16TH EUROPEAN CONFERENCE ON
EARTHQUAKE ENGINEERING THESSALONIKI
18 - 21 JUNE 2018

PROPOSED EVALUATION CURVE FOR HUMAN SENSITIVITY TO SEISMIC MOTION BASED ON SUBJECT EXPERIMENTS

Rie OKAZAWA[1], Hiroshi KAMBARA[2], Masaaki SARUTA[3]

ABSTRACT

The purpose of this study is to evaluate the seismic performance of buildings in terms of the influence that seismic motion has on a person. Experiments with human subjects are performed using a shaking table able to simulate seismic motion. The relationship between vibration characteristics (sinusoidal waves) and human senses sensitivity is analyzed and evaluation curves are proposed. The results demonstrate that: 1) Over 50% of people feel a sense of danger and attempt to take protective action at SI (instrumental seismic intensity) ≥5.2. 50% become anxious at SI≥5.6. 2) The ratio of people who feel anxious or have difficulty taking action can be expressed by a normal distribution with acceleration or SI (determined as A x V) of the motion as an index. 3) Anxiety levels are greatly influenced by the direction of the motion and the sight of overturning furniture. 4) Using the predicted response of high-rise buildings in the 23 wards of Tokyo to a major earthquake, the influence of the seismic motion on people was estimated using the evaluation curve obtained from the basal condition in the experiments. Assuming the 2011 off the Pacific coast of Tohoku Earthquake, the ratio of people who feel anxious or have difficulty taking action is lower than their actual response as obtained in another study. To improve the results, it will be necessary to take into account that an earthquake, unlike shaking table motion, occurs unexpectedly and that earthquake motion may continue for a long time with no clue as to how long it will last.

Keywords: Shaking Table Test; Anxiety; Action Difficulty; Evaluation Curve; Subject Experiments

1. INTRODUCTION

Until now, the seismic performance of buildings has been evaluated in terms of the structural damage caused by earthquakes. However, there have been reports (e.g. Iiba et al. 2012) that, during the 2011 off the Pacific coast of Tohoku Earthquake, the long duration of the seismic motion made residents of high-rise buildings anxious even though the buildings suffered no damage. In major cities with many high-rise buildings, places of refuge are limited, so residents of high-rise buildings are expected to remain inside. This might impose a heavy mental burden if those who remain are made anxious by the motion. There is a need to design spaces in which people not only remain physically safe, but also free from anxiety.

The design and evaluation of such spaces requires understanding of the relationship between motion amplitude and human sensitivity to vibration. Quantification of human sensitivity to vibration has conventionally been considered in relation to small motions such as caused by wind or environmental factors (e.g. Goto 1975), but interest in large-amplitude motion such as caused by earthquakes is recent.

Takahashi et al. (2010) performed experiments using human subjects with widely varying vibration intensity and period, and used the results to propose evaluation curves of human sensitivity to seismic motion. In their experiments, they divided human sensitivity to seismic motion into five ranks. Taking the average of subjects' responses for each vibration cases tested in the experiments, they proposed an

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[1] Institute of Technology, Shimizu Corporation, Tokyo, Japan, r.okazawa@shimz.co.jp
[2] Institute of Technology, Shimizu Corporation, Tokyo, Japan, kambara@shimz.co.jp
[3] Institute of Technology, Shimizu Corporation, Tokyo, Japan, saruta@shimz.co.jp

evaluation curve for each rank. Hida et al. (2012a, 2014) carried out questionnaire surveys of high-rise building residents in the Kanto and Kansai regions to examine levels of anxiety and difficulty in taking action (action difficulty) during the 2011 off the Pacific coast of Tohoku Earthquake. They also reproduced the earthquake motion using a shaking table to confirm the correspondence between the real earthquake and experiments with human subjects. Kaneko et al. (2015) also carried out similar questionnaire surveys relating to the 2011 off the Pacific coast of Tohoku Earthquake and performed experiments using a shaking table and human subjects in an effort to quantify human sensitivity to seismic motion with a wider range of periods and greater amplitude.

As this review illustrates, there have been studies in which evaluation curves are proposed. However, most of the proposed curves are not simple functions, so to use them in quantitative evaluation, values must be read from the plots. Further, there are few cases where variations in experimental conditions are considered. In this study, the ratio of people who have the same level of response to motion is simply expressed as a probability distribution function for vibration intensity. In addition to vibration intensity, variation in position of the subjects, the direction of the motion and the indoor environment are also considered as different experimental conditions and reflected to evaluation curves.

Finally, to confirm the applicability of the proposed evaluation curves, the influence of large earthquake motion on people in high-rise buildings within the 23 wards of Tokyo is examined.

2. RESULTS OF EXPERIMENTS WITH HUMAN SUBJECTS AND EVALUATION CURVES

2.1 Outline of Experiments

The shaking table shown in Figure 1 was used. The table measures 4 m x 4 m and a cabin structure was placed on the table within which the experiments with human subjects were carried out. Subjects sat on chairs within the cabin. The brightness of the cabin could be adjusted. VR images (of which an example is shown in Figure 2) could be projected onto a screen to give the impression of overturning furniture caused by the input motion. The protocol used to ensure subject safety is shown in Figure 3. An industrial physician determined whether it was appropriate for each subject to undergo vibration using an inquiry sheet to verify that they were healthy and had no chronic health problems. Preliminary experiments were used to determine a suitable number of shaking tests and their duration for each subject to ensure that subjects' health would not be compromised.

