PROPOSED EVALUATION CURVE FOR HUMAN SENSITIVITY TO SEISMIC MOTION CONSIDERING DIRECTION AND DURATION

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Abstract

In a previous study, experiments with human subjects were performed to propose evaluation curves for human sensitivity to seismic motion. Ratios of people expressing anxiety and difficulty in taking action were 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. However, the ratio of people who feel anxious or have difficulty taking action predicted from the evaluation curves was lower than found to actually be the case in questionnaires completed after past earthquakes.

It is thought that one of the reasons for this is that subject attributes were biased. Therefore, in new experiments conducted in this study, the attributes of subjects were extended to include ordinary people. In addition, two kinds of experiments were performed with the aim of developing evaluation curves that are closer to the results of the questionnaires: experiments with basal condition and experiments with different characteristics of vibration. Following the basal condition experiments, the results were analyzed for each subject attribute and the evaluation curves were updated after comparing the experimental results for researcher subjects and non-researcher subjects. Then experiments with changes in three different vibration characteristics were carried out: duration of motion, direction of motion and type of motion (actual earthquake and sinusoidal). The effect of motion characteristics on human sensitivity are analyzed based on the results of these experiments.

The findings are as follows.

- In previous experiments using research engineers with expert knowledge of earthquakes as subjects, anxiety levels generally varied with seismic intensity (SI). However, in new experiments using subjects with little knowledge of earthquakes, anxiety was found to increase with acceleration. Therefore, the evaluation curves were reconstructed to take into account acceleration using the experimental results obtained with non-researcher subjects.
- In the experiments, the duration of motion had almost no effect on anxiety and difficulty in taking action. However, in questionnaires about past earthquakes, some responses suggested anxiety resulting from not knowing how long the motion would last, so the duration of motion seems to affect at least anxiety. Thus there needs to be more analysis on the impact of earthquake duration on levels of anxiety.
- Results indicated that the direction of motion has a particular effect on anxiety when the wave period is about 2s. It is necessary to consider how to reflect the influence of direction of motion in the evaluation curves.
- In the case of actual earthquakes, the motion reaches maximum acceleration and maximum velocity only instantaneously, and anxiety and action difficulty are found to be lower than with sinusoidal waves. Since the evaluation curves are developed from the sinusoidal wave results, it is necessary to consider how to incorporate actual earthquake motion into the evaluation curves.

Keywords: Shaking table test, Anxiety, Action difficulty, Evaluation curve, Experimental subjects

1. Introduction

The seismic performance of buildings has conventionally been evaluated in terms of the structural damage caused by earthquakes. However, there have been reports[1] that during the 2011 Off the Pacific Coast of Tohoku Earthquake, the long duration of the seismic motion caused anxiety among residents of high-rise buildings even though the buildings themselves suffered no damage. With high-rise residential buildings becoming more common, there is a need to design spaces in which people not only remain physically safe, but are also free from anxiety.

The quantification of human sensitivity to large-amplitude motion such as caused by earthquakes has been considered in the past (e.g. [2-6]). There have been studies in which evaluation curves were proposed. However, most of the proposed curves are not simple functions, so to use them for quantitative evaluation requires reading values from plotted curves.

In a previous study by the authors[7], experiments with human subjects were performed under the same conditions as in other recent studies of similar type. Ratios of people expressing anxiety and difficulty in taking action were 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. However, the ratio of people suffering anxiety or have difficulty taking action predicted from these evaluation curves was lower than found to actually be the case in a questionnaire about past earthquakes[8]

It is thought that one of the reasons for this is that the attributes of subjects selected for the studies were biased. In the authors' previous experiments, subjects were chosen from among research engineers at a construction company. In the new experiments conducted in this study, the attributes of subjects are broadened by extended the selection to employees other than researchers as well as ordinary people. In addition, two kinds of experiments are performed in an effort to develop updated evaluation curves that give results closer to those of the questionnaire about actual earthquake experience: experiments with a basal condition and experiments with different characteristics of vibration.

