Proceedings Third UJNR Workshop on Soil-Structure Interaction, March 29-30, 2004, Menlo Park, California, USA.

Experimental Study on Nonlinear Soil Structure Interaction of Nuclear Power Plants using Large Scale Blast Excitations

Osamu Kontani,[1] **Atsushi Suzuki,**[1] **Yoshio Kitada,**[2] **and Michio Iguchi** [3]

Extensive seismic vibration tests are proposed to promote better understanding of the nonlinear soil-structure interaction of nuclear power plants during large earthquake motions. The influence on structural responses caused by geometrical nonlinearity (uplift) of the base mat as well as the material nonlinearity of the soil under the base mat are the main issues to be investigated.

The proposed vibration tests will be performed at a coal mine. Ground motions from large-scale blasting operations will be used as excitation forces for the vibration tests. Significant aspects of this test method are that vibration tests can be performed several times with different levels of input motions by choosing blast areas at appropriate distances that will generate the desired accelerations at the test sites, and that large scale model structures on the ground can be tested with consideration of three dimensional effects and soil-structure interaction.

INTRODUCTION

"Regulatory Guide for Aseismic Design of Nuclear Power Reactor Facilities" (JNSC 1981) is presently undergoing extensive revision by the Japan Nuclear Safety Commission. The following items are related to nonlinear soil-structure interaction (SSI) of nuclear power plant buildings and might be introduced through the revision.

1. Introduction of New Methodology for Evaluating Basic Design Earthquake
2. Consideration of Dynamic Effects in Evaluating Vertical Seismic Design Load
3. Relaxation of Requirement of Building Construction on Firm Bedrock

---

[1] Kajima Corporation, Nuclear Power Dept., 6-5-30 Akasaka, Minato-ku, Tokyo 107-8502, JAPAN
[2] Japan Nuclear Energy Safety Org., 3-17-1 Toranomon, Minato-ku, Tokyo 105-0001, JAPAN
[3] Tokyo University of Science, Faculty of Science and Engineering, 2641 Yamazaki, Noda-shi, Chiba 278-8510, JAPAN

4. Introduction of PSA for Evaluating Seismic Margin of Nuclear Building

The Nuclear Power Engineering Corporation (NUPEC 1998) had conducted extensive experimental studies on the SSI of the nuclear power plants. The following is a series of major studies related to the SSI of structures.

1. Verification Test for Seismic Analysis Codes.
    (1) Model Tests on Dynamic Soil-Structure Interaction (1980-1986).
    (2) Base Mat Uplift Tests of Reactor Building (1986-1995).
    (3) Tests on Embedment Effects on Reactor Building (1981-1987).
    (4) Model Tests on Dynamic Cross-Interaction of Structures (1994-2002).
2. Verification Test of New Siting Technology(1983-2000).

The above studies contributed greatly to understanding of SSI behaviors and development of earthquake response analysis codes. However, they provide very little information on the SSI of nuclear facilities subjected to large input motions, because the experimental conditions were within the design levels. Therefore, more studies are needed on nonlinear SSI in order to precisely evaluate responses of the nuclear power plants subject to larger earthquake motions.

Common ways for performing seismic tests on structures are forced vibration tests, earthquake observations, shaking table tests and centrifuge tests. These methods are very useful in many ways. However, none are capable of shaking a large-scale SSI system at larger amplitudes.

This paper describes the significance of experimental studies on nonlinear SSI of nuclear power plants. It also provides a method for conducting seismic tests on large scale model structures using ground motions caused by large scale blast excitations.

GREAT NEED TO INVESTIGATE NONLINEAR SSI

Introduction of New Methodology for Evaluating Basic Design Earthquake

Basic design earthquakes S1 and S2 are employed for the seismic design of nuclear power plants in Japan. S1 is based on earthquake history and very active faults, whichever has the greater influence. S2 is evaluated from active faults, the seismic tectonic structure and shallow-focus earthquake of M6.5. Since the Great Hanshin-Awaji Earthquake in 1995, shallow-focus earthquakes of magnitude greater than M6.5 have been observed quite often. It was therefore decided to increase the magnitude of the design shallow-focus earthquake. This is currently under discussion. If the S2 level earthquake is increased, the SSI in the nonlinear region would be very important in precisely evaluating earthquake responses of nuclear structures against basic design earthquakes.

Consideration of Dynamic Effects in Evaluating Vertical Seismic Design Load

In current design practice, horizontal seismic design loads are evaluated from a dynamic response analysis of the building. Vertical seismic design loads are static and are evaluated from a vertical seismic coefficient that is uniform throughout the structural height. After the revision of the regulatory guide, the vertical seismic design load will be evaluated from a dynamic response analysis in the same way as the horizontal seismic design loads. Therefore, it is very important to understand nonlinear SSI behavior and to develop methods for precisely evaluating vertical responses of nuclear structures.

