SEISMIC BEHAVIOR OF OFFICE FURNITURE IN HIGH-RISE BUILDINGS DUE TO LONG-PERIOD GROUND MOTIONS

T. Masatsuki[1], S. Midorikawa[2], M. Ohori[3], H. Miura[4], and H. Kitamura[5]

[1] *Kozo Keikaku Engineering Inc. (formerly Tokyo Institute of Technology), Tokyo, Japan*
[2] *Professor, Dept. of Built Environment, Tokyo Institute of Technology, Yokohama, Japan*
[3] *Senior Researcher, JAMSTEC (formerly Tokyo Institute of Technology), Yokohama, Japan*
[4] *Assistant Professor, Dept. of Built Environment, Tokyo Institute of Technology, Yokohama, Japan*
[5] *Professor, Dept. of Architecture, Tokyo University of Science, Noda, Japan*
Email: toshi-masatsuki@kke.co.jp, smidorik@enveng.titech.ac.jp, ohorim@jamstec.go.jp, hmiura@enveng.titech.ac.jp, kita-h@rs.noda.tus.ac.jp

ABSTRACT :

This paper examines seismic behavior of office furniture in an upper floor of high-rise buildings due to long-period ground motions by shaking table tests and simulations. The results of the tests indicate that a chair on casters and a copy machine move in the low acceleration level of 150cm/s^2, and that the desk does not move in the high acceleration level of 460cm/s^2, but the desk with a chair assumed as a man in a sitting position who clings to the desk during shaking moves in the lower acceleration level of 250cm/s^2. The behavior of the furniture in the shaking table tests is well reproduced by the rigid body simulation. Finally, the behavior of a number of furniture in an upper floor of high-rise buildings is simulated for long-period ground motions at Tokyo, Nagoya and Osaka during the anticipated giant earthquakes. The simulation results show that the furniture continues to move around and collide against each other. The behavior of the furniture can cause fear and injury to people in the floor, and make the evacuation action difficult.

KEYWORDS: long-period motion, high-rise building, office furniture, shaking table test, rigid body simulation

1. INTRODUCTION

The metropolitan areas in Japan are located on large basins where long-period ground motion is easily excited by a large shallow earthquake. In the metropolitan areas, many high-rise buildings have been built up and may vibrate largely by the long-period motion. For example, in Tokyo, more than 200 buildings higher than 100 m have been constructed as shown in Fig. 1. The vibration periods of the building range 2 to 6 second (See Fig. 2). Some of the high-rise office buildings in Tokyo have about 10,000 occupants and high potential for seismic indoor risk. Therefore, seismic behavior of furniture in the buildings needs to be studied in order to evaluate risk of injuries and confusions by overturning or displacement of furniture. The overturning of furniture during earthquakes has been examined (e.g. Ishiyama, 1982). The behavior due to long-period motion, however, has not been well discussed. In this paper, in order to evaluate seismic risk in an office space, the seismic behavior of office furniture is examined in an upper floor of high-rise buildings due to long-period motions by means of shaking table tests and simulations.

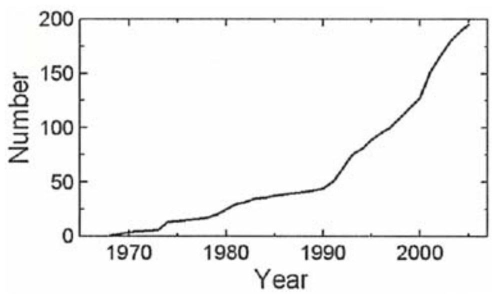


Figure 1 Number of high-rise buildings in Tokyo

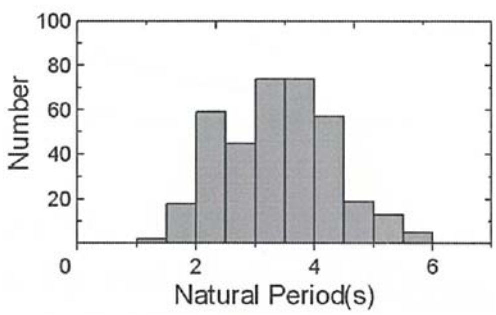


Figure 2 Periods of high-rise buildings in Tokyo

2. SHAKING TABLE TESTS

2.1. Outline of Shaking Table Tests

In order to study fundamental characteristics of behavior of furniture, shaking table tests are conducted using a large-stroke shaking table with maximum displacement of 1m. The maximum acceleration and velocity are 1000 cm/s^2 and 150 cm/s, respectively. The shaking directions are two horizontal. The size of the table is 3.2 m by 2.5 m. The payload is one ton. The appearance of the table is shown in Fig. 3.