The basal conditions experiment is the same as in the previous study. The experimental results are analyzed for each subject attribute and the evaluation curves are modified by comparing the experimental results for researchers with those for non-researchers.

In the experiment with different characteristics of vibration, experimental conditions are varied in following three ways: duration of motion, direction of motion and type of motion. From the experimental results, the effects of motion characteristics on human sensitivity are analyzed.

Taking the results of these experiments, a study of improvements to the evaluation curve to bring it in line with experience during actual earthquakes is carried out.

2. Outline of experiments

The characteristics of human response measured in this study are anxiety and difficulty in taking action, as shown in Table 1. Because attribute bias is suspected in the earlier 2016 experiments[7], where subjects were chosen from among research engineers at a construction company, in this 2019 study subjects were selected from among employees other than researchers and ordinary people, thereby extending the range of attributes, as shown in Table 2. (The researchers included in the 2019 study include some studying seismic ground motion at university in addition to research engineers from a construction company. Employees other than research engineers means employees not working in laboratories. Ordinary people are people recruited from the public and not involved in construction.) Two kinds of experiments were performed in an effort to bring the evaluation curve in line with results of questionnaires about experience during actual earthquakes: base-condition experiments and experiments with different vibration characteristics.

The basal conditions experiment is the same as carried out in 2016[7]. Input waves were a short one-way sinusoidal wave in the left-right direction. The 22 cases shown in Fig. 1 (sinusoidal wave (basal condition)) were used in the 2019 experiment. Excitation cases were narrowed down to the levels of vibration at which people began to feel anxious in the 2016 experiment. The experimental results for 2016 and 2019 were analyzed for each subject attribute and the evaluation curves revised by comparison with the results obtained in the past study.

In the experiments with different seismic vibration characteristics, two types of waves were used: sinusoidal and actual earthquake waves. The levels of vibration for the sinusoidal wave (changing duration) and earthquake wave are compared with sinusoidal wave (basal condition) in Fig 1. The wave period T was used as a parameter: T = 1,2,3,5s. In order to analyze the effects of duration, the duration of the sinusoidal wave was modified by changing the configuration of waveform sections (numbered 1 to 5), with the basic length as one section as shown in Fig. 2. Changing the waveform length around the basic length makes it easier to compare with basal experiment results. The settings of amplitude ratio a_i of each section and its duration are as shown in Table 3. Rising and falling taper were applied at the beginning and end of the waveform to avoid step changes in vibration magnitude. Earthquake waves used in the experiment were observed earthquake waves with a wave period of 1, 2, 3, 5. For each wave period, like sinusoidal waves, two types were used, one with a short duration (basic length: 9 to 25 s) and one with a long duration (20 to 50 s). Also, in order to analyze the influence of the direction of the motion, two types of seismic waves were applied: left-right motions and motions in both back-and-forth and left-right directions. Examples of short and long duration waves with T = 1s are shown in Fig.3.

Analysis of how to make the evaluation curve close to the actual earthquake will be carried out in the next chapter.

Table 1 – Questionnaire list

Level	Anxiety
0	Not anxious at all
1	A little anxious
2	Anxious
3	Very anxious
4	Extremely anxious
Level	**Action difficulty**
0	No difficulty standing
1	Some shaking, but able to remain standing
2	Violent shaking, but be able to remain standing
3	Difficulty standing without holding onto something
4	Not able to remain standing

