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ROCKING MOTION AND CRITERIA FOR OVERTURNING OF BODIES ON A FLOOR -COMPARISON BETWEEN ANALYSIS AND EXPERIMENT

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SUMMARY

We have theoretically analyzed the motion of rigid bodies on a rigid floor subjected to earthquake excitations and developed the computer program to analyze the behavior of the bodies. Then through the computer simulation, the criteria for overturning of bodies by earthquake excitations have been proposed. This paper deals with the experimental study of a rocking body and its overturning using a shaking table, and the analytical study utilizing an improved computer simulation program. The specimens for shaking table tests are rectangular prisms made of laminated wood. The parameters of specimens are breadth (B), height (H), aspect ratio (H/B), etc. The quality of floor finishing is also one of the experimental factors. As to rocking forced by external excitations, the initiation of rocking by the experiment always happens earlier than its estimation by the analysis. A good agreement, however, is observed between them, once the rocking motion starts. This indicates that the initiation of the actual rocking can not be simulated, if it is assumed that a rigid body rests on a rigid floor. Since the actual body is not rigid, it starts to vibrate even if the excitation is lower than that may cause its rocking motion. Therefore some improvement of the previous computer program is necessary. One of tentative attempt to overcome this problem is the horizontal movement of the center of gravity position until the rocking motion starts. This improves the analytical results of the initiation of rocking motion.

INTRODUCTION

Many people were injured because of the overturning or sliding of furniture, or falling objects from the furniture during the 1995 Hyogo-ken-nanbu Earthquake. To make matters worse, the furniture overturned or objects scattered obstructed the people from evacuation activities. For these reasons, it becomes more important to find the criteria of overturning of furniture and its prevention against overturning during earthquakes. The purpose of this paper is to improve the accuracy of the simulation by comparing the shaking table test results and the results of simulation.

PREVIOUS RESEARCH

Many experiments and analysis have been done about the overturning of bodies from a viewpoint of the estimation of the ground acceleration from the overturning of gravestones and the prevention of furniture from overturning. YAZAKI[YAZAKI, 1998] developed the computer program of ISHIYAMA[ISHIYAMA, 1982]

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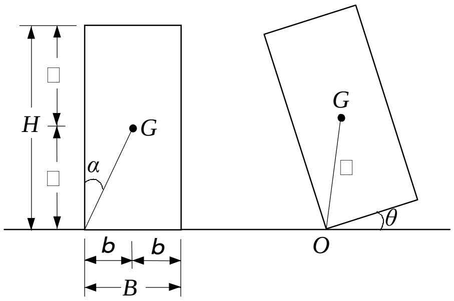


Fig.1: A body in motion

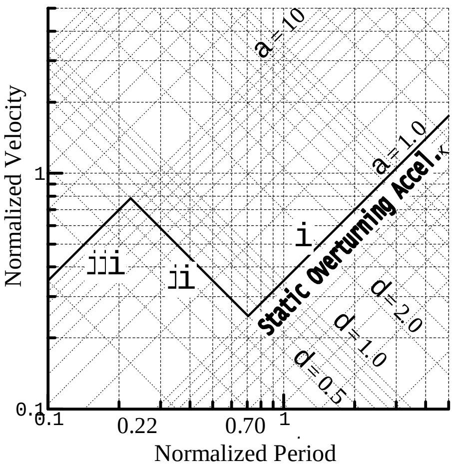


Fig.2: Criteria for overturning of body

that can analyze the two dimensional rigid body models as shown in Figure 1. And YAZAKI proposed the criteria for overturning of the rigid bodies considering the period characteristics of the input motions from the overturning simulation to the sinusoidal motions. The overturning condition is expressed as Equation (1). The relationships between the overturning condition and the acceleration, velocity, displacement and period characteristics are shown in Figure 2.

$$\left.\begin{array}{lll} a = A/A_0 = 1 & (0.70 \,..\, t) & \ldots\ \mathrm{i} \\ d = D/D = 0.5 & (0.22 \,..\, t\ \ f0.70) & \ldots\ \mathrm{ii} \\ a = A/A_0 = 10 & (0.22\ \ f t) & \ldots\ \mathrm{iii} \end{array}\right\} \tag{1}$$

