A FUNDAMENTAL STUDY ON DEVELOPMENT OF A VERIFICATION SYSTEM FOR EARTHQUAKE-PROOF MEASURES FOR FURNITURE

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ABSTRACT :

It is clear from several past disasters caused by strong earthquakes that many people are injured or killed by the sliding and falling over of big pieces of furniture. This is an important problem that needs to be dealt with as furniture is around all of us, both at home and in the workplace. Up to the present, many kinds of equipment and means of earthquake-proofing with furniture have been studied and developed throughout the world. Although, there are still many people in the general public who are completely unaware of such furniture-related earthquake-proofing measures and their use and effectiveness. As a fundamental study a piece of furniture is assumed as a rigid body in this discussion. From the results of analysis of rigid body subjected to strong ground motion, it was found that to reduce the response of rigid body, increase of static frictional coefficient is effective by setting up frictional sliding stoppers and so on, placed under an article of furniture. In addition sway-rocking simultaneous behavior was simulated here and a regression equation of critical aspect ratio (b/h) for turnover of a rigid body was formulated with amplitude and frequency of sinusoidal acceleration. This equation can be used to estimate whether a body under strong earthquake will turnover or not.

KEYWORDS: furniture, rigid body, earthquake-proof, sway-rocking, turnover

1. INTRODUCTION

In the world, Japan is one of the most earthquake-prone countries, with almost 10%of worldwide earthquakes occurring here. Several research projects have been carried out by means of rigid body modeling using actual objects, such studies on toppling over of tombstones and on the earthquake-proof measures preventing turnover of furniture, as already mentioned. It is necessary to know the character of earthquakes and the safety of objects and their stability during strong seismic motions. In Japan the below things can be said, regarding some pieces of furniture considering damage after past earthquakes. In the recent result of research of earthquakes 30~50%person are injured by the falling down and turnover of furniture. And also more persons are injured by stumbling and falling down caused by hitting the fallen and turned over furniture and other persons are injured by cutting part of body by broken pottery matter and by broken pieces of glass. A rigid body is a solid body of finite size in which deformation is neglected and which is used for analysis treating motions of solid body in several fields. Especially, in the civil and architectural engineering fields, this rigid body model is used not only for structural analysis but also for the estimation of seismic maximum acceleration and seismic intensity by the research of turnovers of tombstones after earthquakes. This model is also used for the earthquake-proof measures preventing turnover of furniture and is used for insuring safety of construction machines.

2. SEISMIC BEHAVIOR OF RIGID BODIES

This section presents the basic behavior of rigid bodies when the ground moves and shows the applications of this rigid modeling study for several cases.

2.1 Classification of the seismic behavior of rigid bodies

The behavior of rigid bodies during earthquakes is not simple. It is somewhat complicated and is almost impossible to analyze all situations. As a first step, this study aims to classify the behavior of rigid bodies during earthquakes. Next, equations are derived for each motion. Finally, the different motions are combined. The following are four representative and basic motions of rigid bodies during earthquakes. (A) Rest : State of being before earthquakes occur, there are no external forces acting on the rigid body. (B) Moving with the ground : Contrary to (A), in this state the rigid body is moving with the ground, there is no rotation and sliding of the rigid body to the motion of the ground, as the rigid body and the ground is in the same motion. (C) Sliding (Sway motion) : Sliding on the ground horizontally, and from the state of stopping or moving with the ground the rigid bodies accelerated by earthquake and when the force of inertia of mass exceeds the maximum static friction force and the balance of forces is broken and rigid body moved horizontally on the ground. (D) Rocking vibration : This motion shows the rotation of the rigid body on both bottom ends alternately, both ends of the bottom of the rigid body as center of rotation.

3. FORMULATION OF SEISMIC BEHAVIOR OF RIGID BODIES

This chapter shows the rigid body model used in this study. The frictional forces which are necessary to treat the motion of the moving with the ground and sliding (sway motion) are explained and the basic formulation of the seismic behavior of a rigid body above-mentioned in *2.1* however is shown (A) Stopping is omitted as it is unnecessary to formulate.