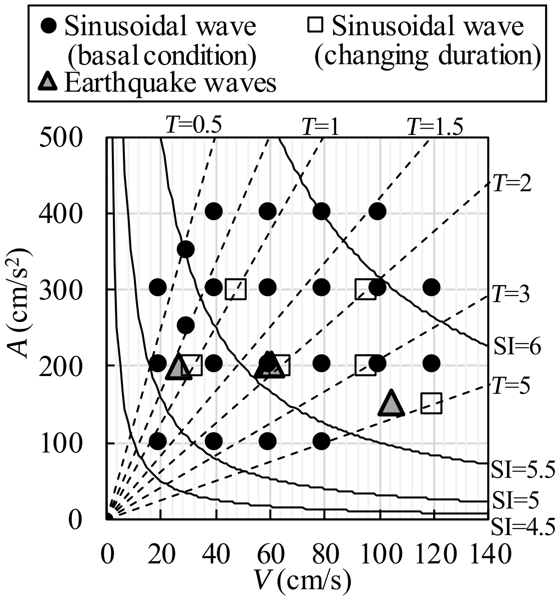


Fig. 1 – Level of vibration

Table 2 – Attributes and number of subjects

Items	Attribute of subjects	Number of subjects
Experiment-2016	Research engineers (employees)	62
	Employees (other than research engineers)	10
Experiment-2019	Research engineers (employees and students)	12
	Employees (other than research engineers)	84
	Ordinary people	83

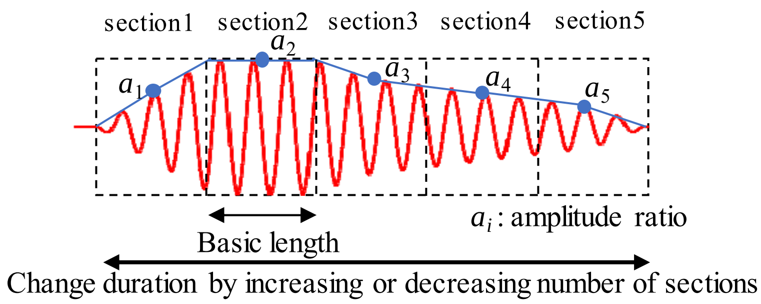
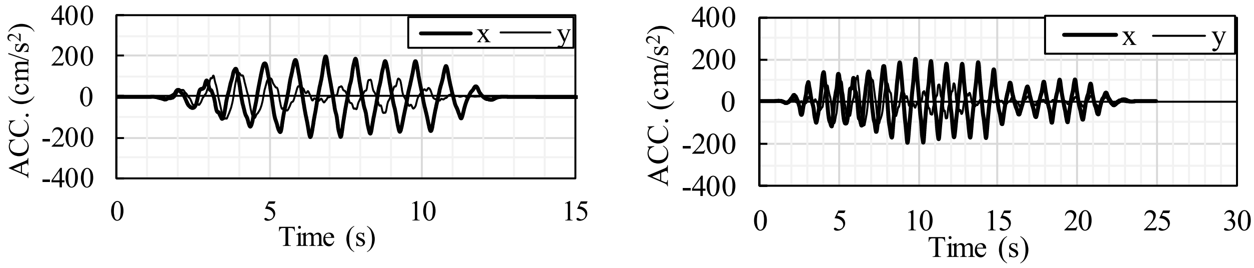


Fig. 2 – Duration setting method

Table 3 – Setting of amplitude ratio and duration

T (s)	Amplitude ratio a_i					Duration (s)
	section 1	section 2	section 3	section 4	section 5	
1	-	1	-	-	-	9
	-	1	0.5	-	-	20
2	-	1	-	-	-	10
	0.5	1	0.7	0.5	-	40
3	-	1	-	-	-	15
	0.5	1	0.7	0.5	0.3	50
5	-	1		-	-	25
	0.7	1		0.7	0.5	50



(a) Short duration (basic length)

(b) Long duration

Fig. 3 – Examples of earthquake waves (T=1s)