Where, a, v, d, and t are the normalized acceleration, velocity, displacement, and period that are respectively divided by following corresponding values, in order to eliminate the influence of the size and proportion of the models.

$$A_0 = \frac{b}{h} g \tag{2}$$

$$V_0 = \sqrt{\frac{8gr}{3}\frac{1-\cos f\text{¿}}{\cos^2 f\text{¿}}} \tag{3}$$

$$D_0 = 0.49\frac{2hr}{3b}\frac{1-\cos f\text{¿}}{\cos^2 f\text{¿}} \tag{4}$$

$$T_0 = 0.7f\,\hat{\text{I}}\frac{h}{b}\sqrt{\frac{8r}{3g}\frac{1-\cos f\text{¿}}{\cos^2 f\text{¿}}} \tag{5}$$

Equation (2) is the horizontal acceleration when the body starts rocking which was indicated by WEST. Equation (3) is the horizontal velocity of the shock to overturn the object which was derived by MALLET. Equiation (4) and (5) are derived from Equations (2) and (3), assuming that the excitation is sinusoidal. Where, g is the acceleration of gravity. The i, ii and iii in Figure 2 correspond to the number of Equation (1). For t ƒ 0.22 and 0.70 ‥t the overturning criteria are expressed by the constant acceleration and by the constant displacement for 0.22 ‥t ƒ0.70.

SHAKING TABLE TESTS

Test Specimens and Procedure:

Table 1 shows the specimens used for shaking table tests. The depth of each specimen body was three times of breadth (B), so that it would not start dimensional motions. Form panels for concrete, carpet, and cushion floor were used as floor materials in the test. Figure 3 shows the measured results of surface static coefficient of friction.

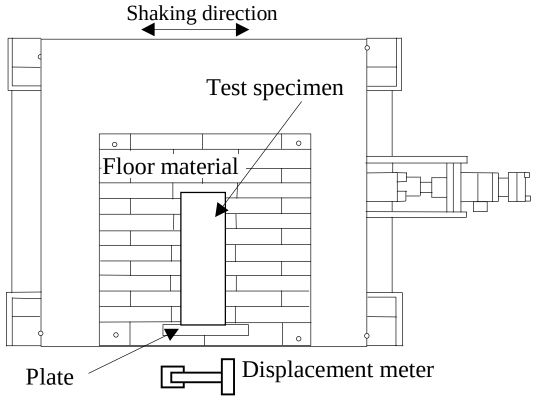
Figure 4 shows the outline of the shaking tests. The rotation angle of the specimen was calculated from its displacement which was measured by laser displacement meters. This device enables us to measure displacements of objects without contacting them. The plate was attached to the specimen to reflect the laser and

Table 1: Test specimens

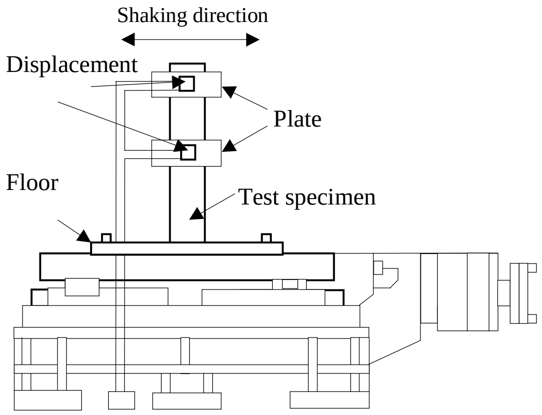
Specimen	Breadth B(mm)	Height H(mm)	B/H	material
1	60	200	3/10	oak
2	60	300	1/5	oak･douglas-fir
3	60	400	3/20	oak･douglas-fir
4	60	600	1/10	oak･douglas-fir
5	40	400	1/10	douglas-fir
6	80	400	1/5	douglas-fir
7	120	400	3/10	douglas-fir
8	40	200	1/5	douglas-fir
9	120	600	1/5	douglas-fir