3.1 Rigid body model

In this study the rigid body model is treated as shown in Figure 3.1. And it is assumed that the rigid body is on the rigid ground or floor. Here, symbols in the figure are as follows.

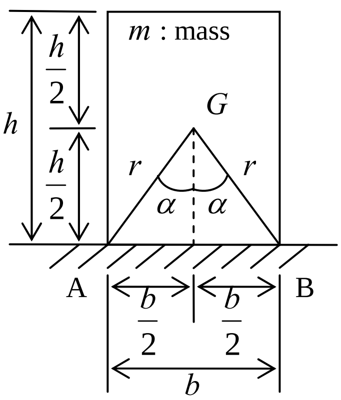

Fig. 3.1 Rigid body model

m : mass
h : height
b : width
G : the center of gravity of rigid body

3.2 Frictional forces

In this study the frictional force between the rigid body and the ground or floor is important in the motion of moving with the ground or floor and sliding (sway motion). Hence the frictional force is explained below. In this study Amonton-Coulomb's frictional force law is used. Here Amonton-Coulomb's frictional force law is as follows.

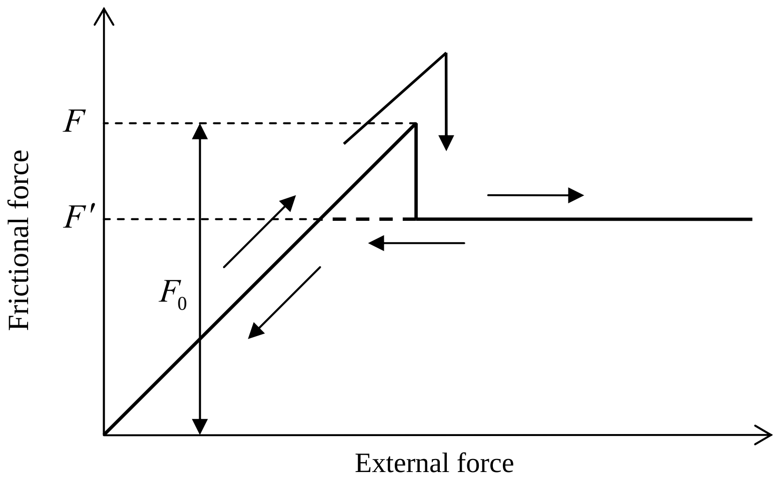

Figure 3.2 Relation between frictional force and external force

(1)Frictional force is in proportion to normal force.
(2)Frictional force is independent of contact area.
(3)Static frictional force is greater than dynamic frictional force.
(4)Dynamic frictional force is constant and independent from velocity.
In (3), above, dynamic frictional force is the force a massive body resists in the reverse direction. And the static frictional force is the force a massive body is necessary to move. On exceeding the limited value of the frictional force the massive body will move by the external force, this limited value is called the static maximum frictional force. As dynamic frictional force is F', static frictional force is F_0 (=external force), the maximum static frictional force is F, these are shown as Eqn. 3.1~3.2.

$$F' = \mu' \cdot mg \tag{3.1}$$
$$F = \mu \cdot mg \tag{3.2}$$

Here, μ' and μ are coefficients of dynamic friction and static friction, and g is acceleration of the gravity. And frictional force is always a positive value. The relation between frictional force and external force is shown as Figure 3.2.

3.3 Formulation

The formulation of basic seismic behavior of a rigid body as stated in *2.1* is shown in this section. To formulate the behavior of a rigid body the center of gravity of the rigid body or fixed point on the rigid body is used to derive the equation of motion considering the equilibrium of forces due to horizontal motion and rotational motion.

