Experimental Study of Seismic Soil-Structure Interaction by using Large Geotechnical Centrifuge System

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ABSTRACT :

The purpose of this study is to obtain empirical data concerning soil-structure interaction and basemat uplift phenomenon, focusing on nuclear power plants built on a hard rock site. Two kinds of vibration tests by using a large geotechnical centrifuge system, which could realize contact pressure almost same as that of real plants with a miniature building model, are performed. Through this experimental study, beneficial knowledge concerning soil-structure interaction and basemat uplift was obtained.

KEYWORDS: Soil-Structure Interaction, Basemat uplift, Embedment effect, Centrifuge test, Impedance functions, Effective input motion

1. INTRODUCTON

Evaluation of dynamic responses of nuclear power plants (NPP) considering soil-structure interaction (SSI) is strictly required for seismic design in Japan. A sway-rocking model is used often, and soil springs are estimated from the vibration admittance theory, which is based on the three dimensional wave propagation theory for the uniform half-space soil medium. Basemat uplift is also considered by using a rotational soil spring with the geometric nonlinear characteristics. It has been requested more reasonably to evaluate basemat uplift phenomenon as the level of earthquake input motion increases accompanied with the recent development of seismology. In the previous study, we proposed a procedure to construct a proper numerical soil model using three dimensional finite elements, in which various geometrically complex site conditions can be considered. As for a NPP built on a hard rock site, there is little data concerning embedment effect and uplift phenomenon, which is obtained by experimental or observational studies. The purpose of this study is to obtain empirical data, conductive to validate the proposed evaluation method mentioned above. Two kinds of vibration tests by using a large geotechnical centrifuge system, which could realize contact pressure almost same as that of real plants with a miniature building model, are performed. One is shaking test using an exciter to validate dynamic soil springs, and the other is shaking table test to validate basemat uplift characteristics and effective input motion evaluated by the proposed method. Through this experimental study, beneficial knowledge concerning SSI phenomena for a hard rock site and effective data to validate the proposed method are obtained.

