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LARGE-SCALE MODEL TESTS ON SOIL-REACTOR BUILDING INTERACTION PART I: FORCED VIBRATION TESTS

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SUMMARY

In order to evaluate the effects of the interaction between soil and nuclear power plant buildings, 17 step tests were carried out on five large-scale models (4 types) constructed on actual soil. This paper describes the results of forced vibration tests and analytical studies with emphasis on dynamic soil stiffnesses for the foundations, effects of differences in superstructure, cross interaction effects and dynamic behavior of the embedded foundation.

INTRODUCTION

Theoretical and experimental studies on the effects of dynamic interaction between structures and soil have been carried out in recent years. Most of the dynamic tests, however, have been conducted using comparatively small-scale models. In order to synthetically evaluate the effects of soil-structure interaction for rigid structures such as reactor buildings, a series of tests, including forced vibration tests and earthquake observations, was carried out from 1980 through 1986. These tests were comprised of 17 steps. Large-scale models constructed on actual soil were used. Their dynamic properities simulated those of reactor buildings in Japan. These tests included forced vibration tests on individual foundations, on foundations with superstructures and on cross interaction through the soil. Besides these, tests on the embedment of the foundation on artificial ground-shaking, on large amplitude excitation, and aging effects in soil properties were carried out. And the analytical studies were carried out in order to investigate the effects of soil-structure interaction. The soil model and the methods used in the analysis are shown in PART II (Ref.1).

TEST CONDITIONS

Outline of Test Models In a series of tests, five models, denoted A, B, C, D1 and D2, were designed in consideration of the fundamental vibration characteristics of the reactor buildings in Japan. Key parameters such as the non-dimensional frequencies and mode shapes were adapted. Fig. 1 shows a procedure plan of the whole series of tests. The series of tests for Models A and C are designated the AC series, and those for Models B, D1 and D2 are designated BD series (Fig. 1). The layout of the test models is shown in Fig. 2 and an outline of each model is shown in Fig. 3.

Model A simulates a BWR-type reactor building and consists of a foundation of reinforced concrete and a steel frame superstructure with concrete slabs. Model B simulates a PWR-type reactor building and has twin steel structures with concrete slabs on a common foundation. The twin structures represent an outer shield wall (O.S.W.) and an inner concrete structure (I.C.). Model C simulates a building adjacent to a BWR-type reactor building and is similar in structure to Model A. Models D1 and D2 are the block models designed so as to compensate for the lower range of the non-dimensional frequencies.

Description of Soil Properties The test area was located on the site of Tokyo Electric Power Company's Fukushima No. 1 Nuclear Power Plant. Topographically, the test area is a gently sloping diluvial plateau. The strata consist of the surface layer of diluvial sandy gravel, a secondary layer of fine sand and a third layer of tertiary mud and stone. The soil properties of each are shown in Table 1. Thorough ground exploration indicates that the surface layer below the foundations forms a mirage layer in which the elastic wave velocity increases as the depth increases.

TEST METHOD

The forced vibration tests were carried out by sinusoidal excitation using an exciter set on the foundations or superstructures. Mainly in order to get resonance curves and mode shapes, measurements were made for displacements of test models, displacements of surrounding soil and earth pressure in soil using displacement transducers, borehole type seismographs and earth pressure gauges, respectively.

TEST RESULTS

From the test results of individual foundations shown in Fig. 4 it was confirmed that the larger the foundation is, the lower the resonant frequency is and the higher the damping ratio becomes. The characteristics of non-dimensional complex soil stiffnesses in frequency domain calculated from the test results, shown in Fig. 5, indicated that the same tendency exists in each component and that frequency dependence is evident in both real and imaginary parts. Considering the layered soil conditions, the theoretical results show better coincidence with the test results than those assumed to be a homogeneous half space. From Fig. 6 it was indicated that the earth pressure distribution form moves from a type similar to Boussinesq to a uniform type as the foundation size increases. It was confirmed that the soil properties were uneffected by aging when compared to the test results of AC2 and AC8 carried out after an interval of four years.