The floor materials used in the tests are a plywood and a tile carpet. The test models are a simple wood box, a cabinet, a desk, a caster chair, a box on casters, and a desk with a chair. The box on four casters is assumed as a copy machine. The desk with a chair is assumed as a man in a sitting position who clings to desk during shaking. The specifications of the models are shown in Table 1.

The shaking is given to one horizontal direction with sinusoidal waves. The cabinet, the desk, the desk with chair are shaken for both longitudinal and transverse direction. The tests are conducted for 12 cases of shaking with acceleration of 90 to 460 cm/s^2 and period of 2 to 5 second, as shown in Table 2. The acceleration levels of shaking case for the test models with casters is relatively low because the test models with casters would easily move in low acceleration level case. The acceleration and the relative displacement of the models are measured by sensors as shown in Fig. 4.

2.2. Result of Shaking Table Tests

The results of the tests are summarized in Table 3. In case that the floor material is the tile carpet, the simple box and the cabinet shaken in the longitudinal direction moves in the acceleration level case of 310 cm/s^2 (Case A5). The cabinet shaken in the transverse direction overturns in the acceleration level case of 250 cm/s^2 (Case A4). The caster chair and the box on casters move in the low acceleration level case of 150 cm/s^2 (Cases A1 and B4). While the desk does not move even in the highest acceleration level case of 460 cm/s^2 (Case A8), the desk with chair easily moves in the lower acceleration level case of 250 cm/s^2 (Case A4). This indicates that the desk begins to move in the lower acceleration level case if a man in a sitting position clings to the desk during shaking.

The behavior of the furniture on the plywood is compared with that on the tile carpet. Significant difference of the behavior for the simple box, the caster chair, and the box on caster is not observed between on the plywood and the tile carpet. However, the cabinet, the desk, and the desk with chair on the tile carpet easily move at lower acceleration level than on the plywood.

Figure 3 Appearance of shaking table

Table 1 Specifications of models

Model	Size(cm)	Weight(kg)
Simple box	120x60x60	30
Cabinet	45x90x110	130
Desk	120x70x70	67
Caster chair with no weight	60x60x70	12
Caster chair with weight(50kg)	60x60x70	60
Box on casters	60x60x120	110
Desk with chair	120x100x70	127

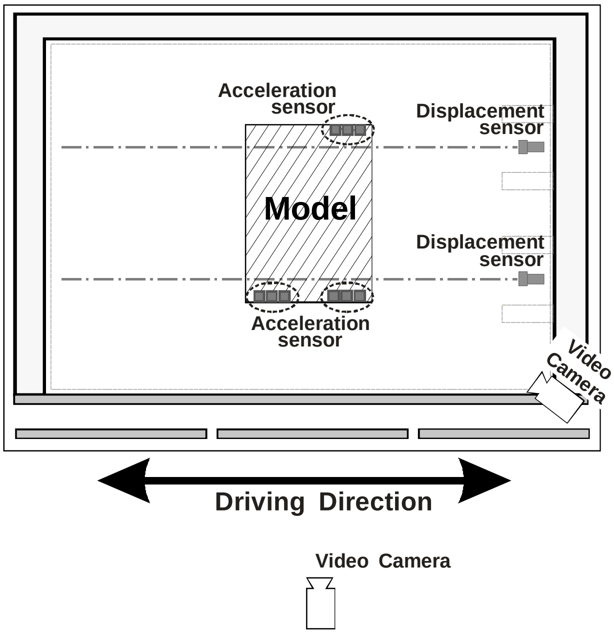


Figure 4 Location of sensors

Table 2 Shaking cases

Without caster

Case	Period(s)	Acc.(cm/s^2)	Vel.(cm/s)	Dis.(cm)
A1	5	157.9	125.7	100
A2	2	197.4	62.8	20
A3	3	219.3	104.7	50
A4	2.5	252.7	100.5	40
A5	3	311.4	148.7	71
A6	2.5	372.7	125.7	59
A7	2	394.8	125.7	40
A8	2	463.8	147.7	47