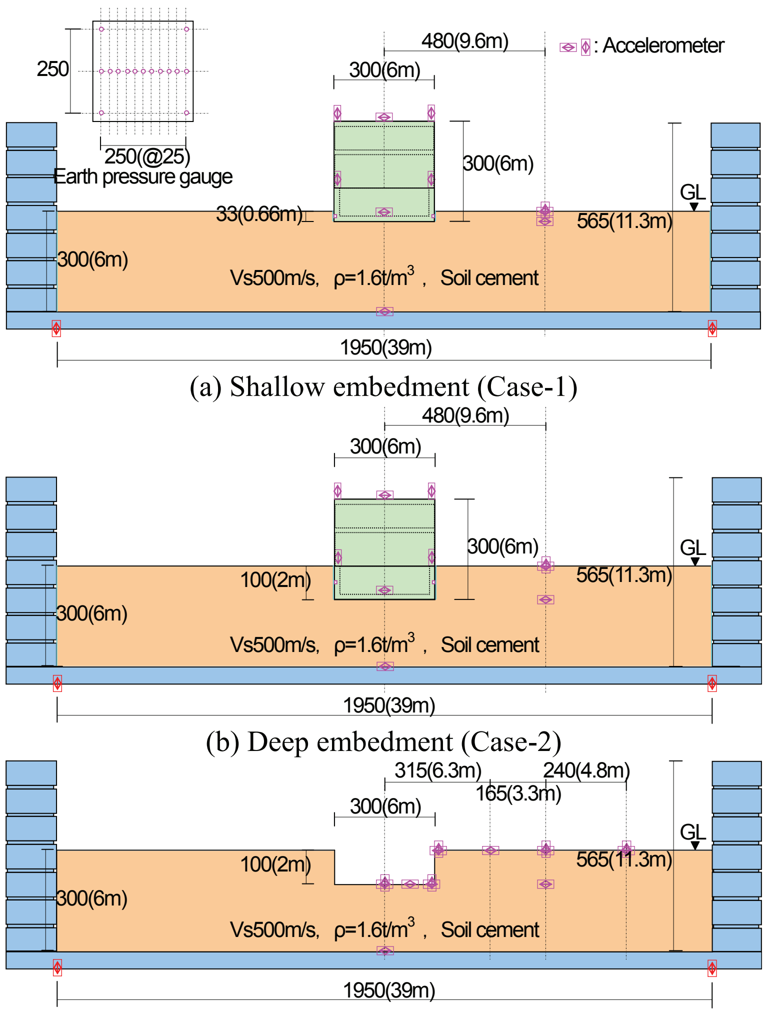
2. EXPERIMENTAL TESTS CONCERNING THE BASEMAT UPLIFT BEHAVIOR

Dynamic soil spring, effective input motion, basemat-overturning-moment, basemat rotational angle and contact ratio are evaluated by the tests. Embedment effects and characteristics of basemat uplift are investigated from the test results.

2.1. Overview of Experiment

Configuration of the test models are shown in Fig.2.1. Shallow embedment model (Case-1), deep embedment model (Case-2) and cavity model (Case-3) are made in a shear box for the centrifuge test. The building is modeled by steel. Considering the non-dimensional frequency (1.0), soil is made by soil cement (shear wave velocity is 500m/s), corresponded to the actual soil of NPP.

Gravitational force field of the centrifuge test is 20G. Converting the gravitational force feild to 1G based on the scaling law, the building footprint is 6*6m, weight of the building is 616tons, the embedment depth of Case-1 is 0.66m (22% of gravity center height), and that of Case-2 is 2m (66% of gravity center height). The cavity depth of Case-3 is same as the embedment depth of Case-2 (2m). In the shaking test for the building model using a small exciter, sinusoidal vibration (2-15Hz) is applied. In the shaking table tests, excitation of sine waves (2,4,8,10Hz) and earthquake waves are applied. Acceleration of the building and the soil (13 points in Case-1,2, 16 points in Case-3), and earth pressure (15 points in Case-1,2,3) are measured. Resonance curve and dynamic soil spring are evaluated from the shaking test results using an exciter. Basemat overturning moment, basemat rotational angle, contact ratio and effective input motion of the cavity are evaluated from the shaking table test results. The following scale is converted to the scale of 1G gravitational force field based on the scaling law.



(a) Shallow embedment (Case-1)

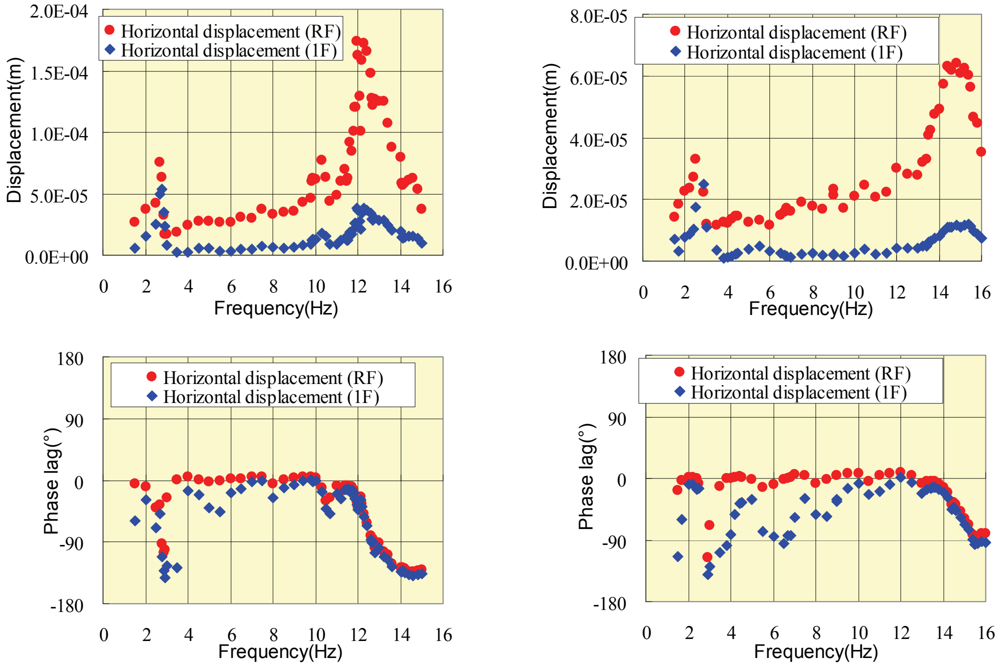
(b) Deep embedment (Case-2)