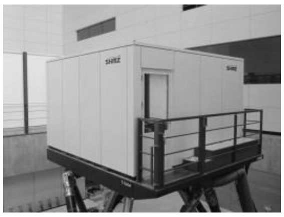


Figure 1. Shaking table and cabin

Figure 2. Example of VR imagery

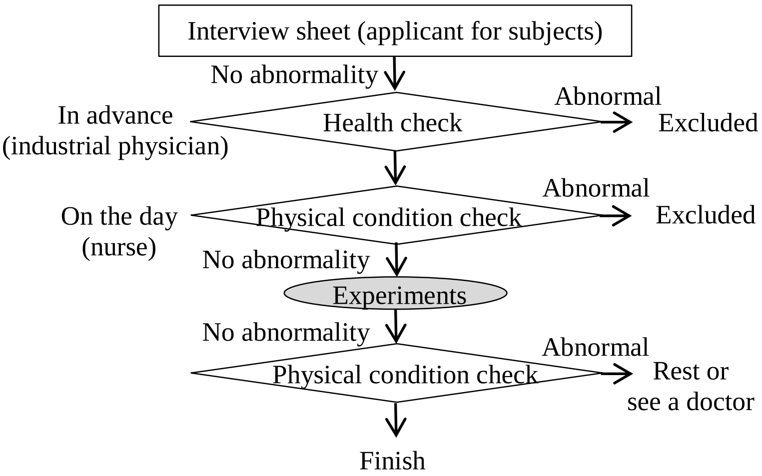


Figure 3. Safety protocol for subjects

Three sets of experiments were performed with different characteristics of vibration intensity, subject pose (sitting or standing), direction of motion (left to right or front to back) and indoor environment. These experimental conditions are shown in Table 1. The input motion was a sinusoidal wave with duration of 5 seconds or 3 wavelengths. In Experiment-1, the acceleration and velocity of the input motion was varied. Other experimental conditions were fixed: subjects were sitting, input motion was left to right, the indoor environment was bright and no VR images were projected. This set of experimental conditions is referred to as the basal condition.

Vibration intensity was determined on the basis of experimental results by Takahashi et al. and preliminary experiments to ensure that it would not unnecessarily burden the subjects. In Experiment-2, subject pose and direction of the motion were varied, while in Experiment-3, indoor environment was changed. There were many excitation cases involved in Experiments-1 and -2, so each subject was exposed to half of the cases only; that is, each full sample is derived from two subjects.

The vibration intensities used in this experiment, where acceleration A (m/s^2) and velocity V (m/s) of the input motion were changed as parameters, are compared with the anxiety evaluation curves proposed by Takahashi et al. in Figure 4.

After each excitation case, subjects completed a questionnaire in which they were asked to rate their experience. Levels of anxiety and action difficulty were ranked into five categories in the questionnaire, while action taken to assure safety (protective action) was divided into four categories, as shown in Table 2. Levels of anxiety and action difficulty were determined in reference to the Takahashi et al. and an additional descriptive phrase was given in parentheses. When ranking action difficulty during the sitting experiments, subjects were asked to imagine that they were standing.

Table 1. Experimental condition

	Experiment-1	Experiment-2	Experiment-3	
	basal condition	influence of subjects' position	influence of brightness	influence of VR images
Number of subjects	72	47	32	32
Direction of motion	left to right	left to right, front to back	left to right	
Subject pose	sitting	standing	sitting	
Excitation case (excitation cases per subject)	36 (18)	left to right:16 (8) front to back:14 (7)	bright environment:7 dark environment:7	overturning furniture:7 no overturning furniture:7