3. Effect of attribute of subjects

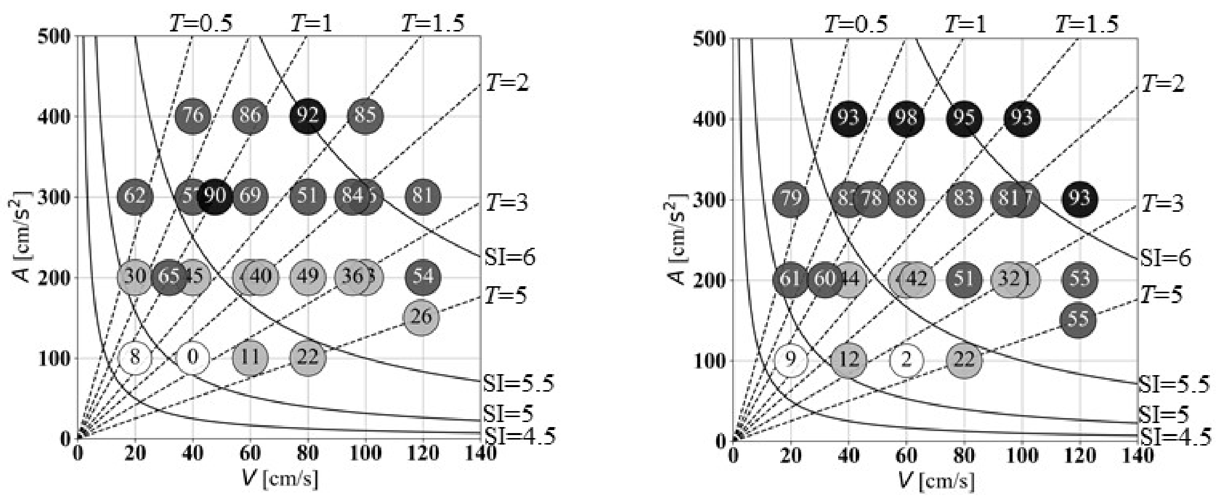
3.1 Results of experiments

Experimental results for each subject attribute are shown in Fig. 4. In each excitation case, experimental results of are compiled as the ratio of subjects who responded with anxiety level 2 or more to all subjects tested. Instrumental seismic intensity (SI), as calculated using Eq. (1)[9], and wave period T (s) are also shown in the figure.

$$SI=\log_{10}AV+1.5 \tag{1}$$

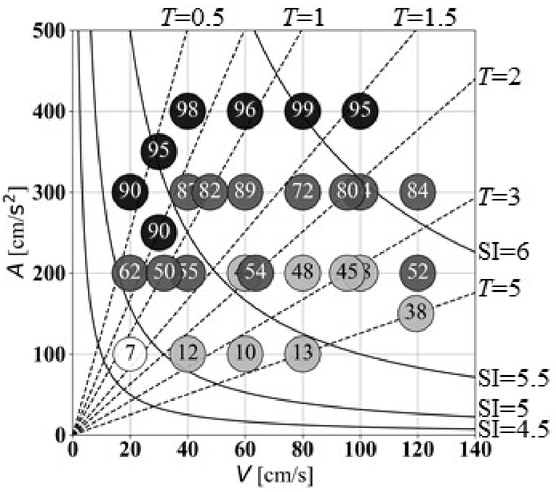
Within the range of acceleration $A \geqq 200$ (cm/s^2) and period T <1.5s, the ratio tends to be higher among employees other than research engineers and ordinary people than among research engineers. For research engineers, with excitation at a particular acceleration, the ratio is getting smaller for short period waveforms T<1s. The value of SI is similar, where the value decreases at a particular acceleration when the period is short. On the other hand, people other than research engineers have increased anxiety in response to acceleration regardless of wave period. Comparing the ratio of researchers and non-researchers who responded with anxiety level 2 or more by the period of the input wave, as shown in Fig. 5, it is clear that people other than researchers are more likely to feel anxious than researchers with input waves of T <1.5s. This difference of up to 25% between researchers and non-researchers may result from having expert knowledge of earthquakes. Not all researchers who participated in the 2016 experiment were involved in earthquake research. However, because research ideas are shared around the laboratory, there is generally more knowledge of earthquakes than among ordinary people. Further, many researchers know what kind of earthquake is dangerous because they have experienced simulated earthquakes on shaking tables. These are considered the reasons for the high level of anxiety among ordinary people who have little knowledge of earthquakes, while employees who have little experience of earthquakes on shaking tables also had higher anxiety than researchers.

