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MODEL TEST ON DYNAMIC CROSS INTERACTION OF ADJACENT BUILDINGS IN NUCLEAR POWER PLANTS - AN OUTLINE AND OUTCOMES OF THE PROJECT-

Yoshio KITADA [1], Michio IGUCHI[2]

SUMMARY

The project introduced here, "The Model Test on Dynamic Cross Interaction of Adjacent Buildings in Nuclear Power Plants", is one of them. The project had aimed at the study of the dynamic cross interaction among buildings of a Nuclear Power Plant (NPP). A reactor building of an NPP is generally constructed closely adjacent to other buildings such as a turbine building 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 building. Nevertheless, the seismic design of a reactor building is performed currently as the building is isolated. The project had performed to study the dynamic cross interaction among buildings of an NPP [1]. A part of the test result was introduced in the previous 12WCEE [2] as for a midterm report. The project had completed March 2002 with many fruitful outcomes. In the paper we describe our major outcomes and some problems remained to be studied hereafter. In particular, trial analyses performed by expanding the laboratory test results to some actual plant conditions, which are characterized by changing model from a 3D Finite Element Method (FEM) model to a 3D Boundary Element Method (BEM) model, showed an unexpected amplification in response acceleration of reactor building for several cases.

INTRODUCTION

Japan Nuclear Energy Safety Organization (JNES) has succeeded the test project entitled "Verification Test for Seismic Analysis Codes" from NUPEC (Nuclear Power Engineering Corporation), which had been performed under the entrustment form METI (Ministry of Economy Trade and Industry) Japan.

A nuclear reactor building (R/B) is generally constructed adjacent to a turbine building (T/B) and auxiliary buildings, and in an increasing number of cases, multiple plants are being planned and built closely together on a single site. In these situations, adjacent buildings are considered to influence each other through the soil during earthquakes and dynamic behavior seems to be different from that of separate buildings which is a generic condition in a current practice of seismic design analysis. Dynamic interaction between buildings through the soil is termed here as "dynamic cross interaction (DCI)". The Model test on Dynamic Cross Interaction of Nuclear Power Plant Buildings consists of both field test and

[1] JNES, Japan Nuclear Energy Safety Organization, Tokyo, JAPAN, Email:kitada-yoshio@jnes.go.jp
[2] Tokyo Science University, Noda, JAPAN, Email:iguchi@rs.noda.sut.ac.jp

laboratory test. In these series of tests, forced vibration test, earthquake observation and shaking table test are performed to evaluate the basic characteristics of the DCI effects. The principal purposes of this research project are to study the DCI effect on the earthquake response of a reactor building of an NPP and to contribute to establish a reliable seismic design assessment method.

The paper covers the overview and the summary of the outcomes obtained from the project.

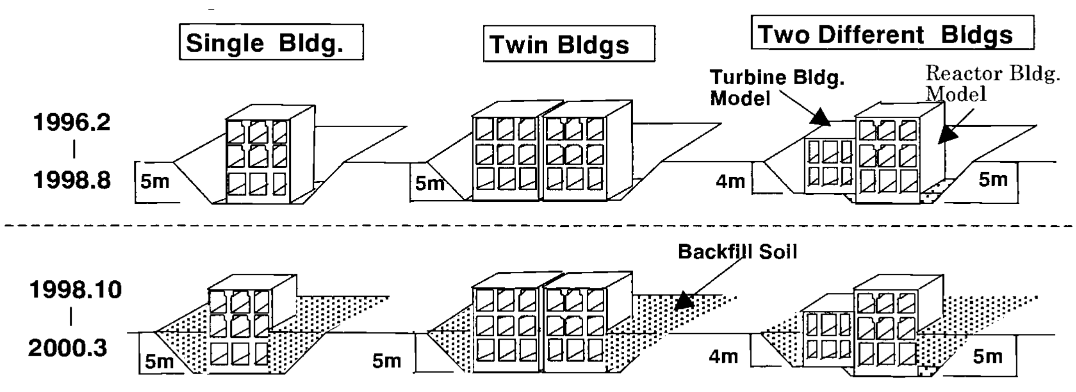
OUTLINES AND GENERAL PLAN OF THE PROJECT

Outline of The Project

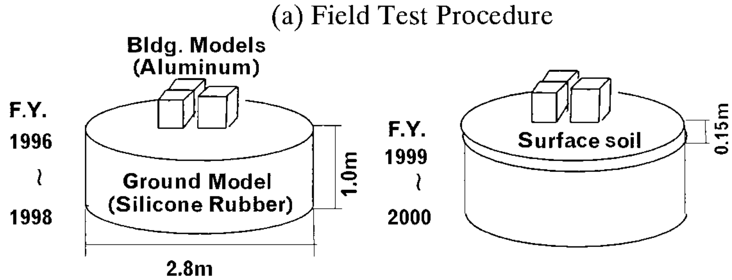
Major factors giving influence to the earthquake response characteristics of a building are dynamic impedance function, foundation input motion and dynamic characteristics of the building itself. The field test and the laboratory test had been planned to study the effects of these factors. The site for the field tests was selected at a place in village of Higashidoori, Aomori prefecture, northern part of Honshyu Island, Japan, whose soil has almost the same conditions as those of existing NPPs in Japan. In the laboratory test, small multiple building models made of aluminum are used with a soil model made of silicone. Building and soil models are placed on a shaking table to excite to study the phenomena associated with DCI effects of building models under various kinds of test parameters. As an overall evaluation of DCI test, whole results obtained from the test in 1994 to 2001 are summarized. Also analytical studies on adjacent effect using the building models are conducted.

