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A STUDY ON EARTHQUAKE RESPONSE MOTIONS OF NON-ANCHORED RIGID BODIES

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SUMMARY

The earthquake response behavior of non-anchored rigid bodies is so complicated that their prediction is very difficult. Especially, if a rigid body is immersed in water, its response will be influenced by the force derived from the surrounding water. In the present study, both shaking table experiments and their analyses were performed to investigate the earthquake response behavior of a non-anchored rigid body. Size effect was obtained and the tendency that rigid bodies immersed in water were less movable than they were out of water was identified.

INTRODUCTION

The earthquake response behavior of non-anchored rigid bodies is so complicated that their prediction is very difficult. Mochizuki and Kobayashi (Ref. 1) and Ishiyama (Ref. 2) proposed generic analytical methods to predict the earthquake response behavior of a non-anchored rigid body, which includes rest, slide, rocking-slide, slide-jump, and rocking jump as the non-anchored rigid body earthquake response motion. The non-linear analysis techniques for rigid bodies were introduced in these methods, by considering the transition from one motion to the others. However, these methods are restricted to two-dimensional (within a vertical plane) motions. The motion of non-anchored rigid body during earthquake is expected to show highly non-linear property in three dimensional space. Therefore, there might be some limitations in application of the method to the prediction of earthquake response motion for non-anchored rigid bodies. Especially, if a rigid body is immersed in water, its response will be influenced by the force derived from the surrounding water as well as the actual earthquake force. In the present study, both shaking table experiments and their analyses were performed using two types of rigid bodies,to investigate the earthquake response behavior of a non-anchored rigid body during earthquakes. In the present study, the effect of model size and the effect of water surrounding the model are discussed with special interest.

EXPERIMENT

Two kinds of cylindrical bodies are used in the shaking table experiment. One is 100 centimeters (cm) in height and 40 cm in diameter, and has the specific gravity of 3.8 (Type A). Another is 100 cm in height and 24 cm in diameter and has a specific gravity of 7.9 (Type B). These specimens are made of SS41, except for bottom plate made of SUS304, which is stuck to the bottom of each specimen. The shape factor, b/h, where b means diameter and h means the height, is 0.40 for the Type A model, and is 0.24 for the Type B model. The friction coefficient between a bottom plate and a floor plate is assumed to be 0.30. The Type A specimen represents a rigid body, which easily tends to slide. The Type B specimen represents a rigid body which easily tends to rock. In order to protect the specimen from overturning/and damage during experiment, a specimen was placed on the bottom of a steel box, which was fixed on the shaking table and had 66 cm x 66 cm in cross section and 246 cm in height. The natural vibration frequency for this box was designed quite high, enough to be considered to be rigid, so that this box may not affect the motion of a specimen. Setup for these experiment is shown in Fig.1. In order to monitor the motion, accelerometers are mounted in the center of a specimen in tri-axial directions. Therefor, a specimen has some void space in the center of the body. In addition to the accelerometers, observation of motion using video cameras and recorders, which are placed in front and just above the box, were also made. Simulated earthquake motion are mainly used as input motion in the experiment. Fig.2 shows an example of the input motion. In order to investigate the size effect of a non-anchored rigid body on their earthquake response motion, the smaller models for each type of specimens, scaled to 75 % and 50 % in length for each type, were also prepared. The specifications for these specimens are listed in Table 1. Shaking table experiments were carried out under the conditions, i.e., with and without water in the box. The experiment, with water in the box, was carried out aiming at a study of motion for a non-anchored rigid body, immersed in water.

EXPERIMENT RESULTS

An example of the tri-axial response acceleration time histories observed at the center of gravity in a specimen is shown in Fig.3. This case is a result of an experiment carried out with the Type A standard model immersed in water. Generally, the Type A specimen tends to move mainly in the shaking direction (i.e. x-direction). On the other hand, the Type B specimen tends to move not only in the shaking direction, but also in its perpendicular direction to some degree. These tendencies are observed, regardless of the existence of water in a box and regardless of the specimen size (scale models). The existence of the cross components in the observed acceleration record indicates that a specimen makes some turn on the floor. The degree of the turn of a specimen increases with the increment of the input acceleration level and decreases with the increment of specimen size. However, the earthquake response prediction method applied in the present study can deal with only the motions within a vertical plane. Thus, in the present study, little attention was paid to motion concerning turn. Fig.4 shows an example of the maximum response of rocking and sliding motion for each size model with water in the box. The following factors were confirmed in the present experiment ;

1) The dominant motions observed were ; slide and turn for the Type A model, and rocking, slide and turn for the Type B model.
2) For the rocking motion, mainly observed with Type B model, there was a tendency, that the larger the model size, the smaller its earthquake response level. (Hereafter, this tendency is called the size effect).
3) For the slide motion, which was observed with both types of model, the size effect was not clearly identified. This tendency was also observed both with and without water in the box.
4) Responses observed in the experiment performed with water in the box generally tended to be smaller than that observed in the experiment performed

without water in the box.