(c) Cavity (Case-3)

Figure 2.1 Configuration of test model

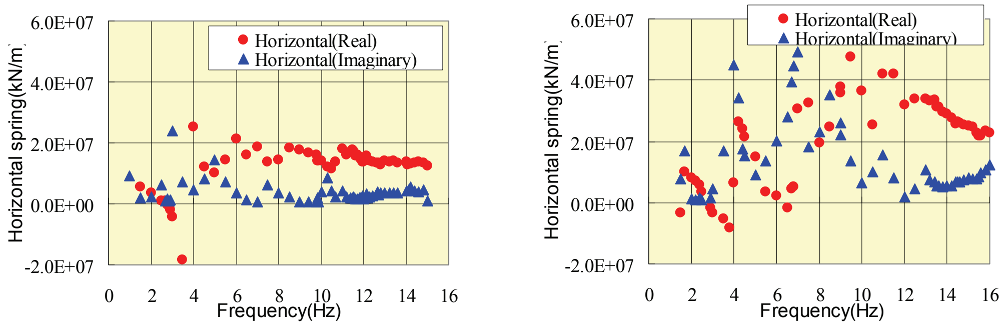
2.2. Shaking Tests for Building Model using Exciter

Dynamic soil springs are evaluated from resonance curves obtained by the shaking test using an exciter set on the building model. Horizontal resonance curves of the building model are shown in Fig.2.2. Natural frequency of Case-1 is 12.7Hz, and that of Case-2 is 15.5Hz. Natural frequency and soil spring increased by the embedment effect. The peak of resonance curve in Case-2 is not so sharp as that of Case-1, and the slope of phase curve in Case-2 is not so steep as that of Case-1. The effect of radiation damping has increased by the embedment effect. Dynamic soil springs are shown in Fig.2.3. Soil spring of Case-2 is larger than that of Case-1. Soil spring has also increased by the embedment effect.

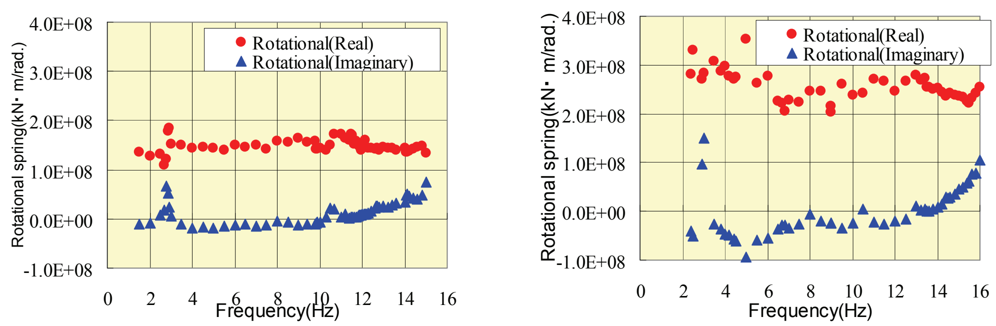


(a) Case-1 (b) Case-2

Figure 2.2 Resonance curves of the building model



(a) Horizontal spring (Case-1) (c) Horizontal spring (Case-2)



(b) Rotational spring (Case-1) (d) Rotational spring (Case-2)

Figure 2.3 Dynamic soil springs

2.3. Shaking Table Tests for Soil Model with Cavity

Effective input motion in embedment foundation is derived from the spectrum ratio of response of cavity to free field of soil model. Comparison of effective input motions for random wave (max. acc. 25gal), earthquake wave

1 (max. acc. 365gal) and earthquake wave 2 (max. acc. 533gal) are shown in Fig.2.4. As for each wave, input motion from 8Hz to 10Hz decrease within the range from 0.75 to 0.9. Characteristic of effective input motion has little difference between each wave. Frequency less than 10Hz, the level of earthquake input motion has an insignificant effect on reduction of effective input motion at a hard rock site.