3.3.1 Moving with the ground

In the case of an earthquake, the center of gravity of a rigid body depends on the seismic acceleration inertia force of mass. The direction of the force is horizontal and acting frictional force in resisting direction. Here, as the rigid body is moving together with the ground, frictional force is the static frictional force. This situation is shown as Figure 3.3. The situation in moving with the ground needed situation division on account of the direction of acceleration of the ground. Hence moving with the ground is shown in Figure 3.3 and equations of motion are Eqn. 3.3 and Eqn. 3.4.

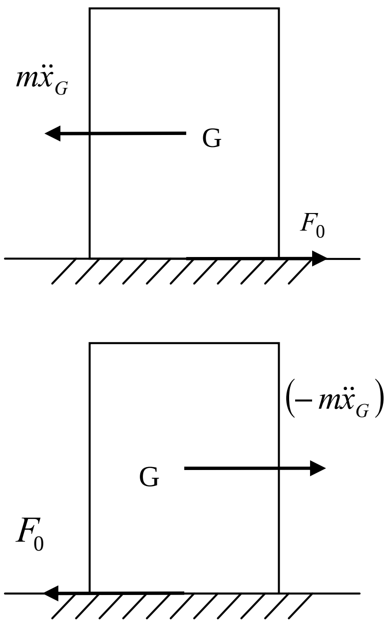

Figure 3.3 Moving with the ground

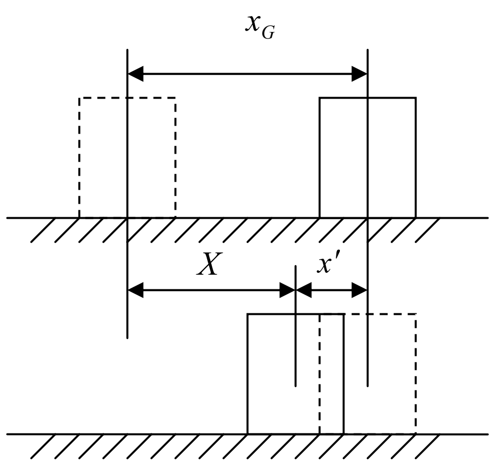

Figure 3.4 Displacement in sliding

1) $\ddot{x}_G > 0$

$$m\ddot{x}_G - F_0 = 0 \tag{3.3}$$

2) $\ddot{x}_G < 0$

$$m\ddot{x}_G + F_0 = 0 \tag{3.4}$$

Here, $\ddot{x}_G$ is acceleration of the ground.

3.3.2 Sliding (Sway motion)

When inertia force $m\ddot{x}_G$ is greater than the maximum static frictional force F, the rigid body is sliding, and dynamic frictional force Eqn.3.1 is applied. If the inertia force due to the ground acceleration were the external force, horizontal constant part of Figure 3.2 shows this situation. If the rigid body starts sliding, displacement comes to result in a special condition. This condition is shown in Figure 3.4. Here symbols are as following.

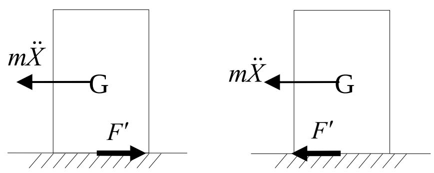

Figure 3.5 Sliding

x_G : ground displacement

x' : sliding displacement

X : relative displacement

Figure3.4 shows a situation that X is the relative displacement between rigid bodies before and after sliding, the rigid body would primarily remain at the original place and then it slide and draws back x' in length. Direction is important when sliding motion is formulated. Hence, Figure 3.5 shows the equations of sliding motion as Eqn.3.5 and Eqn.3.6.

