MODEL TEST ON DYNAMIC CROSS INTERACTION OF ADJACENT BUILDINGS IN NUCLEAR POWER PLANTS

Tatsuo YANO[1], Yoshio KITADA[2], Michio IGUCHI[3], Tsutomu HIROTANI[4] And Kazuhiro YOSHIDA[5]

SUMMARY

Reactor buildings at nuclear power plants are generally constructed closely adjacent to other buildings, such as a turbine building. Given the possibility that an adjacent building might affect to some degree the vibration characteristics of the reactor building, the Nuclear Power Engineering Corporation has been carrying out a "Model Test on Dynamic Close Interaction of Adjacent Buildings in Nuclear Power Plants " for the past five years. The aim of the project is to understand dynamic cross interactions between buildings during earthquakes.

This project consists of both field and laboratory tests. The field tests include forced vibration and earthquake observation. The laboratory tests involve vibration tests using an exciter and a shaking table test that applies simulated earthquake ground motions.

In the field test, changes in Soil-Structure-Interaction related to resonance frequency and reduction of peak acceleration were observed through the comparison of the test results from a single building versus two closely constructed buildings. Also in the laboratory test, a change in damping factor was observed as an adjacent building effect. Furthermore, the field test results were explained using a hybrid of the Three Dimensional Thin Layered Element Method for impedance function and the Three Dimensional Finite Element Method for building model foundations and the soil in the vicinity of foundations.

INTRODUCTION

Reactor buildings at a Nuclear Power Plant (NPP) is generally constructed closely adjacent to a turbine building and/or other such as auxiliary building. In an increasing number of NPPs, multiple plants are being planned and constructed densely on a single site because of site restriction in Japan.

In these situations, adjacent buildings are thought to influence each other through the soil during earthquakes and to exhibit dynamic behaviors different from those of separated building because buildings in NPP are generally heavy and massive. The dynamic interaction between buildings through the soil during earthquakes is termed here as "Dynamic Cross Interaction (DCI)".

To understand DCI and improve seismic design methodologies, the Nuclear Power Engineering Corporation (NUPEC) has been conducting a "Model Test on Dynamic Close Interaction of Adjacent Buildings in Nuclear Power Plants " for the past five years under commission by the Ministry of International Trade and Industry (MITI) Japan. This project succeed a previousc “Model Test on Embedment Effect of Reactor Building”(1986 ▪ 1994).

The test was started in April 1994 and will be completed in March 2002. This paper presents a summary of current progress of this test.

OUTLINE OF THE TEST

The test consists of field and laboratory tests. Outlines of these tests are described in the following sections.

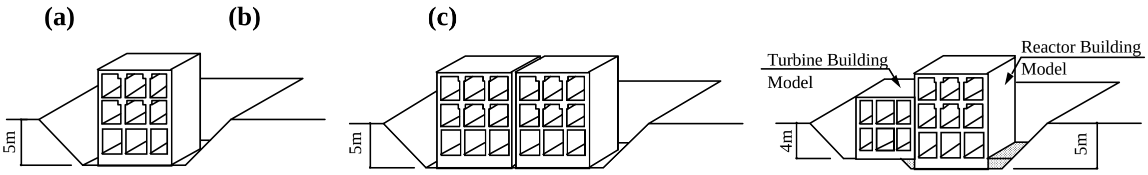
1 *Kajima Corporation, 6-5-30 Akasaka, Minato-ku,Tokyo 107,JAPAN Email:tyano@psa.kajima.co.jp*
2 *Nuclear Power Engineering Corporation, 4-3-13 Toranomon, Minato-ku, Tokyo 105,JAPAN Email: KITADA@nupec.or.jp*
3 *Science University of Tokyo, Noda-shi, Chiba 278, JAPAN Email: iguchi@rs.noda.sut.ac.jp*
4 *Shimizu Corporation, Shibaura 1-chome, Minato-ku, Tokyo 105-07, JAPAN Email: hiro@atom.shimz.co.jp*
5 *Izumi Research Institute, Shimizu Corp., 2-2-2 Uchisaiwaicho, Chiyoda-ku, Tokyo, JAPAN Email:yoshida 1@ori.shimz.co.jp*

Field Tests

Field tests are being carried out under three kinds of building model construction conditions: a single reactor building model used for the comparison as a basic condition (Fig.1(a)), two identical reactor building models used to evaluate pure DCI effects (Fig.1(b)), and a two-different building models; reactor and turbine building models to evaluate DCI effects under actual plant construction conditions (Fig.1(c)). Forced vibration tests and earthquake observations are also being carried out in the field test.