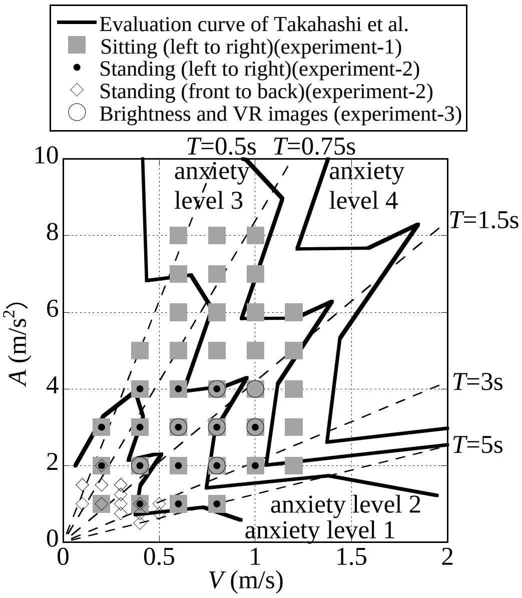


Figure 4. Level of vibration

Table 2. Questionnaire list

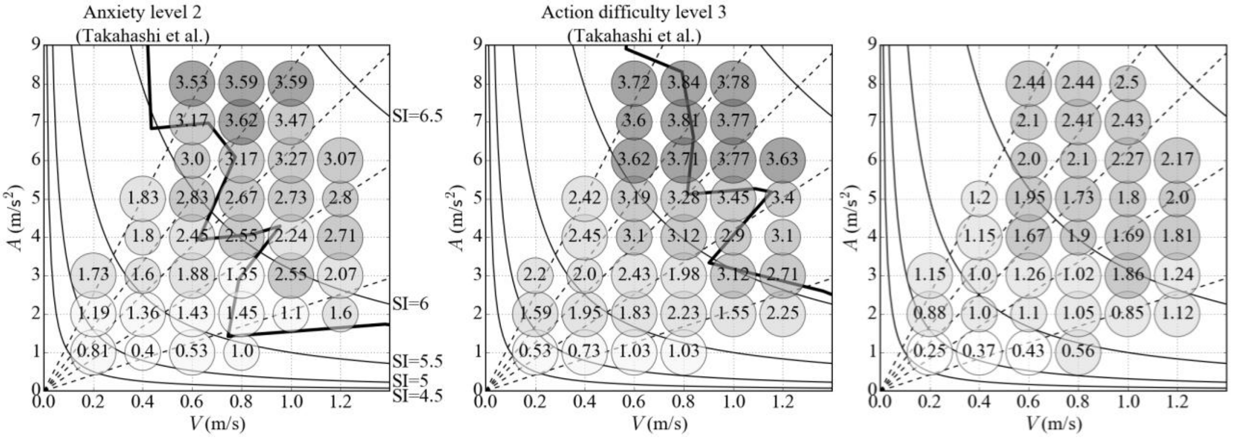
level	Anxiety
0	There was no anxiety (It was nothing.)
1	A little anxious (Nervous but remained calm.)
2	Anxious (Worried but managed to calm down.)
3	Very anxious (Never experienced such motion and not able to remain calm.)
4	Extremely anxious (Frightening; never want to experience it again.)
level	Action difficulty
0	No difficulty standing
1	Shaken a little, but able to remain standing. (Maintained balance by adopting a wide stance.)
2	Shaken greatly, but be able to stand. (Maintained balance only by adjusting feet.)
3	Difficulty standing without holding onto something.
4	Not able to stand.
level	Protective action
0	Didn't feel in danger.
1	Felt in danger and took action to protect myself.
2	Felt in danger, but could not take action to protect myself because of the strong motion.
3	Felt in danger, but could not take action to protect myself because of fear.

2.2 Results of Experiments

As an example of the experiment results, the relationship between vibration intensity and human sensitivity in Experiment-1 (basal condition) is shown in Figure 5. Here, subjects' responses are aggregated for each level shown in Table 2 in each excitation case and the average value is shown. Instrumental seismic intensity (SI) as calculated using formula (1) (Takemura 2003) and the evaluation curves proposed by Takahashi et al. (for level 2 of anxiety and level 3 of action difficulty) are also shown in the figure.

$$SI=\log_{10}AV+5.5 \qquad (1)$$

Figure 5(a), (b) make clear that as A increases, anxiety and action difficulty rise. At high levels of vibration intensity ($A \geq 5$ m/s^2 and $V \geq 0.8$ m/s in the case of anxiety, $A \geq 4$ m/s^2 and $V \geq 0.6$ m/s in the case of action difficulty), changes in V have little effect, but when the vibration intensity is lower, anxiety and action difficulty tend to rise as V increases. In terms of SI, the border between levels 2 and 3 for both anxiety and action difficulty is comparable with SI=6. Comparing these results with the Takahashi et al. evaluation curve for anxiety level 2, although anxiety tends to be slightly higher in the region where A is big, the average value near the curve is about 1.5-2.5, or almost the same as the Takahashi et al. value. For action difficulty, the Takahashi et al. evaluation curve tends to be higher than the experiment results. It is conceivable that this is because subjects were imagining the standing pose when they were responding to the action difficulty question in Experiment-1. As for protective action, as shown in Figure 5(c), people sensed danger when the input motion was $A \geq 2$ m/s^2 and $V \geq 0.4$ m/s, and the ratio of people who felt unable to take any protective action because the motion was too great increased with input motion of $A \geq 3$ m/s^2 and $V \geq 0.6$ m/s.



(a) Anxiety

(b) Action difficulty

(c) Protective action

Figure 5. Average value in each excitation case in Experiment-1(basal condition)

2.3 Construction of Evaluation Curve

Basic evaluation curves are constructed using the results of Experiment-1 (the basal condition). In each excitation case, experimental results are compiled as the ratio (P_R) of subjects who responded higher than a certain level (e.g. anxiety level 2 or more) to all subjects tested. It is presumed that the exceedance probability of reaching each level of human sensitivity to seismic motion x can be represented by the cumulative distribution function with a standard normal distribution $\Phi(x)$, as shown in formula (2). Seismic motion x is expressed using SI, ln$A$ and ln$V$.

$$P_R(x) = \Phi((x-\mu)/\sigma) \qquad (2)$$

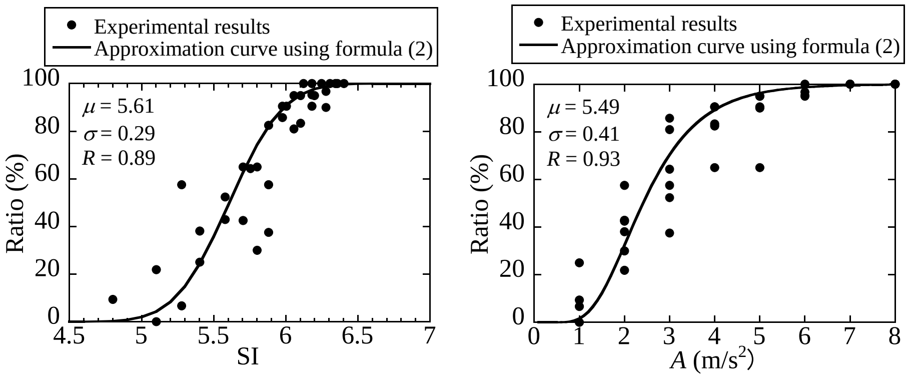
where μ is the mean value and σ is the standard deviation as calculated by the least-squares method.