General Plan of The Project

The project had been performed from 1994 to 2001, 8 years. In the field tests, planning and tests without embedment had been carried out from 1994 to 1997, and tests with embedment are carried out from 1998 to 2000. In laboratory tests, planning and tests to study the basic characteristics of buildings and a soil models as well as the tests without embedment using multiple models were carried out from 1994 to 1997, and the tests with embedment are carried out from 1999to 2000. Furthermore, the study to propose a Seismic Safety Analysis Codes regarding DCI are carried out in 2001. The whole process of DCI test is shown in Fig.1.



(a) Field Test Procedure



(b) Laboratory Test Procedure

Fig.1 Whole Test Procedure

FIELD TEST

Outlines

In the field tests, two kinds of conditions on DCI test are planned using building models made of reinforced concrete (RC). One is the DCI test between twin building models and the other is the DCI test between two different building models. The former corresponds to the DCI test between reactor buildings, and the latter corresponds to that between a reactor building and a turbine one. All building models were RC structures about 1/10 scale of existing BWR type plant buildings in Japan. Each test model was tested with and without embedment whose depth amounted to 5m. Forced vibration tests and earthquake observation were performed to obtain the dynamic impedance function and the foundation input motion using these building models. Details of the building models and test method are described in the papers [3], [4]. Figure 1 shows the conditions of installation and an example of building model.

