Study on Shaking and Damages of Super High-Rise Residential Buildings During The 2011 Off The Pacific of Tohoku Earthquake Based on Questionnaire Survey

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SUMMARY:
The relationship between strong motions experienced by super high-rise RC buildings and interior damage to these buildings during the 2011 off the Pacific coast of Tohoku Earthquake was investigated based on the findings of a questionnaire survey. The degree of anxiety, the difficulty in taking responsive action experienced by the residents, and the percentage of furniture that toppled over in rooms in these buildings were compared with the findings of past studies. The following conclusions were reached: 1) The higher the floor level, the higher the difficulty in movement was experienced by the respondents during the main shock. 2) Many respondents felt anxious regardless of the floor height. 3) Furniture moved or overturned on the higher floors of buildings in the Kanto area. 4) Many interior materials and concrete structures cracked on the lower floors in the Kanto area. 5) The anxiety felt and the difficulty in taking responsive action during the main shock were greater than those of the past studies based on the findings of shaking table tests. 6) The percentage of furniture that toppled over corresponded to that reported in past studies.

Keywords: Tohoku earthquake, Questionnaire survey, Super high-rise residential buildings, Interior damage

1. INTRODUCTION

A large number of super high-rise residential buildings have been built on the plains of the Kanto and the Kansai areas in Japan. During the 2011 off the Pacific coast of Tohoku earthquake, damage to building interiors of super high-rise office buildings in the Tokyo metropolitan area was reported (AIJ, 2011). Similar damage such as the overturning of furniture and the scattering of small household appliances would have occurred in super high-rise residential buildings. Investigation on the evacuation behavior of residents and the risk of overturning of furniture are important in reducing the interior damage during an earthquake.

The degree of difficulty in taking responsive action and the anxiety felt during shaking were investigated on the basis of the shaking table tests, which were conducted in a past study (Takahashi et al., 2010). The findings of this study show that the degree of difficulty in taking responsive action and the anxiety felt during shaking depend on the velocity of the shaking over a short period. On the other hand, these factors are also affected by the degree of acceleration over a long period. These results, however, were based on single axis sinusoidal shaking, and the psychological factor and difficulty in taking action could well differ during an actual earthquake.

The relationship between the overturning of furniture and the frequency, acceleration, or velocity of shaking has been investigated in past studies (Ishiyama, 1982; Kaneko et al., 2002). The findings of this study showed that the percentage of furniture that toppled over depended on the acceleration and velocity in the low-frequency and high-frequency shaking, respectively. Based upon these findings, we propose an evaluation curve for calculating the percentage of furniture in super high-rise residential buildings that will topple over during an earthquake.
The ability of people to evade calamities depends upon their age and the time of occurrence of an

earthquake (Okada et al., 2003). The relationship between the seismic intensity and the probability of injury was investigated on the basis of ability and the percentage of furniture that toppled over in the dwellings of residents. However, the relationship between the probability of injury and the intensity of shaking during an actual earthquake was not investigated.

As mentioned, the degree to which study examined the psychological effects, the difficulty in taking action, and the percentage of furniture that toppled over in super high-rise residential buildings during an actual earthquake were limited. We conducted a questionnaire survey for residents of super high-rise residential buildings to investigate the relationship between shaking during the 2011 off the Pacific coast of Tohoku earthquake and the psychological effects, difficulty in taking action, and percentage of furniture that toppled over.

2. OUTLINE OF QUESTIONNAIRE

The buildings targeted for the investigation were 22 super high-rise residential buildings in the Kanto and Kansai areas. Figure 1 shows the location of these buildings. There were sixteen and six buildings in the Kanto and Kansai areas, respectively. All buildings were located on the Kanto and Osaka Plains, where thick sedimentary layers exist on the seismic bedrock. The prolonged ground motions during the 2011 off the Pacific coast of Tohoku Earthquake would have influenced the dynamic behavior of these super high-rise buildings.

