

PROPOSAL OF A TEST METHODOLOGY TO EVALUATE NON-LINEAR SOIL STRUCTURE INTERACTION

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ABSTRACT

We describe new test methodology to obtain data to be used to evaluate ultimate seismic behavior of Nuclear Power Plants (NPPs) structures. In this paper, we firstly reviews existing seismic test data with emphasis on Soil Structure Interaction (SSI) of NPP structures from the viewpoint of the evaluation of their earthquake response behavior. Secondary, we extracts the issues in the existing data with regard to their applicability to the evaluation of earthquake response of the NPP structures when a big earthquake ground motion strikes them. Then we propose new test methodology for NPP structures to evaluate their ultimate seismic response behavior for a strong earthquake ground motion. The test methodology employs artificial earthquake ground motions generated in a surface coalmine that has a large acceleration up to 2g. The simulation analysis is carried out by applying an observed large artificial earthquake ground motion at the coalmine to a scaled NPP reactor building model. Then we confirm its applicability to the test to evaluate ultimate earthquake response behavior of the NPP structures. The test methodology present herein is cost effective for obtaining the test data. The test data are indispensable for evaluating properly the seismic safety margins of NPPs.

(Keywords : Non-Linear SSI, Artificial Earthquake Ground motion, Scaled Building Model)

1. INTRODUCTION

Major NPP structures in Japan have been designed and constructed carefully because Japan is an earthquake prone country and some damage of NPP building due to an earthquake might cause an accident involving release of radioactive materials. However, after the 1995 Great Hanshin-Awaji earthquake disaster, there arose many opinions requiring the evaluation of seismic design margins of NPPs in the case that an unexpectedly big earthquake ground motion, exceeding the design levels, strikes an NPP site [1]. In order to accomplish such an evaluation, some extrapolations from the existing test data are indispensable. However, the extrapolation itself is a hypothesis, and its adequacy should be confirmed by some test data obtained by applying a large as possible earthquake-like load. In the following, we describe new test methodologies, which may supply some test data to supplement the extrapolation. The seismic performance of the buildings of a Nuclear Power Plant (NPP) had been proven by various tests. However, these test data are not necessarily directly applicable to evaluating ultimate structural strength as well as seismic margins of structures against earthquakes. The reason can be explained that although the ultimate strength of reinforced concrete (RC) structures are gradually unveiled, Soil-Structure Interaction (SSI) under a strong earthquake ground motion remains a difficult issue to evaluate properly. Nuclear Power Engineering Corporation (NUPEC) planned and performed a feasibility study to improve seismic test methodologies for NPP structures. As the result of the study, the concept of new test methodology has been extracted. The test methodology applies a blasting power in a field of a coalmine. In this test, we regard the ground shaking generated by blasting for mining coal as artificial earthquake motion. If we construct an NPP building model close to the blasting area, we could apply huge artificial earthquake ground motion to the model. This test will supply us an important field test data of the SSI under severe earthquake ground motion. Prototypical tests for structures applying newly proposed test methodologies is presented in the paper.

2. EXISTING SEISMIC TEST DATA

Here we briefly review existing seismic test data of NPP structures, paying attention to evaluating their ultimate strength against earthquake ground motions equivalent and/or exceeding design levels. Seismic tests performed for NPP structures are categorized roughly into the RC structure test and the SSI tests.

The RC structure test has been carried out to investigate non-linear behavior of an RC structure during large earthquake ground motion. The test includes static and dynamic tests. The static tests had been carried out by applying static load to an RC structure specimen, using oil-jacks etc., to establish the evaluation methodology of nonlinear characteristics of the RC shear walls up to failure. The dynamic tests had been carried out in general using a shaking table apparatus to confirm whether or not the evaluation methodology of nonlinear characteristics of RC columns and/or RC shear walls obtained by the static test is applicable to that under the dynamic loading condition. Figure 1 shows a typical test example of the dynamic test, the shaking table test of BWR reactor building model. However, the loading capacity and the size of the shaking table are limited, a 1/12 scale is the maximum scale for the whole building model even if the worlds largest Tadotsu Shaking Table is used [2].