Table 2: Input motions

Frequency f(Hz)	2			4			6		
Displace. Amplitude D(mm)	10.0	12.0	14.0	8.0	10.0	12.0	6.0	8.0	10.0
Vel. amplitude V(kine)	12.6	15.1	17.6	20.1	25.1	30.2	22.6	30.2	37.7
Accel. Amplitude A(g)	0.16	0.19	0.23	0.52	0.64	0.77	0.87	1.16	1.45



(□)Plan



(b) Side elevation

Figure 4: Outline of the shaking test

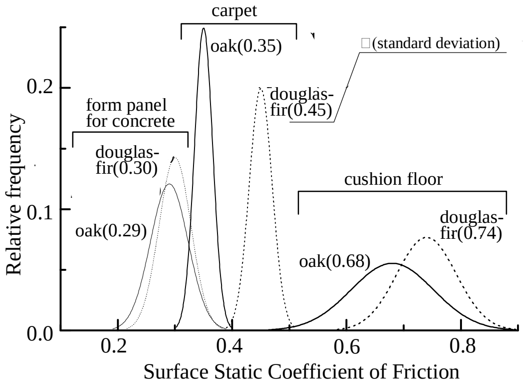


Figure 3: Comparison of surface static coefficient of friction

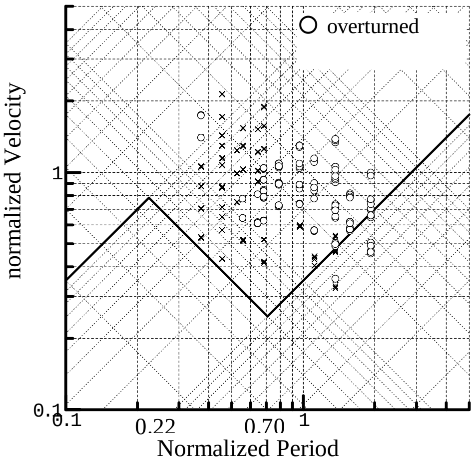


Figure 5: Overturning of bodies by experiments (floor material:capet)

to measure the displacement. The thin and light plate of plastic was used to eliminate the influence on the motions of the specimen. Table 2 shows the input motions of the table. The excitation was sinusoidal. The velocity amplitude *V* [kine] and acceleration amplitude *A*[g] in Table 2 were calculated from the frequency and the amplitude of the displacement. The test was carried out three times for each excitation.

Test Results and Study:

Carrying out the series of the carpet floor, the experimental results were obtained as Figure 5. The aforementioned criteria for overturning are also shown in this figure. According to this Figure, for 0.7 ‥ *t*, most specimens overturned. While for *t* ƒ 0.7, almost all specimens did not overturn even if the excitation was over the criteria for overturning. Although the same trend was seen in the case of the form panel for concrete and the cushion floor, no specimen overturned below the static overturning acceleration.

COMPARISON BETWEEN EXPERIMENTAL AND ANALITICAL RESULTS

The criteria for overturning, which had been derived from the simulation results, was not able to predict the limits of overturning for the specimens appropriately. If the value of the parameter in the simulation is appropriate, we will be able to estimate the criteria for overturning more accurately. In this chapter, to estimate the appropriate values of the parameters in the simulation, we made the comparison between the simulation results and the experimental results for time history response.

Method of Simulation:

The simulations was carried out by the computer program that YAZAKI made on the basis of the study of ISHIYAMA. The nine models shown in Table 1 were analyzed. The acceleration was calculated from the record of displacement of the shaking table. Table 3 shows coefficients that were used to the simulation. Surface static coefficient of friction μ_s, surface kinetic coefficient of friction μ_k and normal restitution coefficient‚‥$_y$ were the measured values. Judging from the situation of measuring those values μ_k of the carpet was assumed to be the same as μ_s because it was impossible to measure it. Since it was also impossible to measure the edge static coefficient of friction $\bar{\mu}_s$, edge kinetic coefficient of friction $\bar{\mu}_k$, and tangent restitution coefficient‚‥$_x$, we used the same values as in the research of YAZAKI[YAZAKI , 1998] .