Relaxation of Requirement of Building Construction on Firm Bedrock

In current design practice, nuclear buildings are required to be constructed on the firm bedrock layer. The revision may relax the construction requirement. Then, building construction on quaternary deposits needs to be investigated in order to alleviate long-term siting problems for nuclear power plants. Since the quaternary deposit is softer than the bedrock, nonlinear SSI should be properly incorporated into the earthquake response analysis method as well as seismic design.

Introduction of PSA for Evaluating Seismic Margin of Nuclear Building

The probabilistic technique is very important for investigating seismic redundancy of nuclear structures, because deterministic methods are just too uncertain to deal with earthquake hazard and building fragility. In order to evaluate fragility of nuclear buildings, it is necessary to develop an earthquake response analysis method that can be employed during large input motions.

Thus, understanding of nonlinear SSI of nuclear power plant buildings is very important, and needs to be incorporated into an earthquake response analysis method that can be used during large input motions, and also needs to be incorporated into seismic design of nuclear structures. Major issues in nonlinear SSI are geometrical nonlinearity (uplift) of the base mat and material nonlinearity of soil under the base mat.

SURVEY OF INFORMATION ON SOIL-STRACTURE INTERACTION

1. Verification Test for Seismic Analysis Codes

NUPEC had conducted extensive experimental studies on the SSI of nuclear power plants. The following titles are major studies performed on the SSI as a part of a series of "Verification Test for Seismic Analysis Codes."

(1) Model Tests on Dynamic Soil-Structure Interaction (1980-1986)

A series of forced vibration tests and earthquake observations were performed in the field to evaluate the SSI for rigid structures (Odajima 1987, Iguchi 1987). Three structural models representing reactor buildings and two concrete block specimens were employed. Figure 1 shows a structural model representing a BWR building. In the tests, the effects of base mat size on dynamic soil stiffness, radiation damping and soil pressure distributions were investigated. This study provided very basic and important information on the SSI that is used practically nowadays.

(2) Base Mat Uplift Tests of Reactor Building (1986-1995)

Shaking table tests in the laboratory and forced vibration tests in the field were conducted to investigate uplift phenomena of the rigid structures (Hangai 1991). Figure 2 shows one of two test specimens employed for the shaking table tests. The soil was modeled with silicon rubber. This study provided the following findings. 1) As the contact ratio decreased with increasing input motions, response amplification of the structure became low and resonance frequencies of the SSI system shifted toward longer periods. 2) Horizontal motions with higher frequency were induced by uplift phenomena.

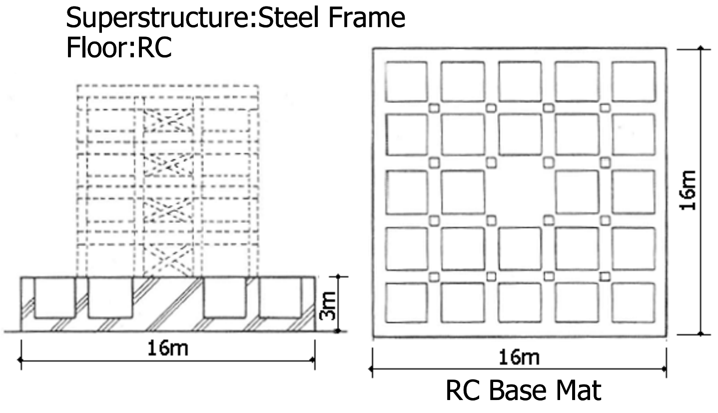


Figure 1 BWR Building Model

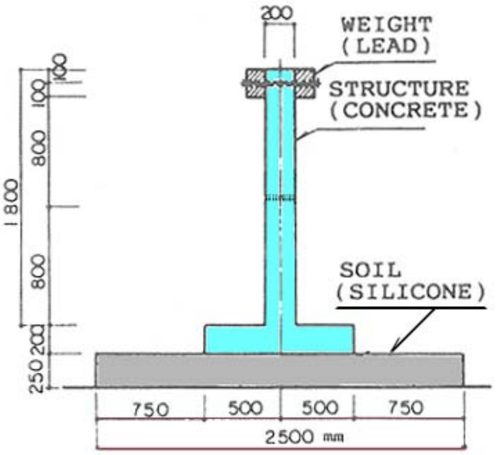


Figure 2 Uplift Test Specimen

(3) Tests on Embedment Effects on Reactor Building (1981-1987)

Forced vibration tests with exciter and earthquake observation were performed in the field in order to investigate the embedment effects on SSI (Kobayashi 1991). Shaking table tests using silicone rubber as soil model were also conducted to supplement field test. Two types of structural models are shown in Figure 3. Model B is the 1/10 scale model of BWR building. Major finding was that the embedment of the building reduced response of structure and increased natural frequencies and damping factors of the SSI system.