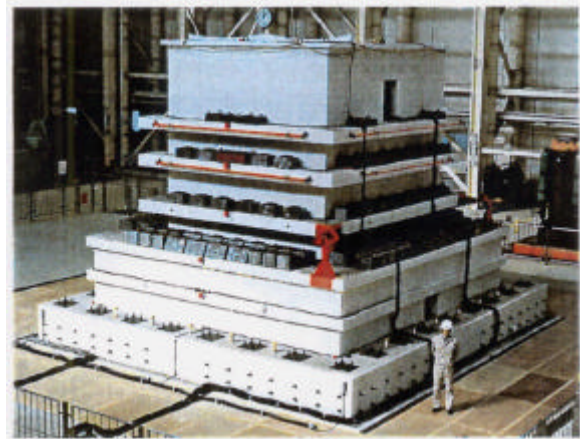


Fig.1 : A Example of Shaking Table Test of NPP Reactor Building. (A 1/12 Scale Model on The Tadotsu Shaking Table)

In this test, a simulated earthquake ground motion having maximum acceleration of 2.36g was applied to the model. The test brought many fruitful results, however, the phenomena of basemat uplift and rocking motion of the building model were excluded because the test model was fixed to the shaking table.

The SSI test has been carried out to confirm a composite soil-structure system response behavior to earthquake motions as it is described in the theoretical solutions. The test includes field and laboratory tests. The laboratory test applying artificial soil model made of rubber and a building model made of metal i.e., aluminum etc. The test is carried out placing the soil-structure model on a shaking table and applying simulated earthquake ground motions. The test is handy because the whole scale of the model is small, i.e., less than 1/250 so that the test is suitable for detailed investigation. However, the limited scale of the soil model generates some unexpected vibration mode caused by the finite boundary of the soil model, which is not observed in an actual building at actual field where the soil stretches infinitely. Furthermore, in general, the soil model tends to response linearly even to a large acceleration input motion. Therefore the laboratory test is limited for its application to nonlinear SSI test. The field test categorized into two types. One is vibration test of an actual NPP reactor building using unbalanced-mass rotating shaker, which is performed as an item of pre-operation tests of NPPs [3].

Also, in some of actual NPPs, earthquake observation is carrying out in their safety related important structures. The other is a model test, which is carried out using scaled structure models constructed on a field representing a typical NPP site. Figure 2 shows a SSI field test example of this kind, "Model Test on Dynamic Cross Interaction Effects of Adjacent Structures". The test is carried out as an ongoing project by NUPEC to investigate the effect of buildings adjacent to a reactor building on the earthquake response of the reactor building [4]. In the test, we conduct vibration tests using a shaker and earthquake observation in the building models. However, applicable vibration energy is limited in the vibration test, furthermore, observed earthquake motions are also limited in their maximum acceleration, i.e., in general 10-20Gal. and 170Gal. at most. Under those limitations, the SSI phenomena are considered to be within a linear response category.



Fig.2 : A Typical Test example of SSI (Soil-Structure Interaction) model test. "Model Test on Dynamic Cross Interaction Effects of Adjacent Structures"

Figure 3 summarizes seismic test, earthquake experiences and seismic design analyses of NPP structures in Japan. The figure shows the state of arts of the relationship between seismic design analyses and test data as well as the applicability of the data of the seismic tests and earthquake experiences to the evaluation of nonlinear earthquake response and seismic margins of NPP structures. As shown in Fig.3, seismic design analyses have been performed for design earthquakes ranging from 180 to 600Gal. Linear Seismic design analyses have been carried out for the maximum design earthquake. However, nonlinear design response analyses have been introduced for the ultimate design earthquakes. In these nonlinear analyses, nonlinear stress-strain characteristics of RC shear wall and basemat uplift phenomenon have been introduced. Although, a rich data-base of nonlinear

behavior of RC shear wall supports the nonlinear analyses, almost no test data supports the basemat uplift analyses.

