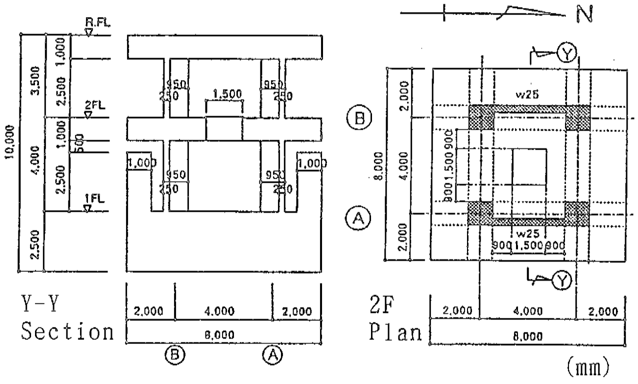


Fig. 2 Shape of Test Model

Table 1 Test Results

TEST	Position of Excitation	Direction of Excitation	Order	Natural Frequency (Hz)	Damping Factor (%)	Ratio of Disp.		
						Sway (%)	Rocking (%)	Deformation of Structure (%)
D1 Non − Embedment	RF	NS	1st	11.0	1.9	9	41	50
		EW	1st	8.4	1.1	5	25	70
			2nd	30.9	1.3	− −	− −	− −
	BF	NS	1st	11.0	1.9	9	41	50
D2 Full − Embedment (5m)	RF	NS	1st	11.3	4.4	10	38	52
		EW	1st	8.65	1.5	5	21	74
			2nd	31.2	2.5	− −	− −	− −
	BF	NS	1st	11.3	4.5	10	39	51