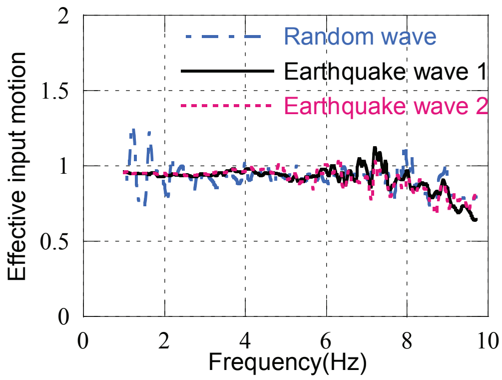
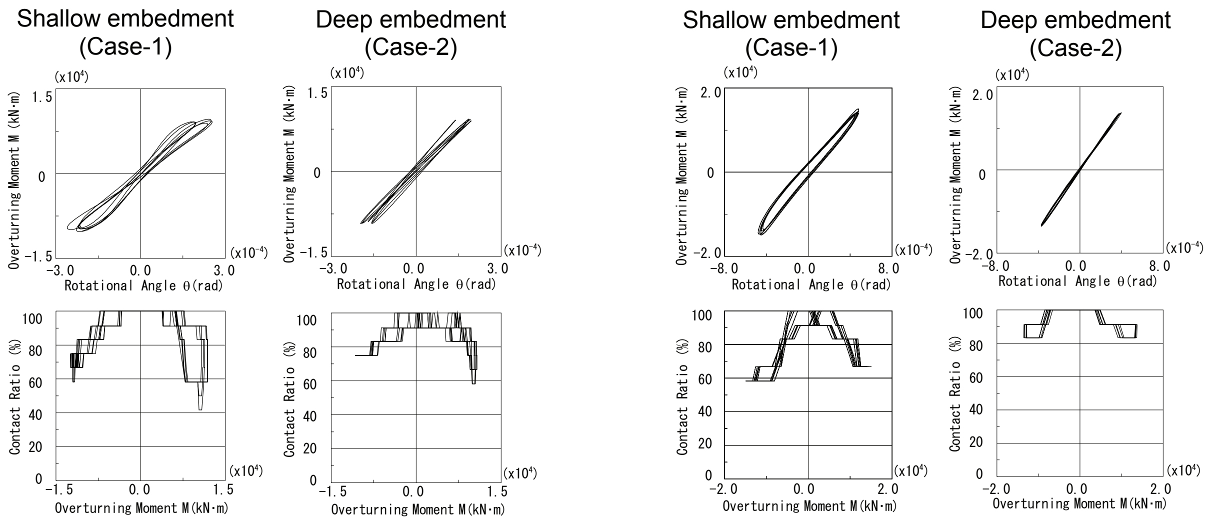


Figure 2.4 Effective input motion

2.4. Shaking Table Tests for Building Model

Relations between overturning moment and rotational angle (M-θ), overturning moment and contact ratio(M-η) of the basemat in the shaking table tests are investigated. M-θ and M-η relations are shown in Fig.2.5. Minimum contact ratio of Case-1 is from 40 to 60%, and that of Case-2 is from 60 to 75%. The increase of contact ratio caused by the embedment is recognized in the test results.



(a) 40Hz [2Hz]
(b) 160Hz [8Hz]

Figure 2.5 Relations of M-θ, M-η

3. SIMULATION ANALYSES FOR EXPERIMENTAL TESTS

Simulation analyses listed below are performed based on the experimental test results mentioned in the previous section.

(1) Impedance functions for the building model
(2) Effective input motion for the soil model with a cavity
(3) Basemat uplift characteristics for the building model

3.1. Analytical Model

3.1.1 Experimental soil medium and shear box system

A three dimensional finite element (3D FE) analytical model about experimental soil medium and shear box is shown in Fig. 3.1. Solid elements are used to model the soil medium for both shallow and deep embedment models (embedment depths are 3.3cm and 10.0cm for each) and the shear box (rubber layers between steel frames). Steel frames of the shear box are hollow structures, whose thickness is varying from 0.23cm to 0.6cm, but they are modeled as dense solid with equivalent density and elastic modulus.