With caster

Case	Period(s)	Acc.(cm/s^2)	Vel.(cm/s)	Dis.(cm)
B1	2.5	126.3	50.3	20
B2	3	87.7	41.9	20
B3	3	131.6	62.9	30
B4	5	142.1	113.0	90

Table 3 Results of shaking table tests

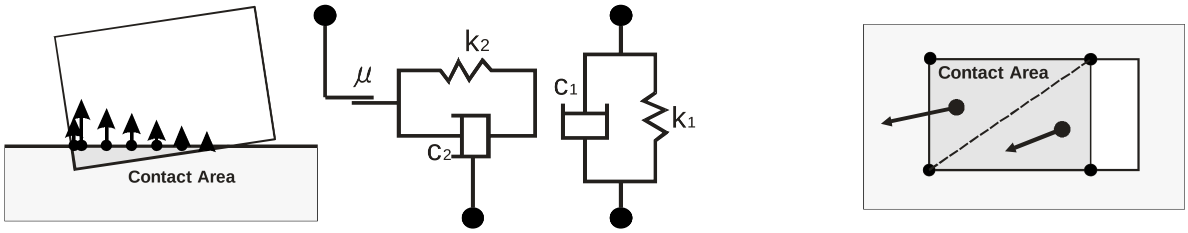
C: Floor material is tile carpet, W: Floor material is plywood, ○: Moved, ×: Not moved, △: Overturned, -: Not tested

Case	Simple box		Cabinet				Desk				Caster chair with no weight		Caster chair with weight		Box on casters		Desk with chair			
			Longitudinal direction		Transverse direction		Longitudinal direction		Transverse direction								Longitudinal direction		Transverse direction	
	C	W	C	W	C	W	C	W	C	W	C	W	C	W	C	W	C	W	C	W
A1	×	×	×	×	-	-	×	×	×	×	○	-	○	-	○	○	×	×	×	×
A2	×	×	×	×	-	-	×	×	×	×	-	-	-	-	○	○	×	○	×	○
A3	×	×	×	×	×	-	×	×	×	×	-	-	-	-	○	○	×	○	×	○
A4	×	×	×	×	△	-	×	×	×	×	-	-	-	-	○	○	○	○	×	○
A5	○	○	○	×	△	×	×	×	×	○	-	-	-	-	○	○	○	○	○	○
A6	○	○	○	×	-	△	×	○	×	○	-	-	-	-	-	-	○	○	○	○
A7	○	○	○	○	-	△	×	○	×	○	-	-	-	-	-	-	○	○	○	○
A8	○	○	○	○	-	-	×	○	×	○	-	-	-	-	-	-	○	○	○	○
B1	-	-	-	-	-	-	-	-	-	-	○	○	○	○	-	×	-	-	-	-
B2	-	-	-	-	-	-	-	-	-	-	○	○	○	○	-	×	-	-	-	-
B3	-	-	-	-	-	-	-	-	-	-	○	○	○	○	-	×	-	-	-	-
B4	-	-	-	-	-	-	-	-	-	-	○	○	○	○	-	○	-	-	-	-

3. SIMULATION OF SHAKING TABLE TESTS

3.1. Outline of Simulation Method

The behavior of the furniture in the shaking table tests is simulated by a rigid body simulation program called Springhead (Hasegawa and Sato, 2004). In Springhead, contact forces are computed by the penalty method (Erleben *et al.*, 2005). A contact area is divided into several triangle elements, and springs and dampers are set at the triangle element (See Fig. 5). The contact force computed from the triangle elements is used in the simulation. It is possible to quickly and accurately calculate the contact forces such as dynamic and static friction force using Springhead. In the simulation, rolling mechanism such as a caster is also computed. The GJK algorithm (Gilbert *et al.*, 1988) is used for the contact detection of arbitrary convex objects in Springhead. Dynamic parameters of the furniture used in the simulation such as friction, spring and damper coefficients are determined from the comparison of the computed behavior with the behavior in the shaking table tests.



(a) Springs and dampers are set at contact area

(b) A contact area is divided into several triangle elements and the reaction force is computed for each element.