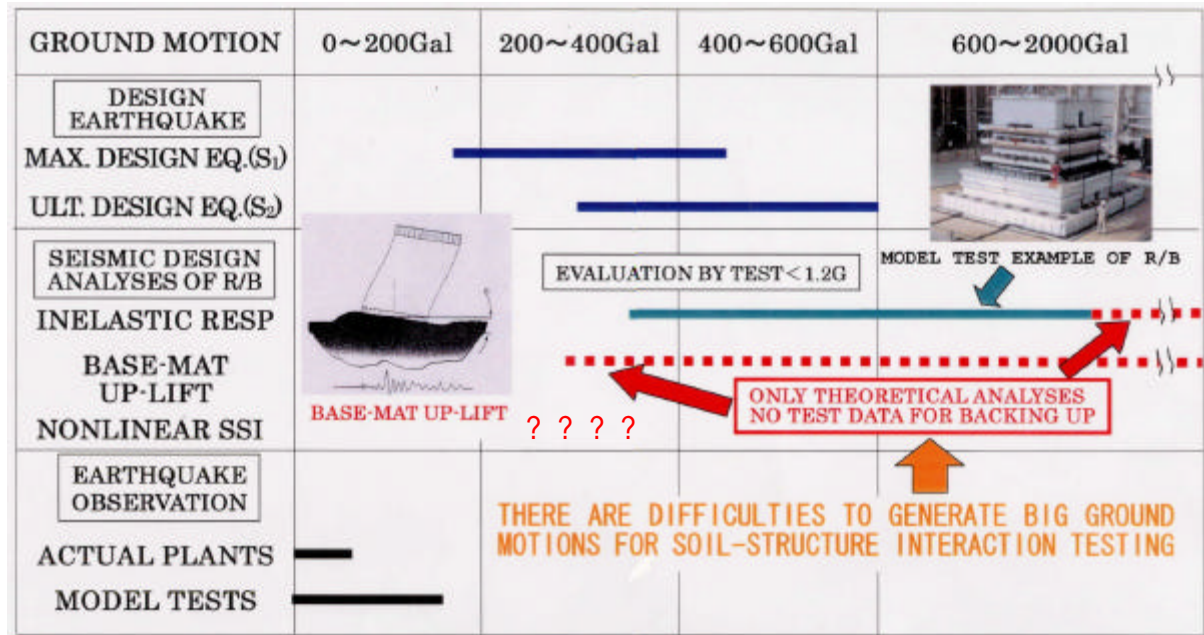


Fig.3 : Design Analyses, Seismic Tests and Actual Earthquake

The situation is mainly caused by the difficulties of catching big earthquake ground motion at the SSI test site and/or NPP plant sites. Our experience of earthquake observation is very limited with regard to the maximum acceleration of earthquake ground motions at free field in SSI test sites and NPP plant sites, a 170Gal. is the maximum for SSI test sites and a 68 Gal. for NPP plant sites. Also there is the difficulty in generating artificial earthquake ground motion resembling actual earthquakes for use in the SSI test. So the analyses had been carried out based on theoretical hypotheses. It is also pointed out that there might be some nonlinear SSI behavior even a rock site for a strong earthquake ground motion. There is information that SSI related natural frequencies tend to decrease with the increment of acceleration magnitude of earthquake ground motion [5]. Because the information is based on the observed acceleration earthquake ground motion of 170Gal. at most, much nonlinear behavior related to of SSI is anticipated for big earthquake ground motion over the design earthquake ground motion.

Thus some SSI-related field test data are needed for big earthquake ground motion equivalent and/or exceeding the acceleration level of typical design earthquake ground motion to confirm adequacy of the current seismic design methodology and to evaluate ultimate seismic strength of NPP structures.

3. PROPOSAL OF NEW TYPE TESTS

3.1 Test Method

Two types of issues are pointed out relating to evaluating the ultimate strength of NPP structures. These are; i) nonlinear characteristics of SSI phenomenon [6], and, ii) nonlinear behavior of an RC structure under three-dimensional loading condition [7]. Naturally, the later issue can be resolved by a shaking table test of structure.

It is pointed out that handling of the scale effect of the specimen on the ultimate strength evaluation of the actual structure is another essential issue for the scaled model test [8]. Thus, for the test, the largest specimen possible and the biggest input motion possible are necessary. Taking into account the above issues, new test methodology, which utilizes artificial earthquake ground motion, is considered desirable if it can be performed at a realistic cost.

With this motivation, we have investigated the test methodology which applying blasting power as for a big earthquake ground motion. The information from a coalmine company in the U.S. indicates that the works performed in the surface coalmine to blast a rock covering a coal layer generates a big artificial ground motion, which is similar to earthquake ground motion.

Application of this artificial earthquake ground motion for the SSI test is considered very promising because the blasting work is carried out periodically for mining coal so that we can applied artificial motions generated by the work if we construct a building model at a closed point to the blasting work area.

3.2 Vibration Source

Figure 4 shows a picture of the coal mining site. As it can be seen in the figure, sand-rock, coal and mud-rock form strata, and a sand-rock stratum 25-30meters thick covers the coal stratum, so that the sand-rock stratum is removed to mine the coal.

Blasting power has been applied to remove the stratum as well as to loosen the coal stratum before mining coal. A typical blast is being conducted using an underground explosive array (typically, width is a 100meters, length is 1,000meters, and total amount of explosives is 3,000tons). In order to study the ground motions induced by blasting, the ground motion was observed around the underground explosive array area. Figure 5 shows an outline of the observation arrays of ground motions.



Fig. 4 : A Picture of A Surface Coal Mine (Coal is Mined by Blasting).