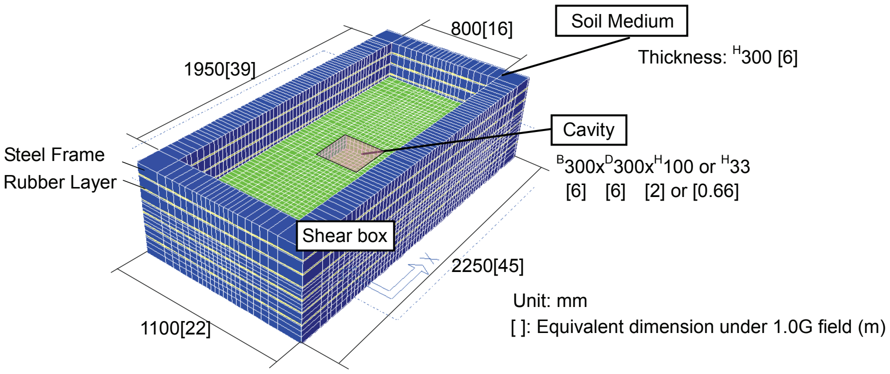


Figure 3.1 Analytical model of the soil medium and the shear box

3.1.2 Building model

The 3D FE building model is shown in Fig. 3.2. The FE model is composed of shell elements which are 1.6 cm thick, and it is connected with the 3D FE soil medium model by joint elements. As the initial stiffness of joint elements, 50 times as large as static stiffness of the soil medium is adopted based on the previous study (Ref 1).

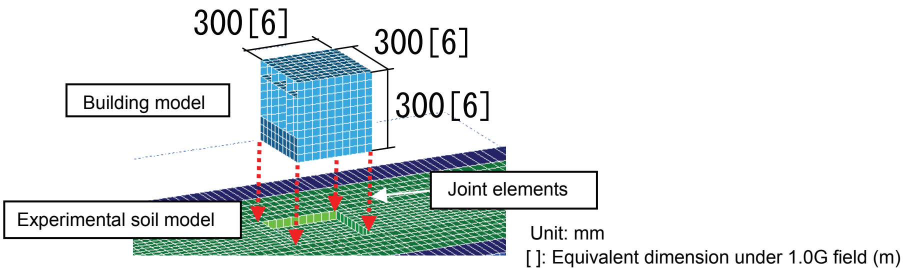


Figure 3.2 Analytical model of the building model

3.2. Impedance Functions for Building Model

Firstly, impedance functions are verified by comparing with the shaking table test results using an exciter. Several sine-wave force time histories with different frequencies are prepared and a series of dynamic analyses are performed by applying the sine-wave force time histories to the area, where the basemat of the building model exists, in order to obtain the responses at the soil surface. Impedance function is defined from the relationship between response displacement and applied force. The basemat area is stiffened in the analysis by using mass-less rigid shell elements in order to provide a uniform displacement distribution under the basemat.

Complex impedance functions evaluated by 3D FE model, which are compared with the experimental results, shown in Figs. 3.3 and 3.4. Fig. 3.3 shows the comparison of the shallow embedment case. Fig. 3.4 shows the comparison of the deep embedment case. These results are shown in 1G gravitational force field converting from 20G field of the centrifuge test based on the scaling law. It can be recognized that the horizontal and rotational impedance functions evaluated by FE model correspond well to the experimental results, but when looking at the comparison in detail, the experimentally evaluated points of the horizontal impedance function for the deep embedment case seems to be a little scattering.