In order to eliminate probabilities $P_R(x) = 0$ and $P_R(x) = 1$, the range of experimental results used for approximation is set to SI≤6.3 for level 2 or more and SI≥5.5 for level 4. (For protective action, SI≤6.3 for level 1 or more and SI≥5.5 for level 3.) A comparison of experimental results and approximations calculated using formula (2) is shown in Figure 6, where R is a correlation coefficient. The normal distribution parameters for anxiety, action difficulty and protective action, as estimated by the least-squares method, are shown in Table 3. The smallest value of correlation coefficient R is obtained when approximated in terms of V, while it is largest when approximated in terms of A. Although R is smaller when approximated in terms of SI than A, approximating in terms of SI allows the influence of V to be taken into account, as in the evaluation curves of Takahashi et al. Therefore, two sets of approximation curves (using SI and A) are proposed for the evaluation of human sensitivities to seismic motion, as shown in Table 3. Hereafter in this study, the evaluation curves using SI will be used, since SI can reflect the wave period. These evaluation curves using SI are shown in Figure 7. 50% of people feel a sense of danger and attempt to take protective action (protective action level 1 or more) at SI=5.2 and they become anxious (anxiety level 2 or more) at SI=5.6. The motion level at which people feel no longer able to stand (action difficulty level 3 or more) is about the same as that at which people feel anxious (anxiety level 2 or more). The curves for anxiety level 4 and protective action level 3, both of which represent situations where people feel fear, almost overlap.

Next the evaluation curves for other experimental conditions are examined. First of all, the influence of changing experimental conditions is analyzed from the results of Experiments-2 and -3. The influence of the subject pose and the direction of the input motion are shown in Figure 8 and the influence of the indoor environment is shown in Figure 9. Approximation curves are also shown in the figures. These curves were approximated using formula (2), assuming that standard deviation σ is the same as in the basal condition so that the deviations from the basal condition can be expressed by difference in average μ. In Figure 8, anxiety is higher in a standing position than when sitting, but difficulty of action is lower in the standing position. Subjects are answering that it is difficult to take action by imagining that they are standing. Thus, subjects tend to feel that taking action would be

Table 3. Normal distribution parameters (basal condition)

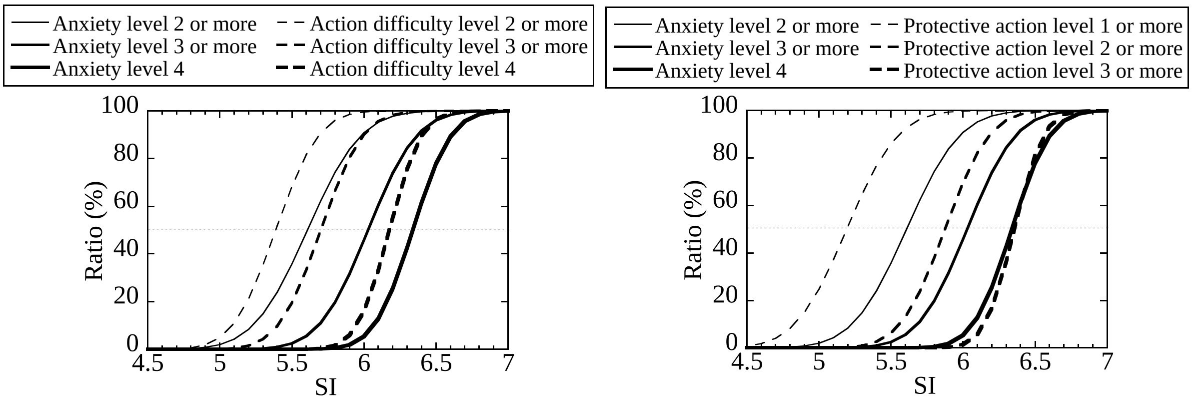
Items	level	SI			A			V		
		μ	σ	R	μ	σ	R	μ	σ	R
Anxiety	2 or more	5.61	0.29	0.89	5.49	0.41	0.93	3.58	0.85	0.57
	3 or more	6.03	0.27	0.92	6.07	0.37	0.93	4.62	0.69	0.43
	4	6.34	0.21	0.82	6.54	0.32	0.93	16.48	8.29	0.41
Action difficulty	2 or more	5.39	0.23	0.86	5.10	0.37	0.93	3.24	0.51	0.53
	3 or more	5.70	0.23	0.89	5.60	0.34	0.93	3.84	0.50	0.52
	4	6.18	0.18	0.89	6.36	0.35	0.94	4.86	0.61	0.38
Protective action	1 or more	5.19	0.28	0.85	4.86	0.42	0.97	2.64	0.70	0.44
	2 or more	5.88	0.24	0.92	5.86	0.37	0.90	4.22	0.51	0.52
	3	6.36	0.16	0.80	6.68	0.31	0.93	5.72	0.68	0.19



(a) Approximated in SI

(b) Approximated in A

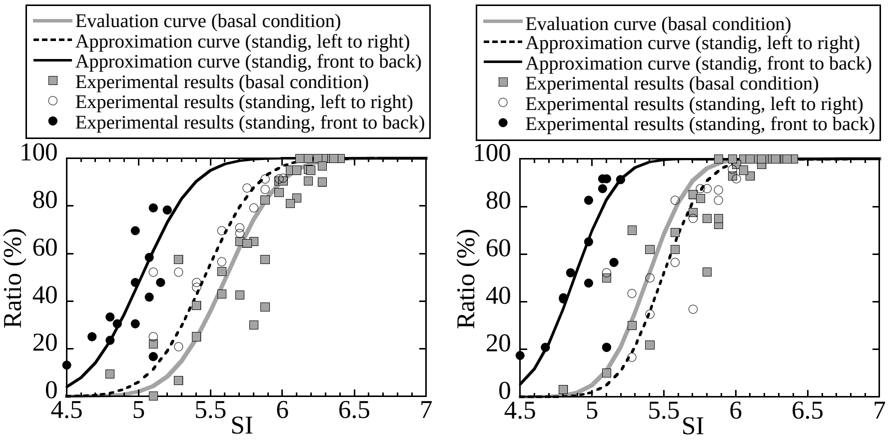
Figure 6. Approximation by normal distribution function