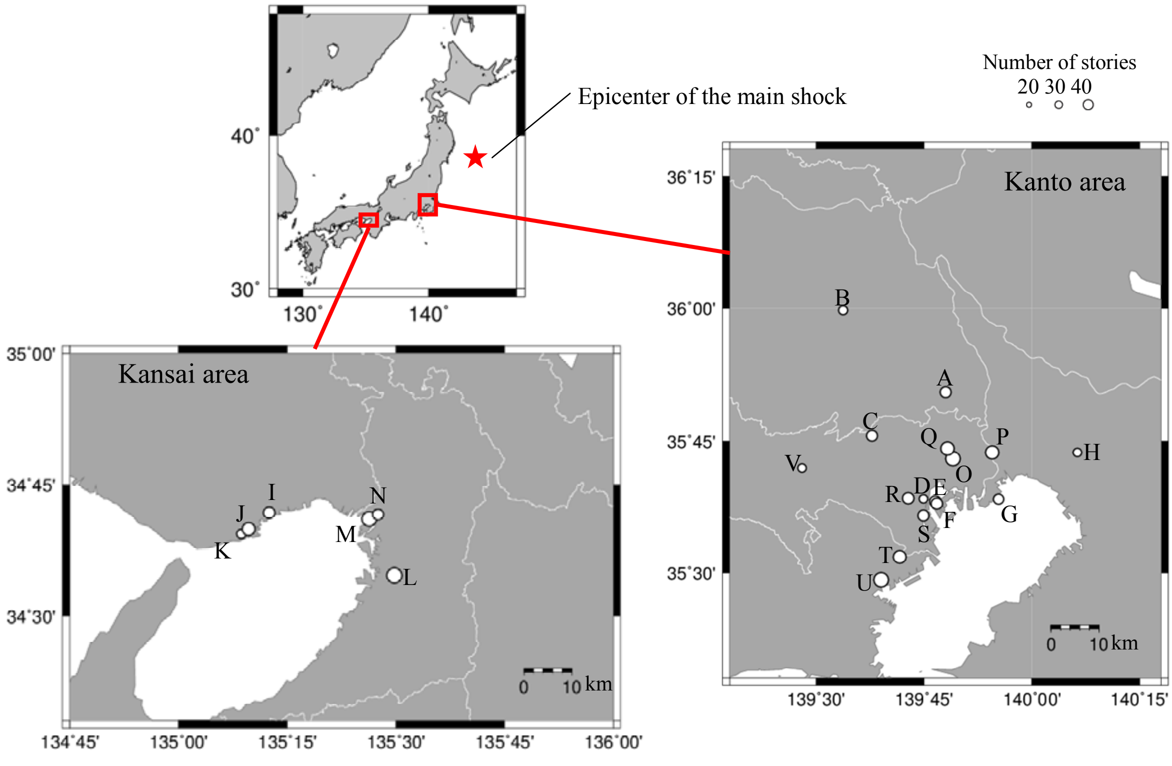
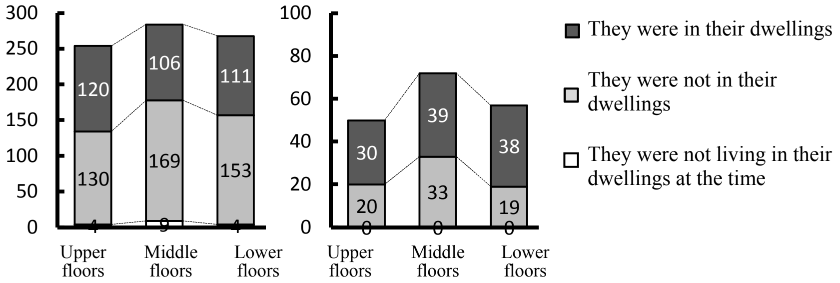


Figure 1. Construction site maps of target buildings scoped in this paper

The questionnaire survey was conducted twice. The first survey was conducted in late July 2011, about four months after the main shock. The second survey was conducted in the middle of October 2011, about seven months after the main shock. Questionnaires were posted in mailboxes of five consecutive stories around the floors that equip a seismometer. The floors were divided into three levels: Upper floors, Middle floors, and Lower floors. A total of 985 responses returned.

Figure 2 shows the number of respondents and whether they were in their dwellings during the main shock (about a half were). The questions mainly concerned the shaking during the main shock, although there were several comments on shaking and damage during the aftershocks.