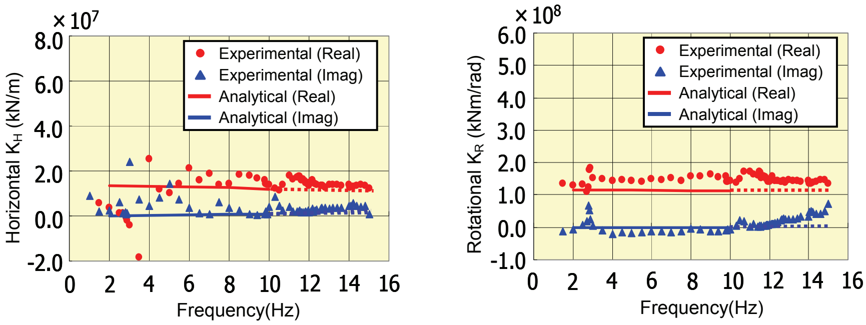


Figure 3.3 Comparison of the experimental and analytical impedance functions (Shallow embedment)

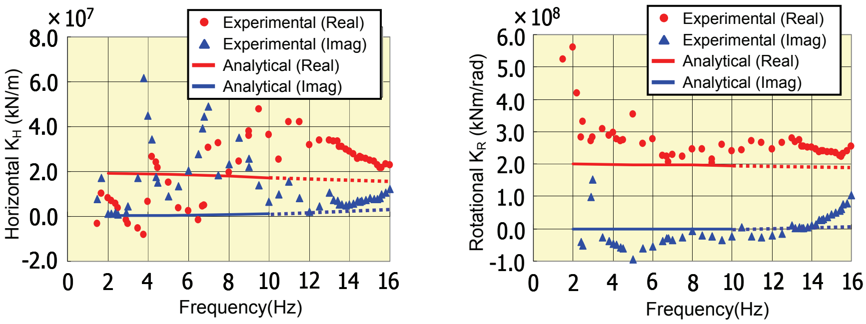
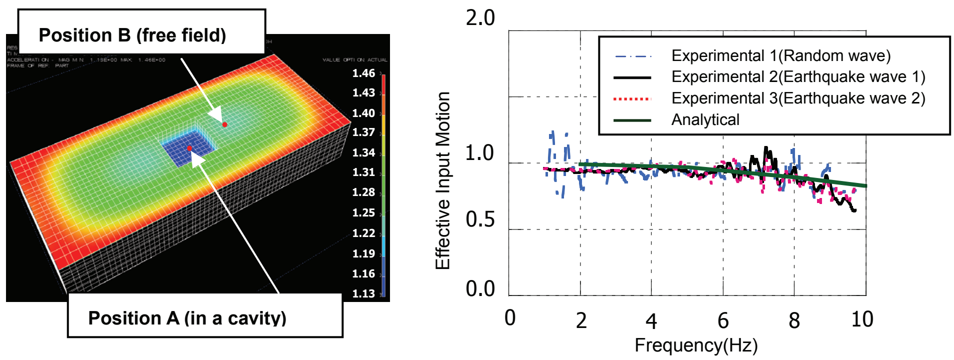


Figure 3.4 Comparison of the experimental and analytical impedance functions (Deep embedment)

3.3. Effective Input Motion for Soil Model with Cavity

Secondly, effective input motion for the soil model with a cavity is verified by comparing with the shaking table test results. Several sine-wave acceleration time histories with different frequencies, whose amplitude are 1.0Gal, are prepared. Applying these sinusoidal acceleration time histories at the bottom of the soil media modeled by solid elements, maximum acceleration distribution of the surface of soil model is evaluated in each frequency. Fig.3.5(a) shows acceleration distribution at the surface of the soil model for sinusoidal acceleration time history of 160Hz in 20G field (8Hz in 1G field). It could be recognized that maximum response at the cavity is smaller than that of the area surrounding the cavity. Maximum response at the peripheral area of the soil model is relatively large because the response of this area is affected by the existence of the shear box. In the experimental test, an accelerometer is set at the point whose distance from the center of the cavity is 48 cm along the excitation direction (Point B in Fig.3.5(a)). This point is considered to be little affected by the existence of both the cavity and the shear box, and it is also considered that the response of this point is treated as that of the free field. Effective input motion at the cavity could be evaluated by dividing the maximum acceleration of Point A by that of Point B. Effective input motions for each frequency are evaluated by repeating this procedure, using a series of acceleration time histories with different frequencies.



