MODEL TEST ON DYNAMIC CROSS INTERACTION OF ADJACENT BUILDINGS IN NUCLEAR POWER PLANTS
-OVERVIEW AND OUTLINE OF EARTHQUAKE OBSERVATION IN THE FIELD TEST-

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ABSTRACT

This paper provides an outline of NUPEC's (Nuclear Power Engineering Corporation) on-going study, "Model Test on Dynamic Cross Interaction of Adjacent Buildings in an Nuclear Power Plant". The project is being carrying out to study the effect of an adjacent building, such as a turbine building (T/B), on a reactor building (R/B) when an earthquake strikes them. In general, an R/B of a Nuclear Power Plant (NPP) is constructed closely adjacent to other buildings, i.e., T/B and a control building. In such situations, the adjacent buildings are thought to affect the R/B through the soil during earthquakes and to force the R/B to exhibit dynamic behaviors different from those of an isolated R/B. Nevertheless, R/Bs are currently seismically designed as though the building were isolated. We have carried out both field and laboratory tests in this project to study the effect of an adjacent building on an R/B. Many important conclusions were obtained through the tests. Currently, the project is in its final stage of its entire eight year schedule. We are wrapping up the test results and performing a final simulation to quantify the effect for use in the detailed evaluation of NPP R/B behavior during earthquake.

INTRODUCTION

A reactor building (R/B) of a Nuclear Power Plant (NPP) is generally constructed closely adjacent to other buildings such as a turbine building (T/B) and a control building. In such situations, adjacent buildings are thought to influence each other through the soil during earthquakes and to exhibit dynamic behaviors different from those of isolated buildings. Nevertheless, R/Bs are currently seismically designed as though the buildings were isolated. In order to investigate the adjacent building's effect on earthquake response characteristics of an NPP R/B, a Dynamic Cross Interaction (DCI), Nuclear Power Engineering Corporation (NUPEC) is conducting a test project under a commission from METI, the Ministry of Economy, Trade and Industry, of the Japanese government [1]. The test consists of field and laboratory tests.

The field tests have been carried out under three kinds of building model construction conditions: a single R/B model, twin R/B models, and two different building models (R/B and T/B models). The scale of these models is about 1/10 of a typical existing NPP building in Japan. Forced vibration tests and earthquake observations have been carried out in the field tests. The field tests were completed at the end of March 2000. The earthquake observation data were obtained for both buildings conditions in the cases of with and without embedment of the base floor of the buildings. Hereafter we identify them by the names of the "embedment condition" and the "without embedment condition" both for field tests and laboratory tests. A total of 95 categories of earthquake data were obtained. Fourteen earthquakes have maximum accelerations over 10Gal.(cm/sec^2) at the free field surface. Above all the record obtained in Dec.28, 1994 has a maximum acceleration of 174Gal.

The laboratory tests were planned and carried out to supplement the field tests. A study of the effect of the space between adjacent buildings and the adjacent effect among three closely constructed buildings are the major objectives of the tests. In order to investigate such effects, tests were carried out using 1/230-scale building models made of aluminum and an artificial ground model made of silicone rubber. The tests were completed at the end of November 2000.

In this paper we provide the outline of the test project and some test data examples.

OUTLINE OF THE TEST

The project is being carried out as an 8-year project from fiscal 1994 to 2002. The tests carried out in the project consist of field and laboratory tests. Outlines of these tests are described in the following sections.

FIELD TESTS

The field tests were carried out under three kinds of building model construction conditions as shown in Fig.1: a single R/B model used for the comparison as a basic condition, twin R/B models used to evaluate basic DCI effects, and a two-different building models; R/B and T/B to evaluate DCI effects under actual plant conditions. Forced vibration tests and earthquake observations were carried out in the field test. All the R/B models used in the tests are identical. Each model is a reinforced concrete structure, having an 8m by 8m foundation, three stories and a height of 10.5m. The total weight is about 660tonfs.

The T/B model is also a reinforced concrete structure, having a 6.4m by 10m foundation, two stories and a height of 6.75m. The total weight is about 395tonfs. The scale of these models is about 1/10 of a typical existing NPP building in Japan. Typical model dimensions in the NS direction and test model deployment in the test field are shown in Fig.2 and Fig.3 respectively.

