SHAKING TABLE TEST ON INDOOR SEISMIC SAFETY OF HIGHRISE BUILDINGS (PART II. MOVEMENT OF FURNITURE UNDER LONG PERIOD EARTHQUAKE GROUND MOTION)

T. SAITO[1], T. TAKAHASHI[2], R. HASEGAWA[3], K. MORITA[4], T. AZUHATA[5] and K. NOGUCHI[6]

[1] *Chief Research Engineer, Building Research Institute, Tsukuba, Japan, Email: tsaito@kenken.go.jp*
[2] *Professor, Faculty of Engineering, Chiba University, Chiba, Japan*
[3] *Graduate Student, Faculty of Engineering, Chiba University, Chiba, Japan*
[4] *Senior Research Engineer, Building Research Institute, Tsukuba, Japan*
[5] *Head, National Institute for Land and Infrastructure Management, Tsukuba, Japan*
[6] *Researcher , National Institute for Land and Infrastructure Management, Tsukuba, Japan*

ABSTRACT :

Long period components of earthquake ground motions may amplify the response of large scale structures with long natural periods such as high-rise buildings, long-span bridges and oil storage tanks. From the computer simulation, the maximum displacement at the top of a 40 story high-rise building in Tokyo exceeds 1.5 m under a long period earthquake ground motion caused by Tokai, Tonankai and Nankai Earthquakes, and the shaking of the building continues several minutes. To examine the safety of the living space in high-rise buildings, a new shaking table called “BRI Large Stroke Shaking Table” was developed in the Building Research Institute. Using this shaking table, movement of furniture inside the rooms of high-rise buildings was examined to find the safety criteria for the design of high-rise buildings.

KEYWORDS: high-rise buildings, long period earthquake ground motion, shaking table

1. INTRODUCTION

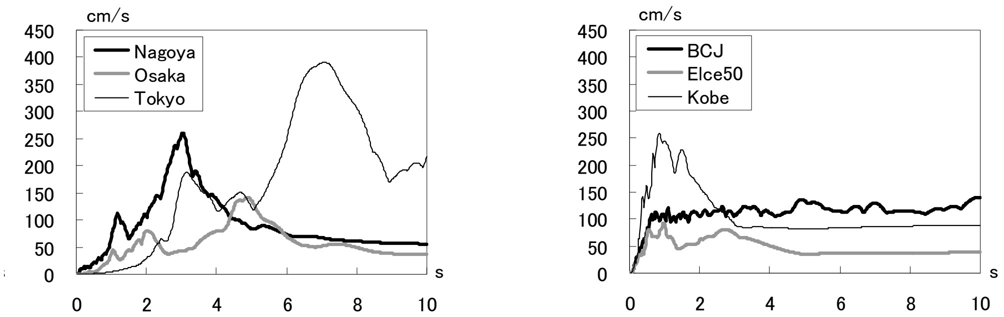
The Tokachi-oki Earthquake on 26 September, 2003 caused severe damage to the oil storage tanks in the city of Tomakomai, Japan, 220 km far from the epicenter. The cause of damage was the resonance phenomena between the sloshing period of the oil storage tanks which is around 7 sec. and the long period component of the ground motions generated in the deep sedimentary plain around Tomakomai area. The big cities in Japan such as Tokyo, Osaka and Nagoya are also located on the deep sedimentary plains, and it is anticipated that the earthquake ground motions having 2-10 sec. dominant periods, so called “Long-Period Earthquake Ground Motion”, will be generated in the case of a massive earthquake with a magnitude level equal to that of the Tokai, Tonankai, or Nankai Earthquakes. The long period components of the earthquake affects not only the oil storage tanks but also the other large structures with long natural periods such as high-rise buildings and long-span bridges, and the responses of those structures may become extraordinary large.

In March 2006, the Building Research Institute (BRI) in collaboration with Chiba University, the National Research Institute for Earth Science and Disaster Prevention (NIED), and the National Institute for Land and Infrastructure Management (NILIM) developed the “BRI Large Stroke Shaking Table”, which is capable of reproducing shaking with a maximum amplitude larger than 2 m, in order to conduct experiments on simulated shaking at the top story of a high-rise building. The objective is to examine the effects of large-amplitude and long-period shaking on human evacuation behavior and movement of furniture in the living space of high-rise buildings. If particularly large-amplitude shaking continues for a long time, it is predicted that furniture on casters, which have a small friction factor, will move around within the living space. This research paper reports the results of our experiment and analysis on the displacement of furniture on casters when long-period, large-amplitude shaking is reproduced on the large-stroke shaking table.