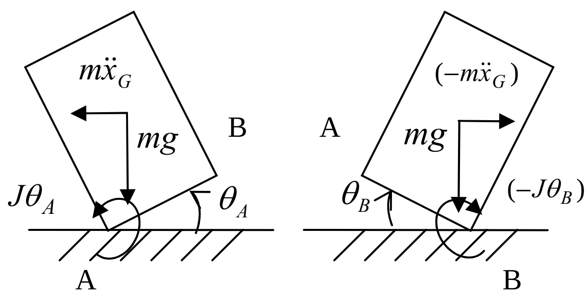

Figure 3.6 Rocking vibration

1) When sliding velocity is positive

$$-m\ddot{X} - F' = 0 \tag{3.5}$$

2) When sliding velocity is negative.

$$-m\ddot{X}+F'=0 \tag{3.6}$$

Here,, relative displacement X is expressed as shown in Figure 3.4.

$$X=x_G+x' \tag{3.7}$$

From Eqn.(3.7), relative velocity $\dot{X}$, relative acceleration $\ddot{X}$ is expressed respectively as follows,

$$\dot{X}=\dot{x}_G+\dot{x}' \tag{3.8}$$

$$\ddot{X}=\ddot{x}_G+\ddot{x}' \tag{3.9}$$

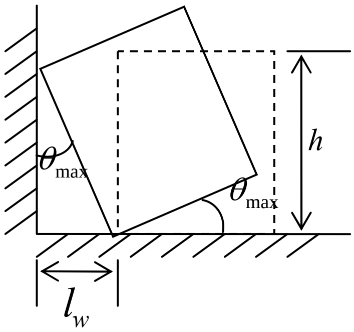

Figure 3.7 Collision of rigid body with wall

There expressed as these, Eqn.3.5 and Eqn.3.6 are also expressed as :

1) When sliding velocity is positive

$$-m(\ddot{x}_G+\ddot{x}')-F'=0 \tag{3.10}$$

2) When sliding velocity is negative

$$-m(\ddot{x}_G+\ddot{x}')+F'=0 \tag{3.11}$$

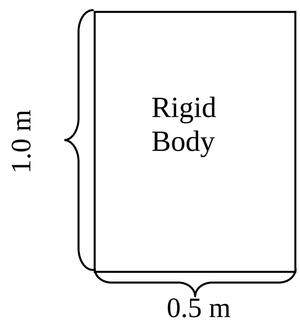

Figure 4.1 Rigid body

3.3.3 Rocking vibration (Figure3.6)

1) Rotation on fulcrum A

$$J\ddot{\theta}_A+mgr\sin(\alpha-\theta_A)=m\ddot{x}_G r\cos(\alpha-\theta_A) \tag{3.12}$$

2) Rotation on fulcrum B

$$J\ddot{\theta}_B+mgr\sin(\alpha-\theta_B)=-m\ddot{x}_G r\cos(\alpha-\theta_B) \tag{3.13}$$

Table 4.1 Conditions

Rigid body	m : 100kg
	h : 1.0 m
	b : 0.5 m

3.3.4 Collision (Figure3.7)

1) Collision with floor (moving the fulcrum)

$$\dot{\theta}'=\frac{J_G+mr^2\cos 2\alpha}{J_G+mr^2}\cdot e\cdot\dot{\theta} \tag{3.14}$$

2) Collision with the wall or other matter

$$\dot{\theta}'=e_w\cdot\dot{\theta} \tag{3.15}$$

Table 4.2 Analytical conditions

Rigid body	*m : 100kg*
	Aspect ratio (b/h) : 0.339
Ground (floor)	*Collision coefficient : 0.6*
	Static frictional coefficient:0.2
	Dynamic frictional coefficient : 0.1
	Rotational static frictional coefficient : 0.4
	Rotational dynamic frictional coefficient : 0.3
Wall	*Collision coefficient :0.6*
Time	*Analysis time : 30 sec*

Turnover occurs when $\theta=90°$. Here, $\theta_A,\dot{\theta}_A,\ddot{\theta}_A,\theta_B,\dot{\theta}_B,\ddot{\theta}_B$:angular displacement, angular velocity, angular acceleration on each fulcrum, J,J_G :rotational inertia momentums around fulcrums and the center of gravity respectively,, $\dot{\theta},\dot{\theta}'$:angular velocity before and after collision, θ_{max} : angle when hitting against wall, e,e_w :collision coefficient against floor and wall, h,b,r,α :variables related to the form of rigid body (Figure 3.1), m :mass, g :gravitational acceleration.