Taking into account these results, analysis in the following sections will make use of experimental results from subjects other than researchers.



(a) Research engineers (b) Employees (other than research engineers)

Fig. 4 – Ratio of people who responded with anxiety level 2 or more in each excitation case (basal condition)



(c) Ordinary people

Fig 4 – Ratio of people who responded with anxiety level 2 or more in each excitation case (basal condition)

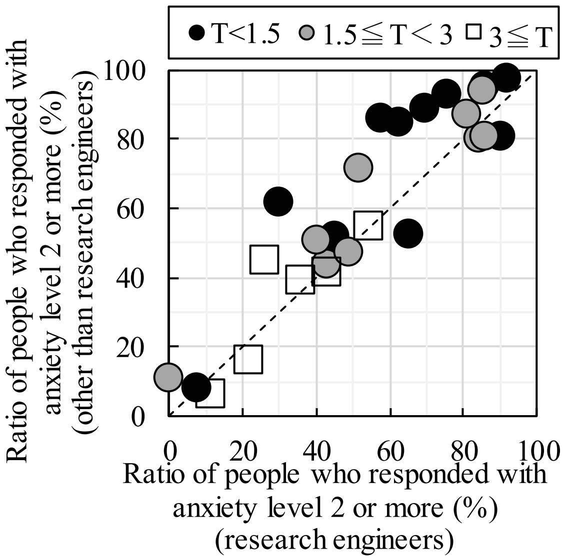


Fig. 5 – Difference between research engineers and others

3.2 Modification of evaluation curve

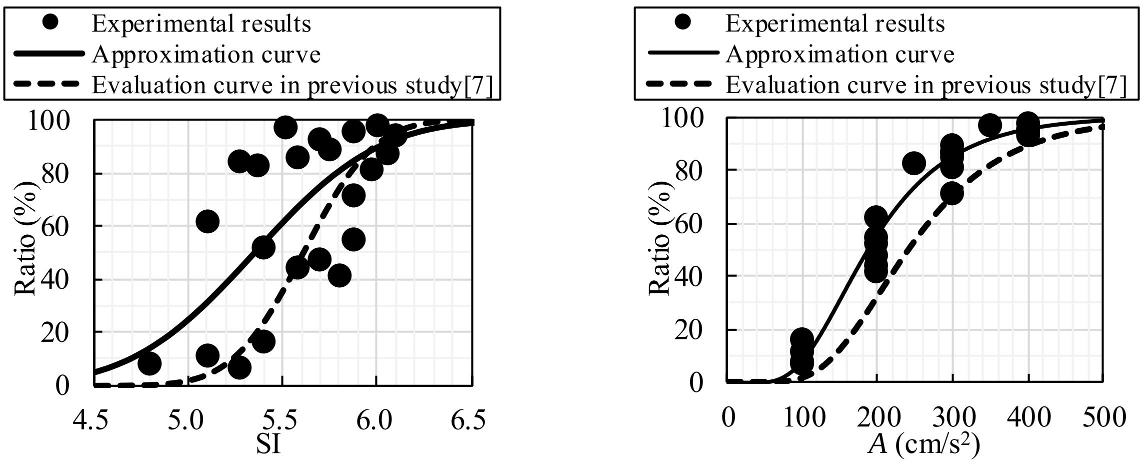
As in the previous study [7], evaluation curves are constructed but in this case using the results for subjects other than researchers. In each excitation case, experimental results are compiled as the ratio (P_R) of subjects who responded higher than a certain level (e.g. anxiety level 2 or more) to all subjects tested. It is presumed that the probability of exceeding 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$A$.

$$P_R(x) = \Phi((x - \mu)/\sigma) \tag{2}$$

where μ is the mean value and σ is the standard deviation as calculated by the least-squares method. A comparison of experimental results and approximations calculated using formula (2) is shown in Figure 6, where R is a correlation coefficient. The evaluation curves proposed in previous study [7] are also shown in the figure. The evaluation curve from the earlier study is lower than the result for subjects other than researchers, indicating that it was an underestimate.