The maximum observed earthquake responses of rocking and slide motions, for the type B standard model, are listed in Table 2 for cases with and without water in the box, respectively. The rocking responses are smaller with water than without water in the box. Although it is difficult to quantify the response decrement because of large variation in rocking motion, a tendency toward large reduction in the response motions was observed. However, in the slide motions, this tendency was not clearly observed.

ANALYSIS

A computer program which predicts an earthquake response behavior for a non-anchored rigid body was developed. The basic motions considered in this program include rest, slide, rocking, rocking-slide, slide-jump, and rocking-jump. Moreover, an algorithm to predict a rigid body motion, when it is immersed in water was installed in this program. A feature of this algorithm is the intoduction of added mass and added moment of inertia, to the equations of motion for a rigid body immersed in water. This effect is described as the following equations of motion for slide and rocking, respectively.

$$(m+\Delta m)\ddot{x} = -(m-m_d)\ddot{X}-S\mu_k(m-m_d)g \tag{1}$$

$$(mi^2+mr^2+\Delta I)\ddot{\theta} = r(m-m_d)\ddot{X}\cos(\alpha-|\theta|)-S'r(m-m_d)g\sin(\alpha-|\theta|) \tag{2}$$

$$\text{and} \quad r = ((h/2)^2+(b/2)^2)^{1/2}$$
$$\alpha = \tan^{-1}(b/h)$$

where, m is the mass of a rigid body, Δm is the added mass, m_d is the mass of displaced water, $\ddot{x}$ is response acceleration for a rigid body at the center of gravity relative to the floor, g is the gravity constant, $\ddot{X}$ is the floor acceleration, μ_k is the dynamic coefficient of friction, and S is a sign which indicates the direction of friction force by taking a value of +1 or −1. Also, i is the gyration radius, h and b are the height and diameter for a rigid body, is the rocking angle, ΔI is the added moment of inertia, and S' is a sign which indicates a rocking direction. As the evaluation method for the added mass, both methods proposed by Fritz (Ref. 3) and by Chung and Chen (Ref. 4) were used on a trial basis and it was confirmed that the effects of the difference between these methods were very small. So, the added mass evaluation method, proposed by Chung and Chen, is used to maintain consistency with the added moment of inertia, which is evaluated based on the method proposed by Chung and Chen. The evaluation of restitution coefficient and coefficient of friction is very difficult but is not essential in this study. Thus, these coefficient values assumed in the present study, were −0.8 for the normal restitution coefficient, 0.2 for the tangent restitution coefficient, 0.3 for the static cooefficient of friction, and 0.15 for the dynamic coefficient of friction, by referring to several pertinent papers and expert opinions. An example of a response acceleration time history for the type A standard model immersed in water, obtained by this analysis, is shown in Fig. 5. In this manner, the analytical result shows good agreement with the experimental result, but tends to indicate a larger acceleration response than that observed in the experiments. So, it can be said that some conservatism exists in this analytical method. In order to investigate the size effect in the acceleration response, analyses for various scale models were carried out. Figure 6 shows the maximum responses in rocking angles and in slide displacements obtained by these analyses. In this figures, as observed already in the experimental results, the size effect in the slide response is not clearly observed, whereas it is clearly observed in the rocking response.