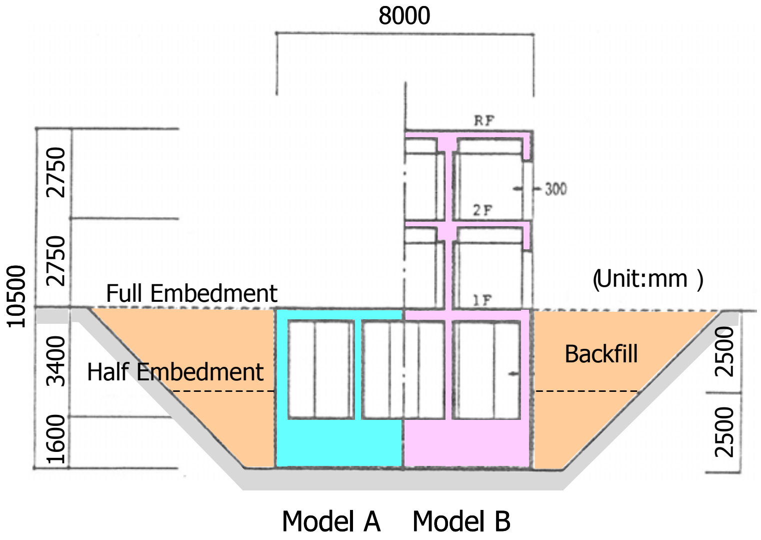
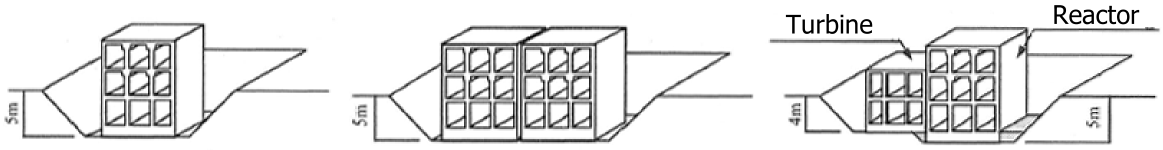


Figure 3 Models for Forced Vibration Tests

(4) Model Tests on Dynamic Cross-Interaction of Structures (1994-2002)

Experimental studies were performed to investigate dynamic cross-interactions of structures (Yano 2000, Kusama 2003). Forced vibration tests and earthquake observations were conducted in three different conditions as shown in Figure 4. Two identical building models in the field test are shown in Figure 5. Vibration tests using a shaking table were performed on 1/230 scale aluminum-building models as shown in Figure 6. It was found that the two identical building models showed lower amplification in the series direction and almost the same amplification in the parallel direction compared with the single building model.



Single Building Model
(Reactor Building)

Two Identical Building Model
(Two Reactor Buildings)

Two Different Building Model
(Reactor & Turbine Buildings)

Figure 4 Building Model Arrangement

Two Identical Building Model

Figure 5 Building models in field Test

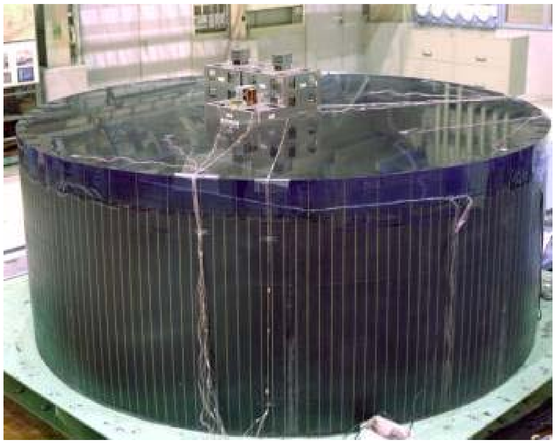


Figure 6 Vibration test using shaker

Verification Tests of New Siting Technology (1983-2000)

For higher seismic resistance, nuclear structures are required to be constructed on firm rock layers, which gave problems in finding new construction site. In order to alleviate long-term siting problems for nuclear power plants, NUPEC performed an extensive investigation program on soil stability during large earthquake, seismic safety of buildings, and so on (Uchiyama 1992). Forced vibration tests were carried out on concrete blocks on quaternary deposits, as shown in Figure 7. Block A was designed to provide the same contact pressure as an actual reactor building. As a result, SSI behaviors were well-understood and dynamic soil properties were obtained.