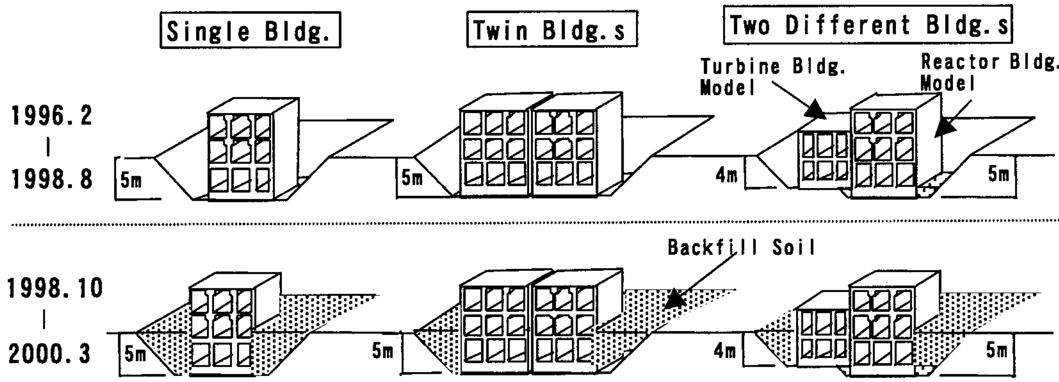


Fig.1 Embedment Conditions of the Building Models

The single R/B and twin R/B models were built at the bottom of pits. The depth of each pit was 5m below the ground surface. The twin R/B models are spaced at 60cm. The R/B model for the two different building models is also constructed on the soil in a pit. The T/B model was built on the soil at 1m above the R/B model installation level in the same pit. The R/B 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.

The vibration test and earthquake observation were firstly performed in accordance with the building models construction condition described above from February 1996 to August 1998. Then all test pits were filled with sand in September 1998. Under this condition, the vibration test and earthquake observation was performed from October 1998 to March 2000. In order to evaluate the ground motion applied to each building model, the earthquake observation was carried out also at two free field points as shown in Fig.3.

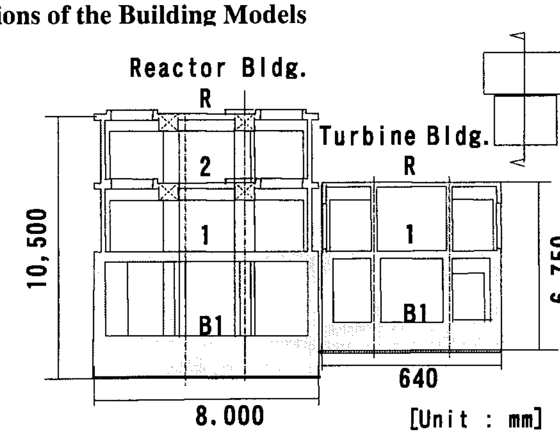


Fig.2 Dimensions of Two Different Bldg. Models

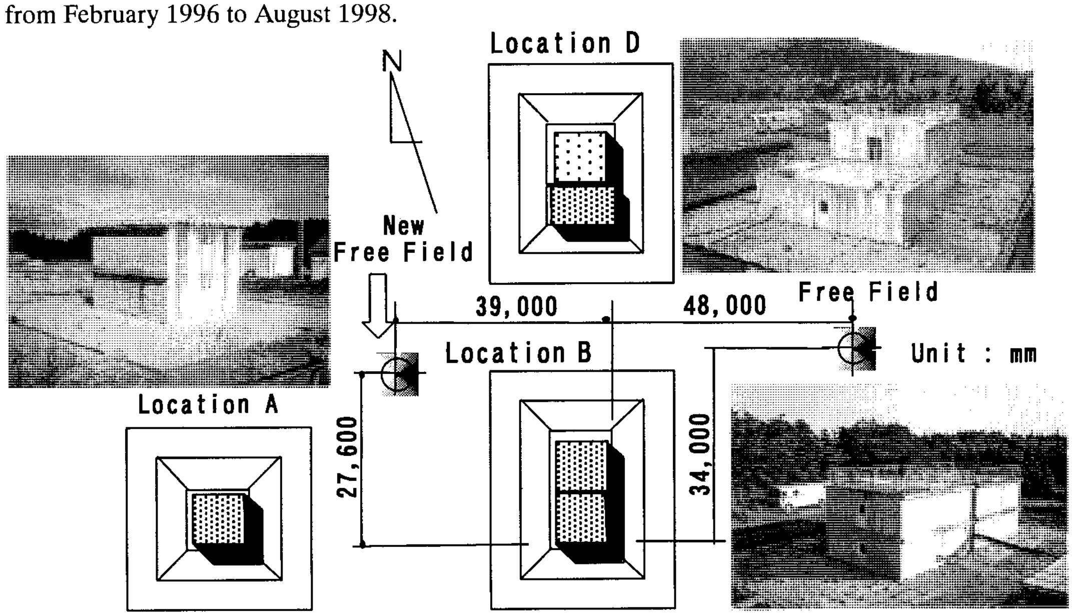


Fig.3 Embedment Conditions of the Building Models

LABORATORY TESTS

The laboratory tests were planned to supplement the field tests. Distance between adjacent buildings and the adjacency effect among three closely constructed buildings are the main test parameters for which detailed investigations are almost impossible through the field test. To investigate such effects on small-scale building models, a ground model and a shaking table apparatus were employed. The test model consists of a ground model made of silicone rubber and three building models made of aluminum. Figure 4 shows an outline of the test model. The figure shows test cases of three building models. As shown in this figure, the test was carried out firstly under the condition that the building models were placed on the ground model without embedment from 1996 to 1998.