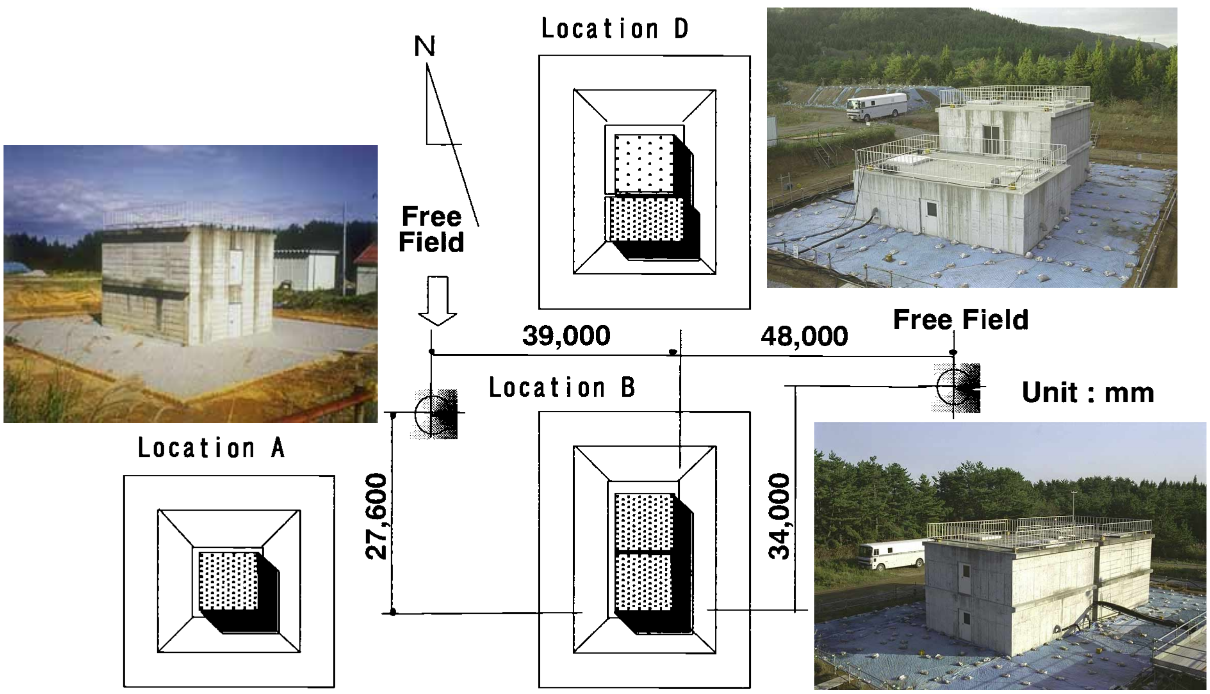


Fig.2 Embedment Conditions of the Building model

Results of the field tests

Among many outcomes of the field test, one major result is analytical comparison of seismic response between a single building and adjacent buildings. First, through some simulation analyses for forced vibration tests, we have got appropriate soil properties to be used in seismic response analysis by 3D-thin layered element method. In the analytical model, the soil properties obtained by averaging several boring tests data were applied. Furthermore a loose stratum was introduced in the part just beneath the model foundation. With those models, simulation analyses for the earthquake observation data were performed for both single and twin buildings under the condition with and without embedment. In those analyses, common soil properties are used for building models to ignore the effects due to different soil conditions. Two earthquake records obtained under the conditions with and without embedment are used for the analysis. As an example of the analytical result for embedded case, acceleration response spectra at model roof are shown in Fig. 3. With embedment case, in the direction of the twin buildings models in series showed lower amplitude by approximately 20% than that of the single building model. But in the direction of building in parallel, this tendency was not so clear and the amplitude of both single and the twin-buildings models were almost the same. The analytical conditions as well as the results of analyses are introduced in detail in a paper [3].

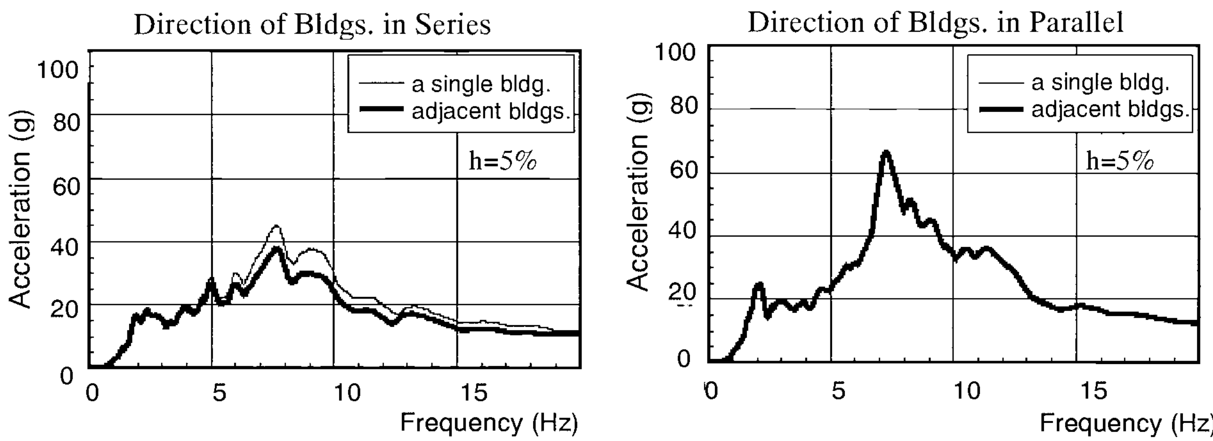
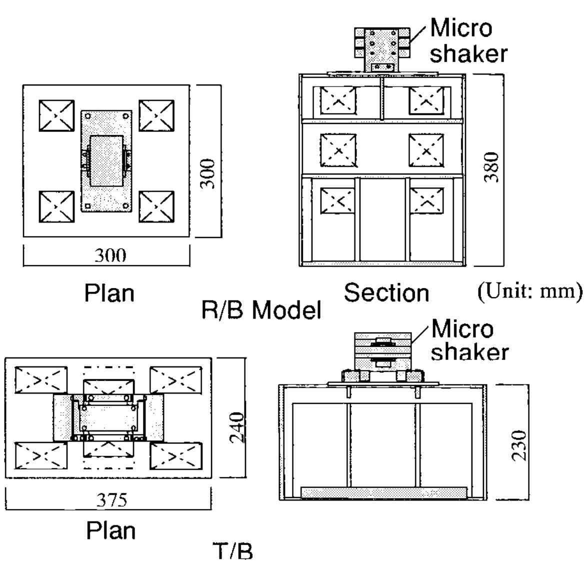


Fig. 3 Comparison of seismic response of a single building with that of adjacent buildings
(Spectrum of acceleration response, embedded case)

LABORATORY TEST (ANALYTICAL EVALUATION FOR TEST RESULTS)

Outlines of The Test

In the laboratory tests, the effect of the space between adjacent buildings and the adjacent effect among three closely constructed buildings on the building earthquake response is a major concern. In order to investigate such effects, tests had been conducted using 1/230-scale aluminum-building models with an artificial ground model made of silicone. Series of tests had been completed by 2000 and the evaluations of test results were carried out in 2001. Simulation analyses using 3-D FEM. are performed for the test results of laboratory tests to examine agreement between analysis results and test results. Furthermore, analyses using 3-D BEM are performed by taking into account the differences in the boundary conditions between the laboratory test model and actual plant, to apply the results of laboratory test to the an actual plant. Figure 4 shows the dimension of the building models used in the laboratory test and the installation of the test models on to the artificial ground model made of silicone.