The reactor-building models are identical. They are reinforced concrete structures having 8m by 8m foundations. They are three stories and 10.5m high. Total weight is about 660 tonf.

The turbine building model is also reinforced concrete structure, having a 6.4m by 10m foundation, two stories and a height of 6.75m. Total weight is about 395 tonf. The scale of these models is about 1/10 of existing NPP buildings in Japan.
Single building and two identical reactor building models were built on the bottom of pits without embedment. The depth of each pit was 5m below the ground surface. The two identical reactor building models are spaced at 60cm. The reactor model for the two different buildings model is constructed on the soil in a pits, which was excavated down to 5m from the ground surface. The turbine building model was built on the soil at 1m upper portion from the reactor building model installation level in the same pit. The reactor building model was embedded into the soil at a depth of 1m from the beginning of the test. These two building models are spaced at 10cm. All test pits are filled with sand in 1998.



Single Building Model (Reactor Building)   *Two Identical Building Model* (Reactor Buildings)   *Two Different Building Model* (Reactor and Turbine Buildings)

Fig.1 Outline of the building models (without embedment)

Laboratory Tests

Laboratory tests were planned to supplement the field tests. Distance between adjacent buildings and adjacent effect among three closely constructed buildings are the main test items. To investigate such effects, small-scale model tests are being carried out in a laboratory.

The test model consists of ground made of silicone rubber and three building models made of aluminum. The building models were designed to be similar to the reactor and the turbine building models used in the field test. The ground model is dimensions of 2.8m in diameter and 1.0m in height (refer to Fig. 6(d)). The two reactor-building models have the same dimensions of 30cmx30cm in area and 38cm in height, and total weight is about 25 kgf. The turbine building model is 37.5cmx24cm in area and 23cm in height, and total weight is about 16kgf. The scale of these building models is about 1/260 of existing NPP buildings in Japan. The models are also designed to have similar SSI characteristics to those of the building models used in the field test.

Sine waves and several artificial earthquake ground motions were applied to the ground model through the shaking table. Forced vibration tests were performed using very small exciters to investigate the DCI effect in detail.

Overall Test Plan

The “Model Test on Dynamic Cross Interaction of Adjacent Buildings in Nuclear Power Plants” is being carried out as an 8-years project from fiscal 1994 to 2002. Tables.1 and 2 show the overall plans for the field and laboratory tests, respectively. Test period for both tests can be divided into two parts. In the first part, total planning and model tests without embedment were carried out. In the second part, model tests with embedment are performed to investigate the influence of building embedment on DCI, and overall evaluation will be carried out as the final step of this test.

Table.1 Overall Plan for Field Tests

		1994	1995	1996	1997	1998	1999	2000,2001
A	Test model construction	Existing model constructed in NUPEC's ex-project				Embedment		Overall evaluation
	Earthquake Observation	Without embedment				With embedment		
B	Test model construction	Existing	Excavation Manufacture of test model			Embedment		
	Testing							
	Earthquake observation	With embedment	Without embedment			With embedment		
C	Test model construction			Excavation Manufacture of test models	Manufacture of test model	Embedment		
	Testing							
	Earthquake observation			Without embedment		With embedment		
Remarks		¥A:Single Building Model(Reactor building) ¥B:Two Identical Building Model(Reactor Buildings) ¥C:Two Different Building Model (Reactor and Turbine Buildings)			:Reactor Building Model :Turbine Building Model : Excitement direction	Superstructure Embedment Foundation		