(a) Analytical Max. Acc. Distribution (8Hz)   (b) Effective input motion

Figure 3.5 Comparison of experimentally and analytically evaluated effective input motion

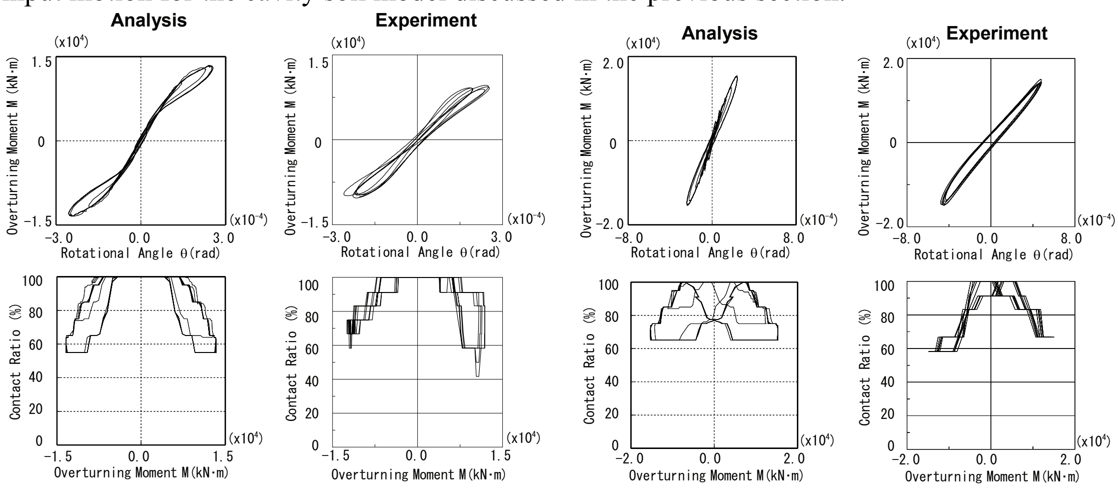
Effective input motion for the cavity evaluated by 3D FE model, which are being compared with the shaking table test results, are shown in Fig. 3.5(b). This result is also shown in 1G gravitational force field converting from 20G field of the centrifuge test based on the scaling law. It can be recognized that the effective input motion at the cavity evaluated by 3D FE model corresponds to the experimental result very well. As the excitation frequency becomes higher, effective input motion at the cavity decrease. It is admitted that the input motion to the building model decreases to 0.8 or 0.9 times of the original input motion near the excitation frequency of 10 Hz.

3.4. Basemat Uplift Characteristics for Building Model

Finally, basemat uplift characteristics for the building model are verified by comparing with the shaking table test results. Dynamic analyses for the building-soil model system are performed by applying sinusoidal acceleration time histories at the bottom of the soil medium modeled by solid elements. Basemat overturning moment, basemat rotational angle, and contact ratio are evaluated as the indices of basemat uplift characteristics. Basemat overturning moment M is obtained from the horizontal acceleration distribution of the building model, same as the M obtained from the test where acceleration distribution is measured by accelerometers attached to the building model in the experimental tests. Basemat rotational angle θ is obtained from vertical response displacement distribution of the basemat. Contact ratio η is obtained from the response of joint elements.