Laboratory Test
Two identical buildings model (with embedment)

Fig. 4 Dimension of the bldg. models and a shot of the dynamic loading test model

Results of the laboratory tests

(a) Results from tests

The laboratory test has been carried out to evaluate the influence of building layout; the space between buildings, a number of buildings or the existence of backfill soil between buildings. From the tests results, we have obtained the sense that adjacent effects appear strongly when the same type of buildings are closely adjacent in the vibration direction. These adjacent effects influence on the resonant frequency of a SSI system and the maximum amplitude of response of each building. Some detailed tests results were presented in a paper [5].

(b) Simulation analysis

3-D FEM. analytical models are used in simulation analyses for laboratory tests. Figure 5 shows the analytical model for three buildings test without embedment as for example. Soil specimen is modeled by 3-D solid element. The bottom of the soil specimen attached to the shaking table is modeled by fixed boundary. Side part of the soil specimen is modeled by lateral roller boundary. The building specimen is modeled by rigid lumped mass model. The mass and inertia momentum of the superstructure is concentrated to the center of gravity of the building model. The analysis is performed in the frequency domain for sinusoidal wave shaking test, which is carried out by using shaking table. The frequency range of the analysis is from 2Hz to 10Hz and the frequency pitch applied is 0.2Hz. As for embedment cases, simulation analyses are also performed as the same manner as for test results without embedment case using alternative embedded model.

Figure 6 show example of the comparison of test and analytical results for twin buildings and different two buildings without embedment case. It is confirmed that the results of simulation analysis had agreed well with the test results.

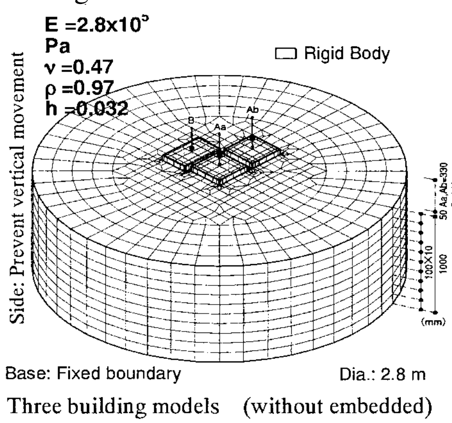


Fig. 5 3-D FEM. analysis model

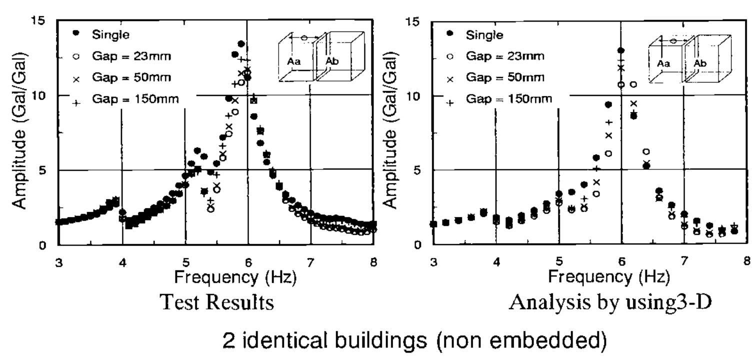


Fig. 6 Comparison between test and analysis

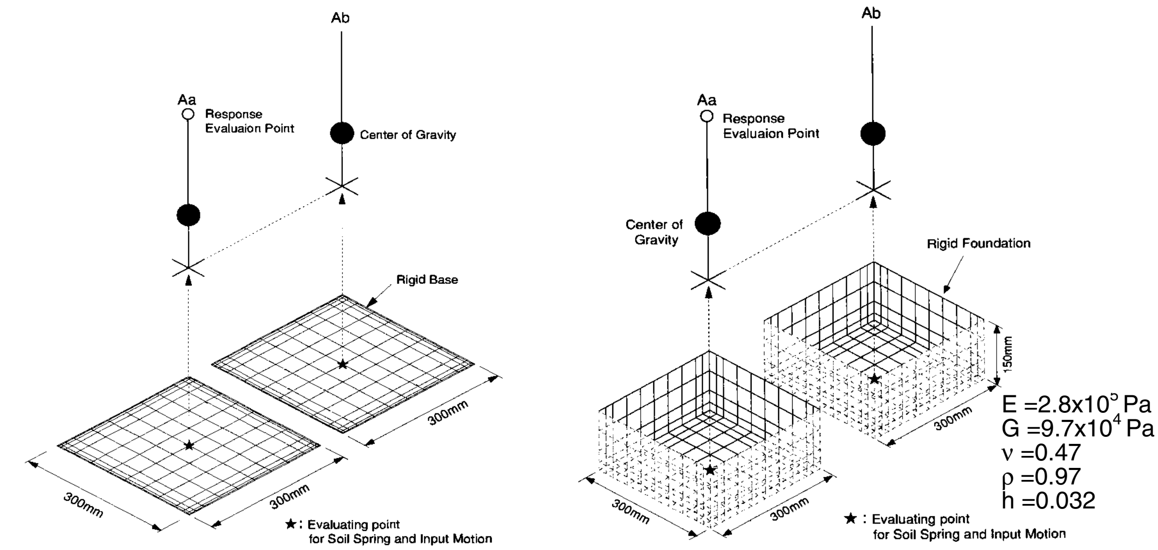
(c) Examination to apply the laboratory test results to infinite half-space