Table.2 Overall Plan for Laboratory Tests

Fiscal Year	1995	1996	1998	1999	2000	2001
Test Plan	Manufacture of ground model	Ground model characteristics test Manufacture of reacter building Single building model test (without embedment)	Manufacture of turbaine building model Test of 2 identical buildings Test of 2 different buildings Test of 3 buildings	Embedment Single building model test Test of 2 different buildings (proximate) Test of 3 buildings (proximate)	Test of 2 identical buildings(proximate) Test of 2 idendical buildings (distant) Test of 3 buildings (distant) Test of 2 different buildings (distant)	Overall evalnation
		Basic characteristic tests	Vibration tests without embedment parameter:interval between building models	Vibration tests with embedment		
Remarks	:Reacter Building Model :Turbine Building Model			Excitation by exciter Building model Embedment Ground model Excitation by shaking table		

CURRENT STATUS OF THE TESTS

Because the test is being carried out as a long term project, in this paper we will present the current progress of the field and laboratory tests as an interim report.

Field Test

The field test of two different buildings, constructed to simulate the actual NPP buildings construction conditions, is the main topic of the following sections.

Forced Vibration Test

Figures 2(a)～(c) show the resonance and phase curves of the two different buildings model obtained by excitation tests. Figure 2(a) show the excitation test results for the turbine model in the direction of the buildings standing in a row (series). Figure 2(b) show the results for the turbine model in the direction perpendicular to the buildings in a row (parallel). In these figures, both in resonance and phase curves, the test results before and after the construction of the adjacent reactor building model, are superimposed. Figure 2(c) shows the excitation test results for the reactor building model excited in both directions (buildings in series and in parallel).

In Fig. 2(a), reduction of the dominant natural frequency of Soil Structure Interaction (SSI) in the direction of the buildings in series can be seen after the construction of the adjacent reactor building model. On the other hand, in Fig. 2(b), the dominant natural frequency of SSI in the direction of the buildings in parallel after the construction of adjacent reactor model is slightly larger than that before the reactor model construction. A clear peak caused by the adjacent model appears at 8.5Hz.
Figure 2(c) indicates that the amplitude at the dominant natural frequency in the direction of the buildings in series is larger than that in the direction of the buildings in parallel. It is thought that the reactor building model has the same dynamic characteristics in both directions. Therefore, the difference in these amplitudes can be assumed to be due to the adjacent building effect. In other words, buildings in the forced vibration test excited each other more in series than in parallel.