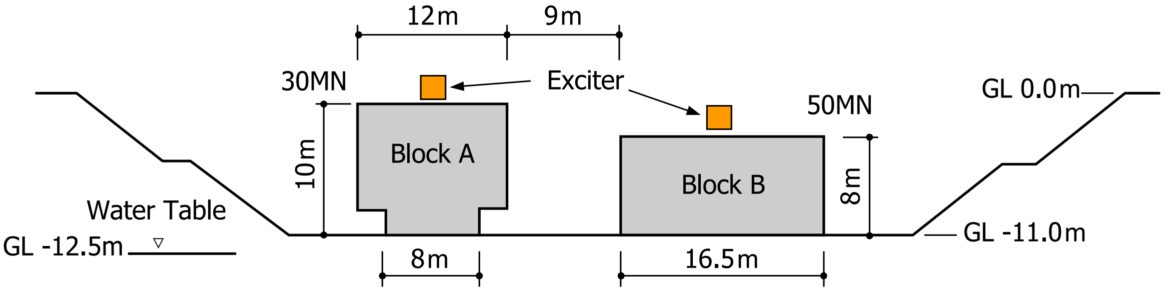


Figure 7 Forced Vibration Tests on Concrete Block Specimens

The above studies contributed greatly to our understanding of SSI behaviors and development of earthquake response analysis codes. However, the responses obtained from forced vibration tests are relatively small, and the maximum observed acceleration at ground level was 171cm/s^2. They provide very little information on nonlinear SSI of nuclear facilities with large input motions, because the experimental conditions were within the design levels. Therefore, more studies are needed on nonlinear SSI to precisely evaluate responses of the nuclear power plants subject to large earthquake motions.

PROPOSAL FOR VIBRATION TEST AT MINING SITE

Basic Idea of Vibration Test at Mining Site

The vibration test method using ground motions caused by mining blasts is shown schematically in Figure 8. This method has the following advantages over conventional test methods, such as forced vibration tests, earthquake observations, shaking table tests and centrifuge tests.

1. Large-scale structures can be tested.
2. Ground motions of various amplitudes can be applied to the test structure.
3. Three-dimensional effects can be considered.
4. The SSI in the actual ground can be considered.

Large-scale vibration tests can be conducted at Black Thunder Mine (BTM). BTM is one of the largest coal mines in North America and is located in northeast Wyoming, USA. Since its operation is very active, it provides many opportunities to observe large ground motions.

At the mine, there is an overburden over the coal layers. The overburden is dislodged by large blasts called "Cast Blasts" and the rubble is removed by huge earthmoving equipment. After the coal surface is exposed, smaller blasts called "Coal Shots" are applied to loosen the coal layers. The coal is then mined out by truck and shovel operation. The ground motions caused by Cast Blasts were used for the vibration tests. The smaller Cast Blasts or Coal Shots were used to check and calibrate the instrumentation.

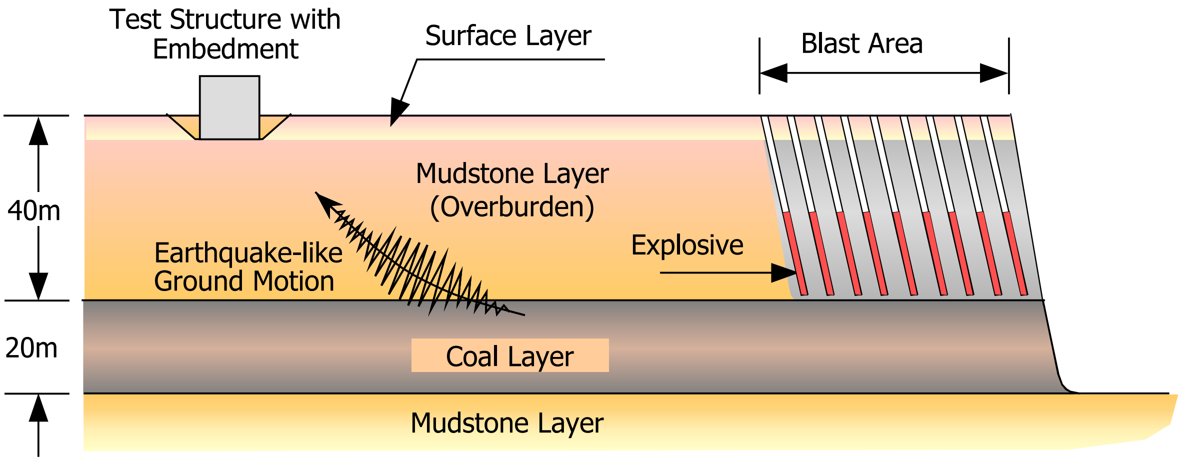


Figure 8 Vibration Test Method at Mining Site

Soil Profile and Ground Motions at BTM

Figure 9 shows the typical soil profiles. The shear wave velocities at the surface layer were around 200m/s. Below GL-5m, the shear wave velocities gradually increased from 400m/s to 600m/s with increasing depth.

Acceleration time histories recorded at 100m points from the blast areas and their response spectra are shown in Figure 10 (NUPEC 1998). They vary widely in terms of wave forms and dominant frequency components. The differences resulted from the blast operations, particularly the time lag between blasts. At 100m points from the blast area, the maximum acceleration usually exceeded 1G at the ground surface. The duration of motions was 2 to 3 seconds depending upon the length of the blast areas.