To examine applicability of the laboratory tests results to the design of actual plant, analyses are performed by removing base and side boundary conditions. The ground part is modeled by 3-D BEM model and assumed to be infinite half-space whose property is the same as that of silicone as in 3-D FEM analysis. The analysis is performed using dynamic substructure method. The soil spring and input motion are evaluated at the center of the base. Building specimens are modeled by lumped mass and rigid stick system whose mass and inertia moment are concentrated on the center of gravity. The soil spring and input motion are combined to the bottom of the building model.

The analysis is also performed in the frequency domain for sinusoidal wave shaking test, which is performed using the shaking table. The frequency range calculated for the without embedment case is from 4Hz to 7Hz whose pitch of analytical frequency is 0.1Hz. For the embedment case, the frequency range calculated is from 8Hz to 14Hz whose pitch of analytical frequency is 0.2Hz. Figure 7 shows the examples of both analytical models of with and without embedment.

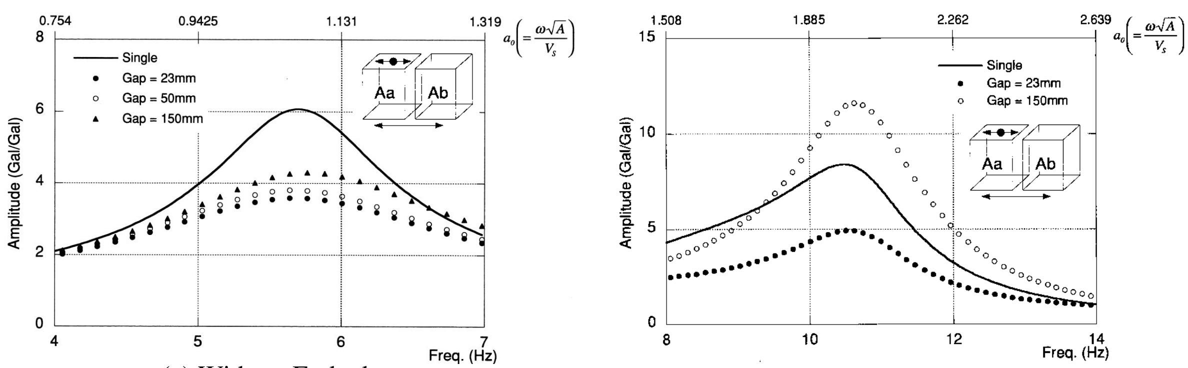
As an example, we shows Fig.8 which comparing the transfer functions of absolute acceleration from a point of base bottom to a top part of the building model for the case of excitation in the direction of building in series.

Without embedment case in Fig 8, the resonant frequencies of soil-structure interaction system are almost the same as that of a single building though the boundary condition has changed from the test condition to an infinite half-space. Damping is increasing, i.e. the amplitude of the transfer function was decreasing, with decreasing of the gap between buildings. With embedment case, amplitude of the transfer function is decreased when the gap of the two building model becomes small. However, there is an exception in the case that the gap is 150mm. In this case amplitude of transfer function becomes larger than that of single building. The tendency cannot be seen in the test results. For this case, the influence of the side boundary condition might not be neglected in the laboratory test.



Twin building model (without embedment) Twin building model (with embedment)

Fig. 7 3-D BEM Analysis Models



(a) Without Embedment (b) With Embedment

Fig. 8 3-D BEM Analysis Results of Twin Building (In The Direction of Bldgs.in Series)