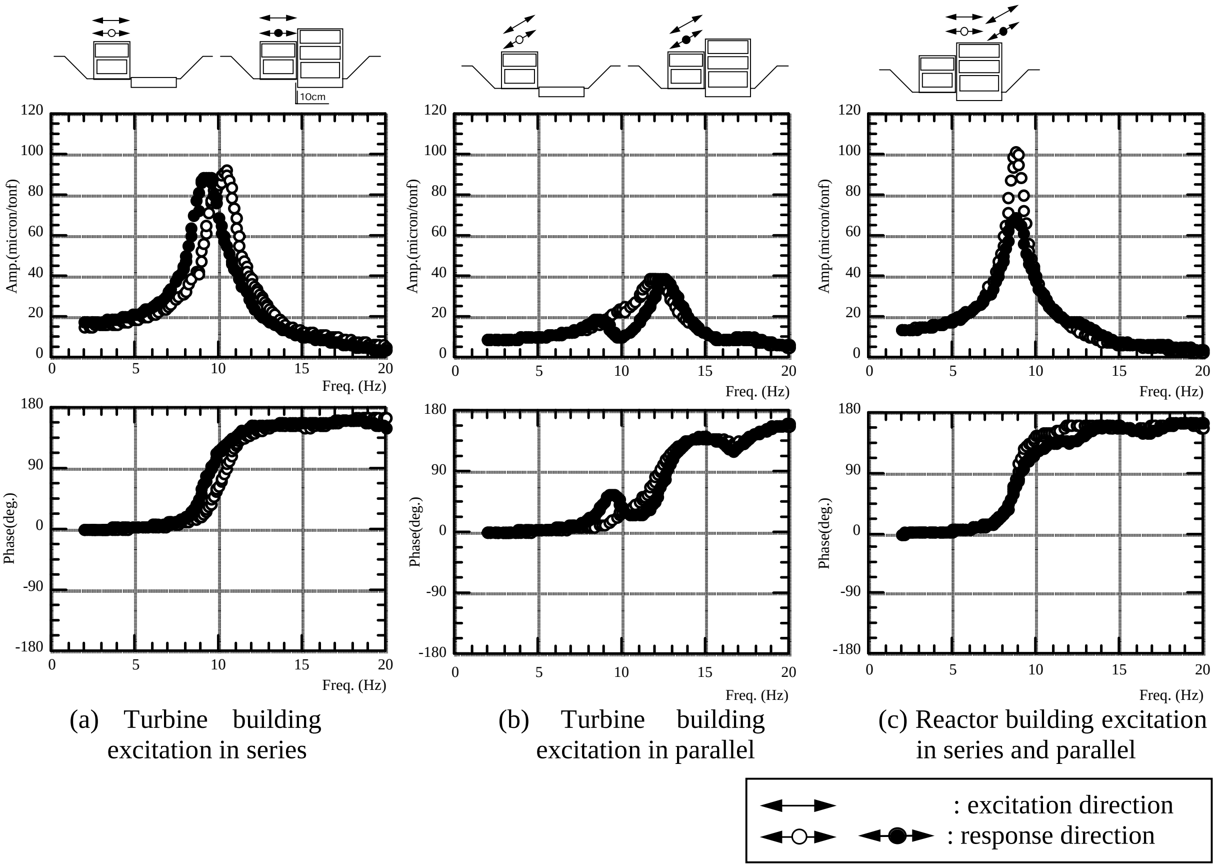
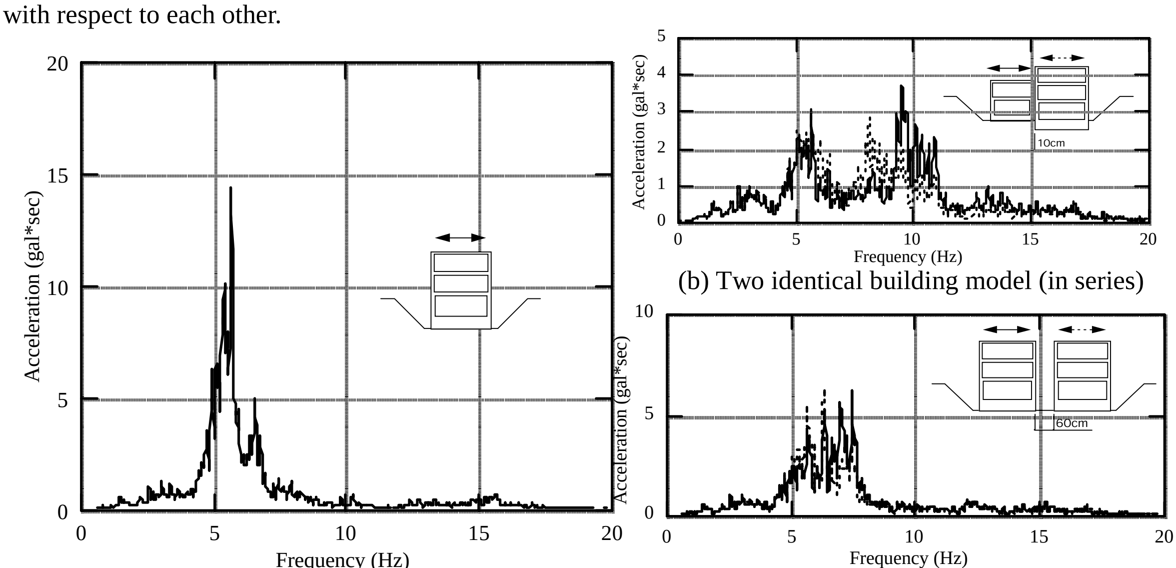


Fig.2 Resonance and phase curves in two different buildings test (without embedment)