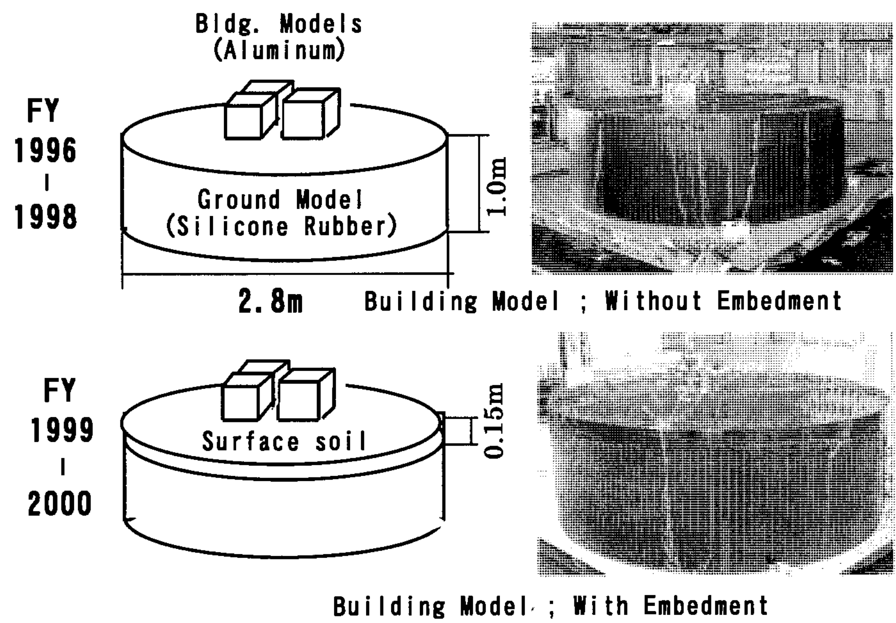


Fig.4 An Outline of The Laboratory test models

After the test, we added a thin layer to the ground model. The added soil part is also made of silicone rubber. The stiffness of the added soil part is designed to represent the surface soil which is much softer than the original ground. Using this ground model, the secondary test was carried out under the building embedment condition from 1999 to 2000. The building models used in the laboratory test were designed to be similar to the R/B and the T/B models used in the field test. The ground model has the dimensions of 2.8m in diameter and 1.0m in height (see Fig. 6(d)). The soft soil part has a thickness of 15cm. The two R/B models have the same dimensions of 30cm x 30cm in area and 38cm in height, and the total weight is about 25kgfs.

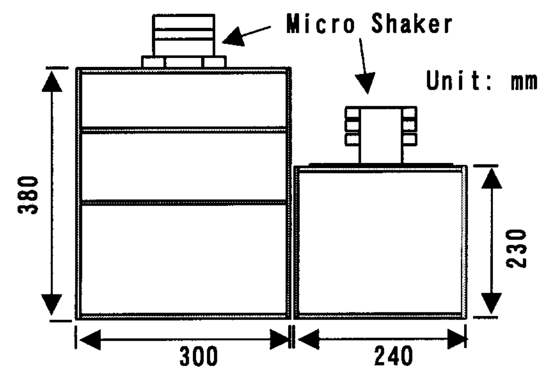


Fig.5 Dimensions of Two Different Bldg. Models

The T/B model has a 37.5cm x 24cm in area and 23cm in height, and has a total weight of about 16kgfs. The scale of these building models is about 1/260 of a typical existing NPP building in Japan. The models are also designed to have similar SSI characteristics to those of the building models used in the field test. Drawings of typical R/B and T/B models are shown in Fig.5. As shown in this figure, we equipped a small shaker at the top of each of the building model to simulate the vibration test performed in the field test.