DISCUSSION

The size effect can be explained from the following point of view. When a rigid body placed in a box without water, goes on rocking with very small angle without any external force, Eq.(2), which represents the rocking motion of a rigid body, can be approximately expressed as ;

$$(mi^2+mr^2)\ddot{\theta} = -S'rmg\sin(\alpha) \quad (3)$$

This equation indicates that parameters i and r are dependent on model size, and rocking angle θ is dependent on the inverse of model size. However, this expression is not exact, because Eq.(2) is very complicated. Furthermore it is non-linear, such that the parameter, θ, is not proportional to the inverse of model size in the rigorous sense. However, roughly speaking, as this tendency presented above can be considered to conserve for generic cases, the size effect might be generally appropriate for the rocking response. For the slide response, when a rigid body is placed in a box without water, no external force acts on a rigid body. In this case, Eq.(1) is modified as ;

$$m\ddot{x} = -Sm\mu_k g \quad (4)$$

Eq.(4) shows that the slide motion of a rigid body does not depend on model size. The fact that the slide response was not clearly observed in the experiment can be explained with this equation. Since the specimen response includes rocking, slide, rocking-slide, and two jumping motions, and moreover, since these motions are entangled with each other, the size effect in slide motion cannot always be clearly differentiated. This might be another reason why the size effect was not clearly observed in the slide motion. However, in case the dominant motion is strong rocking, the size effect was clearly observed.

CONCLUSION

The following results were obtained from this study.

(1) A tendency, wherein the larger the model scale, the smaller its earthquake response, is observed in the experiment.
(2) The above tendency (i.e. size effect) is also obtained by the analysis, applying the analytical method developed in the present study.
(3) Rigid bodies immersed in water are less movable than they are when out of water.

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Table 1 Specimens specifications

	Type A			Type B		
Scale	100%	75%	50%	100%	75%	50%
Height (cm)	100	75	50	100	75	50
Diameter (cm)	40	30	20	24	18	12
Gyration radius (cm)	33	25	17	31	24	16
Mass (kg)	770	325	96	380	160	48
Mass of water displaced (kg)	212	90	27	48	20	6
Shape factor	0.40	0.40	0.40	0.24	0.24	0.24

Table 2 Maximum earthquake response for rocking and sliding motions, with and without water in the box for Type B standard model (maximum acceleration of input motion = 500gal)

	Scale	Rocking	Sliding
With water	100%	0°	> 5cm
	75%	0°	> 5cm
	50%	5°	2-5cm
Without water	100%	10°	2-5cm
	75%	overturn	overturn
	50%	overturn	overturn

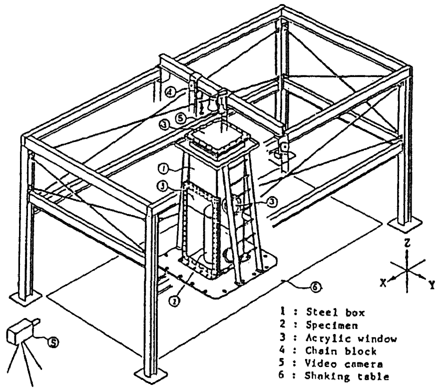


Fig. 1 Setup for these experiments

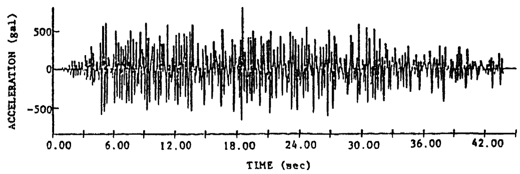


Fig. 2 Input motion example

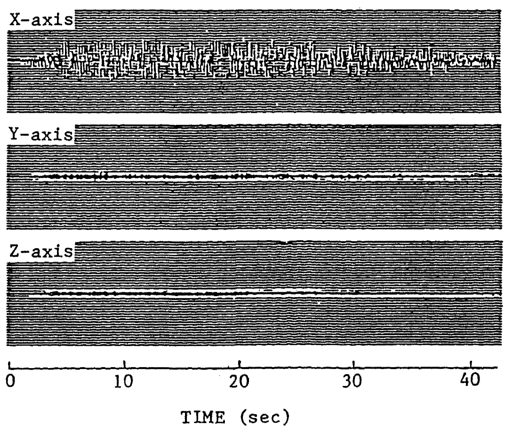


Fig. 3 Anexample of tri-axial response acceleration time histories observed at the center of gravity of 100% scaled Type A specimen

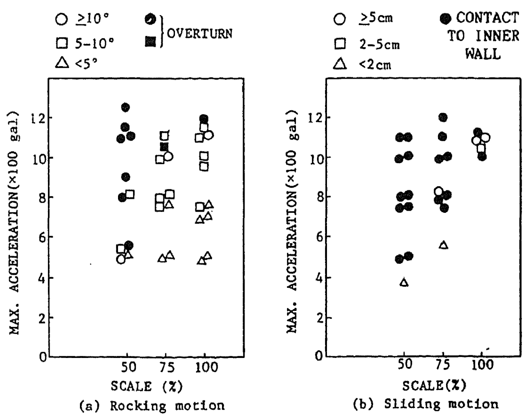


Fig. 4 Maximum responses showing rocking motion for Type B specimen and sliding motion for Type A specimen with water in the box