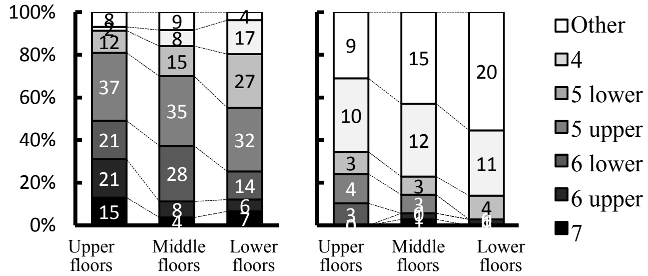


(a) Kanto area (b) Kansai area

Figure 2. Number of respondents

3. PSYCHOLOGICAL EFFECTS DURING THE MAIN SHOCK

Questions regarding the psychological condition of residents during the shaking were asked from those who were in their dwellings during the main shock. Figure 3 shows the response to the question regarding seismic intensity. The responses received in the Kanto area were greater than those received in the Kansai area. In both areas, the number of responses tended to increase with the floor level.

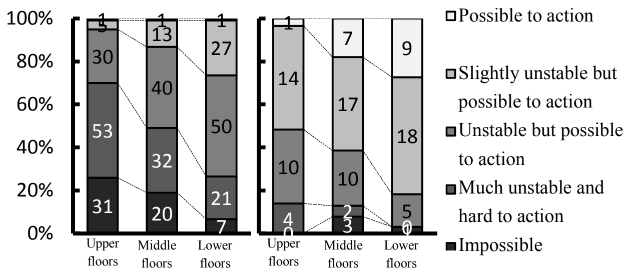


(a) Kanto area (b) Kansai area

Figure 3. Responses to question regarding seismic intensity

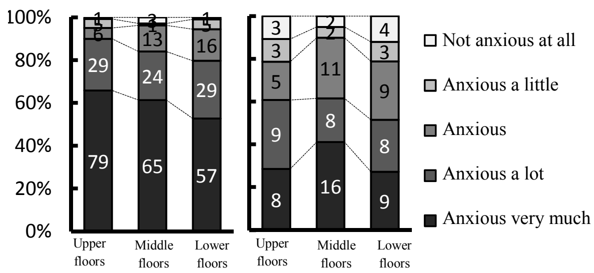
Figure 4 shows the difficulty faced by residents in movement (Takahashi et al., 2010) during the main shock. More than half of the residents on upper floors in the Kanto area felt unstable during the main shock. The difficulty encountered in movement in the Kanto area was greater than that in the Kansai area. Furthermore, the higher the floor level was, the higher was the difficulty that was experienced in movement. This suggests that the difficulty in movement tends to increase with seismic intensity.

Figure 5 shows the anxiety (Takahashi et al., 2010) felt during the main shock. The anxiety felt in the Kanto area tended to be greater than that in the Kansai area. In both areas, most respondents felt anxious regardless of the floor height. The conclusion is that anxiety is not necessarily affected by seismic intensity.



(a) Kanto area (b) Kansai area

Figure 4. Difficulty faced by the residents in movement



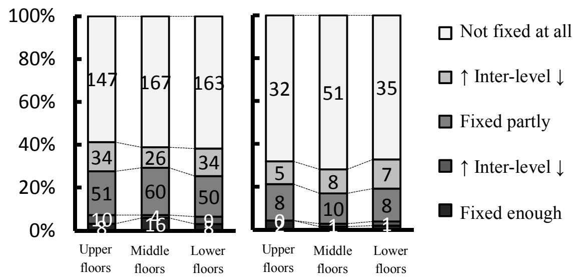
(a) Kanto area (b) Kansai area

Figure 5. Anxiety felt during the main shock

4. INTERIOR DAMAGE

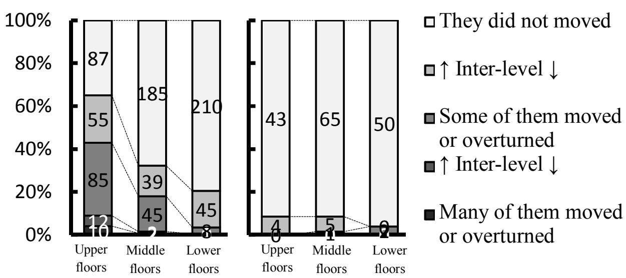
All respondents were asked questions concerning the state of furniture, household appliances, and small appliances on tables or in cupboards placed in rooms after the main shock. Figure 6 shows the fixation degrees of drawers, refrigerators, and cupboards. The percentage of respondents who had taken measures to secure their furniture in the Kanto area was slightly larger than that in the Kansai area. In both areas, the percentage of respondents who had secured their furniture adequately was very little. More than half of all respondents had not secured their furniture at all.