Earthquake Observation

As mentioned in the previous section, earthquake observation is underway. Up to date, acceleration records from nearly one hundred earthquakes have been observed. The records include small acceleration with a maximum acceleration of less than several Gal on the surface of the free field. As a typical example, an earthquake observation record in November 1997 is shown in Fig. 3. The figure shows Fourier spectra of earthquake acceleration time histories observed on top of the building models. Figure 3(a) and (b) show the Fourier spectra of single model and two identical building models respectively. Although the Fourier spectra of two identical building models show nearly the same spectral pattern, there is much difference in the spectral pattern between the single building model spectrum and the two identical building model spectra. The dominant peak height in the Fourier spectra of two identical building models was lower than that of the single building model. The cause of this difference might be explained by the adjacent building effect. However, because the detailed soil conditions under the building models are slightly different, it should also be studied whether the difference explained above is caused by the local soil conditions. It should also be evaluated statistically using numerous earthquake records. Figure 3(c) shows Fourier spectra of earthquake acceleration records on top of the two different building model for reference. Because the reactor building model is embedded in the soil to 1m, the dominant natural frequency is higher and the dominant peak acceleration is lower in the Fourier spectrum compared to those of single and two identical building models. The models demonstrate complicated behavior with respect to each other.



(a) Single building model

(b) Two identical building model (in series)

(c) Two different building model (in series)

Fig.3 Fourier spectra of observed earthquake on top of models (without embedment)

Analysis On Excitation Test Of Two Different Building Model

Analytical evaluation of forced vibration test data for two different buildings without embedment was performed to compare the test results with analytical results quantitatively and to study the method of simulating DCI. The analyses were performed using building models and soil models obtained by soil exploration in three steps.

Figure 4 shows a model used in the analyses and Table 3 indicates the characteristics of the soil model used. The analysis model for the two different building model consists of rigid solid elements without mass for foundations and multi-lumped mass sticks standing on the center of foundations for upper structures. The foundation of the reactor building model is embedded in the soil to 1m. Therefore, two foundations and the soil in the vicinity of two building models were modeled untidily by the 3 dimensional FEM together with horizontally divided layered soil (Fig. 4(b)). The analysis was carried out using an impedance function obtained from dynamic Green's function by the Tree Dimensional Thin Layered Element Method. The soil model has a viscous boundary at the bottom.

In the first step, the soil was modeled without taking into account the inclined cut-soil. Thus a lower peak frequency and larger peak amplitude were obtained for the dominant frequency component of building model as compared with test results. Therefore, in the second step, we modeled the inclined part of the soil in detail. The modeling gave reasonable analytical results for the reactor building model compared with the test results. However the peak frequency of the turbine model was higher than that of the test result. Thus, the surface elastic wave exploration was performed at the test location, and the existence of a loose surface stratum was discovered.

Therefore, in the third step, we introduced the loose surface stratum in our analytical model. The final analytical model considering the inclined cut soil and the loose surface stratum gave reasonable analytical results for the dynamic cross interaction behavior of the single turbine building model and the two different building models (Figs. 5(a),(b),(c)). We will apply the model for simulating the other earthquake observation data.