2. RESPONSE OF HIGH-RISE BUILDINGS UNDER LONG PERIOD GROUND MOTIONS

2.1. Long Period Earthquake Ground Motions

The amplification of earthquake wave in the soft and thick sedimentary strata is the main cause of the long period ground motion. Tokyo is located on the Kanto Plain with 3-6 km sedimentary strata and the components of 7-10 sec. period of earthquake ground motions become dominant. Osaka and Nagoya are located on the Osaka plain and Nobi plain, respectively. Both plains have the sedimentary strata with more than 3 km thickness and the components of 3-5 sec. period of earthquake ground motions become dominant. Many seismologists conducted simulation of long period earthquake ground motions at Tokyo, Osaka and Nagoya in the event of massive earthquakes, such as Tokai, Tonankai and Nankai Earthquakes. The intensities of some simulated waves are much larger than the level of earthquake ground motion speculated in the building design code in Japan. Figure 1 shows the velocity response spectrum with 5 % damping factor (h = 0.05) of the long period earthquake ground motions simulated in Tokyo, Osaka and Nagoya, comparing with the spectrum of the design earthquake ground motion (BCJ, Elce50) and that of the observed record (Kobe). Prominent components are observed near the 3 sec. for the Nagoya wave, 5 sec. for the Osaka wave, and 7 sec. for the Tokyo wave.



(a) Long period earthquake ground motions (b) Design and observed waves

Figure 1 Velocity response spectrum of earthquake ground motions (with 5% damping factor)

Table 1 Description of earthquake ground motions

	Name	Description
1	Nagoya	simulated for Tokai and Tonakai Earthquake *1
2	Osaka	simulated for Nankai Earthquake*1
3	Tokyo	simulated for Tokai, Tonankai and Nankai Earthquake*2
4	BCJ	Design earthquake by Building Center of Japan*1
5	Elce50	1940 El Centro NS-wave standardized to be max. 50cm/sec*1
6	Kobe	Kobe J.M.A NS-wave at 1995 Hyogo-ken Nanbu Earthquake*1

*1 Architectural Institute of Japan (2007), *2 Furumura et. al. (2004)

2.2. Response of High-Rise Buildings

The response on the top-story floor of a 40-story high-rise reinforced concrete condominium building was analyzed during long-period earthquake ground motions at the city center of Tokyo. The building was designed to be a common type of high-rise residential buildings in Japan under the following conditions: 128.8 m building height, 3.14 sec. primary natural period, 3% damping constant and initial rigidity proportional damping matrix. The simulation model of long-period earthquake ground motions was Tokyo wave in Table 1 assuming that the Tokai, Tonankai, and Nankai earthquakes occur simultaneously. The space-frame response analysis program “STERA 3D” developed at the Building Research Institute was used for the analysis. Figure 3 shows the absolute displacement response on the ground, 10-, 20-, 30-, and 40-story floors to the given long-period earthquake ground motion. At higher stories, the shaking level increased, reaching 153 cm in amplitude at the top story 103 sec. after the earthquake. The interlayer distortion angle (a shear component) reached 1/85 in the intermediate story with the maximum member-edge plasticity factor of 3.9.