4. MOTION ANALYSIS OF RIGID BODIES

4.1 Analysis model and seismic behavior of a rigid body

In this study, 2-dimensional rigid body model shown in Figure 4.1 is assumed. The floor and wall are also assumed to be rigid. Representative seismic behavior of a rigid body is generally supposed to move with the ground, sway motion, collision and turnover. In this study sway motion, rocking vibration and sway-rocking simultaneous behavior are simulated.

4.2 Influence of frictional coefficient and sway motions

Figure 4.2 shows input acceleration and response of rigid body with conditions shown in Table 4-1 was analyzed under the changing of static frictional coefficient μ and dynamic frictional coefficient μ', Results of the analysis are shown in Figure 4.3. When $\mu=$ 0.4 and $\mu'=$ 0.1 maximum sliding displacement is 5.44cm and when $\mu=$ 0.4 and $\mu'=$ 0.3 maximum sliding displacement is 3.10cm. From these results it can be seen that 0.2 difference of the dynamic frictional coefficient makes 2.34cm difference in sliding displacement. And when $\mu=$ 0.6 and $\mu'=$ 0.1 the maximum sliding displacement is 2.34 cm.

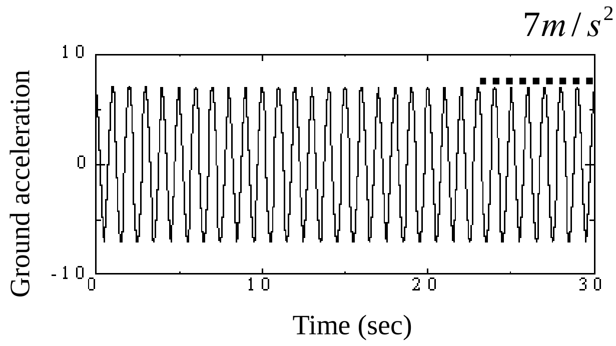

Figure 4.2 Input acceleration

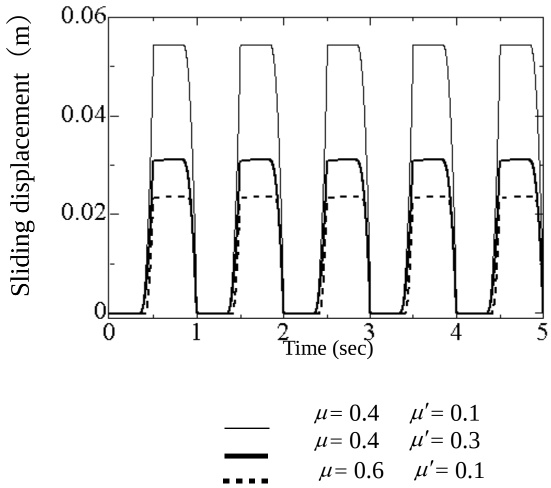

Figure 4.3 Sliding displacement

Therefore, 0.2 difference of maximum frictional coefficient makes 3.10 cm difference of sliding