Comparative Method and Results:

As an example, the time history response of the specimen of Type 1 that was on the carpet and subjected to the excitation of 2Hz and 12mm amplitude is shown in Figure 6. In this Figure, the ordinate is the normalized rotation angle ƒ which was divided by the ƒ in Figure 1. In this experiment, the specimen overturned below the static overturning acceleration. Figure 7 shows the comparison between the simulation result using the coefficients in Table 3 and the experiment result. In this simulation, the specimen was rest. We consider that this is due to the some shock which started the rocking motion of the specimen in the experiment[ISHIYAMA, 1982].

Figure 8 shows the comparison between the experiment and the simulation after starting rocking motion. Here, the beginning of rocking motion is supposed as the instant when the normalized rotation angle ƒ exceeded 0.05 for the first time and the starting point of the simulation is shown with ☐ in the figure. From this comparison, we can see that the difference between the experiment and the simulation becomes very small.

Table 3: Coefficients used to the simulation

Floor material	Specimen	μ_s	μ_k	$\bar{\mu}_s$	$\bar{\mu}_k$	‚‥$_x$	‚‥$_y$
form panel for concrete	oak	0.29	0.14	0.60	0.45	-0.40	0.52
	douglas-fir	0.30	0.11	0.60	0.45	-0.40	0.49
carpet and	oak	0.35	0.35	0.60	0.45	-0.40	0.49
	douglas-fir	0.45	0.45	0.60	0.45	-0.40	0.49
cushion floor	oak	0.68	0.34	0.60	0.45	-0.40	0.49
	douglas-fir	0.74	0.35	0.60	0.45	-0.40	0.51

Note

μ_s: surface static coefficient of friction
μ_k: surface kinetic coefficient of friction
$\bar{\mu}_s$: edge static coefficient of friction
$\bar{\mu}_k$: edge kinetic coefficient of friction
’‥$_x$: tangent restitution coefficient
’‥$_y$: normal restitution coefficient

Furthermore, to obtain better values shown in Table 3, the motion of the specimen was repeatedly simulated by a trial and error method. In this simulation, only $\bar{\mu}_s$ and $\bar{\mu}_k$ were changed, and μ_k and $,.._x$ were kept constant. Because μ_k has little effect on the rotation angle f after starting rocking motion, and also the influence of $f._x$ on the motion is very small in comparison with other coefficients. Furthermore, the coefficients obtained from measurement were kept as they were measured. As a result, the difference of time history response between the experiment and the simulation value became the minimum when $\bar{\mu}_s$ was 0.21 and $\bar{\mu}_k$ was 0.80 (See Figure 9). In this example, the influence of $\bar{\mu}_s$ and $\bar{\mu}_k$ on the motion of a rigid body is small because the specimen overturned as soon as the rocking motion started.

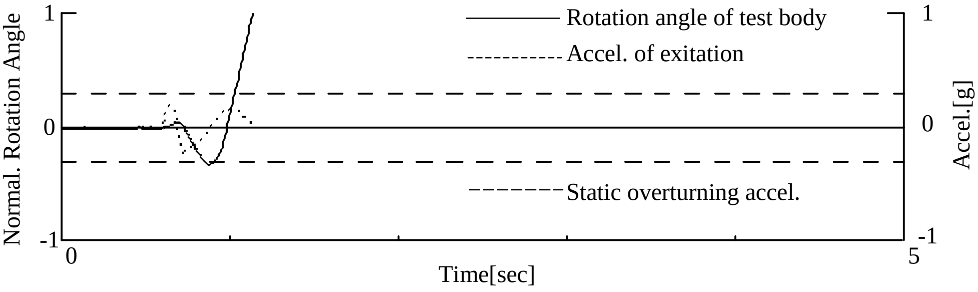


Figure 6: Experiment result (Type 1,2Hz, 12mm, carpet)