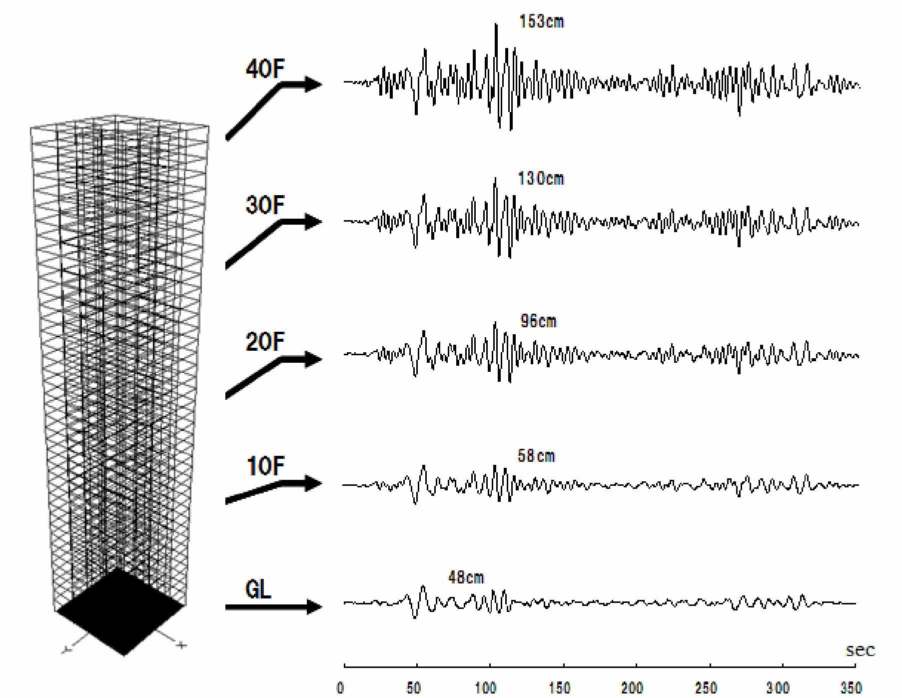


Figure 2 Response of a high-rise building under long period earthquake ground motion

3. DEVELOPMENT OF BRI LARGE STROKE SHAKING TABLE

In March 2006, a new shaking table called "BRI Large Stroke Shaking Table" was developed and constructed in the large structure testing laboratory in the Building Research Institute, Japan (Saito, et. al., 2006). Our large-stroke shaking table was designed based on the concept that the movement of a dynamic actuator is amplified 13 fold by means of a displacement amplification mechanism composed of a series of six moving pulleys and one fixed pulley to transfer the amplified movement to the table via a wire. The specifications of the dynamic actuator are: ±500 kN load output, ±30 cm stroke, and ±30 cm/s velocity. The rack is capable of moving along a 10 m long rail under the conditions of approx. 2.5 m maximum displacement (depending on rail length) and approx. 1.5 G maximum acceleration with no load. A wooden table approx. 4.7 m wide and approx. 2.6 m deep is mounted on the rack and a 0.6-m-high handrail is attached around three of the sides to ensure safety. Walls and a ceiling are partially constructed on the table. Figures 3 and 4 show panoramic views of the shaking table.