Figures 5　Schematic diagrams of Springhead

3.2. Results of Simulation of Shaking Table Tests

Figure 6 shows the comparison of the shaking table tests and the simulations of the cabinet shaken in the longitudinal direction. The shaking cases are A7 (395 cm/s^2) and A8 (464 cm/s^2), respectively. Solid line and dashed line show the displacement of the test models observed in the shaking table test and the computed displacement, respectively. The computed displacements show good agreement with the observed displacements in the both cases of A7 and A8.

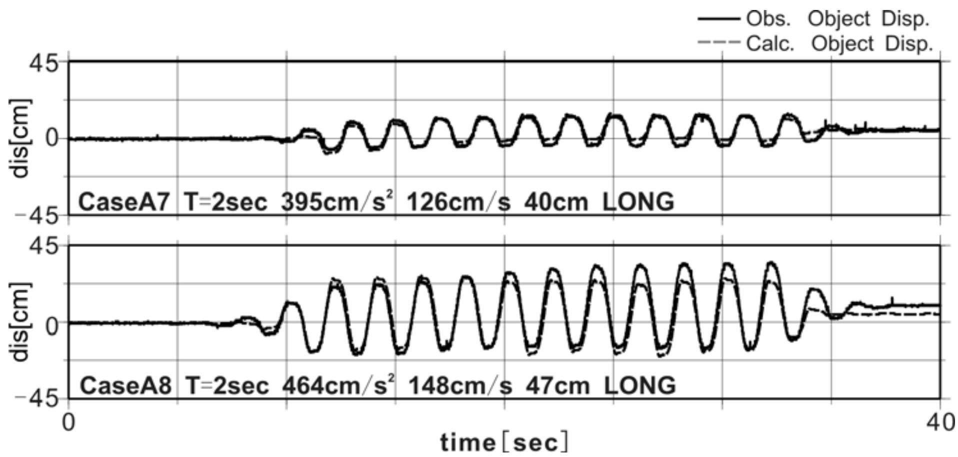


Figure 6　Comparison of shaking table test and simulation(Cabinet : Case A7 and A8)

Figure 7 shows the simulation model of the caster chair. The chair is modeled from four parts such as top of chair, bottom of chair, brace of caster, and wheel of caster. Rotative parts are included in this model. Figure 8 shows the comparison of the shaking table test and the simulation for the caster chair with no weight in the Case A4 (253cm/s^2). The computed displacement also agrees with the observed displacement. The results show that the behavior of test models in the shaking table tests is well reproduced by the simulation.