Figure 6 shows acceleration ground motion examples (radial and vertical directional motions) observed at a point 100meters away from the area of explosive array, and their acceleration response spectra of 5% damping. The ground motion induced by the blast has a maximum acceleration of 2.0g and an effective duration of 6.0seconds. Although the dominant frequency band of the motion are somewhat higher than those of typical design earthquake ground motion, the potential of the motion for future application is promising. If we constructed a building model near the explosive array area, a big ground motion could be applied to the model. In that case, the model should compensate by being scale down for the high frequency dominating characteristics of the ground motion. Figure 7 shows acceleration attenuation characteristics of radial and vertical ground motions. From the figures (Fig.6 and Fig.7), the motion equivalent to design earthquake motion in acceleration magnitude can be observed even from a distance of 300 meters from the explosive array area except that the motion has a lager maximum acceleration

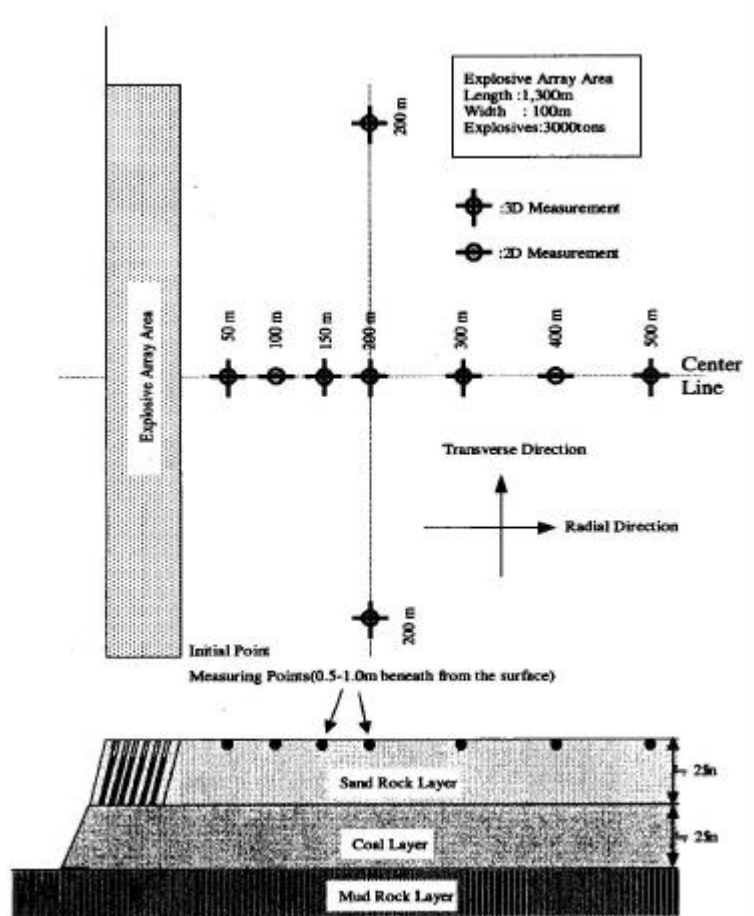


Fig. 5 : Ground Motion Observation Array for Artificial Earthquake Motion by Blasting in A Coal Mine in The U.S.

in the vertical component than the horizontal component

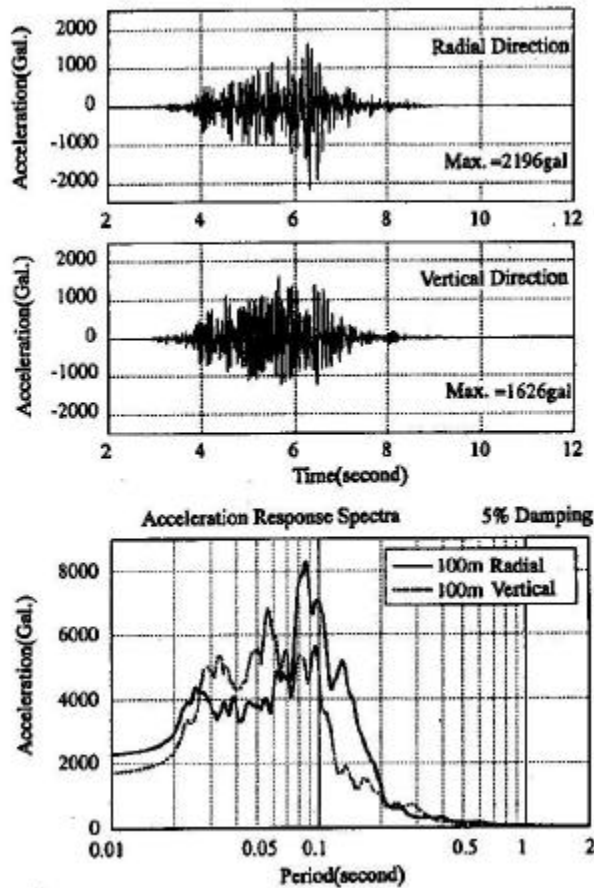


Fig.6 : Observed Acceleration of The Artificial Earthquake Ground Motion and Their Acceleration Response Spectra of 5% Damping.