The results of tests and analyses of the soil-foundation superstructure systems are shown in Figs. 7, 8 and Table 2. The high damping ratios were obtained from those results when the sway of the foundation was predominant. Even for the same foundation, the vibration characteristics of those systems varied according to the weight or the stiffness of the superstructure. Specifically, the heavier and the stiffer the superstructure is the larger the effect of interaction is. When those systems were excited on the foundation, the amplitude of the resonance curve at the foundation dropped near the natural frequency of the superstructure. The analytical results corresponded well with those test results.

The test and analytical results of the cross interaction systems are shown in Fig. 9. The vibration characteristics indicate that those of the active structure differ little from the test results of the single structure and that the effects of cross interaction are outstanding in the passive structure. The effects of cross interaction show different characteristics depending upon the direction of excitation. For example, the effects of cross interaction appeared on the rocking component in the excitation of the horizontal direction parallel to the line through the two foundations and on the torsional component in the right angle excitation against the former.

From the test results of external excitation on the foundation located some distance away from the passive structure, it was shown that the resonant frequencies and mode shapes of the passive model are similar to those measured when the soil-foundation-superstructure system itself was excited. Compared with free fields, the response of the ground near the passive model is small because of the confining effect produced by the rigid foundation, as shown in Fig. 10. When the foundation is embedded more deeply, the dynamic soil stiffnesses for the foundation and the radiation damping increase. For this reason, as shown in Fig. 11, the deeper the foundation is embedded, the higher the resonant frequency becomes, and the resonance amplitude decreases. It is from Fig. 12, that the resonance frequency becomes lower due to the influence of non-linear soil properties, as the exciting force becomes stronger.

CONCLUSION

The following are summaries concluded from the said test and their analytical results.

1) Non-dimensional complex soil stiffnesses under the same ground conditions shows a similar tendency regardless of foundation size.
2) From the comparison between the test results and the analytical results, it can be seen that the layered soil conditions influence those test results.
3) The analytical results in consideration of the layered soil conditions can almost simulate the results of the forced vibration tests.
4) The vibration characteristics of the soil-foundation-superstructure system vary according to the weight or the stiffness of superstructure. The heavier and the stiffer the superstructure is, the larger the effect of interaction is.
5) The cross interaction effects tend to be different according to the location of the structures and the direction of excitation.
6) Embedding the foundation more deeply increases the dynamic soil stiffnesses and the radiation damping by the surrounding soil.

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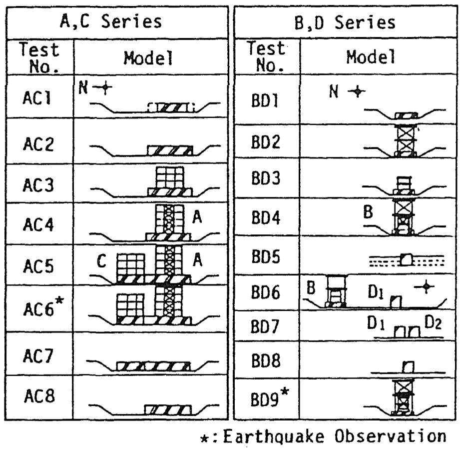