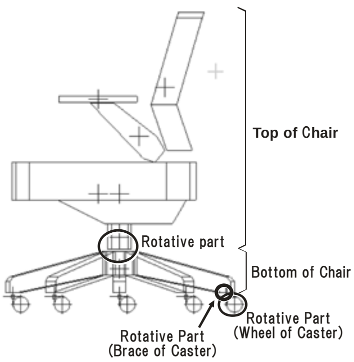


Figure 7　Simulation model of caster chair

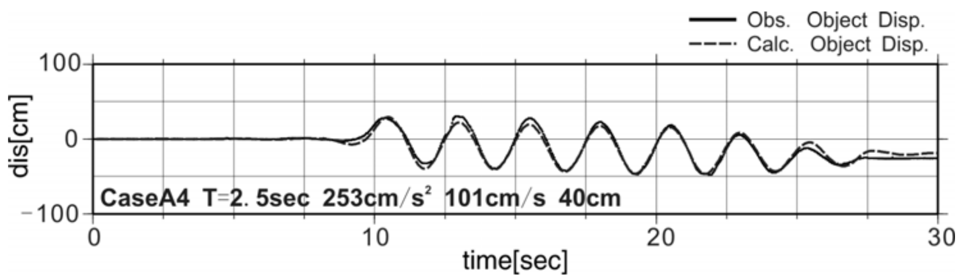


Figure 8　Comparison of shaking table test and simulation

4. SIMULATION OF BEHAVIOR OF FURNITURE AT OFFICE ROOM

4.1. Outline of Simulation

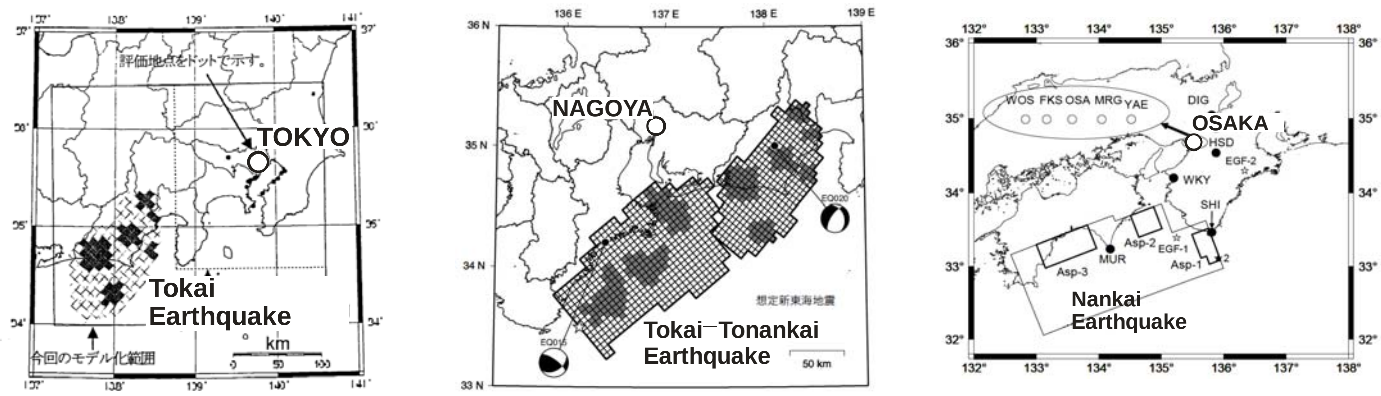
The seismic behavior of furniture at an office room in an upper floor of high-rise buildings is simulated at Tokyo, Nagoya and Osaka metropolitan areas due to the anticipated giant earthquakes (Tokyo for the Tokai earthquake (M_W8.0), Nagoya for the Tokai-Tonankai earthquake (M_W8.3), Osaka for the Nankai earthquake (M_W8.4)). The ground motions of the Tokai earthquake, the Tokai-Tonankai earthquake, and the Nankai earthquake are simulated by Hijikata *et al.*(2006), Chubu Regional Bureau, MLIT (2004) and Kamae *et al.*(2004), respectively (See Figs. 9). The simulated ground motions are used to calculate the floor response of the high-rise buildings.

Figures 10 shows the time histories of the ground motions and the floor responses. The floor responses at Tokyo and Nagoya are computed for a 30-story steel structure building (Kojika *et al.*, 2007, Mayahara *et al.*, 2007, Kawasaki *et al.*, 2007). The natural period of the building is about 3 sec. The floor response at Osaka is computed for a 40-story steel structure building (Atsumi and Kitamura, 2008). The natural period of the building is about 5 sec. The floor response of the Tokai-Tonankai earthquake is largest of all the earthquakes (about 171cm/s). The duration time of the floor response of the Nankai earthquake is longest (over 250 sec). The model of the simulation is constructed based on a standard office space. The area of the model is about 90 m^2. In the model, 10 desks, 10 caster chairs, 12 desks with chair, five cabinets, and one box on casters are distributed (See Figs. 11).

4.2. Results of Simulation

Figures 11 show the results of the simulations. The left part of the figure shows the result of the simulation at Tokyo during the Tokai earthquake. Since the velocity of the floor response becomes large (about 150 cm/s) from about 30sec to 80sec, the caster chairs, the box on casters, and the desks with chair move around during about 50 seconds. However, the cabinets are not overturned.

The central part of the figure shows the result of the simulation at Nagoya during the Tokai-Tonankai earthquake. The acceleration of the floor response of the Tokai-Tonankai earthquake is about 490 cm/s^2, which is twice as the acceleration of the Tokai earthquake. The result of the simulation shows that all of the cabinets are overturned. The furniture continues to move around and collide against each other during about 150 seconds. The desks with a chair and a box on casters are displaced over 1 m. The behavior of the furniture can cause fear and injury to people in the floor, and make the evacuation action difficult.