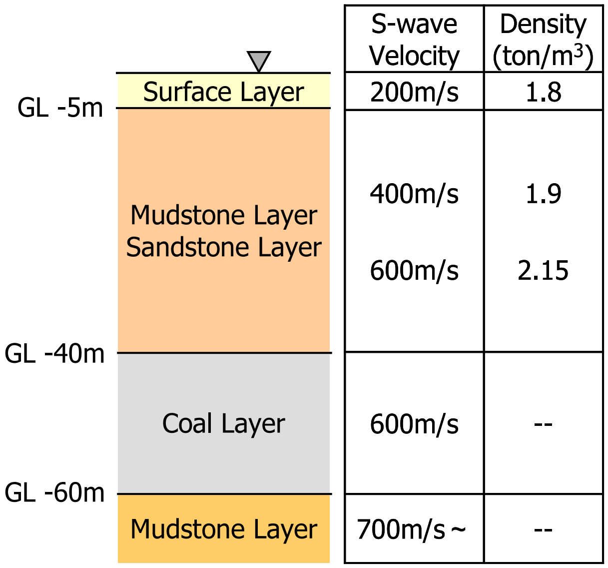


Figure 9 Typical Soil Profile at BTM

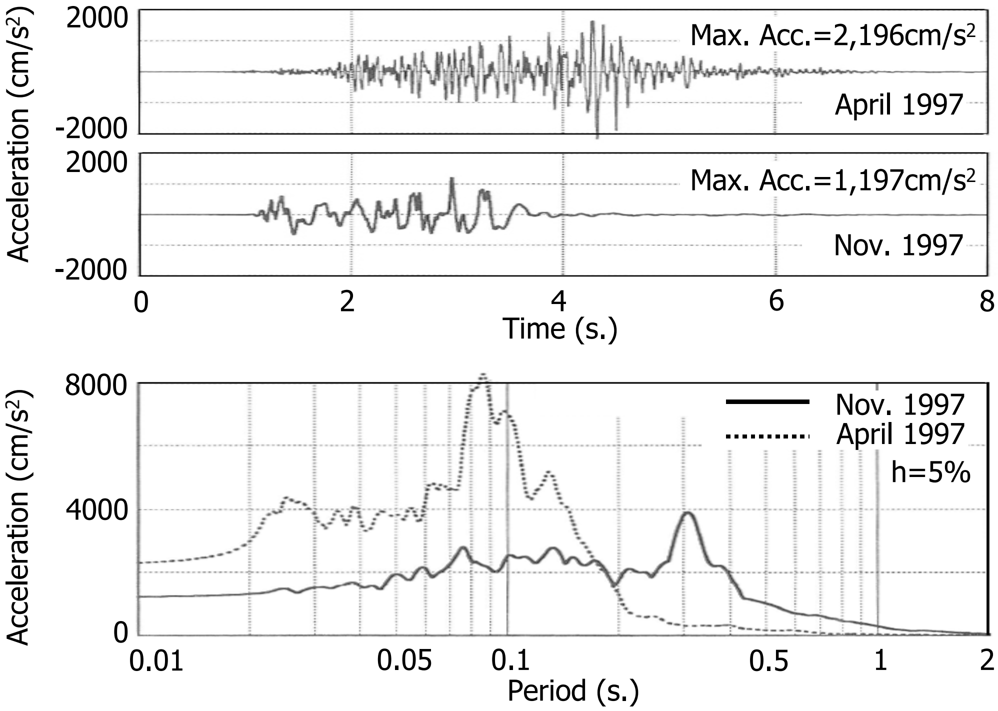


Figure 10 Acceleration Time Histories and Response Spectra

Details of Scaled Model Structure

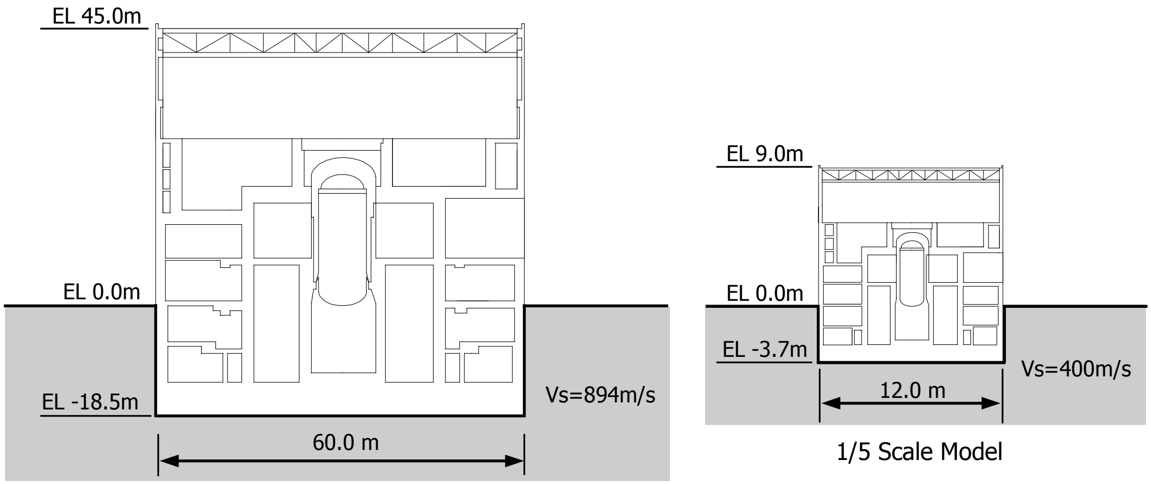
Scale model structures for vibration tests at BTM were investigated in the studies conducted by NUPEC (Kitada 2000, 2001). The Advanced Boiling Water Reactor (ABWR) building was selected to investigate its nonlinear SSI behavior. Scale model rules were established to precisely simulate the motions of the real scale ABWR in the gravity field, including SSI behaviors. The following are important aspects of these scale model rules.