Fig.1 Procedure Plan

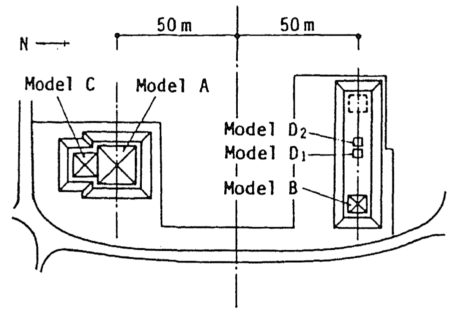


Fig.2 Layout of Test Models

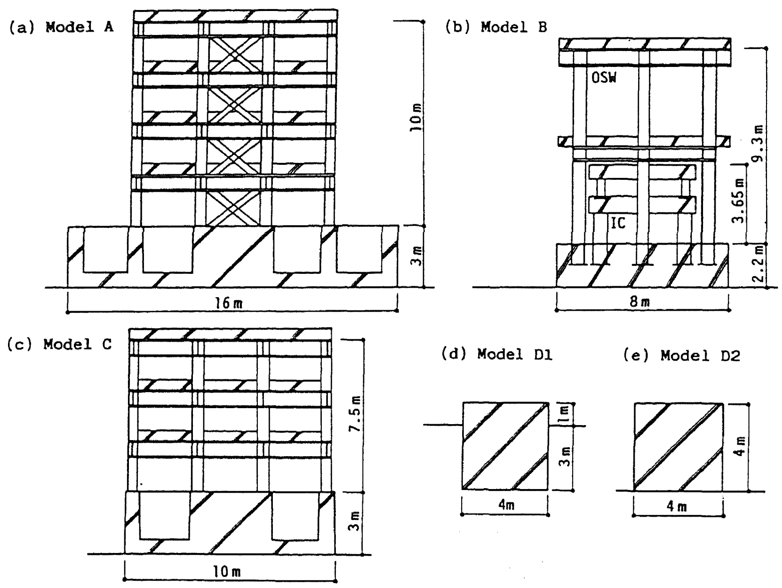


Fig.3 Outline of Each Model

Table 1 Soil Properties

Depth GL(m)	soil profile	Density ρ (g/cm³)	Velocity of S wave V_S (m/s)						Velocity of P wave V_P (m/s)					
			Model A.C Site			Model B,D Site			Model A.C Site			Model B,D Site		
-3 -3.5 -4 -4.5 -5	sandy gravel	1.85 ~ 1.9	270 ~ 290	210~230 310 ~ 320	180~200 ~ 280~300 ~ 330~340 330~340	300	230 380 ~ 390	150~190 ~ 300~310 ~ 390~400 390~400	490 ~ 530	300 490	370 510 610	470 ~ 480	240 430 660	270 490 620
-5 ~ -10	fine sand with gravel	1.95	400						800					
-10 ~ -14		1.9	300						1750					
-14 ~ -24	mudstone with sandstone	1.9	430						1750					
-24 ~ -45		1.75	480						1750					
-45 ~ -100		1.75	550						1750					