(a) Anxiety and action difficulty

(b) Anxiety and Protective action

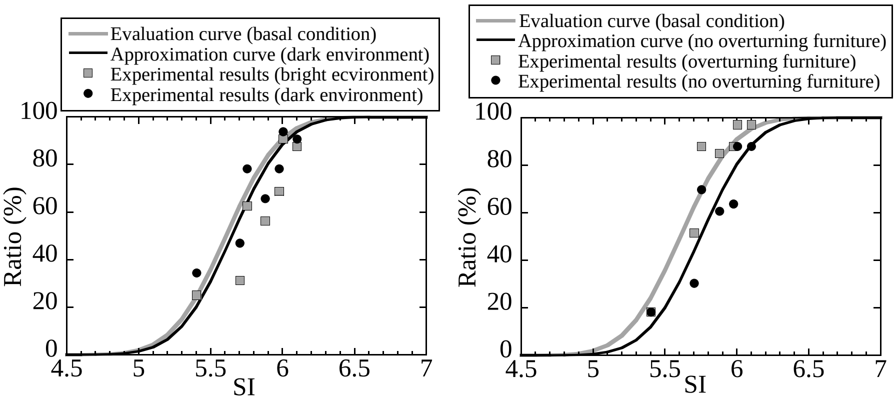
Figure 7. Evaluation curves using SI



(a) Anxiety level 2 or more

(b) Action difficulty 2 or more

Figure 8. Influence of subject position and direction of input motion



(a) Brightness

(b) VR images

Figure 9. Influence of indoor environment

more difficult when in a sitting position than when in a standing position. Clearly, action difficulty should be determined from results obtained from subjects in the standing position. However, considering situation that when an earthquake occurs, sitting people may make a judgment whether they would take action by imagining that they are in a standing position, sitting posture is used as the basal condition, also for the evaluation curve that provides a basis for action difficulty. Looking at the direction of the input motion, difference of μ in front to back and left to right is so big that it is 0.44 in anxiety and 0.61 in action difficulty. Figure 9(a) compares the ratio of subjects who answered anxiety level 2 and more in a well-lighted room (typical daylight; illuminance 454 lx, the same as in the basal condition) with that in a dark room (darkness; illuminance 0 lx). The influence of brightness on anxiety is minimal. Figure 9(b) compares cases with VR images of whether furniture overturning or not. Anxiety tends to be lower when furniture does not appear to be overturning.

Variations in μ in different experimental conditions are calculated in the same way as in Figures 8 and 9 are shown in Table 4. For vibration intensity corresponding to 50% of the basal condition, the difference in exceedance probability is significant, at 5% or more. If the difference in μ was more than 0.05, it would be considered as significant value for different experimental conditions; in Table4, the significant values are shown in halftone grey. The difference is about 0.1-0.2 for changing position and about 0.5 for changing the direction of the input motion. As for the indoor environment, brightness barely influences anxiety and has little effect on difficulty of action and protective action. The influence of overturning furniture is about 0.1-0.2. To compensate for this, the μ value given by the evaluation curve calculated under the basal condition can be modified by adding $\Delta\mu$ when position, motion direction or the indoor environment change, as shown in Table 5. Each value in Table 5 is determined by rounding the value in Table 4. Correction value of the direction of the input motion is determined by comparing values of standing position, assuming that the subject's pose would not affect. Regarding the influence of overturning furniture, there was little difference between the basal condition (no VR images) and when showing VR images with furniture not overturning, so the correction value for no overturning furniture can be directly added.

Table 4. Differences in average μ under different

Items	level	sitting-standing	left to right - front to back	bright - dark	overturning furniture - no overturning furniture
Anxiety	2 or more	0.15	0.44	-0.04	-0.14
	3 or more	0.13	0.40	0.01	-0.05
	4	0.19	0.47	-0.05	-0.07
Action difficulty	2 or more	-0.10	0.61	-0.09	-0.15
	3 or more	-0.06	0.40	-0.08	-0.18
	4	0.26	0.47	0.13	-0.04
Protective action	1 or more	0.02	0.45	-0.26	-0.24
	2 or more	0.08	0.40	-0.03	-0.29
	3	0.19	0.62	0.15	-0.11

Table 5. Evaluation formula corrections under different

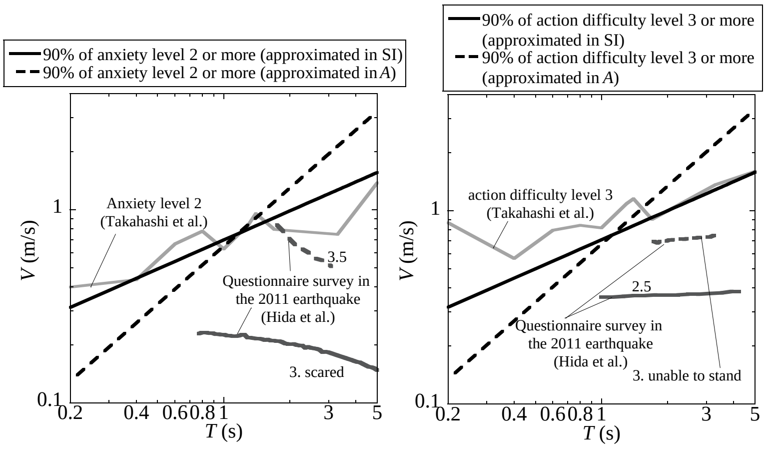
Items	level	basal condition		The difference of $\Delta\mu$ in different experimental condition			
		μ	σ	standing	front to back	dark environment	no overturning furniture
Anxiety	2 or more	5.61	0.29	-0.2	-0.5		+0.1
	3 or more	6.03	0.27	-0.2	-0.5		+0.1
	4	6.34	0.21	-0.2	-0.5		+0.1
Action difficulty	2 or more	5.39	0.23		-0.5		+0.2
	3 or more	5.70	0.23		-0.5		+0.2
	4	6.18	0.18	-0.2	-0.5	-0.2	
Protective action	1 or more	5.19	0.28		-0.5		+0.2
	2 or more	5.88	0.24	-0.1	-0.5		+0.2
	3	6.36	0.16	-0.2	-0.5	-0.2	+0.1