The normal distribution parameters for anxiety and action difficulty, as estimated by the least-squares method, are shown in Table 4. Here, R is moderate with a maximum value of 0.72 when approximated in terms of SI, whereas it reaches 0.98 or more when approximated in terms of A. Although similar results were obtained in the earlier study, approximating in terms of SI allowed the influence of wave period to be taken into account. Since the value of R was bigger than 0.8 at that time, evaluation curves using SI were adopted. However, from the experimental results obtained in this research for subjects other than research engineers, it is found that the correlation of human sensitivity to seismic motion is higher when seismic motion x is approximated by ln$A$ than by SI.

Given the above, approximation curves using A are newly proposed for the evaluation of human sensitivity to seismic motion. These are shown in Fig. 7.



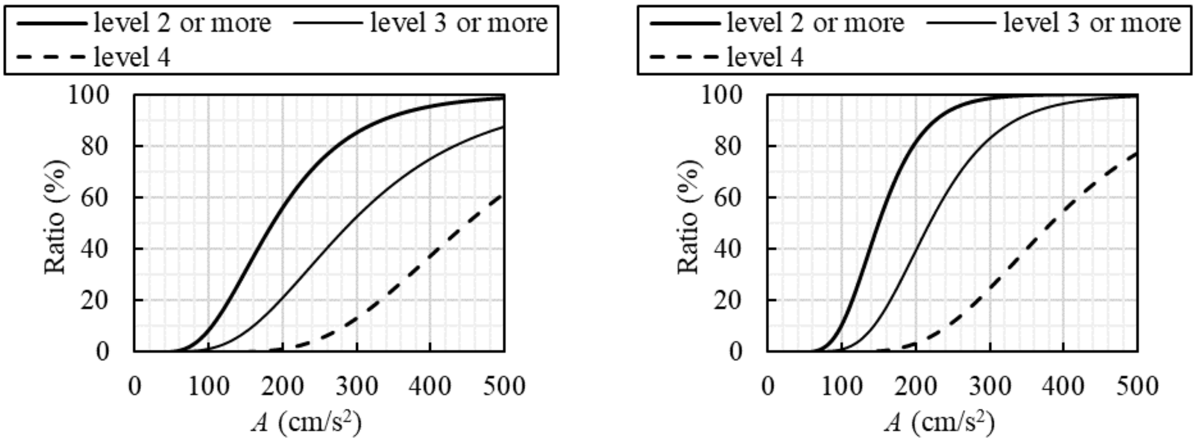
(a) Approximated in SI

(b) Approximated in A

Fig. 6 – Approximation by normal distribution function

Table 4 – Nomal distribution parameters (basal condition)

Items	level	SI			A		
		μ	σ	R	μ	σ	R
Anxiety	2 or more	5.36	0.52	0.62	5.23	0.46	0.98
	3 or more	5.85	0.52	0.58	5.67	0.47	0.98
	4	6.29	0.37	0.60	6.11	0.36	0.99
Action difficulty	2 or more	5.13	0.35	0.72	5.01	0.32	0.98
	3 or more	5.54	0.32	0.63	5.39	0.33	0.99
	4	6.10	0.36	0.66	5.95	0.36	0.98