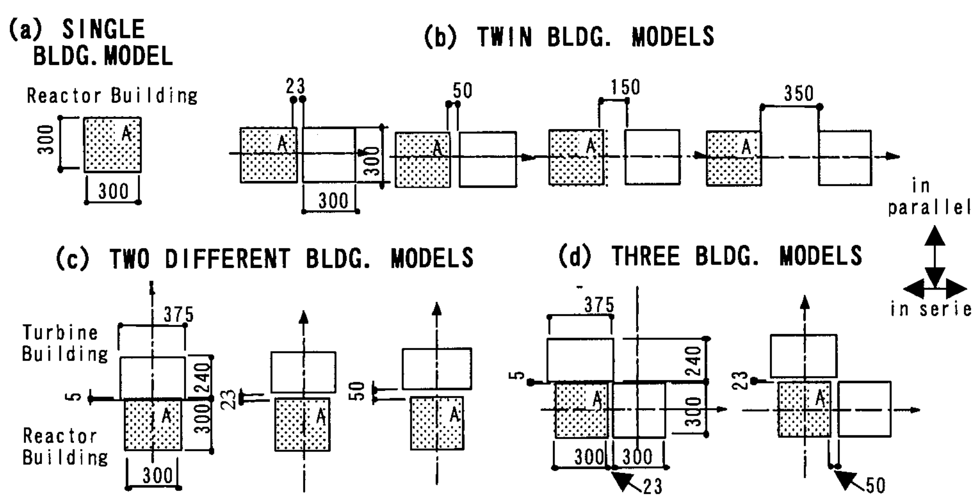


Fig.6 Building Layout Applied in The Laboratory Tests

Figure 6 shows building layouts on the ground model applied in the laboratory test. The building model layouts are classified into four stages, (a) through (d) in Fig.6. Figure 6(a) of the single R/B model is of course the base case, Fig. 6(b) of twin R/B models and Fig.6(c) of two different R/B and T/B models are planned to directly supplement the field test. The three building models shown in Fig. 6(d) are planned to study how the adjacent building affects actual plant layout conditions. In these layouts, the objective R/B model is placed at the center of the ground model. Sinusoidal motions and several artificial earthquake ground motions were applied to the building models through the ground model by the shaking table. Forced vibration tests were also performed using the small exciters in building models to investigate the DCI effect in detail.

OVERALL PROJECT PLAN

Figure 7 shows an outline of the project. The shaking test data of the field test are used to evaluate soil springs supposed installed between the building base-mat and the soil beneath the base-mat. The evaluated springs are compared with those estimated theoretically. Then the comparison results are used for verifying and/or modifying the current soil spring estimation methodology. The earthquake observation data are used for estimating net input earthquake ground motion to the building models. The laboratory test data are used to study how building layout and the space between buildings affects the DCI characteristics of buildings, particularly we are focusing on the natural frequencies and earthquake response amplitudes (or vibration dampings). We firstly conducted a study to obtain knowledge on the DCI effect with these test results. Secondly, we constructed a prototypical analysis model for evaluating building earthquake response, which includes the DCI effect by applying the knowledge obtained from the study. Then finally we analyzed the simulation to confirm the validity of the modeling. The rational modeling methodology will be proposed based on the simulation results. At the same time, we conducted a study to develop a simplified analytical model for use in the design analyses because the simulation model is considered too complicated to apply to the design analyses. Development of the criteria for the evaluation of adjacent building effects to be used in an NPP design assessment is also included in the scope of the project. These tests, test data evaluation, simulation analyses and extrapolation of objective results are performed on both test conditions, with and without building embedment.