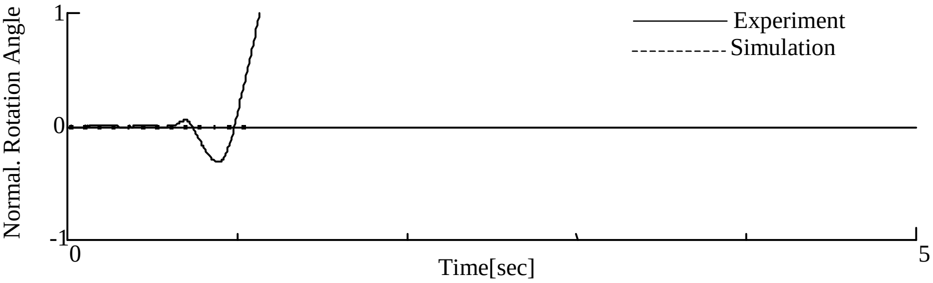


Figure 7: Comparison between analysis and experiment (by the existing simulation program)

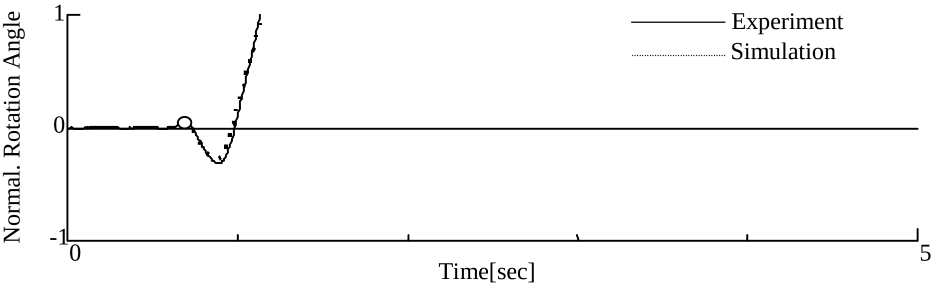


Figure 8: Comparison between analysis and experiment (simulation from rocking start point)

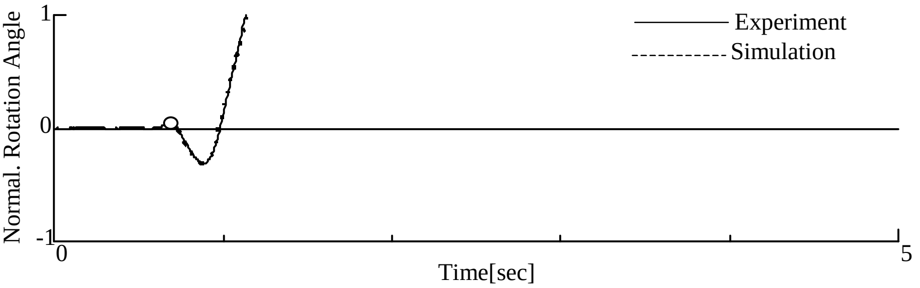


Figure 9: Comparison between analysis and experiment (simulation from rocking start point after coefficient modification)

From the aborvementioned comparative study, it was found that the motion from the rest condition is not able to simulate properly. However, once rocking motion starts, the simulation results is in fair agreement with the experiment results.