Figure 3 BRI large stroke shaking table

Figure 4 Set up of wooden table with furniture

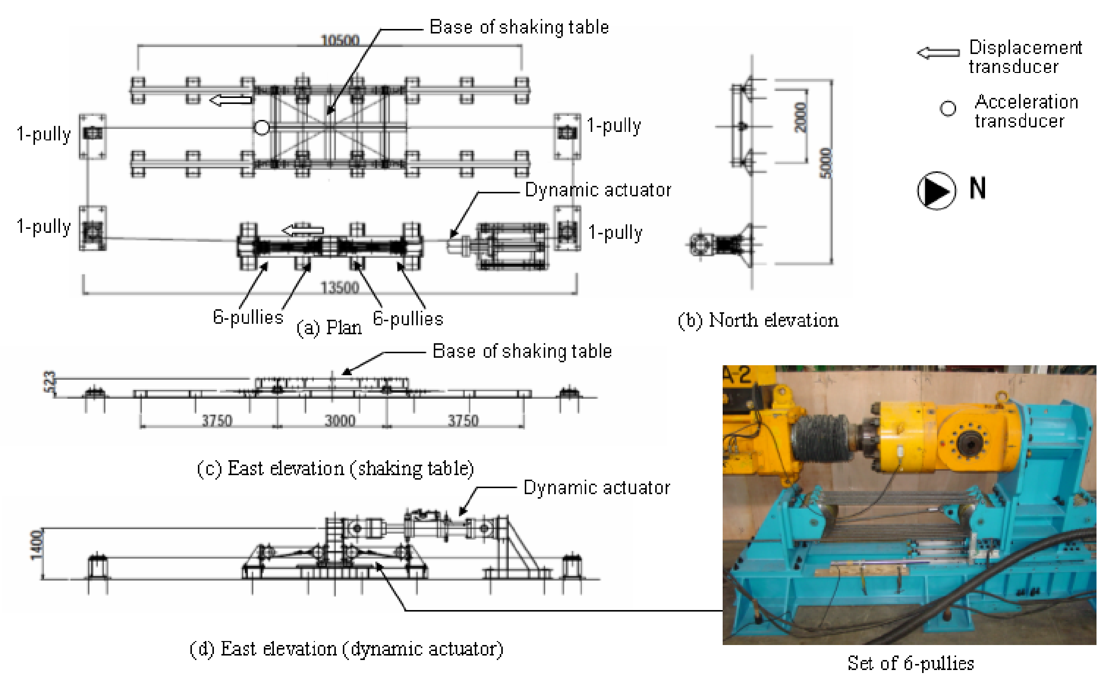


Figure 5 Plan and elevations of shaking table

Figure 5 shows the plan and elevation of the shaking table. Sensors are installed for measuring displacement of the dynamic actuator, displacement and acceleration of the shaking table. Using this shaking table, the displacement response of the top floor of a 40 story reinforced concrete high-rise building shown in Figure 2 was simulated. Figure 6 shows the comparisons between the target response and the response of the shaking table for acceleration and displacement. The acceleration response of the shaking table contains high frequency component which makes the response higher than the target one. As for the displacement response, the response of the shaking table shows relatively good agreement with the target one. Figure 7 shows the Fourier spectrum of acceleration data of target response and the response of the shaking table. The spectrum of the response of the shaking table has the peak in the frequency around 2Hz which corresponds to the first natural period of the wire elongation vibration.

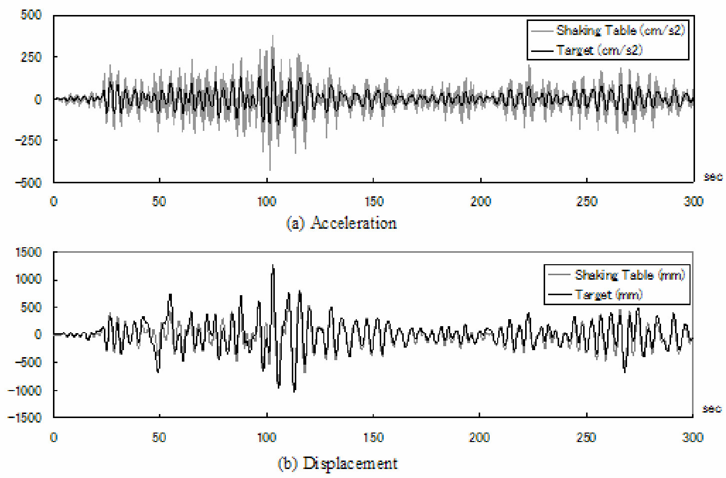


Figure 6 Simulation of high-rise building response

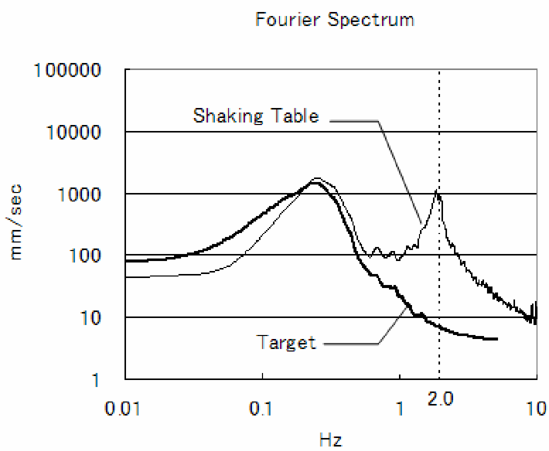


Figure 7 Fourier spectrums of acceleration data

4. SAFETY ASSESSMENT OF LIVING SPACE IN HIGH-RISE BUILDINGS

4.1. Shaking Table Test of Furniture on casters

The first step of the experiment was to reproduce the displacement of furniture at the top story of a high-rise building by inducing long-period earthquake ground motion on the shaking table to examine the displacement of the furniture on casters and to make a model of the movement of the furniture using a single-mass system having elastic/perfectly-plastic restoring force characteristics based on the results of the experiment.

4.1.1 Furniture used in the experiment

Three types of furniture on casters were used in the experiment, as shown in Figure 8. Table 1 lists the friction factors of the furniture measured by a spring balance as shown in Figure 9. The values for friction factors were calculated by dividing the values measured using the balance before and during movement by the weight of the furniture. An average of values obtained from two or three measurements was taken for each value in the table. The entire floor was boarded up. During measurement, a motion capture device was used to record the movement of the pointer attached to the top of each piece of furniture and calculate its coordinate in three dimension space as shown in Figure 10.