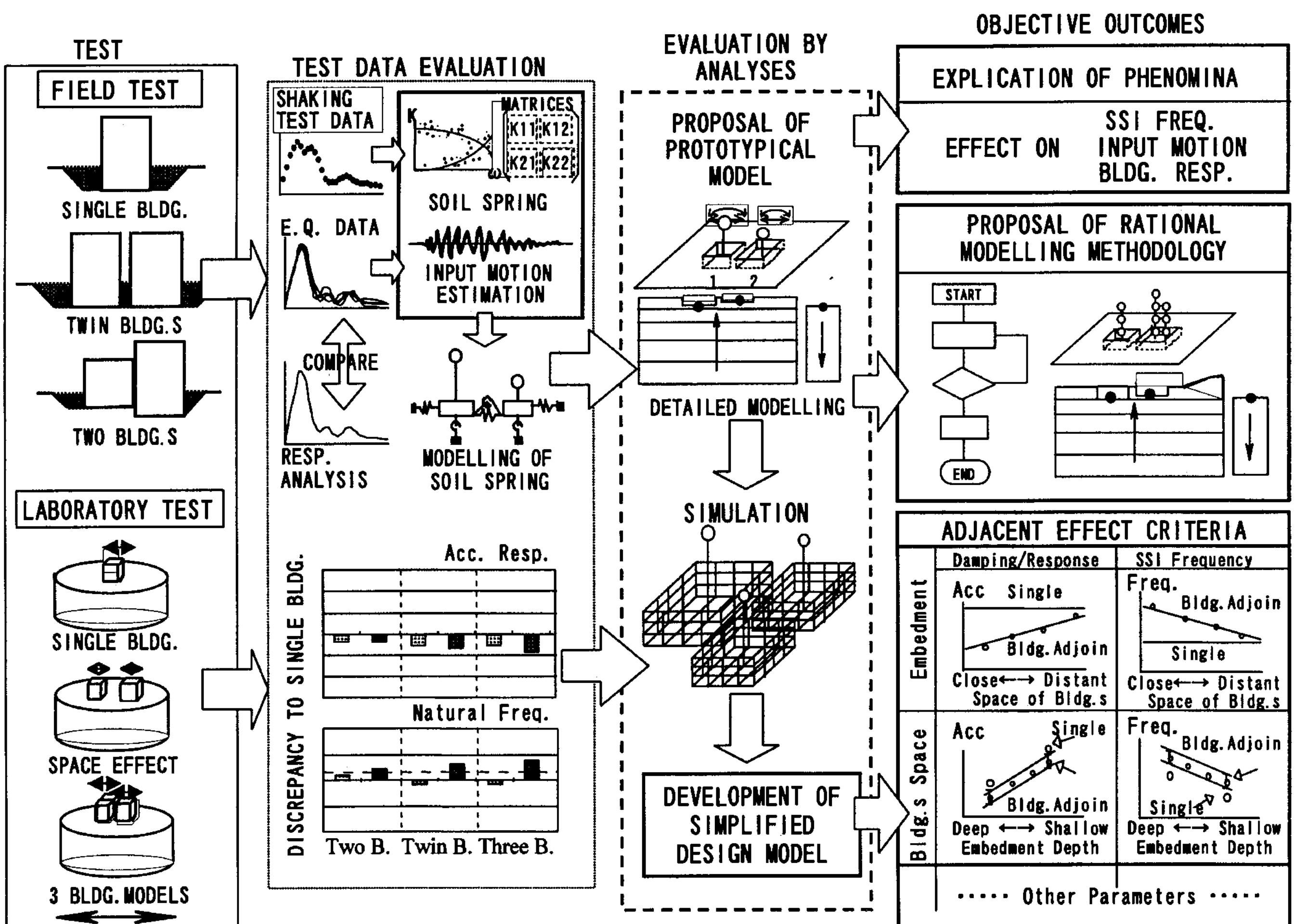


Fig.7 An Outlined Scope of The Project

TEST RESULT EXAMPLES

The tests were completed by the end of November 2000. Currently we are carrying out the simulation study and reaping the results of the long-term project. In this paper we present the test result examples of the field and laboratory tests as a part of the introduction of an outline of the project. Some test results obtained for the building without embedment condition was already been introduced in the preceding papers [2], [3] and [4]. In this paper, we describe typical test results focusing on the tests performed under the building embedment condition.

FIELD TEST DATA EXAMPLE

In the field test we had carried out forced vibration test and earthquake observation. The test result examples are introduced in the following sections. More detailed investigation process and results will be presented another paper for this SMiRT-16, [4].

FORCED VIBRATION TEST

Figure 8 shows typical vibration test results. The figure shows the resonance curve examples obtained by exciting an R/B model at the top in the NS direction, the direction of the buildings in series. Figures 8(a), 8(b) and 8(c) show the excitation test results for the single building model, twin R/B models and two different R/B and T/B models respectively. In Fig.s 8(b) and 8(c), both resonant curves on the base-mat top and on the building top are shown. These data obtained at the building top and at the base-mat top are used to evaluate soil spring constants installed between the base-mat and the soil beneath the base-mat. For the single building model a dominant resonance peak frequency is observed around 9.0Hz. On the other hand, for the twin R/B models, two resonant peaks were observed at frequencies of 9.8Hz and 12.5Hz. The former frequency component is a sway dominant mode. The latter frequency component is a rocking dominant mode in which twin R/B buildings move at almost reverse phases. Comparing the 9.0Hz component of the single R/B model with the 9.8Hz component of the twin R/B models, we can see the effect of the adjacent building because applied excitation energy were the same for all three test cases. For the two different building models, two kinds of resonant peak frequencies were observed at frequencies of 9.8Hz and 11.6Hz. Both frequency components are a sway dominant mode.