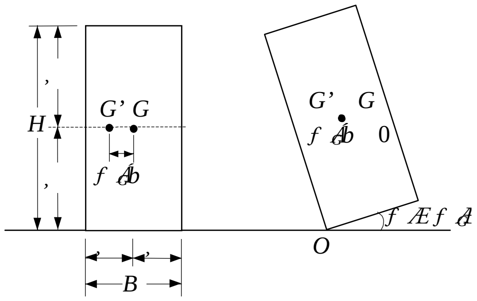


Figure 10: Temporary movement of center of gravity position

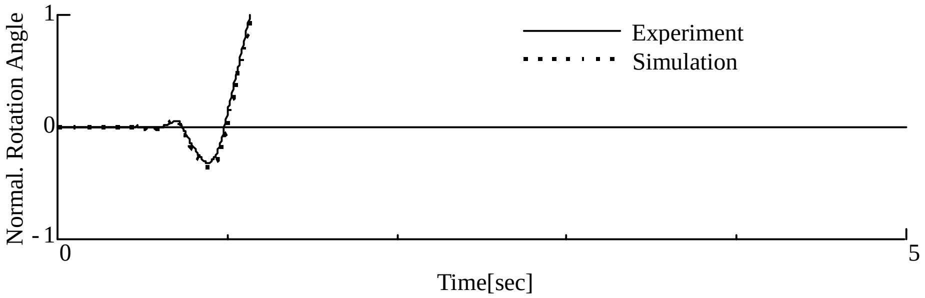
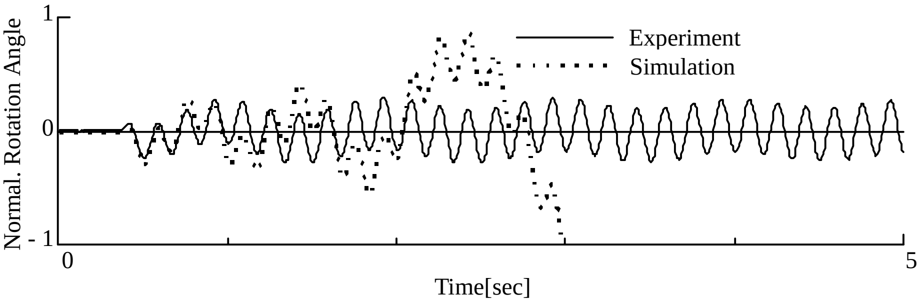
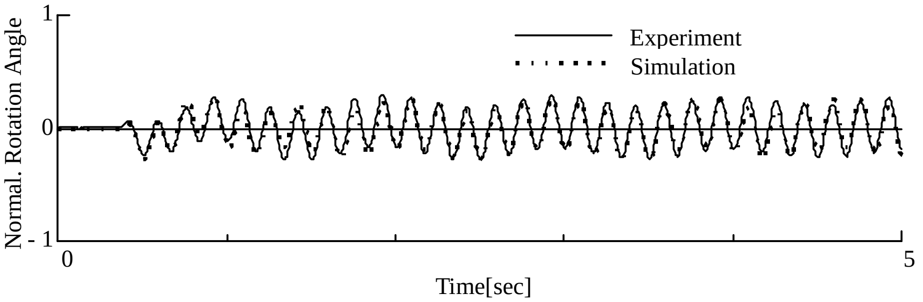


Figure 11: Comparison between simulation and experiment



(a): Comparison between simulation and experiment



(b): Comparison between simulation and experiment
(simulation after adjustment of coefficients and the center of gravity)

Figure 12: Experimental result (Type 1, 6Hz, 10 mm, cushion floor)

In consideration of these results, we introduced a new coefficient in the simulation program (See Figure 10). We assumed that the center of gravity may move to horizontal direction by introducing coefficient γ_G . This coefficient plays a major role in determining the start of rocking motion. As a result, it is possible to simulate the motion of a body which starts rocking motion even below the static overturning acceleration. γ_G is determined by Equation (6).

$$\gamma_G = \gamma_{G0}\left(1-\frac{\theta}{\theta_G}\right) \tag{6}$$

where γ_{G0} is the coefficient to move the center of gravity in the rest and the early stage of rocking, θ_G is standard rotation angle that is considered as rocking motion starts. However, γ_G becomes zero after the instant when exceeded θ_G, because it is such a coefficient that starts the rocking motion. We made simulations changing γ_{G0} and keeping θ_G constant(=0.01). Then the correspondence between the simulation result and the experiment result was best when γ_{G0} is 0.98. This result is shown in Figure 11. The agreement between the experiment and simulation was improved by the introduction of coefficient γ_G .