EXAMINATION ON THE EQUIVALENT CONDITION TO THE ACTUAL PLANT

Outlines

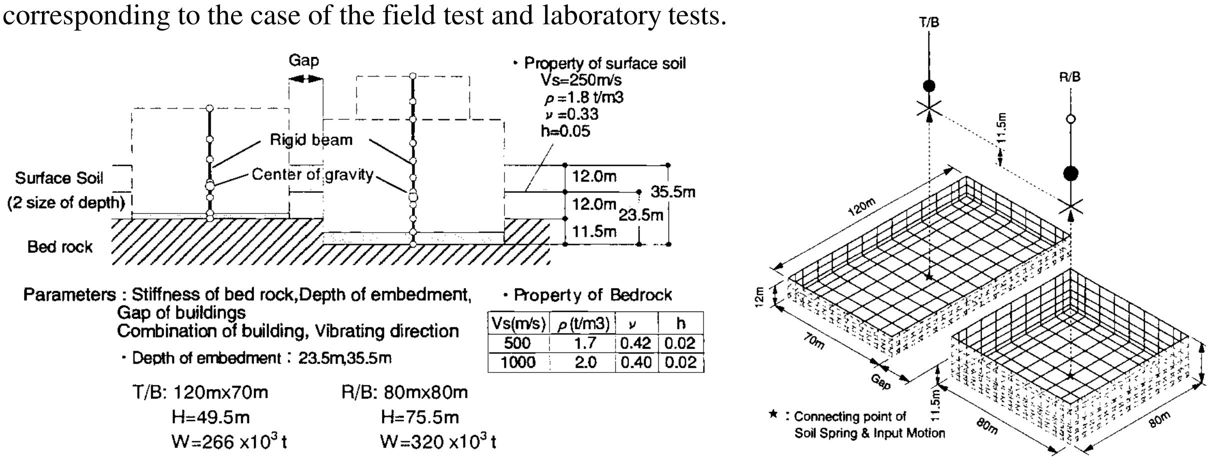
Through the evaluation of the field and laboratory tests, it is confirmed that the behavior of adjacent buildings can be explained by the existing analytical method by taking into account an appropriate condition to the analytical model.

The parametric analyses are carried out using simplified rigid building model, which is taken into account the basic properties of actual plant conditions, by applying the analytical method used in the simulation analysis shown in the previous sections to examine the adjacent effect on an actual scale building. Furthermore, an analysis considering the properties of actual plants is also carried out.

Analysis using rigid building model

(a) Analytical model and parameters

To know how acts the adjacent effect on building response to earthquakes in an actual scale, parametric analyses are conducted using rigid building models with the dynamic substructure method based on 3-D BEM. The parameters of the analyses are soil conditions, gap between buildings and embedment conditions. The analyses are performed for the case of single R/B, Twin R/Bs and an R/B-T/B layout. The building models are composed of an R/B model and a T/B model as different buildings. Figure 9 shows an outline of buildings and soil models and a 3-D BEM model of embedded case. We modeled building a rigid single beam with lumped mass for convenience. Their properties are determined based on a survey for existing NPPs in Japan. For embedded case, the soil model is composed of surface layer whose shear wave velocity (Vs) is 250m/s and half-space bedrock whose Vs value is 500 or 1000m/s. The difference in footing levels of buildings between R/B and T/B is 11.5m for the embedded case (R/B is set deeper). The thickness of surface layer in the embedded cases is 12m or 24m. In this analysis, the gap of buildings is changed parametrically as: 6, 10, and 20meters for the twin R/B model and l, 6, 10, and 20meters (1/4 of the width of R/B) for the R/B-T/B model which corresponding to the case of the field test and laboratory tests.



Building and soil model 3-D BEM analysis model

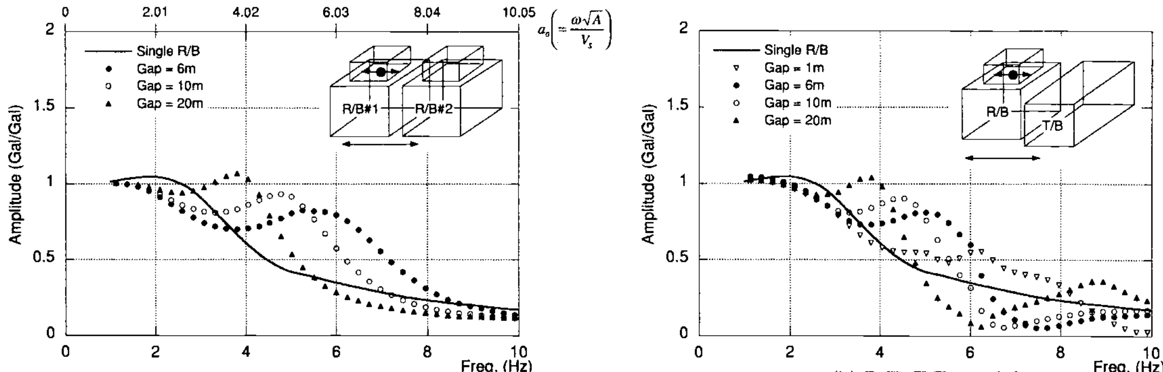
Fig. 9 Analytical model (R/B-T/B model, embedded case)

(b) Analytical result

As an example, analytical results for the case that an R/B is embedded by 23.5m and Vs value of the bedrock is 500m/s are shown in Fig.10. The results are shown in the form of transfer functions at the operating floor of the R/B to the input motion at the bedrock surface.