2.4 Comparison with Past Studies

Figure 10 compares the evaluation curves obtained in this study with those of Takahashi et al. based on shaking table tests and Hida et al. based on a questionnaire in the 2011 off the Pacific coast of

Tohoku Earthquake. The current curves are drawn by calculating the relationship between T and V from the SI and A values at which the exceedance probability becomes 90% for anxiety level 2 and more and for action difficulty level 3 and more. For Takahashi et al., the evaluation curves for anxiety level 2: "anxious" and action difficulty level 3: "very unstable; difficult to take action" are shown, while for Hida et al. the curves for "3: scared" and "unable to stand" are given. It is confirmed that evaluation curves obtained in this study using SI show almost the same inclination against T as those of Takahashi et al. The Hida et al. values for anxiety and action difficulty are higher than those obtained in this study and by Takahashi et al. This is because the current curves and those of Takahashi et al. are derived from experimental results with sinusoidal excitation in one direction, whereas a real earthquake causes shaking randomly in three directions. Further, in a shaking table test, participants know that shaking is about to happen, whereas a real earthquake cannot be predicted. Thus differences in mental state are thought to be one of the factors resulting in the discrepancy.

The index of evacuation difficulty proposed by Hida et al. is compared with the current results in Figure 11. The evacuation difficulty index is based on A, so evaluation curves based on A are used for comparison. Hida et al. define evacuation as impossible when respondents choose "thrown around by the motion; could do nothing" or "unable to remain standing" and hence calculate the difficulty of evacuation. It is considered that this is equivalent to action difficulty level 3 or more and protective action level 2 and more in this study. Figure 11 shows that the evacuation difficulty curve of Hida et al. is almost the same as the evaluation curve for action difficulty level 2 and more and protective action level 1 and more. Comparing the values of A at which the exceedance probability reaches 50%, the value for action difficulty level 3 or more is about twice as high as that for evacuation difficulty while the value for protective action level 2 and more is about two and a half times higher. The reason for A of evacuation difficulty being lower than the equivalent evaluation curve is thought to be that it was calculated from results of shaking table tests using the three-directions motion record of the 2011 off the Pacific coast of Tohoku Earthquake and that the duration is long. These results suggest it is necessary to consider the mental state of subjects during an earthquake when developing evaluation curves.



(a) Anxiety

(b) Action difficulty

Figure 10. Comparison with past studies

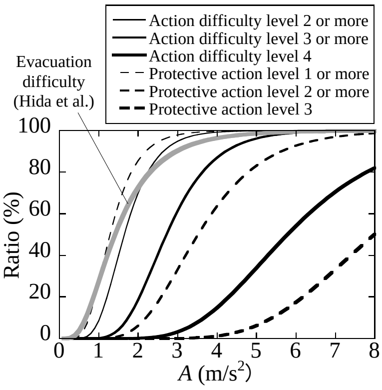


Figure 11. Comparison with evacuation difficulty index by Hida et al.

3. EVALUATION OF EFFECT OF HIGH-RISE BUILDING MOTION USING PROPOSED EVALUATION CURVES

In this section, the evaluation curves are used to examine how the motion of high-rise buildings in Tokyo would affect human residents.

3.1 Method of Estimating Who Feels Anxious or Has Difficulty Taking Action

To determine the effect of high-rise building motion on residents, the number of people who feel anxious or have difficulty taking action is estimated for each building. Specifically, the number of people N_i in these categories under building motion i is calculated using formula (3).

$$ {}_kN_i = \sum_{j=1}^{NF_i} n_{ij} \cdot \left(SI_{ij}\right) \qquad (3)$$

where k is the level of anxiety or action difficulty, f_k is the evaluation curve of human sensitivity (basal condition), SI_{ij} is the vibration intensity on floor j, which can be calculated from maximum acceleration A and maximum velocity V using formula (1), and n_{ij} is the number of people on floor j which can be calculated from formula (4) for each use.

$$ n_{ij} = \begin{cases} \dfrac{(\text{standard floor area})\times(\text{rentable floor area})}{(\text{area per person})} & (\text{office}) \\ \dfrac{(\text{total number of residences per floor})}{(\text{number of floor})} \times (\text{number of people per household}) & (\text{residence}) \\ \dfrac{(\text{total room number})}{(\text{number of floor})} \times (\text{number of people per room}) & (\text{hotel}) \end{cases} \qquad (4)$$

The standard floor area, if unknown, can be calculated by dividing the total floor area of the building by the number of floors. The rentable floor area ratio is determined according to building age from a survey of Tokyo buildings published by the Japan Building Owners and Managers Association (2013). Office area per person is assumed to be 11.9m^2 based on the same survey. The number of people per household is defined by ward in the national Census results (2015). The number of people per hotel room is assumed to be the same as the number of people per household.