(a) Anxiety (b) Action difficulty

Fig. 7 – New evaluation curves

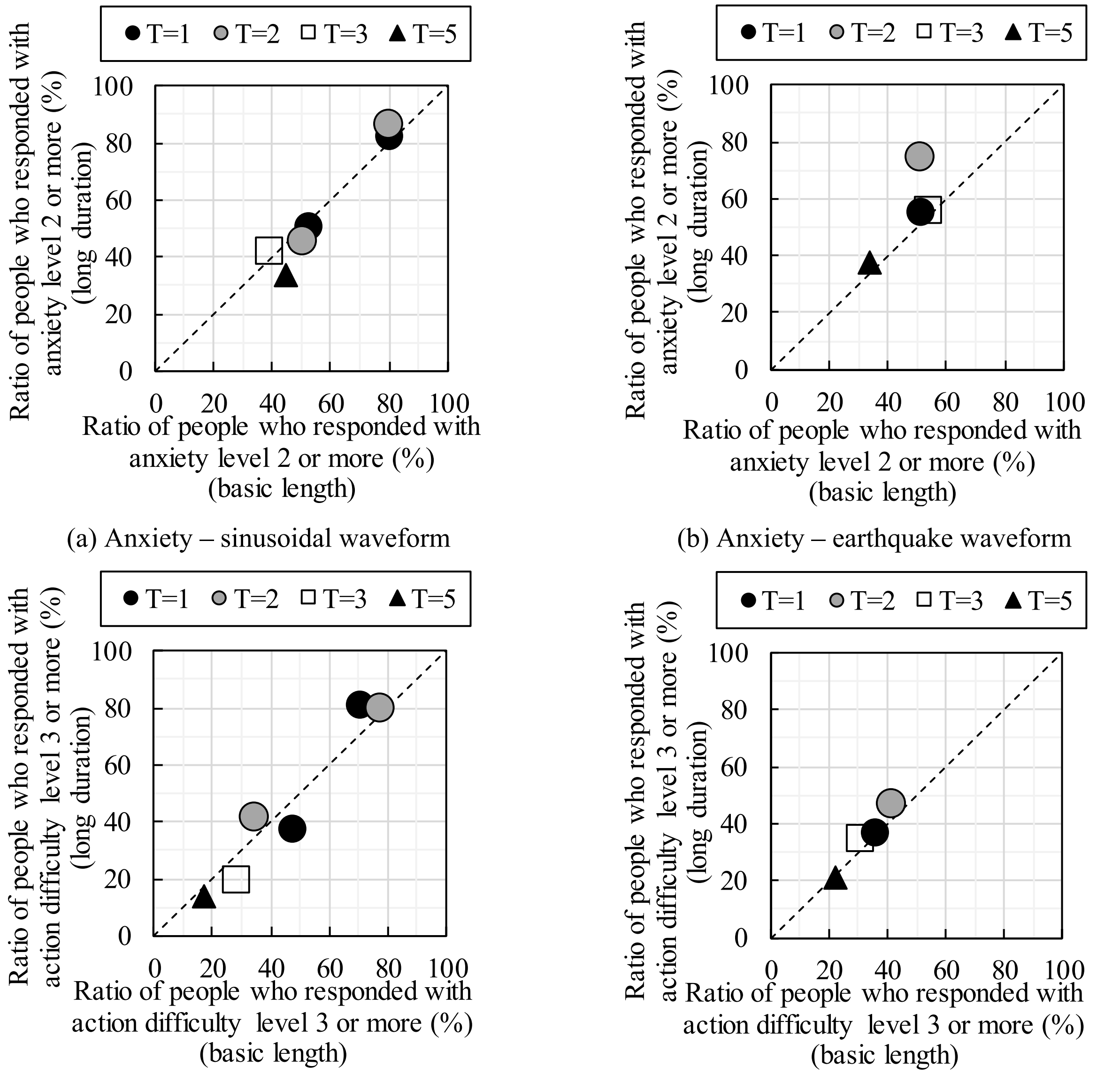
4. Effect of vibration characteristics

In this chapter, the effects of vibration characteristics on human sensitivity are analyzed. Here, the analysis of anxiety is based on responses of anxiety level 2 or more and the analysis of action is based on responses of action difficulty level 3 or more, which means difficulty standing without holding onto something.