Figure 7 shows the situation of drawers, refrigerators, and cupboards after the main shock. Almost none of the furniture and household appliances had moved or overturned in the Kansai area and on the lower floors of buildings in the Kanto area. However, more than 70% of respondents said that the furniture moved and overturned on the upper floors of buildings in the Kanto area.



(a) Kanto area (b) Kansai area

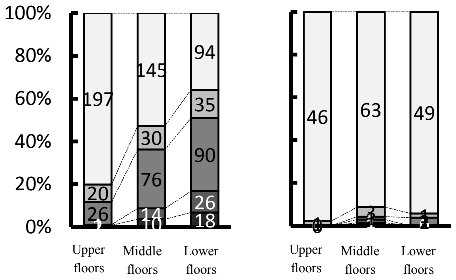
Figure 6. Fixation degree of drawers, refrigerators and cupboards



(a) Kanto area (b) Kansai area

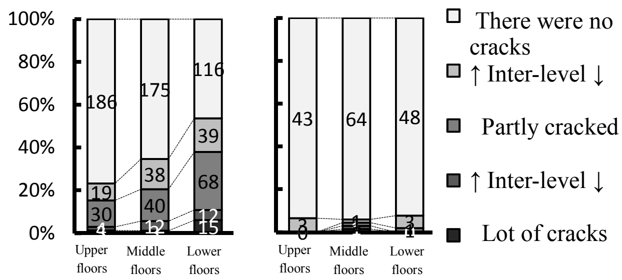
Figure 7. Situations of drawers, refrigerators or cupboards after the main shock

Figure 8 shows cracks in interior materials including wallpaper after the main shock. Figure 9 shows cracks in concrete columns, walls, and beams. The number of cracks in interior materials and concrete was very small in the upper floors of the Kansai area. In contrast, many interior materials and a large amount of concrete cracked in the lower floors, especially in the Kanto area. The relationship between the intensity of the shaking and the damage caused to interior materials or concrete showed an inverse correlation. This visible damage was closely related to the maximum story drift rather than to the amplitude of the floor responses.



(a) Kanto area (b) Kansai area

Figure 8. Cracks in interior materials



(a) Kanto area (b) Kansai area

Figure 9. Cracks in concrete (Columns, walls, and beams)

5. ANXIETY CAUSED BY GRATING SOUNDS MADE BY BUILDINGS

In the second survey conducted in the Kanto area, all residents, irrespective of whether they stayed in their dwellings during the main shock, were asked whether they heard grating sounds being made by their building and the sound of furniture hitting things. Figure 10 shows the results. Many residents living on lower floors reported hearing such sounds. This tendency differed from the tendencies of seismic intensity (Fig. 3), difficulty in taking action (Fig. 4), or moving of furniture (Fig. 7). Considering that cracking in interior materials and concrete was prevalent on lower floors (Figs. 8, 9), the grating sounds made by the buildings was presumably caused by this cracking.

Residents who reported hearing grating sounds were asked what degree of anxiety they felt as a result of the grating sounds. Figure 11 shows the result. The percentage of residents living on upper and middle floors who felt anxious was almost the same. The percentage of residents on lower floors who felt anxious was larger than those living on the upper and middle floors.

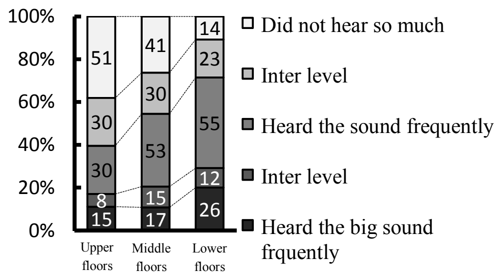


Figure 10. Percentage of residents who heard the grating sound of building or hitting sound of furniture

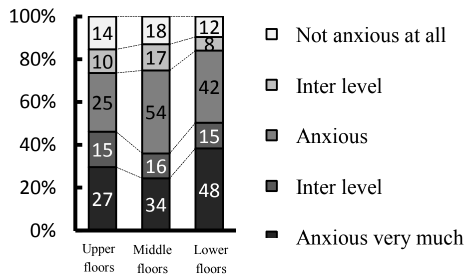


Figure 11. Anxiety caused by grating sound of building or hitting sound of furniture

Figure 12 shows the relationship between the anxiety felt by residents who heard grating sounds frequently and those who did not hear the sounds to such a large degree. The degree of anxiety felt by residents on each floor level was evaluated by the average of values indicated in Table 1. Floors for which the number of responses was less than three were excluded. For almost all floors, the degree of anxiety felt by residents who heard the sound frequently was higher than that for those who did not hear the sound so much. This indicates that the degree of anxiety was heightened by hearing a grating sound for those living on lower floors.