Next, the motion of the test specimen of Type 4 subjected to the excitation of 6Hz and 10mm amplitude on the cushion floor is shown in Figure 12 with the simulation result. This example is different from the above-mentioned results. The rocking continues long and the overturning did not occur in the experiment. (a) and (b) in Figure 12 show the simulation result which started from the rest condition, (a) shows the simulation result that did not change $\bar{\mu}_s$ and $\bar{\mu}_k$ and γ_{G0} with the value of Table 3, and (b) shows the result that adjusted those values. In Figure 12(b), the rotation angle of the simulation is almost equal to the rotation angle of the experiment immediately after the rocking motion. In this case, the value of γ_{G0} does not affect much the start of the rocking motion.

In the Figure 12(a), the rotation angle of the simulation does not agree to the rotation angle of the experiment when the repetition of rocking motion increases. On the other hand, in the Figure 12(b) that adjusted $\bar{\mu}_s$ and $\bar{\mu}_k$ the simulation shows good agreement for whole. This is because $\bar{\mu}_s$ and $\bar{\mu}_k$ became small values so that the bottom edge of the body became easy to slip. Then the rotation angle of the rigid body does not become so large.

Study:
It was shown by using above two examples that to set up $\bar{\mu}_s$, $\bar{\mu}_k$, and γ_{G0} appropriately is one of the methods to improve the accuracy of the existing simulation program.

From the comparisons of experiment and analysis in the above section, we knew that the influence of γ_{G0} is large in the case that the body overturns under the static overturning acceleration. Also, we knew that the influence of $\bar{\mu}_s$ and $\bar{\mu}_k$ are large, in the case that the rigid body repeats the rocking motion.
From the results that the same comparison was carried out about all test bodies, the experiment results and the simulation results almost agree, when coefficients are in the following range. Furthermore the dispersion of $\bar{\mu}_k$ was bigger than the dispersion of $\bar{\mu}_s$ and γ_{G0}.

$$0.1 \le \bar{\mu}_s \le 0.2 \tag{7}$$
$$0.1 \le \bar{\mu}_k \le 0.8 \tag{8}$$
$$0.8 \le \gamma_{G0} \le 0.9 \tag{9}$$

Such a trend was seen in all the comparative results irrespective to the floor materials and test specimens.

COMPARISON OF OVERTURNING SITUATION

The result of simulations from rest condition is shown in Figure 13, where the coefficients and the center of gravity are adjusted with the same manner as explained in section 4. Comparing this figure with Figure 5, both are agreed well(about 80%). The percentages of agreement of overturning on form panel for concrete and cushion floor were about 88% and 87%, respectively.

If we estimate that the simulation program did a safe side judgment in case that specimen did not overturn in the experiment although it overturned in the simulation, the simulation is able to predict about 90% of overturning situation regarding each floor material.

CONCLUSIONS

In this paper, we were able to estimate the values of coefficients that should be used in the simulation, comparing the shaking experiment results with the simulation results. And by introducing the coefficient f_{G0} that moves the center of gravity of the body temporarily in the simulation program, it became possible to simulate the motion of bodies properly. However, the detailed examination is necessary about the values of coefficients, especially f_{G0} and $f_{\Delta G}$, because those values are only temporal cares.

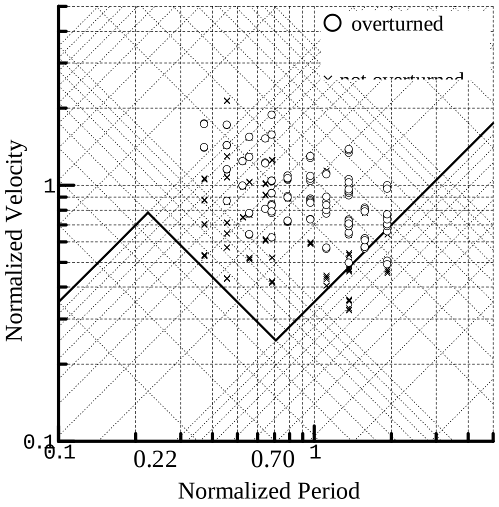


Figure 13: Overturning of bodies by simulation (carpet)

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