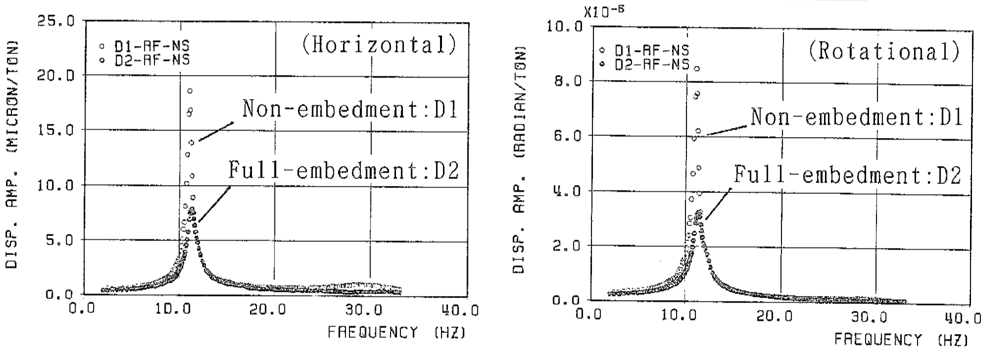


Fig. 3 Resonance Curves of Displacement at Center of Base Bottom

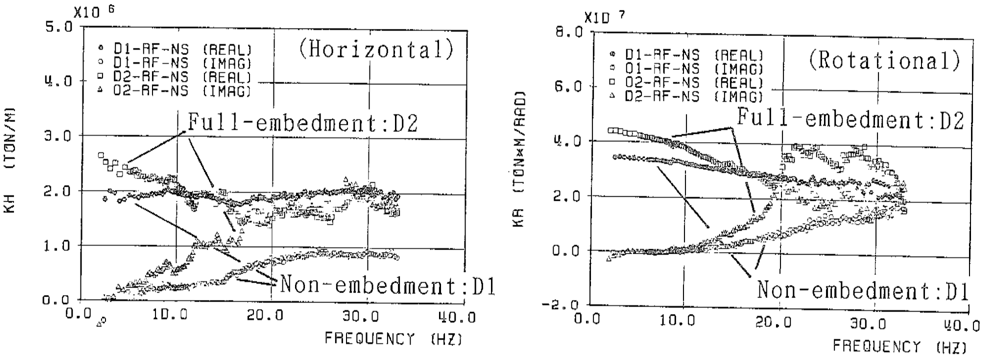


Fig. 4 Dynamic Soil Impedances

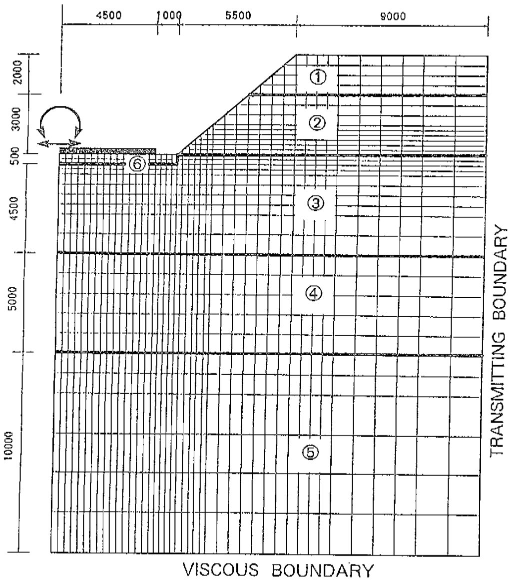


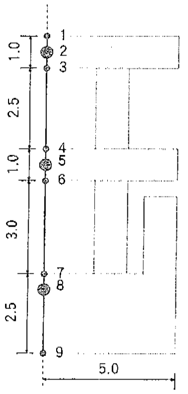
Fig. 5 Axisymmetric FEM Model

Table 2 Soil Constants (FEM)

NO	ρ (t/m³)	Vs (m/s)	E (t/m²)	ν	h (%)
①	1.5	160	11210	0.430	5
②	1.7	350	60780	0.430	2
③	1.9	950	447900	0.280	2
④	1.9	1050	547200	0.280	2
⑤	1.9	1050	581800	0.361	2
⑥	1.7	400	71050	0.280	2

ρ : Density Vs : Shear Wave Velocity
E : Young's Modulus ν : Poisson's Ratio
h : Damping Factor

Table 3 Test Model Properties



		NS			EW		
Mass NO.	W (ton)	I (ton・m²)	As (m²)	J (m⁴)	I (ton・m²)	As (m²)	J (m⁴)
1	0.0	0.0	64.00	341.33	0.0	64.00	341.33
2	169.1	848.1	64.00	341.33	909.9	64.00	341.33
3	0.0	0.0	2.48	15.49	0.0	0.49	23.14
4	0.0	0.0	64.00	340.90	0.0	64.00	340.90
5	182.2	878.7	64.00	340.90	1014.6	64.00	340.90
6	0.0	0.0	2.48	15.49	0.0	0.49	23.14
7	0.0	0.0	64.00	341.33	0.0	64.00	341.33
8	570.5	4493.5	64.00	341.33	4567.6	64.00	341.33
9	0.0	0.0			0.0		

W : Weight
I : Rotatory Mass Moment of Inertia
As : Area of Section
J : Moment of Inertia of Area

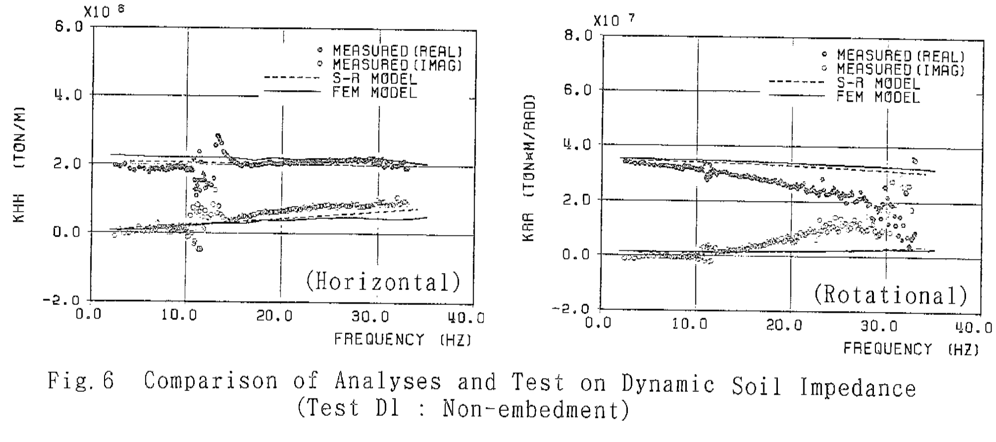


Fig. 6 Comparison of Analyses and Test on Dynamic Soil Impedance
(Test D1 : Non-embedment)