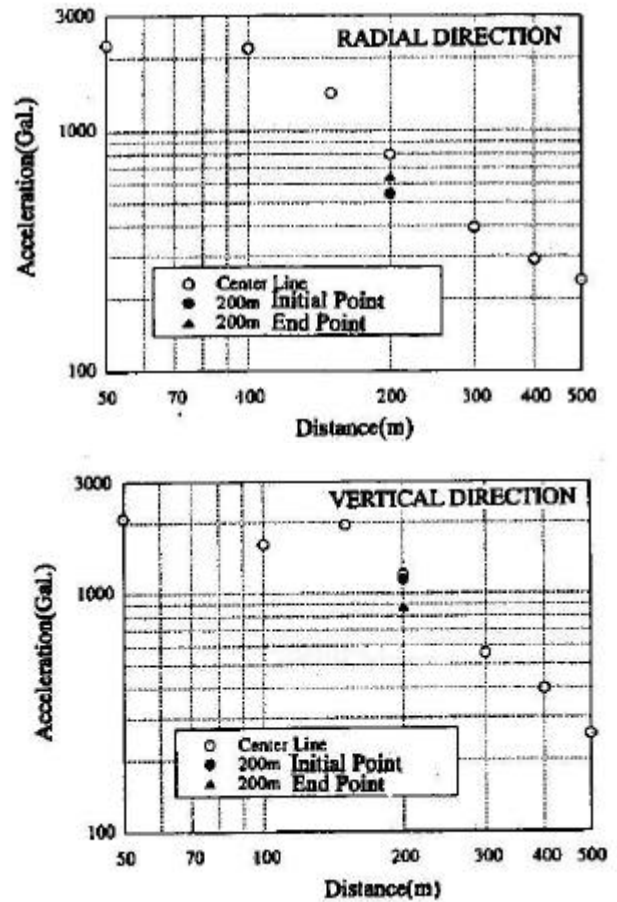


Fig.7 : Acceleration Attenuation of Radial and Vertical Ground Motions.

3.3 Response Analysis of Test Model

A simulation analysis of the test was carried out to investigate the applicability of the motion to a seismic test of an NPP structure, which evaluates the ultimate response behavior of the structure, were a big earthquake that exceeds design level to strike an NPP site. The input motion used for the analysis was the ground motion observed at the point of 100 meters distant from the explosive array area. In the analysis, the building model was scaled down to 1/5 to compensation for the difference between the motion generated by blasting and a typical design earthquake ground motion. Figure 8 shows an outline of the simulation model used.

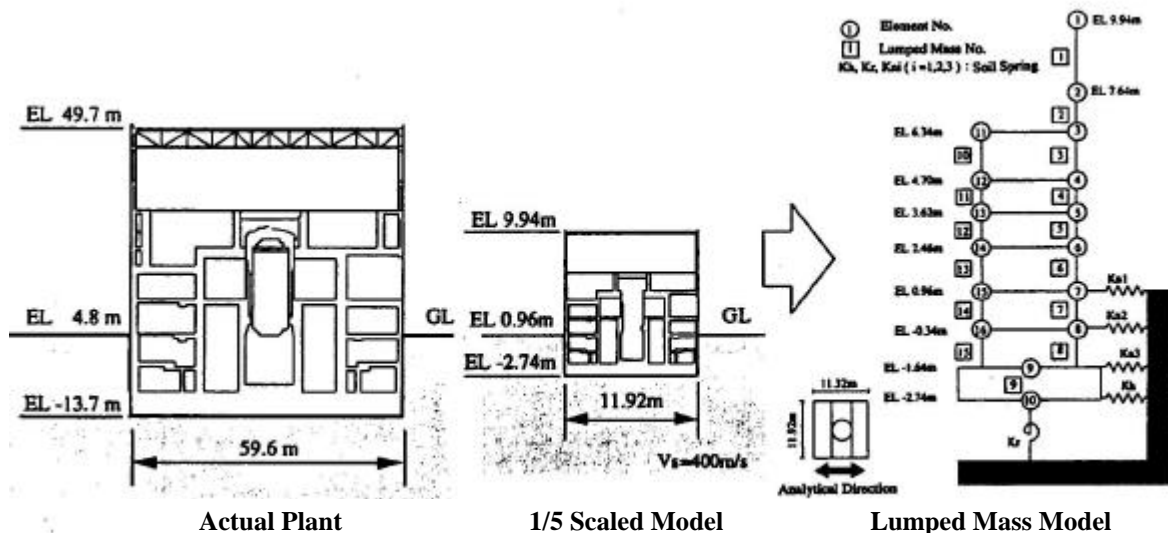


Fig. 8: An Outline of A Typical Analytical Reactor Building Model of 1/5 Scale

The model represents a typical reactor building of an Advanced Boiling Water Reactor (ABWR) [3]. The model is scaled down by 1/5 in length, 1/25 in shear wall thickness, and 1/ 5 in time scale. Meanwhile, the natural frequency of the model becomes 5 time larger as compared with the actual building. The other important parameters, i.e., gravity, response acceleration, and generated stress, are kept actual scale. Figure 9 shows a typical soil profile of the test site. Table 1 shows soil properties used for the simulation analysis. The analytical model includes nonlinear characteristics of base-mat uplift and hysteresis loop of RC shear wall.