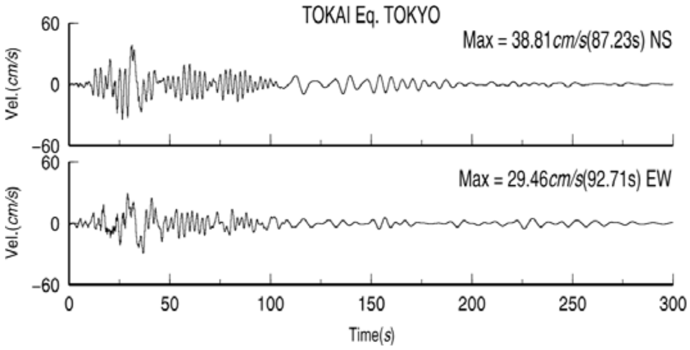


(a) Tokai earthquake and Tokyo (after Hijikara et al., 2006)

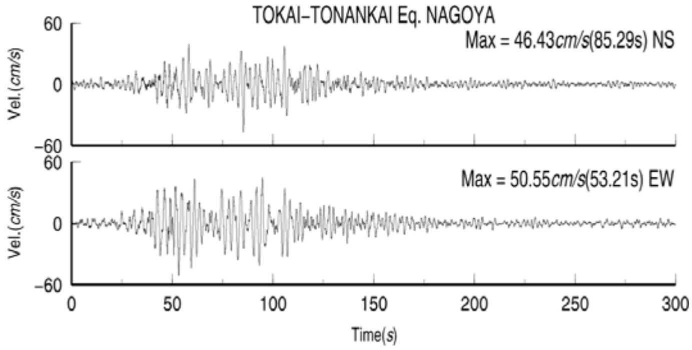
(b) Tokai-Tonankai earthquake and Nagoya (after Chubu Regional Bureau, 2004)

(c) Nankai earthquake and Osaka (after Kamae et al, 2004)

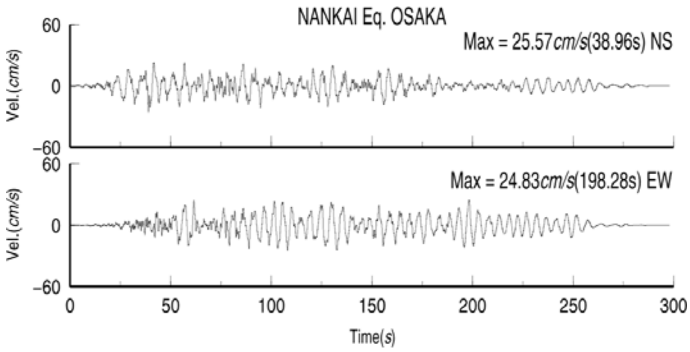
Figures 9 Locations of anticipated earthquakes and sites