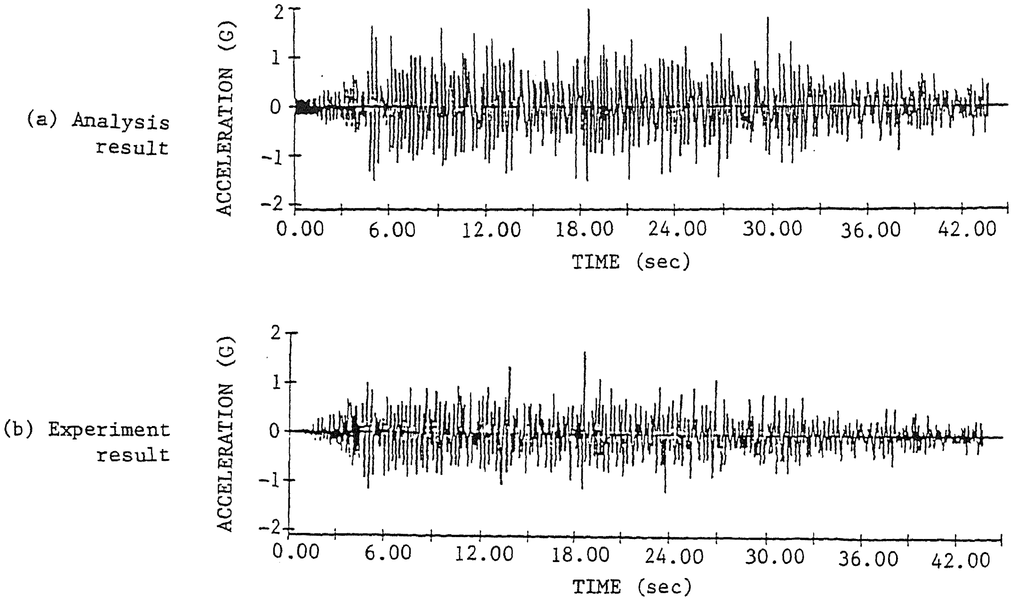
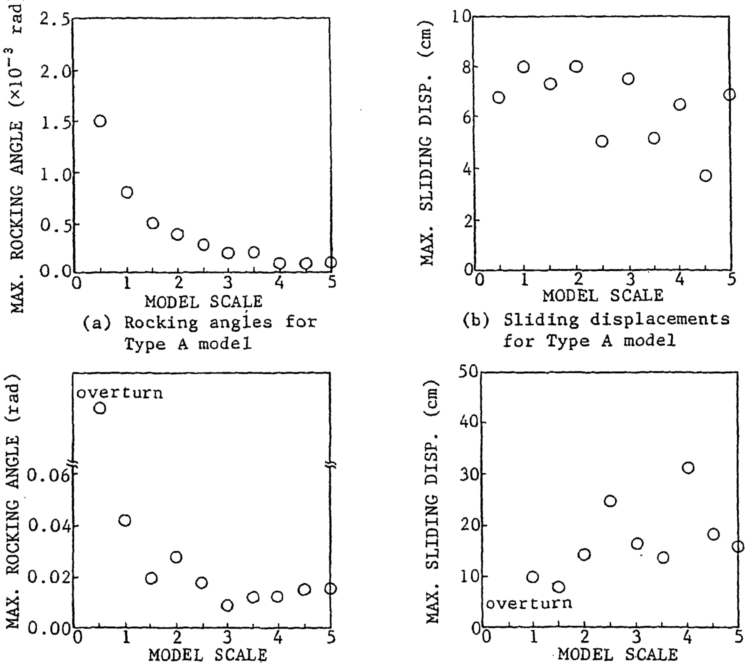


Fig. 5 Acceleration time histories for standard Type A model obtained by this analysis and experiment
(maximum acceleration of input motion = 1G)



(a) Rocking angles for Type A model

(b) Sliding displacements for Type A model

(c) Rocking angles for Type B model

(d) Sliding displacements for Type B model

Fig. 6 Maximum responses in rocking angles and sliding displacements, obtained by present analysis
(maximum acceleration of input motion = 1G)