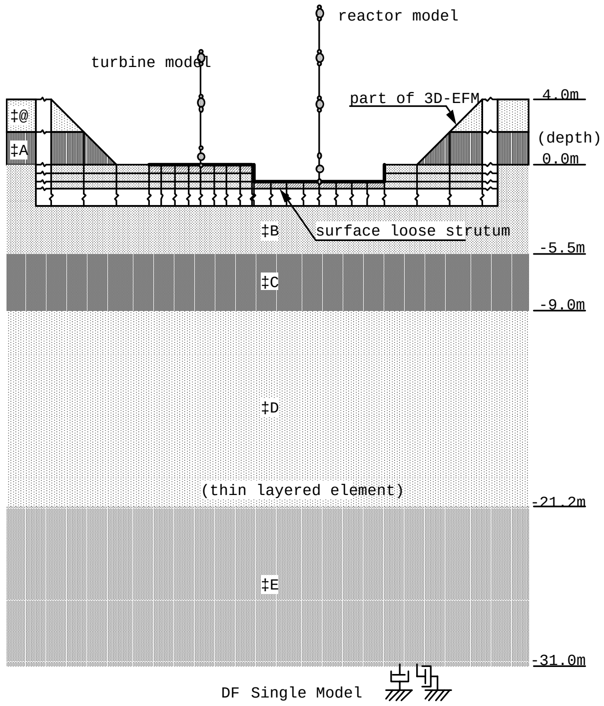


Table3 Characteristics of analytical soil model

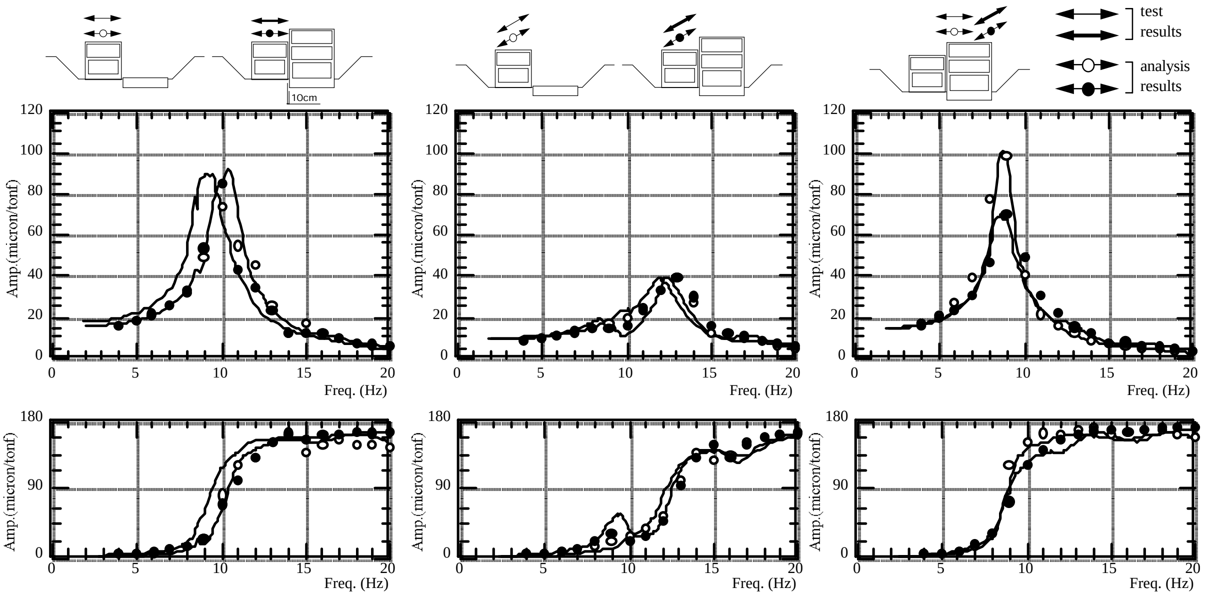
Layer No.	depth (m)	thickness of layer (m)	Vs (m/sec)	Poisson's ratio	density (t/m)	damping factor h(%)
‡@	4.0 `2.0	2.0	165.0	0.20	1.64	5.0
‡A	2.0 `0.0	2.0	250.0	0.25	1.83	5.0
‡B	0.0 `5.5	5.5	255.0	0.445	1.70	5.0
‡C	5.5 `9.0	3.5	510.0	0.450	2.05	2.0
‡D	9.0 `21.2	12.2	1110.0	0.400	2.15	2.0
‡E	21.2 `31.0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

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

: surface loose strutum(t=0.5):Vs150m/sec,ƒË=
ƒÏ=1.70,″/, ,h=5%

(a) whole model (b) Part of 3 dimensional FEM model

Fig.4 Analysis model for the two different building model (final analysis step)



(b) turbine building excitation in series (c) turbine building excitation in parallel (a) reactor building excitation in series and parallel

Fig.5 Comparison between test and analysis results for the two different building model in excitation tests (without embedment)

Laboratory Test

The following section presents a laboratory test using building models on the ground model without embedment. To date, four kinds of tests, (single, two identical, two different, and three building model tests without embedment) have been completed. The tests had been carried out by applying sinusoidal and artificial earthquake motions using shaking table and forced vibration using a small exciter. The purpose was to study the DCI effect on complicated of building layout and the effect of distanse between building models. In the single model test, a reactor building model was installed on the center of the ground model. In the two identical, two different, and three building model tests, an identical reactor building and a turbine building models are installed with at several kinds of distances from the reactor building model (shaded in Fig. 6). Figures 7 and 8 show the relationships between vibration characteristics (SSI related resonant frequency and damping, respectively) and the distanse between buildings both in series and in parallel. The results are briefly summarized as follows;

Resonance frequencies for the reactor building model on the center of the ground model in the three kinds of building layout were almost the same as those of single building model both in series and in parallel. (The largest change ratio of resonance frequency was +2.0% in a series of reactor building models at the nearest distance in the three building model test.)