The results of the simulation analysis are shown in Fig.10. Figure 10 (a) shows maximum response acceleration and (b) shows maximum response shear strain. It is said from the figure that we can obtain large structural response data by the field test up to ultimatum degree together with SSI data under strong earthquake-like ground motion.

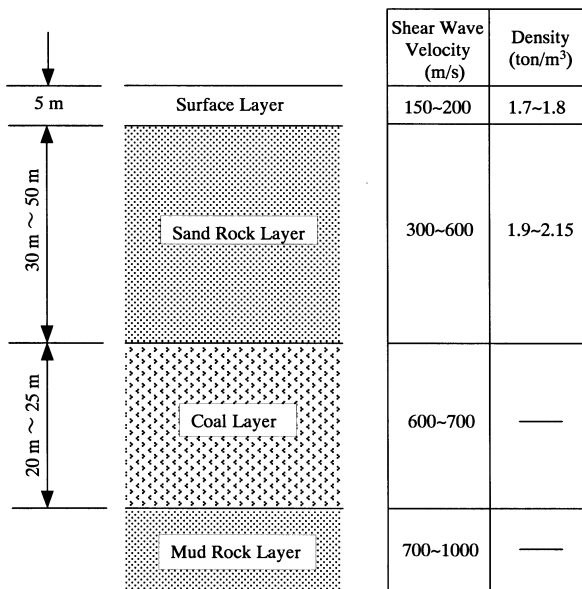
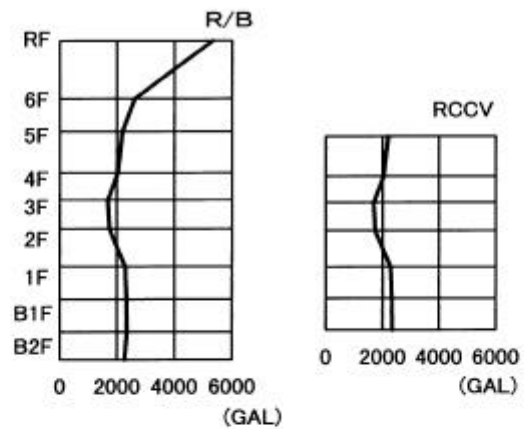


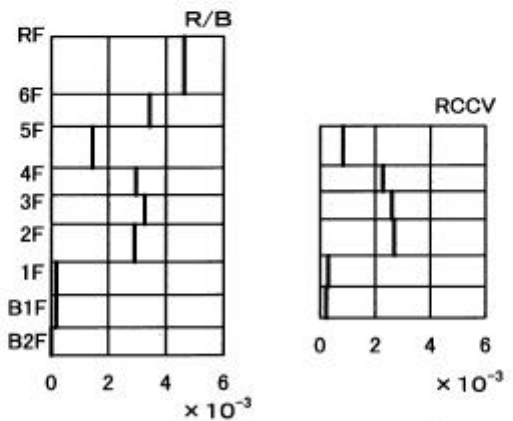
Fig.9: Typical Soil Profile of The Test Site Used for Simulation of The Field Test using Blasting Power.

Table 1: Soil Properties

Item	Pyisical Properties
S-Wave Velocity : Vs	400 m/sec
P-Wave Velocity: Vp	2000 m/sec
Poisson's R atio:	0.479
Density :	2.05ton/m ³
Damping Ratio : h	2 %



(a) maximum response acceleration



(b) maximum response shear strain

Fig. 10: Results of A Simulation Analysis of the Field Test using Blasting Power.