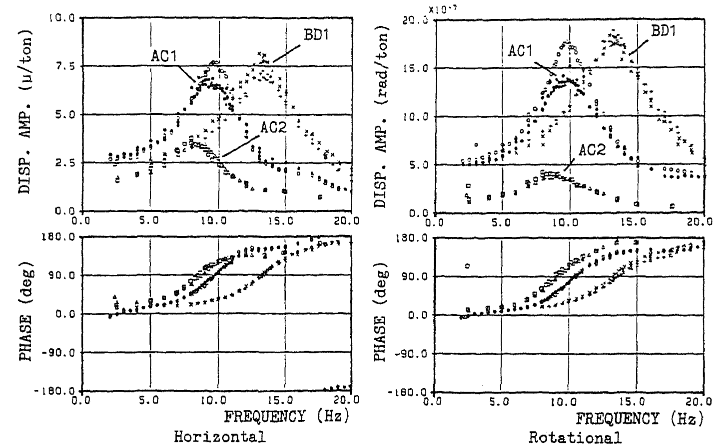


Fig.4 Resonance Curves of Foundations

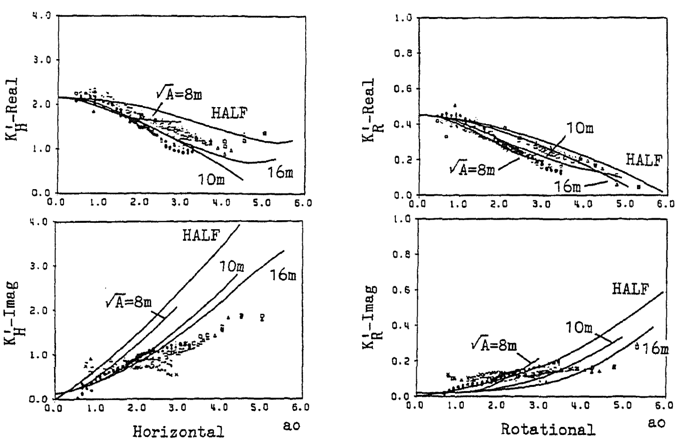
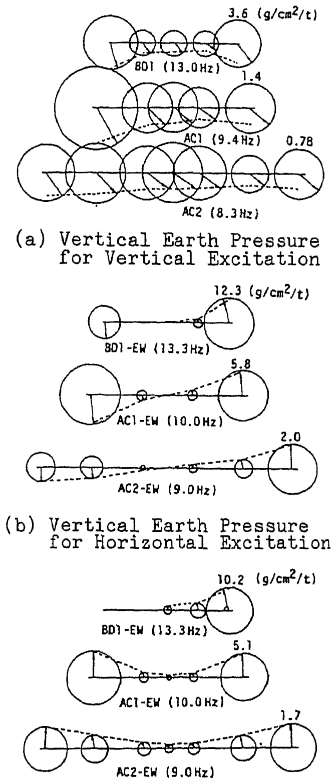


Fig.5 Coefficients of Dynamic Soil Stiffnesses (Non-Dimensional Expression)

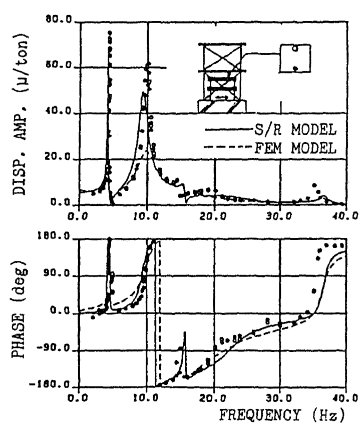


(a) Vertical Earth Pressure for Vertical Excitation

(b) Vertical Earth Pressure for Horizontal Excitation

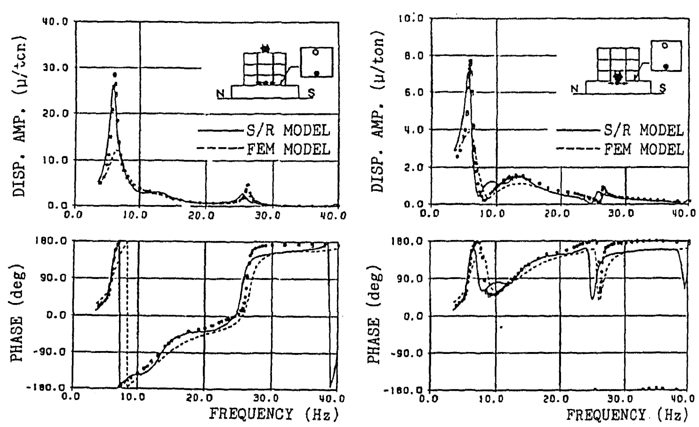
(c) Horizontal Earth Pressure for Horizontal Excitation

Fig.6 Comparison of Earth Pressure Distribution



(BD4)

Fig.7 Resonance Curves of Soil-Structure System



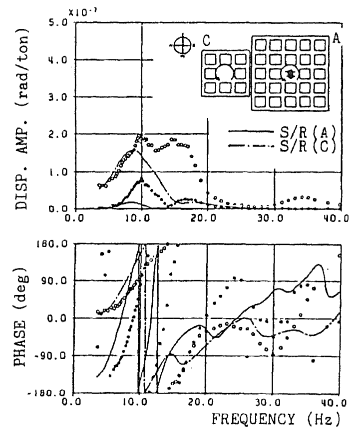
(AC3)