(a) TV set (b) Steel rack (3) Chair

Figure 8 Test subjects of furniture with casters

Figure 9 Measurement of friction factor

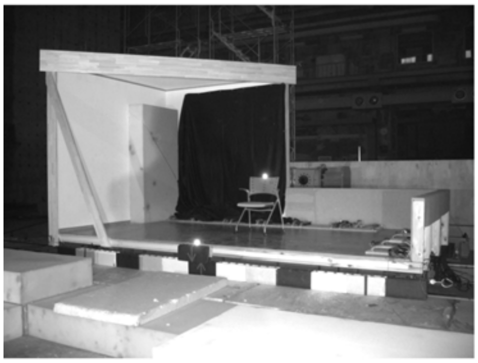


Figure 10 Scene of experiment

Table 2 Characteristics of the test subjects

	Weight	Static friction (factor)	Dynamic friction (factor)	Input Amplification
TV set	500 N	45 N (0.09)	34 N (0.07)	1.0
Steel rack	360 N	15 N (0.04)	10 N (0.03)	0.7
Chair	65 N	2 N (0.03)	1.2 N (0.02)	0.7

4.1.2 Analysis model of furniture on casters

The model for the furniture on casters was made using a single-mass system having elastic/perfectly-plastic restoring force characteristics as shown in Figure 11. The initial rigidity was defined so as to achieve 50 Hz of natural vibration frequency, reproducing its rigid state. The ratio of yield resistance to weight of the furniture was represented by friction factor μ. In the analysis, the readings taken from an accelerator mounted on the shaking table were used to calculate the displacement with a time interval set to a sufficiently small value, 1/1,000,000 sec. using numerical integration by average acceleration method.

4.1.3 Experimental and analytical results

The vibration waveform applied is identical to that of the response on the top-story floor of a 40-story high-rise reinforced concrete condominium building as presented in Figure 6. When the absolute displacement response waveform was applied as a vibration waveform to measure displacement, the chair and server, which have small friction factors, moved too far and collided against the walls. To avoid this problem, another 0.7-fold waveform was applied.

In the experiment, shaking including a principal motion was applied for approx. 160 sec. However, when the furniture collided against the walls of the shaking table or when the measurement points (pointers) of the captured motions were hidden, the measured data taken up to that time point was used. Figure 12 shows the displacement of the furniture relative to the shaking table. The experimental results are represented by a solid line and the analytical results in the single-mass system are indicated by a gray line. In the analysis, the damping constant for the single-mass system was assumed to be 0 (zero) and friction factors with suitable correspondence between the analytical and experimental results were selected from Table 1 (0.03 for a chair, 0.07 for a TV stand, and 0.04 for a steel rack). Profound inconsistencies were observed between the analytical and experimental results. This suggests that factors such as eccentric rotation of the furniture due to shifting of the gravity center, the adverse effects of undulations of the shaking table floor, and possible deformation of furniture not rigidly constructed were not taken into account in the simple analytical model. However, since this analytical model might be useful for grasping the big picture, it was used in the following parametric analysis.