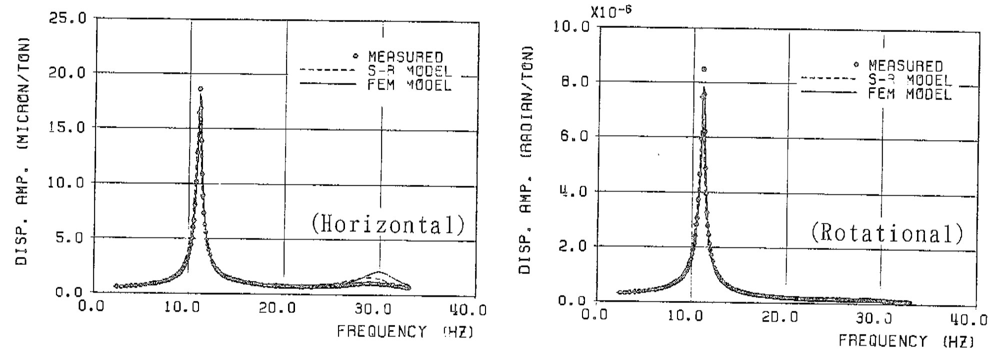


Fig. 7 Comparison of Analyses and Test on Resonance Curve at Center of Base Bottom (Test D1 : NS-direction Excitation)

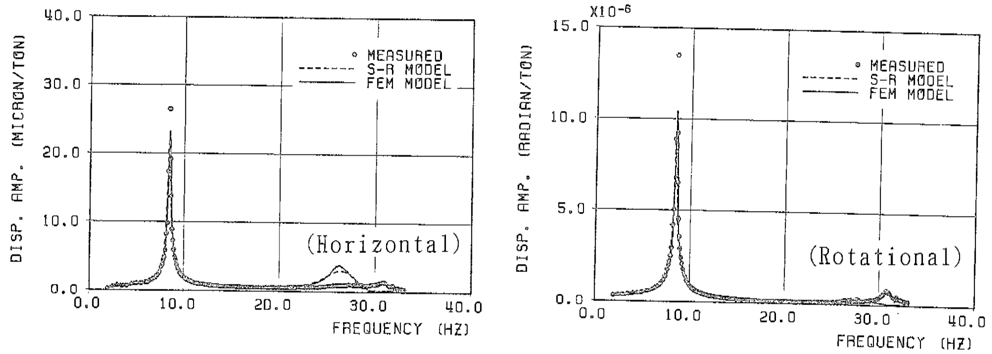


Fig. 8 Comparison of Analyses and Test on Resonance Curve at Center of Base Bottom (Test D1 : EW-direction Excitation)

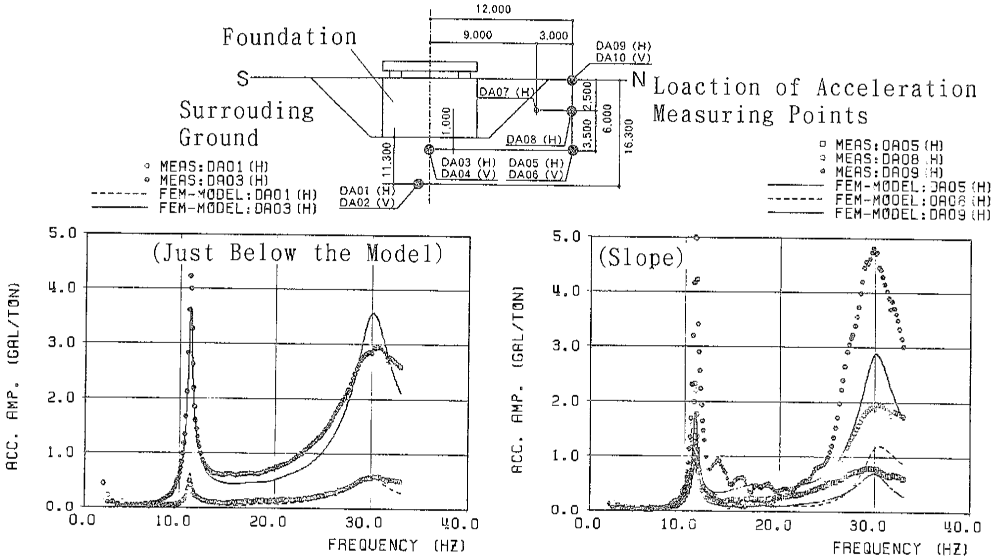


Fig. 9 Comparison of Analysis(FEM) and Test on Resonance Curve in Surrounding Ground (Test D1 :NS-direction Excitation)