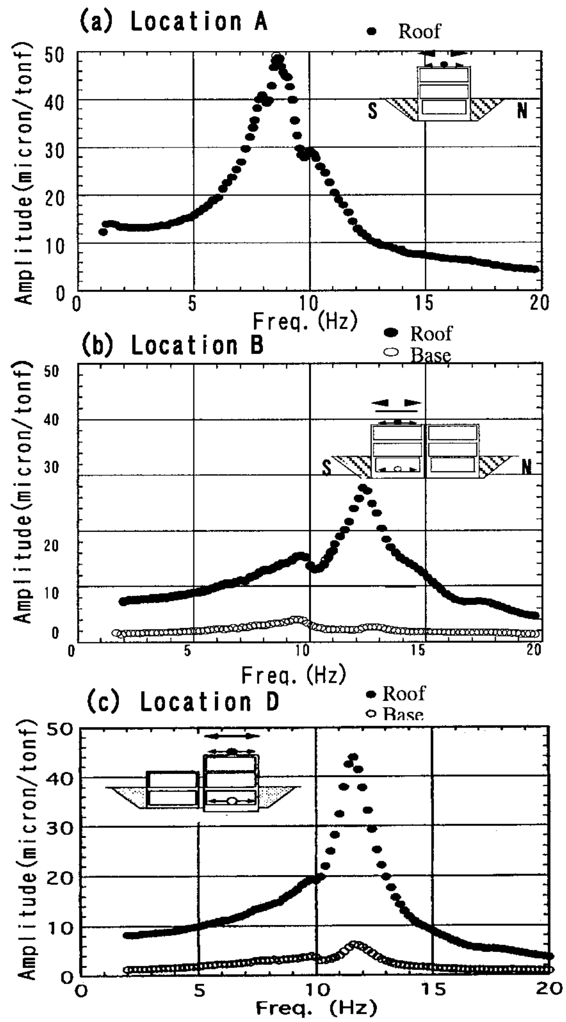


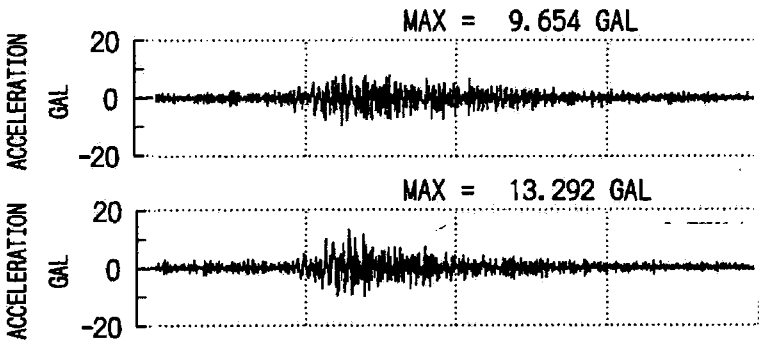
Fig.8 Forced Vibration Test Data Example

EARTHQUAKE OBSERVATION

As mentioned earlier, earthquake observation was carried out. Figure 9 shows an earthquake observation example, which was observed under the building embedment condition.

In the figure, the top left (a) is time histories of the earthquake ground motion observed at free field in the NS and EW directions, and the bottom left (b) summarizes maximum acceleration values observed at the top of the R/B model in three building layouts, the single, twin and the two different building models. Also the top and bottom right in the figure, (c) and (d), show Fourier spectral amplitudes of acceleration time histories obtained at the R/B model in the two different building models in the NS and EW directions respectively. In each Fourier spectra of Figs. 9(c) and 9(d), spectrum at the building top is superimposed on that of the building base-mat. By comparing Figs. 9(a) and 9(b), typical acceleration amplification can be seen in the frequency range higher than 7Hz. The vibration modes of 9.8Hz and 11.6Hz observed in vibration tests (Fig. 8(c)) in the NS direction are clearly observed in Fig. 9(c).

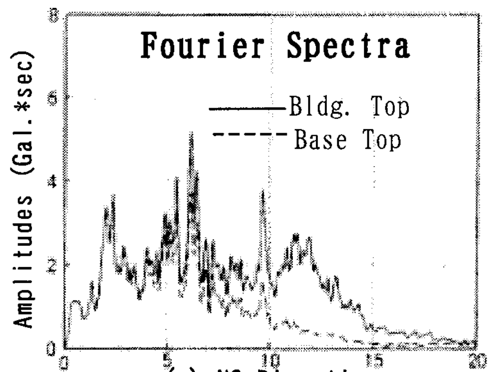
Figure 10 shows averaged spectra of Fourier amplitudes of acceleration time histories observed at the top of the single



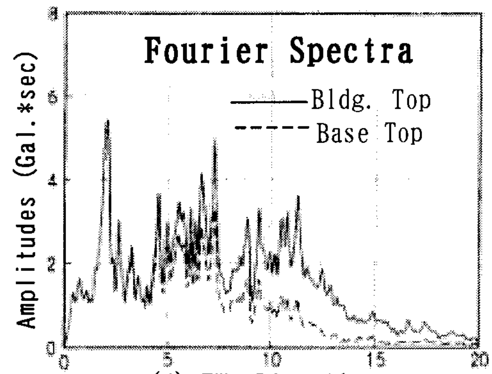
(a) Acceleration Time History at Free Field

Eq. No.	direction	Building model		
		Single	Twin	Different
No.172	NS EW	15.5 14.5	10.8 15.2	9.7 13.3