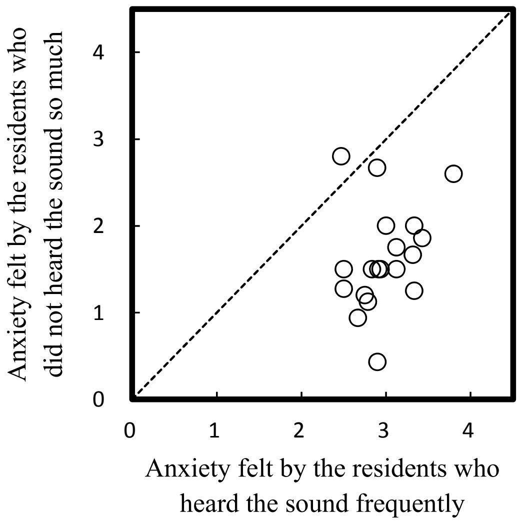


Figure 12. Relationship between the anxiety felt by residents who heard grating sounds frequently and those who did not hear the sounds to such a large degree

6. EVALUATION CURVES OF ANXIETY AND DIFFICULTY IN ACTION

Table 1 shows questions and evaluation values related to anxiety. The questions and evaluation values obtained in the shaking table tests (Takahashi et al., 2010) are also shown. The questions in this study correspond to those asked in the shaking table test. Thus, the degree of anxiety was given a value in the range 0–4, based on the shaking table test.

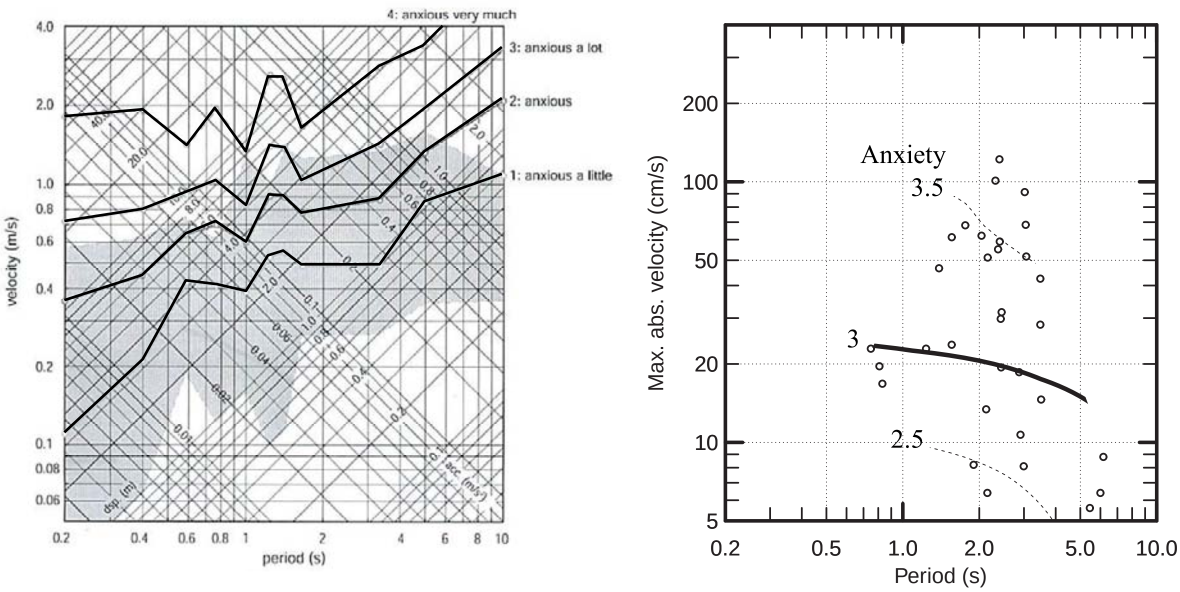
Table 1 Questions and evaluation values for anxiety