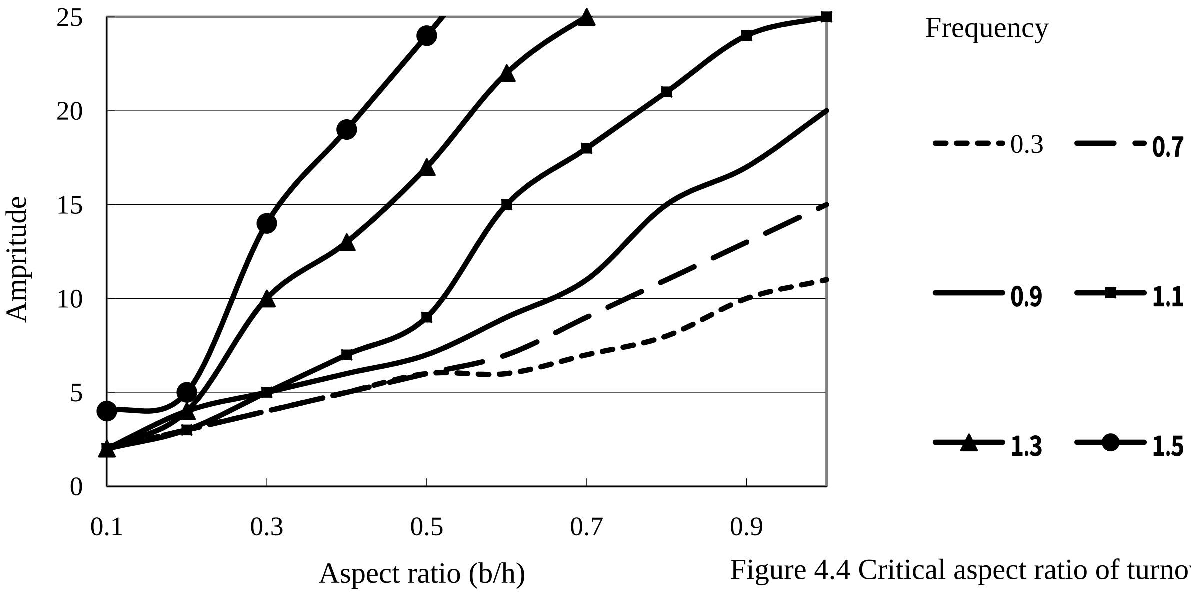

Figure 4.4 Critical aspect ratio of turnover

displacement. From these results it is apparent that difference of static frictional coefficient has some effect on sliding displacement than the difference of dynamic frictional coefficient. Consequently when the rigid body set the frictional sliding stopper is effective for making greater the static frictional coefficient.

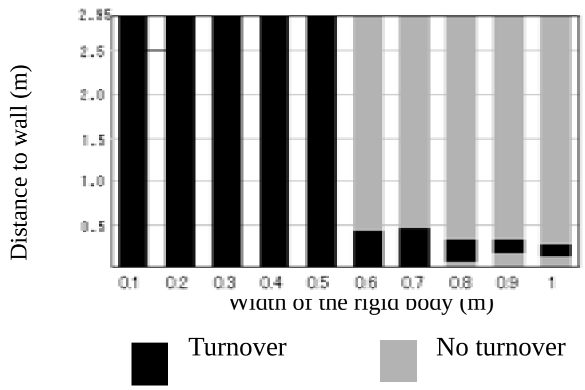

Figure 4.5 Turnover data

4.3 Calculation of critical value for turnover

From the result of rocking analysis under the condition of parameter sinusoidal acceleration, a regression equation of the critical aspect ratio (b/h) against turnover of a rigid body was obtained. Figure 4.4 (vertical axis is amplitude of sinusoidal acceleration depending on frequency and horizontal axis is critical aspect ratio (b/h) when rigid bodies turnover) shows critical line of turnover of rigid body. If amplitude is greater than this line a rigid body will turnover. It is apparent that as greater the aspect ratio (b/h) then the turnover amplitude will be greater. As approximation of Figure 4.4, depends on frequency, linear equation (y=ax+b) is derived. And the regression equation of turnover of the rigid body at critical aspect ratio (b/h) is formulated such as in Eqn.4.1.