(b) Maximum Acceleration at an R/B Top



(c) NS Direction



(d) EW Direction

Fig.9 An Earthquake Observation Example

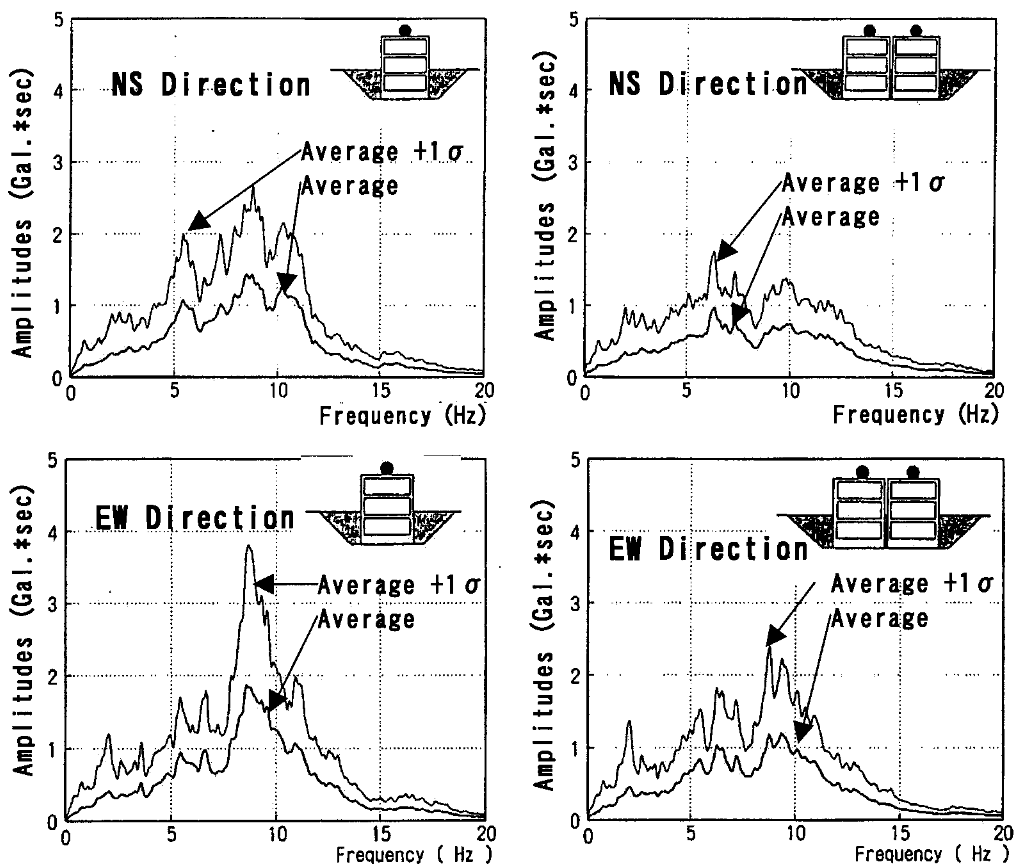


Fig.10 An Averaged Fourier Spectra of Observed Earthquakes

and one of the twin R/B models under the buildings embedment condition. The time histories used in the averaging were observed for 24 earthquakes from November 1998 to February 2000. The highest value of horizontal acceleration observed at free field is 13.6Gal., and that of the lowest value is 1.7Gal., respectively. The two upper parts in Fig.10 show the average spectra of single and twin R/B models in the NS direction and the lower two parts are those in the EW direction. In each part, we show average spectrum and the spectrum of the average plus one standard deviation. By comparing these averaged Fourier spectra, we can comprehend the building adjacency effect. The effects can be summarized as follows;

(1) Fourier amplitude reduction is clearly seen in the R/B in the twin building model spectra as compared with the single R/B model spectra of both NS and EW components in the frequency range from 7Hz to 13Hz,

(2) frequency component around 11-13Hz in the NS component of the R/B of the twin building models is slightly larger than that of the single R/B model, and this component corresponds to the resonant peak observed in the vibration test data shown in Fig.8(b).

LABORATORY TEST DATA EXAMPLE

This section presents a laboratory test result example. Figure 11 shows the shaking table vibration test results example for the building models performed under the building models embedment condition. The figure shows resonant vibration curves of R/B models for three building layouts, a single R/B model, two different building models of an R/B and a T/B, and three building models of an R/B together with a T/B in the Y direction and with an R/B in the X direction. In the figure, a solid line as the reference shows resonant curves in the X and Y directions of the single R/B model. For the models of the two and three building layouts, the test was carried out under both conditions that the building model space of 5mm between a R/B and T/B in Y direction was void and filled with surrounding soil.

It is understood by comparing the resonant vibration curves of an R/B in the two different building models with that of the single R/B model, the level of response decreases in the Y direction, the direction of the building in series, due to the building adjacency effect. The rate of the vibration response reduction became larger as the space between building models is filled and when the space is voided the response of an R/B of the two different building models became closer to that of the single R/B model. For the case of excitation in the X-direction, the direction of the building in parallel, the building adjacency effect on the response in the X-direction appears in the form of the shift of resonant peak frequency to higher rather than in the form of the response level reduction. As an influence of the space between the two buildings on the building adjacency effect, it is understood that when the space between buildings is voided, the resonant vibration curve of the two different buildings become closer to that of the single R/B model.