1. Accelerations for the scale models should be the same as those for the real scale ABWR building because gravity cannot be scaled.
2. The scale models should be dynamically weakened by reducing the dimensions of the structural members and by adding extra weights, since the strength of the scale model increases with increasing scale factor if the same materials are used.

In previous studies (Kitada 2000, 2001), a 1/5 scale model was proposed for large-scale vibration tests at BTM. Figure 11 shows sectional views of the real scale ABWR building and the 1/5 scale model. The shear wave velocity for the 1/5 scale model was determined at 400m/s based on the soil profile shown in Figure 9. For construction, the test site had to be excavated to 5m depth. The 1/5 scale model on the ground for Vs=400m/s corresponds to the real scale ABWR building on the ground of Vs=894m/s through the scale model rules.

The real scale ABWR building was scaled down by 1/5 in length. The shear wall thickness was scaled by 1/25 to reduce the strength of the 1/5 scale model. Extra masses were added to each floor of the 1/5 scale model to keep the axial stresses of structural members the same as in the real scale ABWR. Time was scaled by $1/\sqrt{5}$. Thus, the accelerations, stresses, and strains of the 1/5 scale model were the same as those of the real scale ABWR. The floor thicknesses were constant at 30 cm to support added mass. Therefore, uplift phenomena were the same as for the real scale ABWR, but the vertical motions on the floors were out of scale.

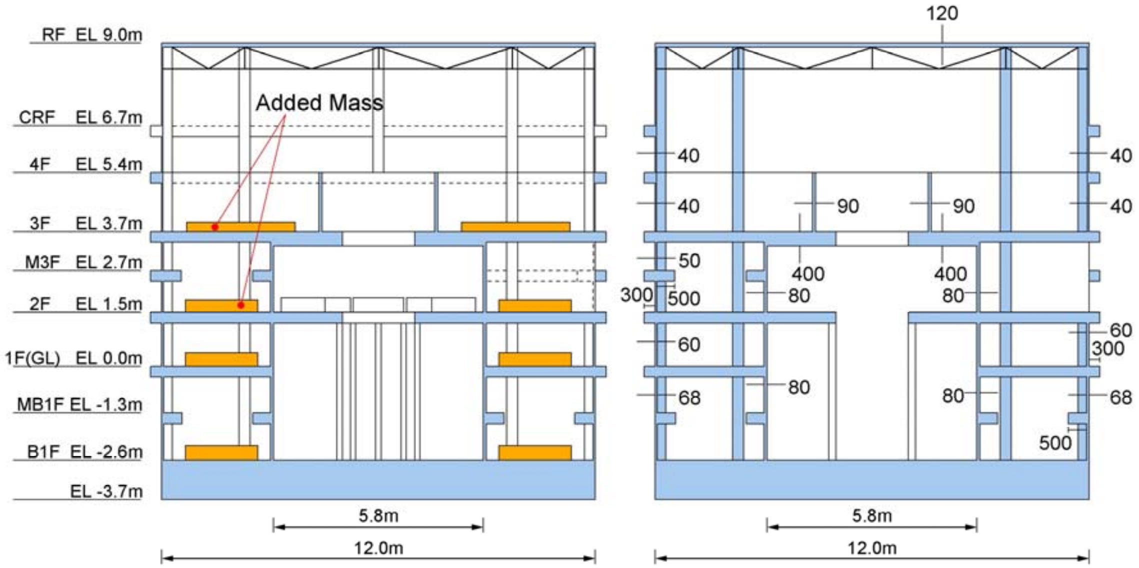
Figure 12 shows details of the 1/5 scale model. Table 1 shows the dimensions and weights of the models. According to the response analysis using a lumped mass model, the 1st natural frequency of the 1/5 scale model was 9.13Hz. The response analysis using the 1/5 scale model with the input motion recorded on April 1997 provided maximum strains in the shear wall of 4,630 micro strain and a contact ratio of 46%. It is considered that the 1/5 scale model can be used to investigate nonlinear SSI as well as nonlinear behavior of the walls.