3.2 Method of Estimating High-rise Building Vibration

The vibration intensity at each floor of each high-rise building is calculated from seismic response analysis using the MDOF model according to structural type and number of floors. Each floor is assumed to have the same mass and the rigidity distribution with height is linear. The natural period of building T (s) is calculated from formula (5) according to structural type and eaves height H (m).

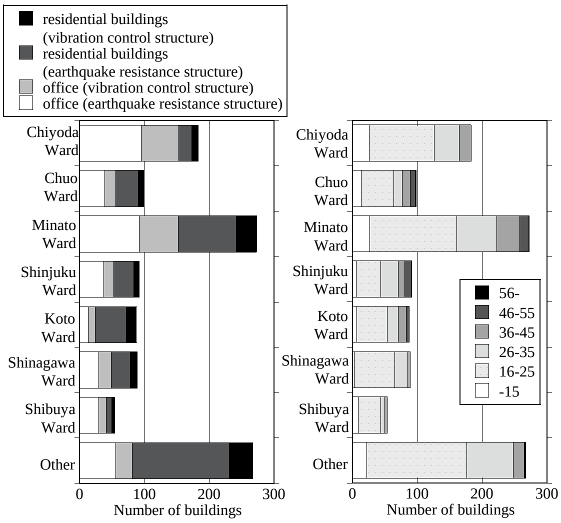
$$T=0.0255H \text{ (S)},\ 0.0223\,H \text{ (RC)},\ 0.024\,H \text{ (SRC)} \qquad (5)$$

Formula (5) is an approximated straight line representing the relationship between eaves height and natural period for the design of high-rise buildings in Tokyo as described in the building letter. The relationship between modification of each floor and yield strength is expressed as a tri-linear curve. Yield strength at the failure point is set to be uniform for the design shear coefficient. Damping is made proportional to stiffness at a ratio to natural frequency of 2% for steel (S), 2.5% for steel and reinforced concrete (SRC), 3% for reinforced concrete (RC) buildings. A 1% increment is added for a vibration control structure. If information about the vibration model was published in the building letter, the natural period and design shear coefficient are set to these values. After calculating the maximum story drift angles when subject to standard 3-directional waves using MDOF models, it is confirmed that almost all are smaller than 1/100.

3.3 Target Buildings and Earthquakes

The targets of this evaluation are buildings 60m or higher within the twenty-three wards of Tokyo, as listed in the Annual Building Construction Report for Tokyo, except for isolated buildings. For building response analysis calculations and estimating numbers of people, information about the site, structural type, number of floors, age, usage and standard floor area (or total floor area) as given in the Annual Building Construction Report are used. Earthquake-resistant structures and vibration-control structures are distinguished through Internet searches and other methods, as are numbers of rooms/residences (in the case of hotels or residential buildings). The number of target buildings by ward is shown in Figure 12. It is confirmed that there are many high-rise buildings in Minato and Chiyoda wards, that more than half of the buildings have 25 floors or less, and 20%-30% of the buildings are vibration control structures. The number of people in each building, as estimated using formula (4), increases as the number of floors rises and is higher in office buildings than in residential buildings, as Figure 13 shows.

The target earthquake is the 2011 off the Pacific coast of Tohoku Earthquake. The ground wave as recorded at the observation point near each building is used. The size of the input motion in each location is shown in Figure 14.



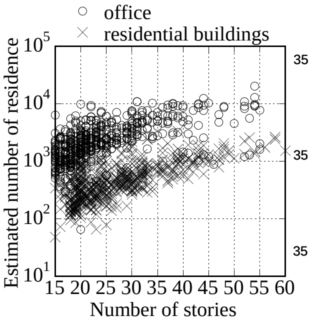


Figure 13. Estimated number of people in target buildings

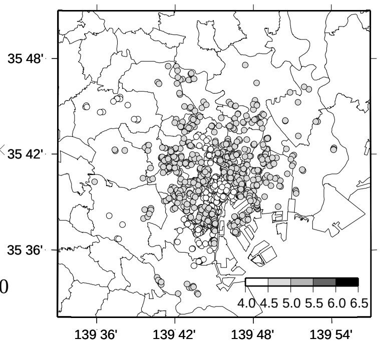


Figure 14. Size of input motion

Figure 12. Number of buildings by ward

3.4 Influence of Seismic Motion

Input motion and maximum response values of each building resulting from the 2011 off the Pacific coast of Tohoku Earthquake are shown in Figure 15. The figure shows minimum, average and maximum values aggregated by the same number of stories. The responses shown in the figure are the maximum value of all floors. Maximum values of earthquake ground motion and maximum response recorded in high-rise buildings (Hida et al. 2012b and Kashima et al. 2012) are shown in the figure for comparison. Values recorded in high-rise buildings are generally included in scope of building response or input motion size. For residential buildings, the minimum, average and maximum values of exceedance probability at anxiety level 2 or more and action difficulty level 3 or more, aggregated by the same number of stories, are shown in Figure 16.