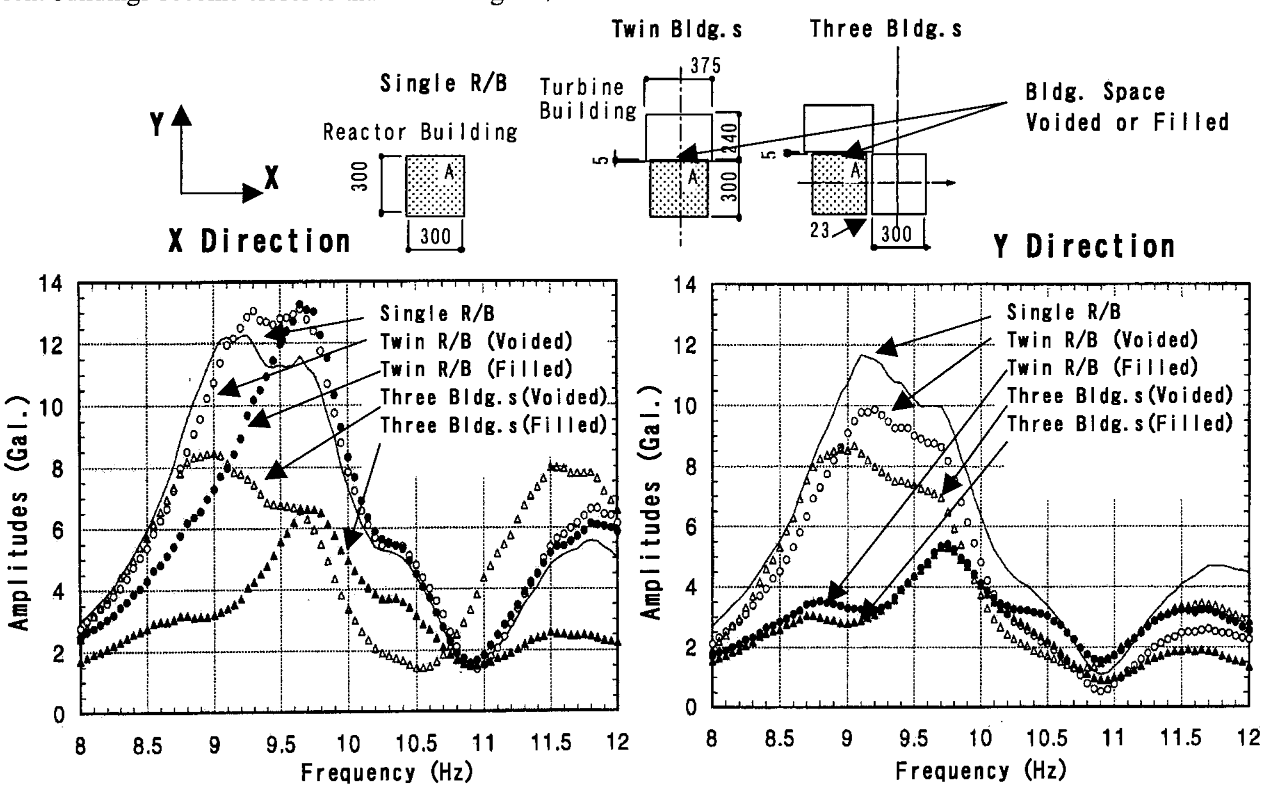


Fig.11 Laboratory Test Data Example – Resonant Vibration Curves

In the case of the three building model, since there is an adjacent building in both directions X and Y, the reduction in an R/B response due to the building adjacency effect is seen in both directions. The resonant vibration curve obtained by the excitation in the Y direction, for which direction a space between the R/B and T/B buildings is small, is nearly the same as that of the R/B in the two different building models, and the influence of an R/B adjacent in the X direction filled with soil. The fundamental tendencies seen in the resonant vibration curve of the objective R/B, i.e., the dominant vibration modes tend to be higher in frequency and smaller in response, is the same as that for an R/B of the two different building models, but the decrement effect appears lager than in the case of an R/B in the two different building models.

CONCLUDING REMARKS

The present paper describes the on-going study, "Model Test on Dynamic Cross Interaction of Adjacent Buildings in Nuclear Power Plants". All the field and laboratory tests have been completed and important test data has been accumulated. Currently we are carrying out a detailed study on these test data to extrapolate the DCI phenomena and establish a method for evaluating the DCI effect. Some results are presented in other papers in this SMiRT-16, [5], [6].

ACKNOWLEDGMENTS

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