3.4 Design of Proposal Test Model

The building model is designed based on the simulation results for the field test as shown in Fig.11. Some details of the model are shown in Table2. The model is 12.7m in height and 12m square in cross section. Total weight of the model is about 1,600tons including the added mass weight of 653tons, which is used to adjust the natural frequencies of the model to the design values. Thickness of shear walls of the building model is determined as 6.0cm for the lower part and 4.0cm for the upper part and that of the RCCV is determined to be 8cm. The thickness of base-mat is determined to be 110cm and that of each floor slab was designed to be 30cm

to support the added mass. The added masses are manufactured of steel or lead. The model is embedded by 2.6 meters (two stories) with regard to actual Japanese NPP building construction condition. Figure 12 shows a schematic of the field test. We construct the model beside an explosive array area taking into account the actual coal-mining plan and waited for the major blasting conducted for mining. We are planning to expose the model to artificial earthquake ground motions by mining blasts at least four times, each of which has maximum acceleration ranging from one to five times of that of a typical design earthquake ground motion.

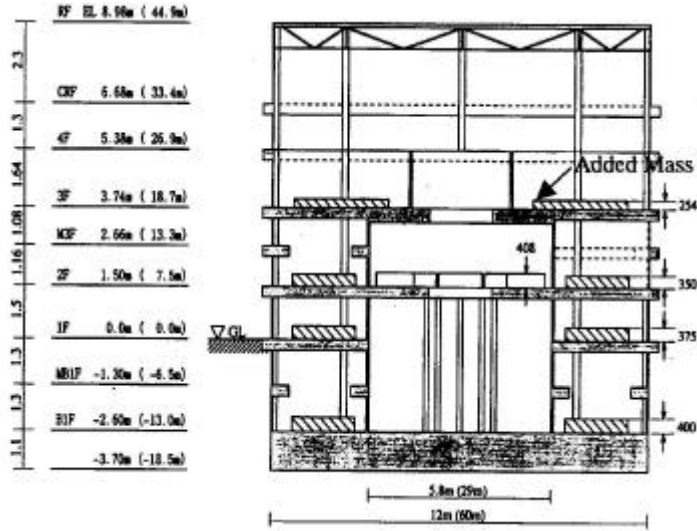


Table 2: Details of the Model

Item	Dimension
Height	12.7 m
Base-mat Size	12 m × 12 m
Thickness of RCCV	8 cm
Shear Wall Thickness	6 cm (For Lower Part) 4 cm (For Upper Part)
Base-mat Thickness	110 cm
Floor Slab Thickness	30 cm
Model Weight	947 ton
Added Mass Weight	653 ton

Fig. 11: The Designed Building Model Based on The Simulation Results for The Field Test.