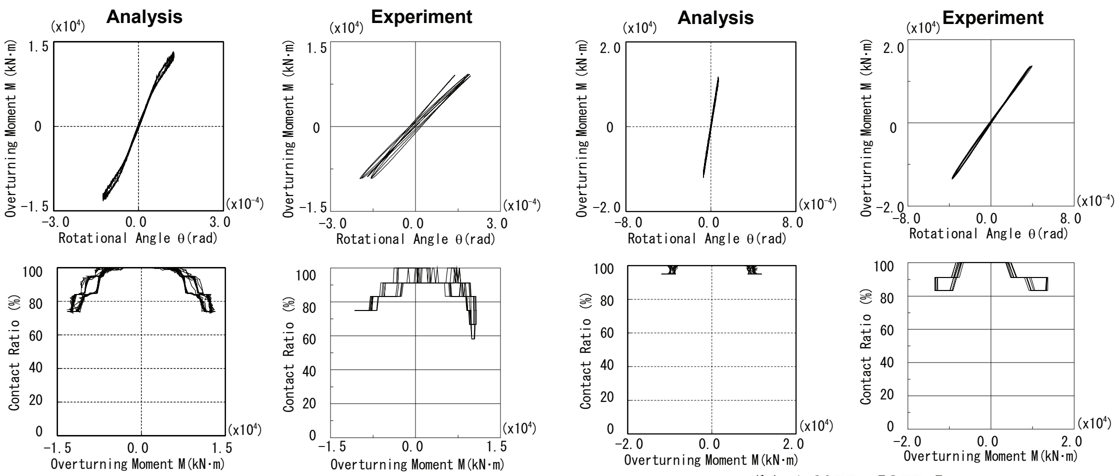
Figs.3.6 through 3.7 show the comparison between experimental and analytical results concerning M-θ and M-η relations of the basemat. The maximum acceleration of input sinusoidal motion for each excitation frequency is decided that the minimum contact ratio becomes about 60% in the shallow embedment case. Fig.3.6 shows the results for the shallow embedment case and Fig.3.7 shows the results for the deep embedment case. These results are also shown in 1G gravitational force field converting from 20G field of the centrifuge test by the scaling law.

From these figures, it can be recognized that the analytical results by FE model correspond to the experimental results qualitatively well. For the quantitative comparison, the maximum amplitude of over turning moments of both experimental and analytical results are almost same, but the gradient of experimentally evaluated M-θ curve is lower than that of analytically evaluated M-θ curve. The soil cement used as experimental soil medium is a strain-dependent material unlike the bedrock of the actual nuclear power plants, and has a nature that the stiffness becomes smaller as the response strain becomes larger. This may be one of the reasons of the difference between experimental and analytical gradients for M-θ curve. Moreover, regarding the difference of the embedment depths of the building model, it is confirmed that the response of the building model apparently tends to decrease in quantity by considering embedment effects, and this tendency becomes more remarkable as the excitation frequency is increasing. It is also confirmed that this result is harmonized with the discussion of effective input motion for the cavity soil model discussed in the previous section.



(a) 40Hz [2Hz]　　　　　　(b) 160Hz [8Hz]

Figure 3.6 M-θ, M-η by experiment and analysis (Shallow embedment)



(a) 40Hz [2Hz] (b) 160Hz [8Hz]

Figure 3.7 M-θ, M-η by experiment and analysis (Deep embedment)

4. CONCLUSIONS

In this paper, the experimental studies concerning soil-structure interaction at a hard rock site are performed focusing on basemat embedment effects and basemat uplift behavior, in order to verify the knowledge concerning basemat embedment effects obtained in the previous analytical study, and to evaluate basemat uplift behavior quantitatively. Three kinds of vibration tests, which are concerning basemat embedment effects and uplift phenomena, are performed. Those are (1) Shaking tests for building model using an exciter settled on the building model, by which impedance functions of the experimental soil model are evaluated, (2) Shaking table tests for soil with cavity, by which the reduction effect of the input motion for the cavity of soil are confirmed, and (3) Shaking table tests for building model, by which base uplift characteristics and embedment effects are confirmed.
Experimental soil model whose shear wave velocity is 500m/s, which is appropriate to capture dynamic behavior of actual NPP around the non-dimensional frequency 1.0, is used and the experimental tests in 20G gravitational force field are performed by the large geotechnical centrifuge system.
Basemat embedment effects and geometrical nonlinearity of basemat uplift could be confirmed from impedance functions and basemat uplift characteristics of the various experimental studies performed by varying the embedment depth of the building model. These correspond with the knowledge obtained from the previous analytical studies, and effectiveness of calculation model for basemat uplift behavior concerning NPP built on a hard rock site, which is proposed in the previous study (Ref 1), is verified.

ACKNOWLEDGEMENT

The authors wish to express cordial gratitude to Dr. Takao Nishikawa, Professor emeritus at Tokyo Metropolitan University, for many useful advices and suggestions given to this study.

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