For the case of the twin R/B model, the transfer function in the direction of the building in series, the frequency of a dominant peak shifted higher and the amplitude decreased to 80% as compared to those of the single R/B model when the gap of two building models is 6m. When the gap increases, the maximum amplitude becomes closer to the result of the single R/B model. For the case of the R/B-T/B model, the maximum amplitude of a dominant peak in the transfer function in the direction of building in series is decreased. The tendency is the same as that of the twin R/B model when the gap between building models is narrow though it becomes closer to the result of the single R/B model when the gap is increased to 20m. According to these results, it is concluded that the adjacent effect of embedded buildings is caused by some kind of restraint of the energy dissipation by the adjacent building.

According to the analytical results for embedment cases, the response characteristics are affected much by the embedded conditions and/or soil properties. We have obtained many analytical results other than shown in Fig.10. With those results (not shown here), we have found some exceptional cases that showed unexpectedly larger transfer functions for the adjacent buildings than that of a single building. The cases indicate that some earthquake response amplification might occur due to building adjacent effect. However we have never confirmed the fact with the test performed on an actual soil condition (field test). Therefore further works are needed to confirm that the amplification of building earthquake response due to building adjacent effect observed by the analytical study is fictitious or not.



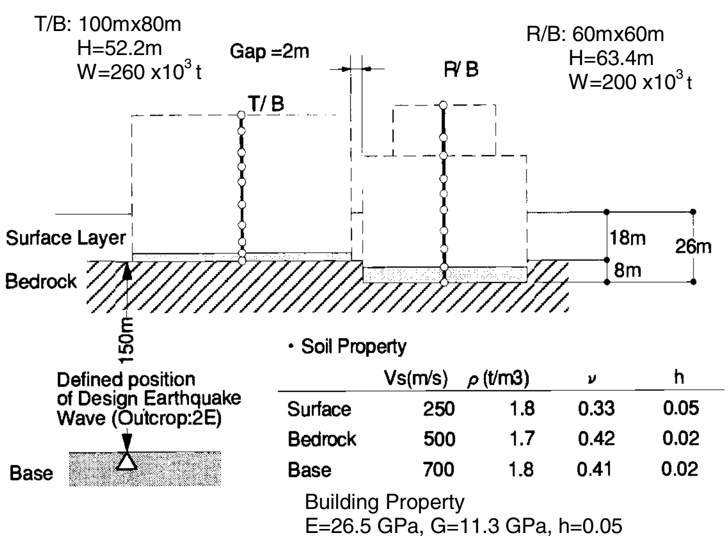
(a) Twin R/B model (b) R/B-T/B model

Fig. 10 3D BEM analysis results of rigid building model
(23.5m Embedded, Bedrock Vs=500 m/s, Series direction)

Examination on practical building model

(a) Analytical model

The practical analytical model used in this study is composed of building models of R/B and T/B. Figure 11 shows the building models with soil model. An R/B model has a plan of 60m by 60m and a T/B model has a plan of 100m by 80m. The depth of embedment is 26m for R/B model and 18m for T/B model. Both R/B and T/B models are represented by single beam for the 3-dimensional analysis. The soil is modeled as 3 layer; surface layer, bedrock and base. The properties of building models and soil are determined by taking in to account existing plants. The position where earthquake ground motion is defined for the design earthquake is placed a 150m below the bedrock. The analytical method applied is dynamic substructure method based on 3-D BEM. Figure 12 shows the overview of the earthquake response analysis for the practical building model.



	Vs(m/s)	ρ (t/m3)	ν	h
Surface	250	1.8	0.33	0.05
Bedrock	500	1.7	0.42	0.02
Base	700	1.8	0.41	0.02