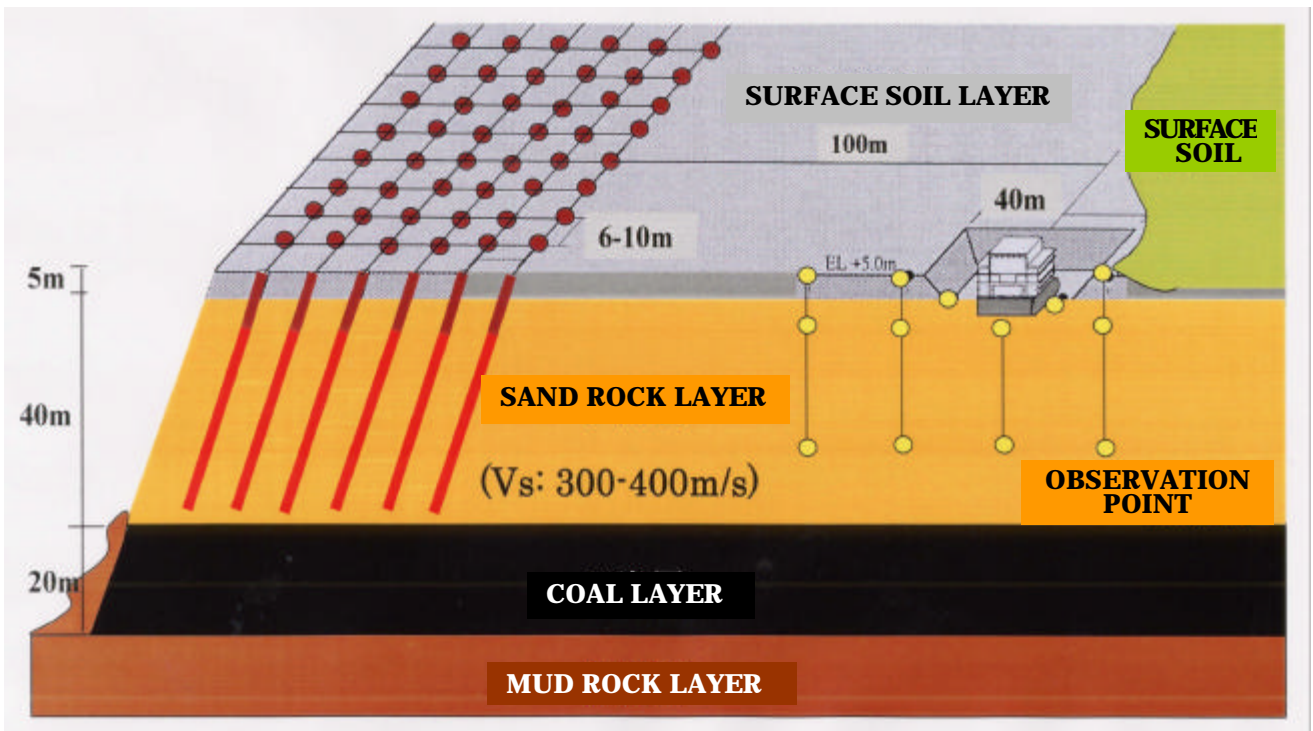


Figure 12: Scheme of Field Test Using Blasting Power of A Coalmine in The U.S.

3.5 Purposes of Proposal Test

The major purposes of the field test are to understand (a) basic earthquake response characteristics of an NPP reactor building when a large earthquake strikes the NPP site and (b) nonlinear characteristics of SSI

phenomenon during a big earthquake. In order to achieve these purposes, the following items should be studied;

- to study whether or not the natural frequencies related to SSI change with the increment of the magnitude of input motions (and if it changes, to evaluate the degree),
- to evaluate the relationship between soil shear stiffness reduction and the soil strain increase due to increase of the magnitude of input motions, (to compare the field test results with the conventional soil sampling test results)
- to evaluate rocking motion of the building model with regard to increase of input motion magnitude,
- to study how decrease the foundation-ground contact ratio of the building model with increment of input motion magnitude (to comprehend the change of the vertical motion induced by the rocking motions),
- to study vibration amplification characteristics of the building model and its nonlinear behavior,
- to study three dimensional earthquake response behavior of the building model together with its nonlinear characteristics under severe earthquake ground motion exceeding the design earthquake ground motion level.

4. CONCLUDING REMARKS

The test methodology to comprehend ultimate seismic performance of NPP structures against earthquakes was studied to evaluate their seismic safety margin, fragility, and other factors. In the study, we first reviewed the seismic tests of NPP structures and extracted the issues related to our purpose. Then, the need to test large-scale specimens was discovered. In the test, we actuated the specimen together with the surrounding ground with big acceleration motions from deep stratum to confirm the SSI phenomenon under big earthquake conditions. Artificial ground motion generated by the large-scale blasting in a surface coalmine in the U.S. was a promising input motion for the test. Such artificial motion tends to have high frequency band characteristics so that test specimen has to be scaled down to be 1/5 at the maximum. Thus the field test methodology was investigated, which applies the artificial ground motion to a 1/5-scale ABWR reactor building model.

As the results of the study, promising test methodology was proposed for NPP structures, which enables evaluation of their ultimate seismic strength.

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REFERENCES

- [1]. Japan Nuclear Safety Commission : “Report on Validity for the Examination Guide of Aseismic Design of Nuclear Power Reactor Facilities” (in Japanese), 1995.
- [2]. Yano, A. et al. : “Vibration Test of A Model of Nuclear Power Plant using A Large Shaking Table (Part 2 BWR 1/12 Scale Model)”, Proc., 9th WCEE, pp. 735-740, Tokyo-Kyoto, Japan, 1988.
- [3]. Kontani O., et al. : “Forced Vibration Test of ABWR Nuclear Reactor Building”, Proc. of 14thSMiRT Conference, vol.K-1, pp.161-168, Lyon, France, Aug., 1997.
- [4]. Kitada, Y., et al. : “Model Test on Dynamic Structure-Structure Interaction”, Proc.,7th International Symposium on Current Issues Related to Nuclear Power Plant Structures, Equipment and Piping”, pp. 4-1-15, Raleigh, N.C., U.S.A., Dec.1998.
- [5]. Tang, H.T. et al. : “Hualien Soil-Structure Interaction Test”, Proc., 7th International Symposium on Current Issues Related to Nuclear Power Plant Structures, Equipment and Piping”, pp. 3-1-19, Raleigh, N.C., U.S.A., Dec.1998.
- [6]. Borja, R.I. et al. : “Nonlinear SSI Analysis”, Proc., UJNR Workshop on Soil-Structure Interaction, pp.9-1-12, Menlo Park, C.A., U.S.A..
- [7]. Bazant Z. P. : “Modeling of Concrete Behavior : State of the Art”, Proc. of 14th SMiRT Conference, vol.0, pp.49-75, Lyon, France, Aug., 1997.
- [8]. Mihashi H. : “Influence of Material Structure on Size Effect Law of Concrete Structures”, Proc. of 14th SMiRT Conference, vol. H, pp.49-56, Lyon, France, Aug., 1997.