Fig.8 Resonance Curves of Soil-Structure System

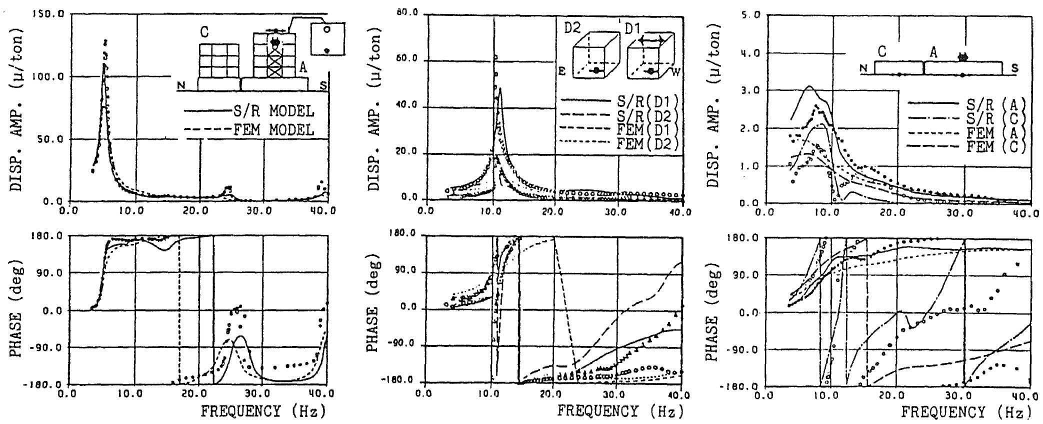
Table 2 Tests Results of Soil-Structure System (BD2,BD3,BD4)

TEST NO	fo (Hz)	ho (%)	MODE SHAPE	DISPLACEMENT RATIO (%)*		
				SWAY	ROCKING	STRUCTURE
BD2	4.3	0.7	1st OSW	3.0	18.0	79.0
BD3	8.7	4.8	1st IC	19.0	22.0	59.0
BD4	4.3	0.9	1st OSW	(OSW) 6.0	20.0	74.0
	9.9	4.3	1st IC	(IC) 24.0	27.0	49.0

* 1st Mode
fo : Resonance Frequency
ho : Damping Ratio



AC7:Torsional Displacement



AC5:Horizontal Displacement BD7:Horizontal Displacement AC7:Horizontal Displacement

Fig.9 Resonance Curves of Cross Interaction System

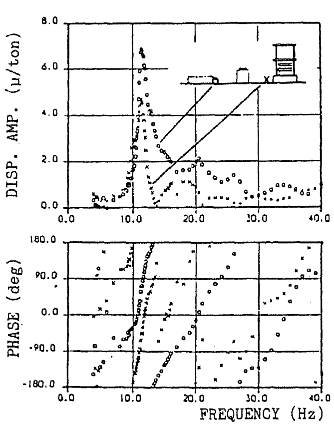


Fig.10 Resonance Curves for External Excitation (BD6)

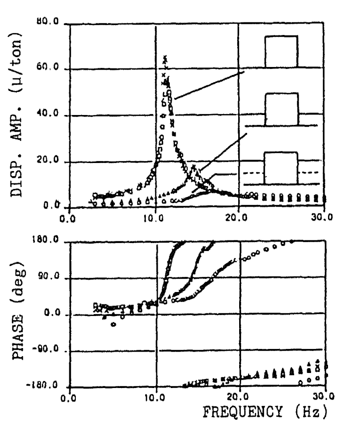


Fig.11 Resonance Curves of Embedded Foundation (BD5)

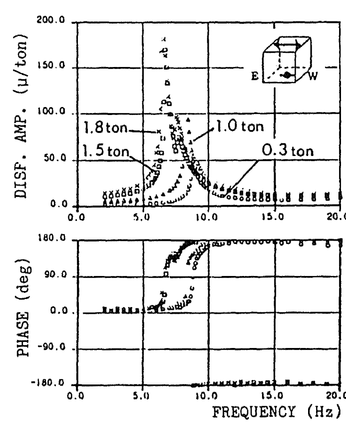


Fig.12 Resonance Curves for Large Amplitude Excitation (BD8)