$$b/h=(S_1+1.6468S_2-0.8758)/6.8983\ e^{1.227S_2} \tag{4.1}$$

Where, S_1:amplitude (m/s^2), S_2:frequency

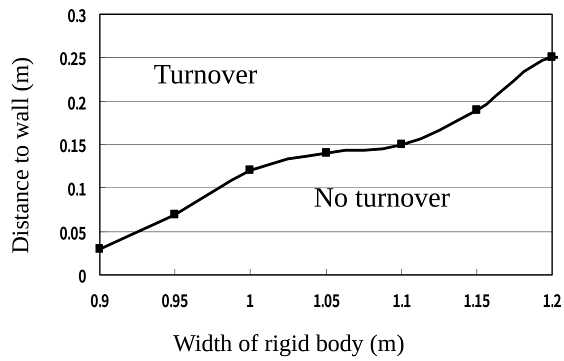

Figure 4.6 Relation between width of rigid body and distance to wall

4.4 Collision analysis of a rigid body with wall for sinusoidal wave

Collision analysis of the rigid body with wall was calculated by sway-rocking analysis. Input acceleration is as shown in Figure 4.2 and conditions are presented in Table 4.2. Aspect ratio (b/h) is constant as shown in Table 4.2. Analysis was carried out by changing the width of the rigid body, and the distance *lw* between the body and wall gradually. The result of the analysis is shown in Figure 4.5. When width is 0.8~1.0*m* .it is interesting to see here that if the distance between the body and wall is even small, the rigid body would turnover. Figure 4.6 shows in the case that the width is greater than 1.0*m* and the distance is smaller than 15% of the width there is no turnover.

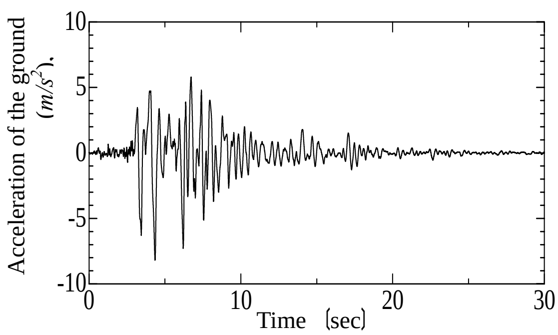

Figure 4.7 Ground acceleration record at 1995 Southern Hyogo Earthquake

4.5 Analysis of collision of rigid body with wall for an earthquake record

Here actual seismic ground acceleration is presented in Figure 4.7 and the results sway-rocking simultaneous analysis for each width is shown in Table 4.3.

6. CONCLUSIONS

To reduce the seismic response of rigid body under strong ground motion, increase of static frictional coefficient is effective by means of frictional sliding stoppers and so on, placed under an article of furniture. Sway-rocking simultaneous behavior was simulated here and a regression equation of critical aspect ratio for turnover of a rigid body was formulated with amplitude and frequency of acceleration. This equation can be used for strong earthquake to estimate whether a body will turnover or not under sinusoidal wave acceleration amplitude. From analytical result for sinusoidal wave it is found that when the aspect ratio is greater than 0.339, the width is greater than 1.0*m* and the distance is smaller than 15% of the width, there will be no turnover of a rigid body.

Table 4.3 Analytical results of the Sway-Rocking

Width(m)	Results	
0.1	T (without influence of wall)	
0.2	T (distance is not more than 0.50m)	
0.3	T (distance is not more than 0.77m)	
0.4	T (distance is between 0.02~0.85m)	
0.5	T (distance is between 0.05~0.93m)	
0.6	N	
0.7	N	
0.8	N	
0.9	N	
1.0	N	
Turnover		T
No turnover		N

It is important that for evoking the general public's awareness of earthquake-proofing measures related to impeding furniture from sliding and falling over, advance preparations may prevent from suffering calamity by using several kinds of frictional sliding stoppers and so on, and in order to avoid interference with the wall near the furniture keeping a certain distance between the wall and a body is preferable. Wider furniture reduces the probability of getting injured during strong earthquakes.

In this study, only horizontal acceleration was applied as seismic force. In future research, vertical acceleration must also be applied. In addition, in this study it is assumed that rigid body is symmetrical in shape and mass distribution is uniformly therefore the center of gravity and the centroid of rigid bodies agree precisely. In future research, practical change of mass distribution is necessary in order to simulate real-life conditions.

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