Damping factors for the reactor building model on the center of the ground model in the two identical and three building layouts differ greatly from those of the single building model. However, at distances greater than the width of the reactor building model, damping was almost the same as that of the single building model. In the two different buildings test, it was almost the same as that of the single building model.

Damping factor for the reactor building model on the center of the ground model in the two identical building test is larger by 25% in series and by 50% in parallel at the nearest distance compared to the single building model.

Figure 9 shows schematic dynamic behaviors for the two identical building model obtained in the shaking table test and the vibration test using an exciter. The rocking motion observed in the shaking table test was restrained when the excitation is in the direction of buildings in series. When the excitation was in the direction of buildings in parallel, the buildings excited each other. However, resonance frequency in series was higher by only 1% and that in parallel was lower by only 0.7% compared to the single building model. On the contrary, in excitation test, rocking behavior in series caused the buildings excited each other.

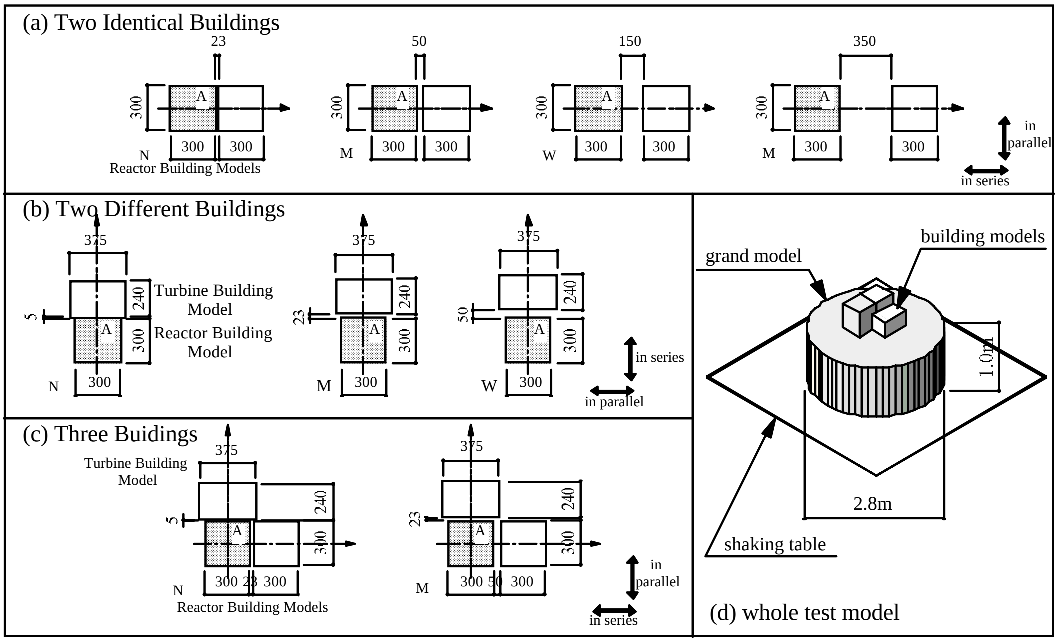


Fig.6 Variation of Building Installation

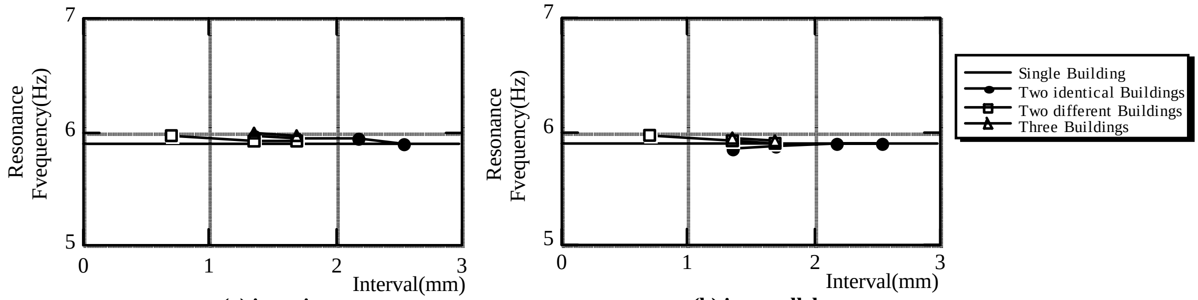


Fig.7 Relationships between Resonance Frequencies(h) of Reactor Building Model A

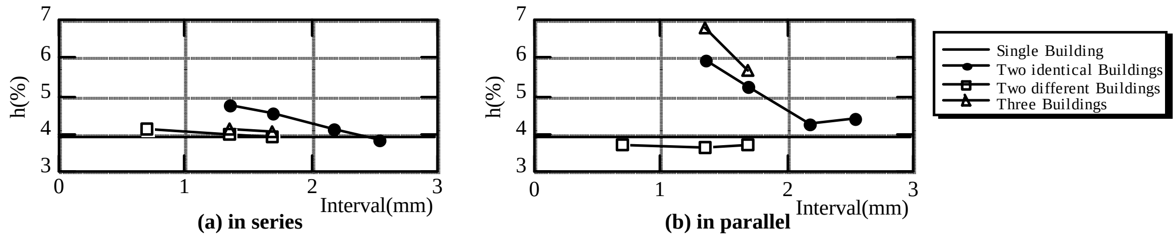


Fig.8 Relationships between Damping Factors(h) of Reactor Building A and Other Models

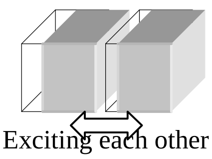
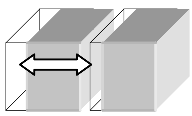
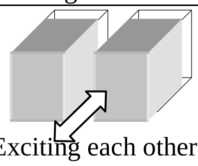