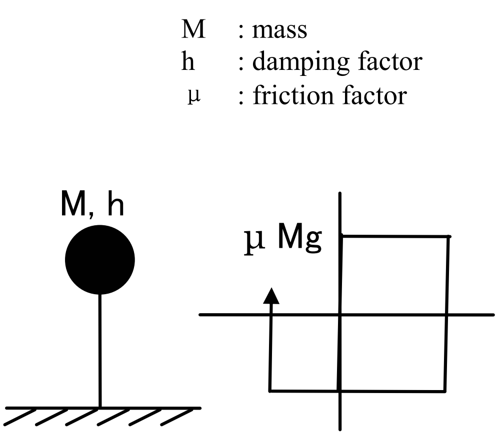


Figure 11 Analysis model of furniture on casters

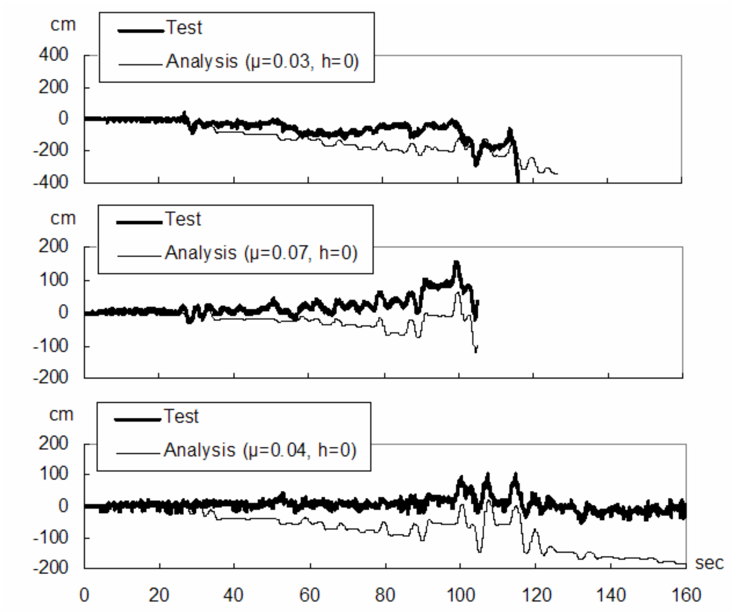


Figure 12 Movement of furniture on casters

4.2. Displacement of Furniture in the living space of a high-rise building

The displacement of furniture in the living space of a high-rise building during an earthquake was evaluated using a single-mass-system model with 0 (zero) damping constant for the furniture on casters with the friction factor μ for the casters ranging from 0.02 to 0.1. Twelve types of earthquake waves were applied: six types of waves (assumed to be the responses on the first floor) listed in Table 1 and another six types of waves (assumed to be the responses to the applied earthquake waves on the top-story floor of a 40-story high-rise building). The values obtained using the simple evaluation formula for calculating the displacement of furniture proposed by Kaneko et al. (1999) were used for comparison. The simple evaluation formula has been proposed based on the parametric analysis of applied transient vibrations. The average displacement is calculated using the following formula:

$$D = 0.02\mu^{-0.3} F_e^{-0.5} (V - V_0)^{1.56} \tag{1}$$

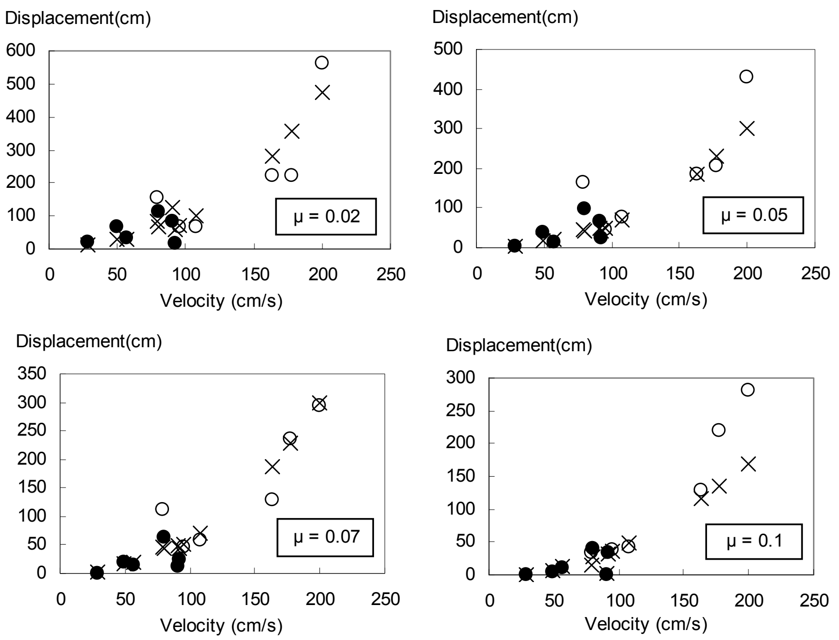
where μ is the friction factor, *Fe* is the equivalent frequency of the applied wave, *V* is the max. velocity of the applied wave, and V_0 (=V_{max}) is the initial velocity when the furniture moves. The equivalent frequency *Fe*, was obtained from the max. acceleration A_{max} and the max. velocity V_{max} of the applied wave using the following formula:

$$F_e = A_{max} / (2\pi V_{max}) \tag{2}$$

The initial velocity V_0 was obtained from the acceleration μg (g is gravity acceleration) and the equivalent frequency *Fe* while the furniture is under the yield condition using the following formula:

$$V_0 = \mu g / (2\pi F_e) \tag{3}$$

Figure 8 shows plots illustrating the correspondence between two parameters: max. velocity of the applied wave and displacement of furniture for each of four cases with the friction factor μ set to 0.02, 0.05, 0.07, or 0.1. In the figure, ● indicates the displacement of furniture on the first-story floor and ○ indicates the displacement of furniture on the top-story floor. × indicates the value obtained using the simple evaluation formula. As seen in the figure, at smaller friction factors, the displacement of the furniture increases, and the max. velocity of the response as well as the displacement of the furniture are larger on the top-story floor than on the first-story floor. The results obtained by the simple evaluation formula coincide relatively well with the analytical results.