Question in this study	Shaking table test (Takahashi et al., 2010)	
	question	Evaluation value
Very much anxious	Anxious very much	4
Anxious	Anxious a lot	3
A little anxious	Anxious	2
Not too much anxious	Anxious a little	1
Not anxious at all	-	0

To compare the degree of anxiety as ascertained in this study and the shaking table test, an evaluation curve for anxiety was calculated. The curve was calculated by using the smoothing method of a thin-plate spline (Bookstein, 1989). The function of the thin-plate spline was calculated by minimizing the residual sum of squares (*RSS*) indicated by following equation:

$$RSS = \sum_{i=1}^{n} \left[y_i - s(x_{1i}, x_{2i})\right]^2 + \frac{\lambda}{2}\iint\left[\left(\frac{\partial^2 s(x_{1i}, x_{2i})}{\partial x_1^{\ 2}}\right)^2 + 2\left(\frac{\partial^2 s(x_{1i}, x_{2i})}{\partial x_1 x_2}\right)^2 + \left(\frac{\partial^2 s(x_{1i}, x_{2i})}{\partial x_2^{\ 2}}\right)^2\right]dx_1 dx_2 \qquad (1)$$

, where y_i is the objective variable, x_{1i}, x_{2i} is the explanatory variable, and λ is the parameter for smoothing. The degree of anxiety was set as an objective variable. The maximum velocity and the predominant period were set as explanatory variables. The predominant period is the period of maximum amplitude of the Fourier spectrum of floor response acceleration. Figure 13 shows the evaluation curves of anxiety in this study and in the shaking table test. The feeling of anxiety for both results tended to be higher with an increase in velocity. In the shaking table test, it is clear that the longer the predominant period, the higher the feeling of anxiety at each velocity. On the other hand, no such tendency was reported in this study. The velocity that corresponds to Anxiety 3 is smaller than that which corresponds to Anxiety 1, as experienced in the shaking table test. This result indicates that the anxiety felt during an actual earthquake is higher than that felt during a shaking table test.



a) Shaking table test b) This study

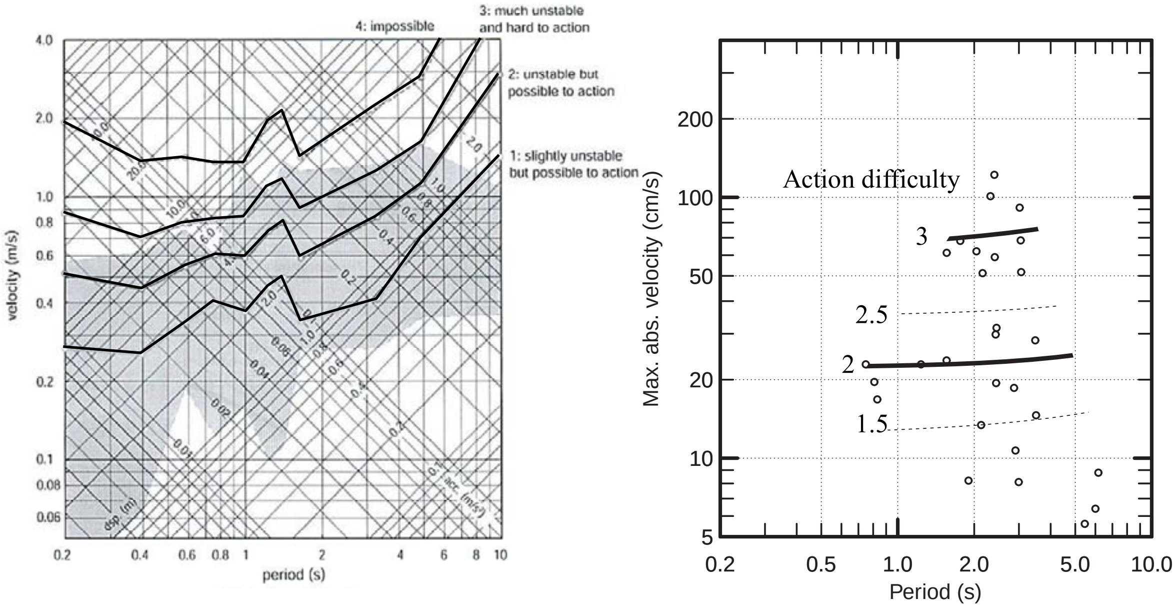
Fig. 13 Evaluation curve of anxiety

Table 2 shows the questions and evaluation values related to difficulty in taking action. The questions and evaluation values obtained in the shaking table tests (Takahashi et al., 2010) are also shown. The questions in this study correspond to those asked in the shaking table test. Thus, the degree of difficulty in taking action was given a value in the range 0–4, which is based on the shaking table test. An evaluation curve for the difficulty in taking action was calculated by using the smoothing method of a thin-plate spline to compare the difficulty in taking action in this study with that for the shaking table test.