Real Scale ABWR Building

1/5 Scale Model

Figure 11 Real Scale ABWR Building and Scaled Models



Model with Extra Weight

Dimensions of Walls and Slabs

Figure 12 Details of 1/5 scale model

Table 1 Model Dimensions and Weights

		Real Scale ABWR	1/5 Scale Model
Length	Model Height (m)	63.5	12.7
	Basemat Size (m)	60 X 60	12 X 12
	RCCV Thickness (cm)	200	8
	Shear Wall Thickness (cm)	30 to 170	4* to 7
	Basemat Thickness (cm)	550	110
	Slab Thickness (cm)	50 to 100	30*
Weight	Model Weight (ton)	---	947
	Added Mass (ton)	---	653
	Total Weight (ton)	200,000	1,600

*: out of scale

Outline of Proposed Vibration Test on Model Structure

The objective of these seismic vibration tests was to obtain a better understanding of nonlinear SSI of nuclear power plants during large earthquake motions. The influences on structural responses caused by uplift phenomena as well as material nonlinearity of the soil were main issues to be investigated.

Figure 13 shows a schematic view of the vibration test plan at BTM. The width of the blast areas was 60m and its length varied from 200m to 800m depending on the mining plans. There were hundreds of downholes with explosions in the blast area. The explosions were detonated from one side to the other. The detonation front remained at some angle to the blast direction to efficiently remove mudstone at the adjacent pit bottom. There was a time lag between detonations to reduce the maximum accelerations, in other words, to reduce environmental influences that make ground motions look like earthquake.

An example of the vibration test sequence is shown in Figure 14. In this way, it is possible to measure and record different vibration levels of the test models with different levels of input motions by choosing blast areas at appropriate distances to generate the desired accelerations at the test area.

CONCLUSIONS

First of all, this paper described the needs and significance of experimental studies, that might be aroused from the major revision of the regulatory guide, on nonlinear SSI of nuclear structures subject to large earthquake motions.

Then, by reviewing the extensive experimental studies on the SSI by NUPEC, it was clarified that those studies contributed greatly to understanding SSI behaviors and developing earthquake response analysis codes. It was also revealed that those studies provided very little information on nonlinear SSI of nuclear buildings with large input motions because the experimental conditions were within design levels.

Finally, the vibration tests at a mining site were proposed in order to promote better understanding of nonlinear SSI of nuclear power plant buildings. The advantages of the proposed test methods are that large-scale test structures could be tested using earthquake-like ground motions caused by large-scale blast excitations and that the three dimensional effects and the SSI in actual ground could be considered.

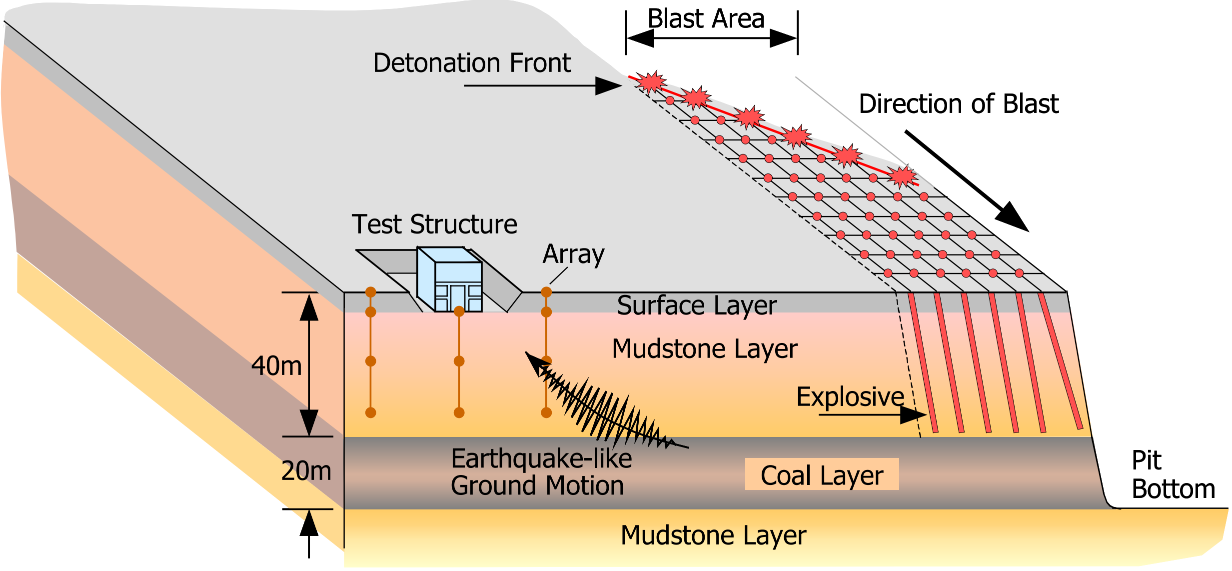
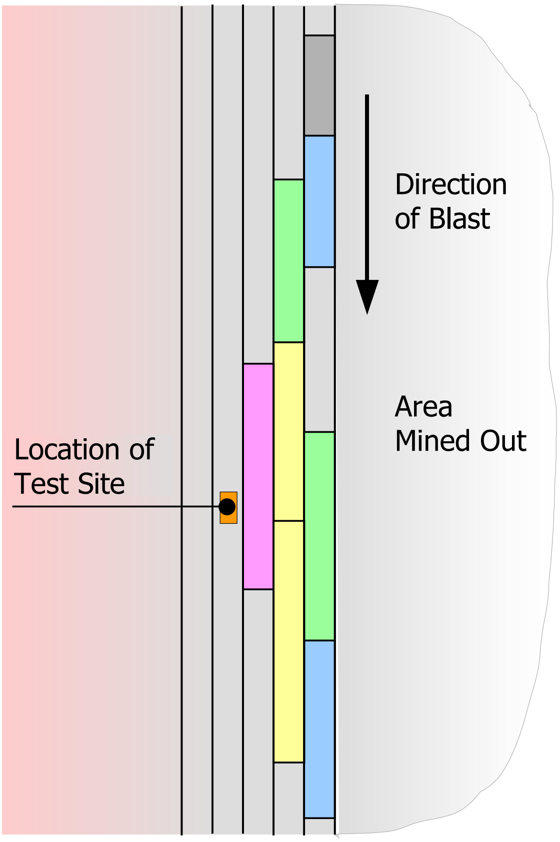