(● 1st floor , ○ 40th floor, × Equation (1))
Figure 13 Relationship between the max. velocity of floor and displacement of furniture on casters

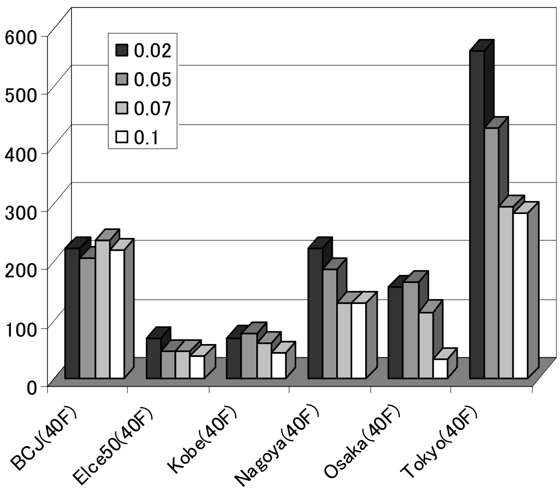


Figure 14 Effect of friction factor to the displacement of furniture

Figure 14 shows the correspondence between the friction factors and the displacement of furniture in terms of the response on the top-story floor. When long-term earthquake ground motions (Nagoya (40F), Osaka (40F), Tokyo (40F)) occur, the displacement of furniture on the top-story floor tends to decrease at higher friction factors. Thus, it is expected that increasing the friction factor for the furniture may reduce the displacement during long-period earthquake ground motions significantly.

5. CONCLUSIONS

In this experiment, the displacement of furniture on casters was measured using a motion capture device on our "BRI Large Stroke Shaking Table" installed at the Building Research Institute. The objective of the experiment was to grasp the movement of the furniture during long-period, large-stroke earthquake ground motion, for which empirical data could not previously be obtained, on an actual large-stroke shaking table. Shaking at the top-story of a 40-story high-rise building was reproduced on the shaking table in order to measure the displacement of the furniture on casters. The results show that the displacement of the furniture may be evaluated based on analysis using the model in the single elastic/perfectly-plastic mass system. Moreover, the analysis model was used to conduct parametric analysis using varied ground-shaking motions and friction factor parameters in order to analyze their effect on the displacement of furniture. The results imply that the furniture moves within a wider area of the living space at upper stories compared to that at lower stories and that the displacement may reach several meters. Also, the displacement of the furniture during long-period earthquake ground motion may be reduced by increasing the friction factor. This shows us the need for countermeasures, for example, a movement inhibiting device attached to the furniture, especially large-size furniture.

REFERENCES

Architectural Institute of Japan (2007). Structural Response and Performance for Long Period Seismic Ground Motions, published by Architectural Institute of Japan.

Kaneko, M., Hayashi, Y., Tamura, K. (1999). Evaluation of Sliding Displacement of Furniture during Earthquake - By using Revised Formula to Estimate Sliding Displacement of Furniture -, Technical Papers of Annual Meeting of Architectural Institute of Japan, B-II, pp.537-538.

Furumura, T., Hayakawa, T., Nakamura, M., Koketsu, K., and Baba, T. (2004). Development of long-period ground motions from earthquakes within the Nankai Trough, Japan: Observations and computer simulation of the 1944 Tonankai (Mw8.1) and 2004 SE Off-Kii Peninsula (Mw7.4) earthquakes, *Pure and Applied Geophysics*.

Saito, T., Takahashi, T., Azuhata, T., Noguchi, K. and Minowa, C. (2006). Development of BRI Large Stroke Shaking Table for Simulating Earthquake Response of Long Period Buildings, *Proceedings of the 12th Japan Earthquake Engineering Symposium* (in Japanese)