Table 2 Questions and evaluation values for difficulty in taking action

Question in this study	Shaking table test (Takahashi et al., 2010)	
	Question	Evaluation value
Impossible to action	Impossible	4
Could not stand	Much unstable and hard to action	3
It was a little difficult to move and walk	Unstable but possible to action	2
The shaking was felt clearly, but there was not interference to action	Slightly unstable but possible to action	1
The shaking was felt slightly, but there was not interference to action	-	0

Figure 14 shows the evaluation curve for difficulty in taking action. The difficulty in taking action in this study and in the shaking table test tended to be higher with an increase in the velocity of shaking. The degree of difficulty in taking action in the shaking table test tended to be higher within the predominant period in a certain velocity but no such tendency was obvious in this study. The difficulty in taking action corresponding to the predominant period 1 s and the velocity 20 cm/s was lower than 1 in this study. On the contrary, the difficulty in taking action corresponding to that period and the velocity was 2 in the shaking table test. The difficulty in taking action corresponding to the predominant period 2 s and the velocity 70 cm/s was 2 in this study. On the other hand, the difficulty in taking action corresponding to that period and velocity was 3 in the shaking table test.



a) Shaking table test b) This study

Fig. 14 Evaluation curve of action difficulty

Thus, the degree of anxiety felt and the difficulty in taking action in this study were higher than those recorded in the shaking table test. These differences depend upon the following factors; 1) Single axis sinusoidal shakings were performed in the shaking table test. On the other hand, the floor shook 3-axial during an actual earthquake. 2) Residents cannot predict when an earthquake is about to occur. 3) In the shaking table test, furniture was not placed. The moving and overturning of furniture during an actual earthquake can affect residents' psychological condition.

7. PERCENTAGE OF FURNITURE THAT TOPPLED OVER

The percentage of furniture that toppled over, R, is evaluated by following equation (Kaneko et al., 2002).

$$R = \alpha \cdot \Phi\left(\frac{(\ln A_{\max} - \lambda)}{\zeta}\right) \tag{2}$$

$$e^{\lambda} = \begin{cases} A_{cr}\left(1+\dfrac{B}{H}\right) = \dfrac{B}{H} g\left(1+\dfrac{B}{H}\right), & F_e \le F_b' \\ V_{cr}\left(1+\dfrac{B}{H}\right)^{2.5} \cdot 2\pi F_e = 10\dfrac{B}{\sqrt{H}}\left(1+\dfrac{B}{H}\right)^{2.5} \cdot 2\pi F_e, & F_e > F_b' \end{cases} \tag{3}$$

$$F_b' = \frac{15.6}{\sqrt{H}}\left(1+\frac{B}{H}\right)^{-1.5} \tag{4}$$

, where Φ is the normal probability distribution with mean λ and standard deviation ζ. α is the factor for the slipping effect of furniture. A_{max} is the maximum input acceleration (cm/s^2). B and H are the width and height of furniture, respectively. A_{cr} and V_{cr} are the minimum acceleration and minimum velocity, respectively, of the overturning furniture. g is the gravity acceleration. F_b' is the boundary frequency (Hz). B, H, ζ, and α were set as shown Table 3. Boundary frequency, F_b', corresponds to B, and H is 0.85 Hz. F_e is the equivalent frequency and is calculated by the following equation:

$$F_e = \frac{A_{\max}}{V_{\max} 2\pi} \quad (5)$$

, where A_{max} and V_{max} are the maximum input acceleration and the maximum input velocity, respectively. The velocities of strong motions were calculated by the integration of acceleration. The percentage of furniture that toppled over depends on acceleration when F_e was lower than F_b'. On the contrary, it depends on velocity when F_e was higher than F_b'. The percentage of furniture that overturned, obtained in the questionnaire survey, was evaluated as shown in Table 4.