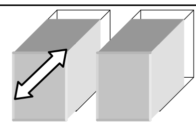
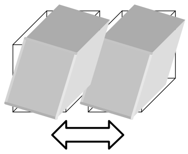
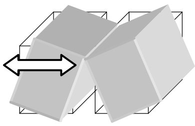
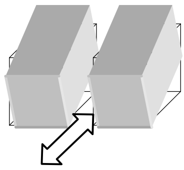
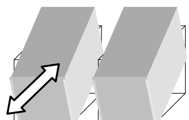
	In Series		In Parallel	
	Shaking Table Test	Forced Vibration Test	Shaking Table Test	Forced Vibration Test
Sway Behavior	 Exciting each other	 Exciting each other	 Exciting each other	 Exciting each other
Rocking Behavior	 Restraining each other	 Exciting each other	 Exciting each other	 Exciting each other

Fig.9 Dynamic behaviors of two identical buildings model in shaking table test and excitation test

CONCLUDING REMARKS

The present paper describes the on-going study, "Model Test on Dynamic Cross Interaction of Adjacent Buildings in Nuclear Power Plants" which is being carried out by NUPEC under a commission from MITI. At present, the tests without embedment have been completed and important basic test data are gradually accumulating. We will make additional effort hereafter to accumulate basic test data for evaluating the embedment effect on DCI. We will also conduct a detailed examination of the existing test data to establish a method for evaluating the DCI effect.

ACKNOWLEDGMENTS

This project is being carried out in consultation with the sub-committee on the "Model Test on Dynamic Cross Interaction of Adjacent Buildings in Nuclear Power Plants" (Chair person: Dr. Michio IGUCHI, one of the authors). In addition, annual test results have been examined by the executive committee on "Verification Tests for Seismic Analysis Codes" (Chair person: Dr. Akinori SHIBATA, Prof. Emeritus of Tohoku Univ.). The authors would like to express their thanks to members of the committee and the sub-committee for their encouragement and advice.