Tokyo

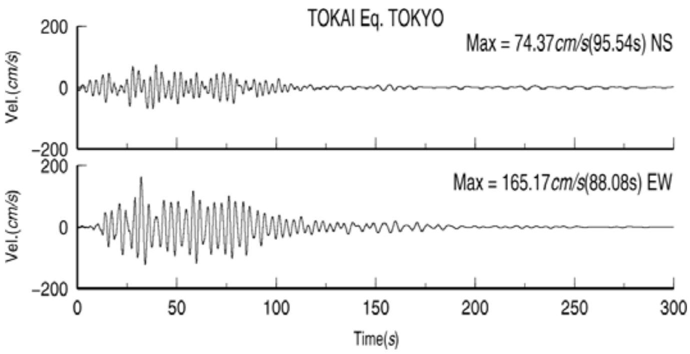


Nagoya

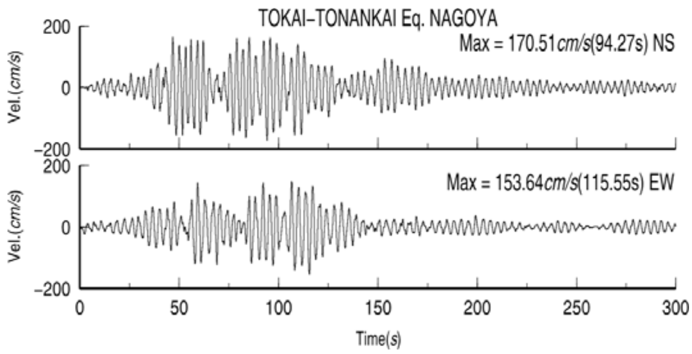


Osaka

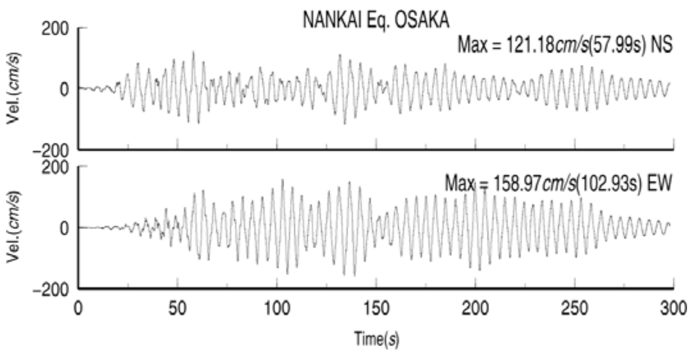
(a) Input Ground Motion



Tokyo



Nagoya

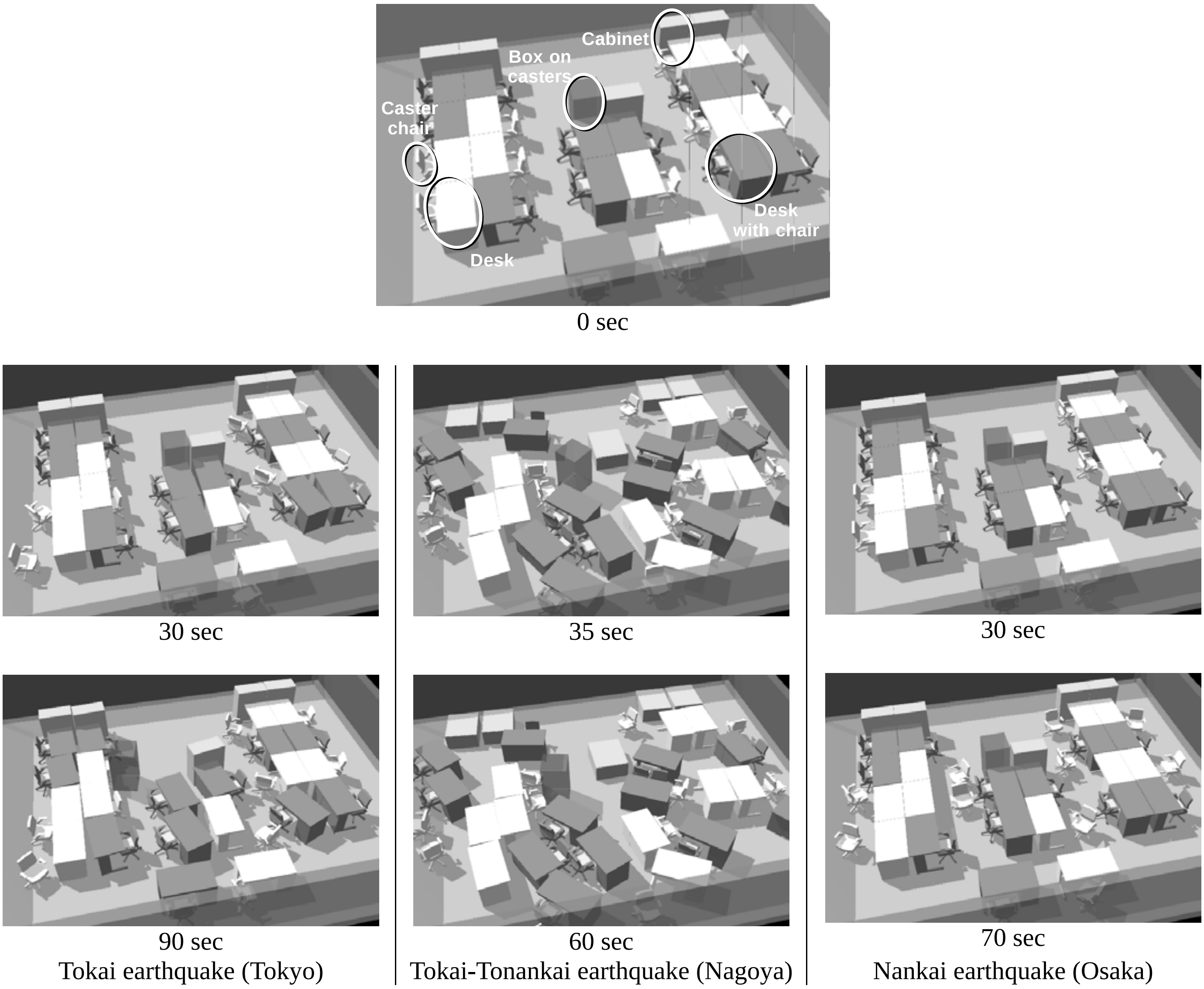


Osaka

(b) Building Floor Response

Figures 10 Time histories of ground motions and floor responses

The right part of the figure shows the result of the simulation at Osaka during the Nankai earthquake. Although the maximum velocity of the floor response is about 160 cm/s, the maximum acceleration is rather small (about 200 cm/s^2). The displacements of the furniture in this case are smaller than those in the other cases.



Figures 11 Behavior of office furniture in upper floor of high-rise building

5. CONCLUSIONS

The seismic behavior of office furniture in high-rise buildings due to long-period ground motions is examined in order to evaluate risk of injuries and confusions by overturning and displacement of furniture. The shaking table tests are conducted to grasp the fundamental characteristics of the behavior of the furniture. The behavior of the furniture in the shaking table tests is well simulated by a rigid body simulation program, indicating the validity of the simulation method. The behavior of a number of furniture is simulated in an upper floor of high-rise buildings at Tokyo, Nagoya, and Osaka due to the anticipated giant earthquakes, such as the Tokai earthquake, the Tokai-Tonankai earthquake, and the Nankai earthquake. During the Tokai earthquake and the Tokai-Tonankai earthquake, the furniture continues to move around and collide against each other for long duration. The desks with chair and the box on casters are displaced over 1 m. The behavior of the furniture can cause fear and injury to people in the floor, and make the evacuation action difficult.

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REFERENCES

Atsumi, T. and Kitamura, H. (2008).Seismic vibration control system using combinations of hysteretic and viscous dampers for high-rise steel structure. *Summaries of Technical Papers of Annual Meeting A.I.J*, **B-2**, 543-544 (in Japanese).