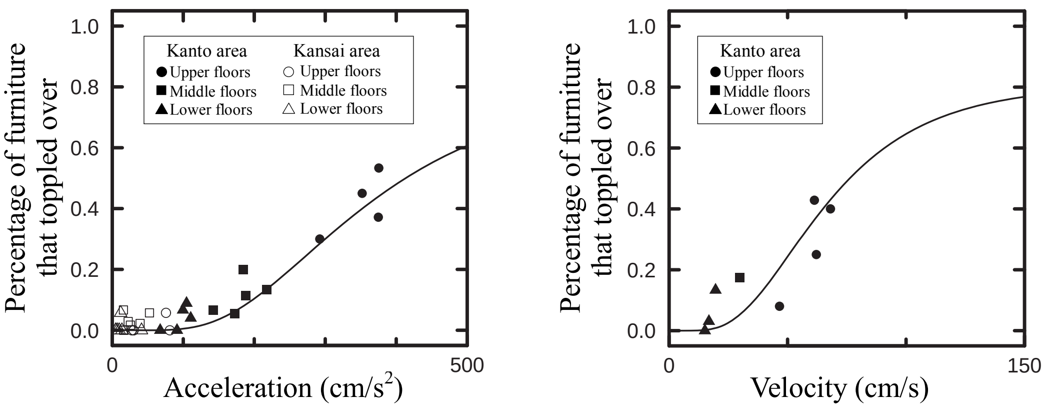
Table 3 Parameter for estimation of percentage of furniture that toppled over

Width of furniture, B (cm)	Height of furniture, H (cm)	ζ	α
45	160	0.5	0.8

Table 4 Questions and percentage for furniture that toppled over

Question	Percentage of furniture that toppled over
They did not move	0.8
↑ Inter-level ↓	0.6
Some of them moved or overturned	0.4
↑ Inter-level ↓	0.2
Many of them moved or overturned	0

Figure 15 illustrates the relationship between the percentage of furniture that toppled over when it was not secured in place and the maximum acceleration or maximum velocity. The correlation factor and the percentage of furniture that toppled over, as evaluated by Eqs. (2)–(5), are also shown in the figure. The larger the maximum acceleration and the maximum velocity, the higher is the percentage of furniture that toppled over. The maximum acceleration, the maximum velocity, and the percentage of furniture that toppled over in the Kansai area were less than those for the Kanto area. In addition, the percentage of furniture that toppled over on lower and middle floors in the Kanto area was 0-0.2. The value was between 0.3 and 0.5 on the upper floors in the Kanto area. The percentage of furniture that toppled over corresponds to that evaluated by Eqs. (2)–(5).



a) Relationship between acceleration and percentage of furniture that toppled over

b) Relationship between velocity and percentage of furniture that toppled over

Figure 15. Relationship between strong motion records and percentage of furniture that toppled over

8. CONCLUSION

A questionnaire survey was conducted for the residents of super high-rise buildings. The psychological factor, the degree of difficulty in taking action, and the percentage of furniture that toppled over were investigated based on the responses to the questionnaire survey and strong motion records during the 2011 off the Pacific coast of Tohoku earthquake. The results were compared with past studies. The following conclusions were reached: 1) The higher the floor level, the higher the difficulty in movement was experienced by the respondents during the main shock. This suggests that difficulty in movement tends to increase with seismic intensity. 2) Many respondents felt anxious regardless of the floor height. This indicates that anxiety is not necessarily affected by seismic intensity. 3) Many small appliances and pieces of furniture were moved, overturned, and scattered on the upper floors of buildings in the Kanto area. This indicates that the greater the shaking intensity, the more furniture and small appliances were moved, overturned, and scattered. 4) A lot of interior materials and a large amount of concrete cracked on the lower floors in the Kanto area. Many respondents living on lower floors reported hearing a grating sound produced by their buildings. This suggests that the grating sound was related to the cracking of the interior materials or the concrete. Residents also commented that their feelings of anxiety were heightened by sounds during the main shock or during aftershocks. 5) The feeling of anxiety and the difficulty in taking action were higher in this study than in a shaking table test, which was performed earlier. These differences depended on the fact that single axis sinusoidal shaking was conducted during the shaking table test while the floor was shaken three-axial during an actual earthquake. 6) The percentage of furniture that toppled over corresponds to that investigated in a past study.

ACKNOWLEDGMENTS
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