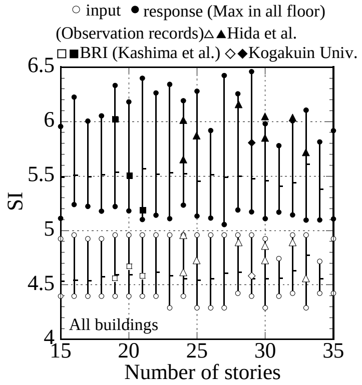


Figure 15. Range of input and response

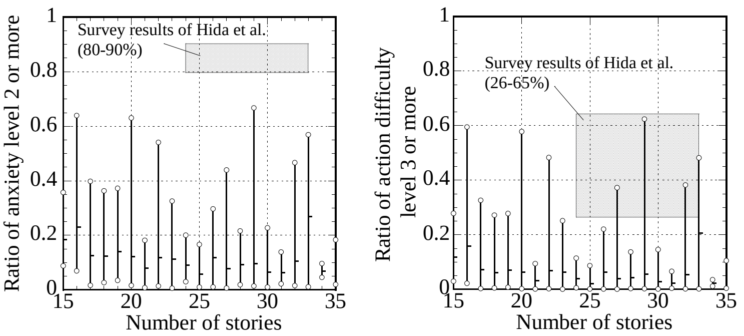


Figure 16. Ratio of people influenced by the motion (residential buildings)

According to Hida et al. survey of residents in eight high-rise residential buildings with 24-33 stories, the proportion answering that they were “very scared” or “scared” (which are the responses most closely corresponding to anxiety level 2 or more) was 80%-90% (an average of 83% for all buildings). Also, the proportion answering “unable to take action” and “unable to remain standing” (which are the responses most closely corresponding to action difficulty level 3 or more) was 26-65% (an average of 48% for all buildings). These estimated ratios vary by building. For buildings with the same number of stories as in Hida et al. survey, anxiety is so low that the average exceedance probability by the same number of stories is about 10% and the maximum is about 20%-60%. Values would be higher if the subject pose or the input motion direction were to be considered, but, according to Figure 8, even then anxiety would only be about double at SI=5.5 and action difficulty would only be about 1.5 times if subjects were standing and the input motion was front to back. This discrepancy is considered a result of basing the evaluation curve on a short duration of motion rather than taking into account the influence of long-duration motion.

The ratio of people who feel anxious is compiled by ward and shown in Figure 17. A high ratio of people in Koto ward feels anxious. This is because Koto ward faces the Tokyo bay and the input motion was larger than other wards. Anxiety levels in earthquake resistance structures and vibration control structures are compared in Figure 18; in most wards, the ratio of people who feel anxious is lower in vibration control structures. As Figure15 shows, building response of tall buildings tend to be smaller than low buildings, so people in buildings with vibration control structures which tend to have more floors than earthquake resistance structures less likely to feel the anxiety.

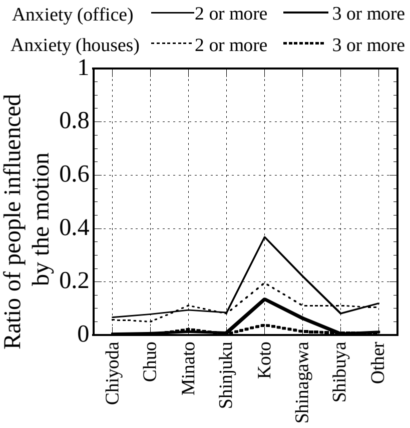


Figure 17. The ratio of people who feel anxious

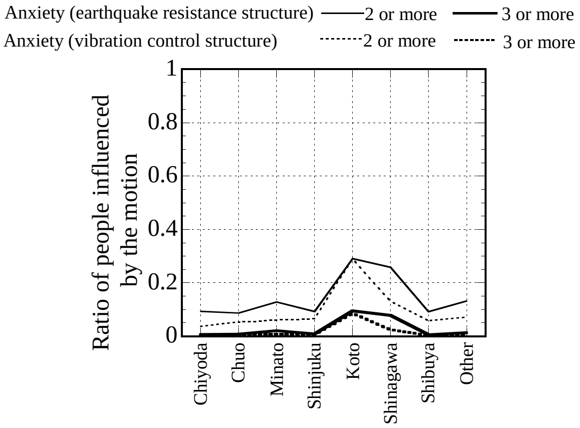


Figure 18. Comparison of earthquake resistance structures and vibration control systems

4. CONCLUSIONS

In this study, experiments with human subjects are performed under the same conditions as similar recent studies. Ratios of people expressing anxiety and action difficulty are adopted as indexes of sensitivity to each level of vibration, assuming a normal probability distribution function. The relationship between vibration characteristics and human sensitivity can then be determined using evaluation curves based on simple functions. Further experiments were performed with parameters other than vibration amplitude, such subject pose (standing or sitting) and ambient brightness and so on. From the results, differences in experimental conditions were simply expressed as an average difference from the normal probability distribution function.

The conclusions reached in this work are as follows.

1) The ratio of people who feel anxious or have difficulty taking action can be expressed by as a normal distribution using the acceleration or SI (determined as A x V) of the motion as an index.
2) Over 50% of people feel a sense of danger and attempt to take protective action at SI=5.2.

They become anxious at SI=5.6.

3) Anxiety levels are greatly influenced by the direction of the motion and by the sight of overturning furniture (as shown using VR images). However, anxiety is reduced when furniture remains in place. The level of anxiety is affected somewhat by light level.
4) By predicting the response of high-rise buildings in the 23 wards of Tokyo to a the 2011 off the Pacific coast of Tohoku Earthquake, the influence that seismic motion has on a person was estimated using the evaluation curve for the basal condition in the experiments. The ratio of people who feel anxious or have difficulty taking action is lower than found to actually be the case in other recent studies. Even if direction of motion and subject pose (standing or sitting) is taken into account, the evaluated levels do not come close to the actual value. To improve the results, it will be necessary to take into account that an earthquake, unlike shaking table motion, occurs unexpectedly and that earthquake motion may continue for a long time with no clue as to how long it will last.

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