Building Property
E=26.5 GPa, G=11.3 GPa, h=0.05

Fig. 11 Building model and soil model

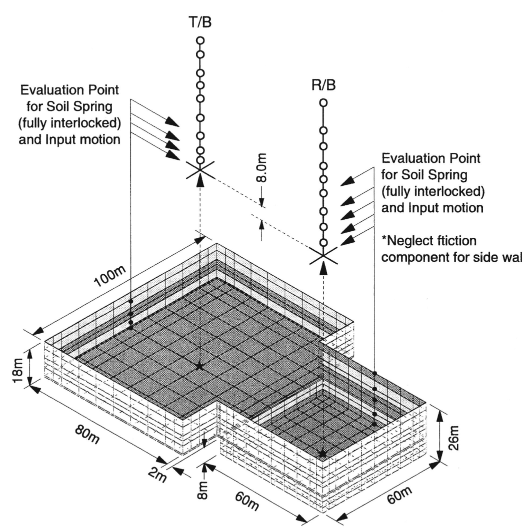


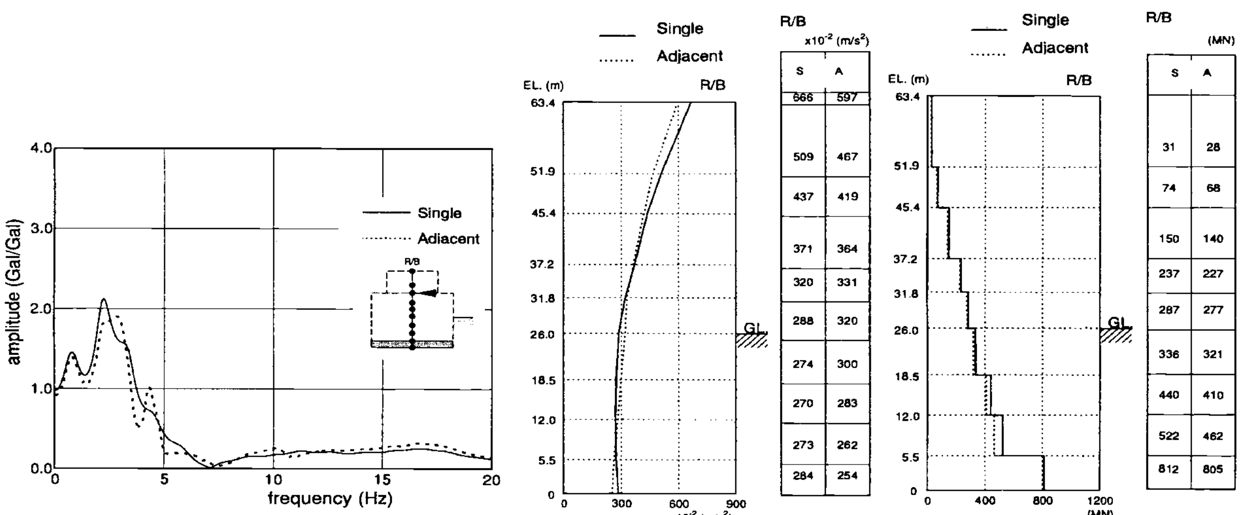
Fig. 12 Overview of earthquake response analysis

We have applied an earthquake ground motion of the S1-far field, which have been frequently used in Japan as for checking design ground motion in a trial earthquake response analysis in an NPP design stage. In this analysis, the input motion at the beneath of the building base was calculated with the computer program “SHAKE” as a de-convoluted outcrop wave of “2E” components. Maximum acceleration of the input ground motion is 407cm/s/s.

(b) Analytical result

Figure 13 show the results of the earthquake response analysis both for single R/B and R/B-T/B models in the direction of buildings in series. Figure 13(a) shows the transfer function of the absolute acceleration at operating floor of R/B model to the control point of the input ground motion. According to this result, the dominant frequency of the soil-structure interaction system shifts higher a little bit and the amplitude between 2 and 7Hz is changed from the result of single model. Figures 13 (b) and (c) show the maximum response acceleration and shear force in the direction of the buildings in series. In the figure, it is found that the maximum acceleration is decreased to a 90% above the ground level as compared to the result of single model though it is increased to a 110% below the ground level. The maximum shear force is decreased to a 90%.

With the results, we can consider that the building adjacent effect is judged to exist actually in a typical design model however its magnitude is not so large. In a design model of an NPP we have to make some conservative model by taking into account some uncertainties in soil conditions, embedded conditions, and surrounding soil damping etc. Therefore we are judging that the building adjacent effect is not necessary to take into account in the seismic design for NPPs.



(a) Transfer function at operating floor (b) Maximum acceleration (c) Maximum shear force

Fig. 13 Analysis results of idealized building model (in the direction of R/Bs in series)

CONCLUDING REMARKS

We have conducted a series of tests to study dynamic cross interactions of adjacent effect of NPP buildings since 1994, because the buildings closely constructed are considered to affect each other through the soil during earthquake. Through the examinations on the test and analytical results performed in the project, we have found that there are some adjacent effects among adjacent buildings. In general the effect works on the earthquake response of the adjacent buildings to restrain as compared to that of the single building, particularly in the direction of buildings in series and that being embedded.

As the whole, the analytical methods introduced in the present study are confirmed to be applicable to the evaluation of the building adjacent effect. However we have experienced some exceptionally unexpected cases in the analytical study, e.g., the earthquake responses of adjacent buildings became lager than that of single building. The exceptional cases had occurred when we expanded the laboratory test results to an actual buildings and soil conditions. The phenomena had never been observed in the field test results. Therefore further works are needed to confirm that the unexpectedly large amplification of building earthquake response due to building adjacent effect obtained peculiarly in the analytical study is fictitious or not.

Also it is confirmed that to examine the adjacent effect, the precise analysis model is required such as shown in above mentioned example analysis. Furthermore it is important to take into account that the variety is exists in the adjacent effect caused by some parameters; i.e. soil conditions, embedded conditions, layout of buildings, and surrounding soil damping.

We have concluded that it is not necessary to take into account the adjacent effect to the seismic design practice for NPPs, because the current seismic design practice for NPPs includes many margins and factors of conservativeness to cover the uncertainties in the soil, structures, and the applied analytical methodologies. However, for the precise analysis such as simulation analysis for earthquake response observation data, the adjacent effect cannot be neglected to obtain satisfactory results.

ACKNOWLEDGMENTS

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