Figure 13 Schematic View of Vibration Test at BTM



Blast Sequence

Blast #	Level
0	Very Small *
1	Small
2	Medium
3	Small
4	Medium
5	Large
6	Large
7	Very Large

* : Instrument Calibration

Blast Sequence

🟪	Very Large Level Test
🟨	Large Level Test
🟩	Medium Level Test
🟦	Small Level Test
⬜	Instrument Calibration (Very Small)

Figure 14 Sequence of Vibration Tests

REFERNCES

Odajima, M., Suzuki, S., and Akino, K. 1987. Analytical study on Model Tests of Soil-Structure Interaction, 9th International Conference on Structural Mechanics in Reactor Technology (SMiRT 9), Lausanne, Swiss, pp311-316

Iguchi, M., Akino, K., and Noguchi, K. 1987. Model Tests on Interaction of Reactor Building and Soil, 9th International Conference on Structural Mechanics in Reactor Technology (SMiRT 9), Lausanne, Swiss, pp317-322

Hangai, Y., Akino, K., and Kurimoto, O., 1991. Model Test of Base Mat Uplift of Nuclear Reactor Buildings Part 1:Laboratory Test, 10th International Conference on Structural Mechanics in Reactor Technology (SMiRT 10), Anaheim, USA, Vol. K, pp169-174

Kobayashi, Y., Fukuoka, A., Izumi, M., Miyamoto, Y., Ohtsuka, Y., and Nasuda. T., 1991. Forced Vibration Test on Large Scale Model on Soft Rock Site (Embedment Effect Test on Soil-Structure Interaction), 11th International Conference on Structural Mechanics in Reactor Technology (SMiRT 11), Tokyo, Japan, Vol. K, pp129-134 (K06/4)

Yano, Y., Kitada, Y., Iguchi, M., Hirotani, T., and Yoshida, K., 2000. Model Test on Dynamic Cross Interaction of Adjacent Buildings in Nuclear Power Plants, 12th World Conference on Earthquake Engineering (12WCEE), Auckland, New Zealand, (0477)

Kusama, K., Kitada, Y., Iguti, M., Fukuwa, N., and Nishikawa, T., 2003. Model Test on Dynamic Cross Interaction of Adjacent Buildings in Nuclear Power Plants-Overview and Outcomes of the Project, 17th International Conference on Structural Mechanics in Reactor Technology (SMiRT 17), Prague, Czech Republic, Paper# K06-1

Uchiyama, S., Suzuki, Y., Konno, T., Iizuka, S., and Enami, A., 1992. Dynamic Tests of Concrete Block on Gravel Deposits, 10th World Conference on Earthquake Engineering (10WCEE), Madrid, Spain, pp1859-1864

Nuclear Power Engineering Corporation (NUPEC), 1998. Report on Method for Evaluating Limit State Properties and Behaviors of Nuclear Power Plant Buildings, (written in Japanese)

Kitada, Y., Kinoshita, M., Kubo, T., Seo, K., and Konno, T., 2000. The Test Methodology to Evaluate Earthquake Response of a NPP Building using Earthquake Ground Motion by Blasting, 12th World Conference on Earthquake Engineering (12WCEE), Auckland, New Zealand, (0900)

Kitada, Y., Kubo, T., Seo, K., and Fukuwa, N., 2001. Proposal of A Test Methodology to Evaluate Non-Linear Soil Structure Interaction, The 2nd UJNR Workshop on Soil-Structure Interaction, March 6 to 8, Tsukuba, Japan

Japan Nuclear Safety Commission, 1981, Regulatory Guide for Aseismic Design of Nuclear Power Reactor Facilities, (written in Japanese)