Chubu Regional Bureau, MLIT (2004). http://www.cbr.mlit.go.jp/eizen/policy/seismic/sannomaru.pdf. (in Japanese)

Erleben, K. *et al.* (2005). Physics-based animation, Charles River Media Inc.

Gilbert, E. *et al.* (1988). A fast procedure for computing the distance between complex objects in three-dimensional space. *IEEE Journal of Robotics and Automation* **4 (2),** 193-203.

Hasegawa, S. and Sato, M. (2004). Real-time rigid body simulation for haptic interactions based on contact volume of polygonal objects. *Eurographics* 2004 **23,** 529-538.

Hijikata, K. *et al.* (2006). Simulation of broad-band ground motion in the Kanto basin due to the Tokai earthquake. *Proceedings of the Second Symbosium on large Subduction Earthquakes*, 83-90 (in Japanese).

Ishiyama, Y. (1982). Criteria for overturning of bodies by earthquake excitations. *Transaction of A.I.J.* **317,** 1-14.

Kamae, K. *et al.* (2004). Strong ground motion prediction for huge subduction earthquakes using a characterized source model and several simulation techniques. *Proceedings of the 13th World Conference on Earthquake Engineering, Paper*#655.

Kawasaki, M. *et al.* (2007). Damage evaluation of a steel structure super high-rise building for long period earthquake vibration: Part 3. Reply prediction-style inspection. *Summaries of Technical Papers of Annual Meeting A.I.J*, **B-2**, 465-466 (in Japanese).

Kojika, Y. *et al.* (2007). Damage evaluation of a steel structure super high-rise building for long period earthquake vibration: Part 1. The maximum of a member level, accumulation value. *Summaries of Technical Papers of Annual Meeting A.I.J*, **B-2**, 461-462 (in Japanese).

Mayahara, T. *et al.* (2007). Damage evaluation of a steel structure super high-rise building for long period earthquake vibration: Part 2. A reply prediction on the basis of balance of the energy that paid its attention to a member. *Summaries of Technical Papers of Annual Meeting A.I.J*, **B-2**, 463-464 (in Japanese).