4.1 Duration of motion

Figure 8 shows the difference in anxiety ratio and action difficulty between short duration (basic length) and long duration motion. The effect of duration time is compared for two the types of waveform: sinusoidal and the actual earthquake waveform. Regarding anxiety, there is almost no variation with duration when the input waveform is sinusoidal. One of the reasons for this is thought to be that, when setting up a long sinusoidal wave, the amplitude ratio of the added section is small, so the duration of motion at the maximum acceleration and maximum velocity is not different from that in the case of the basic length. On the other hand, in the case of the earthquake waveform, the anxiety ratio increases by about 25% with the longer duration of the T = 2s wave. This suggests that for earthquake waves with a wave period close to 2s, the ratio of people who feel anxiety will increase with a longer duration. Regarding action difficulty, duration had hardly any effect for both sinusoidal and earthquake waveforms. This cause is considered to be similar to the cause of anxiety.

These results demonstrate that there is almost no effect of duration on anxiety and action difficulty in the experiment. However, in a past earthquake questionnaire [1], some expressed the opinion that they became anxious because of not knowing how long the earthquake would last, so the duration of motion does seem to affect at anxiety at least. This analysis of how motion duration affects anxiety needs to be continued.



(a) Anxiety – sinusoidal waveform

(b) Anxiety – earthquake waveform

(c) Action difficulty – sinusoidal waveform

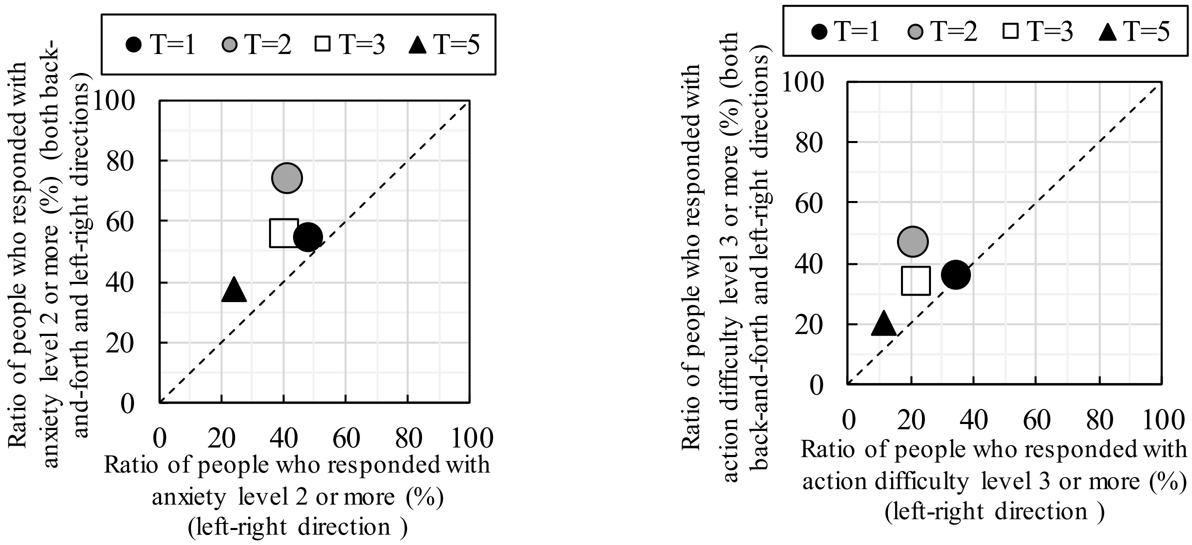
(d) Action difficulty – earthquake waveform

Fig. 8 – Effect of motion duration

4.2 Direction of motion

Figure 9 plots anxiety and action difficulty for shaking in the left-right direction against that in both back-and-forth and left-right directions. In these experiments, only the earthquake waveform was used and the results reflect this. The anxiety and action difficulty ratios are both higher for shaking in both back-and-forth and left-right directions. The difference is greatest in the T = 2s case. On the other hand, there is very little difference in the T = 1s case.

From these results, it seems that direction of motion has a particularly strong influence in the case of a waveform with a period of about 2s. The evaluation curve presented in Chapter 3 is for evaluating left-right motion, so it is necessary to further consider the influence of the direction of motion according to the wave period.

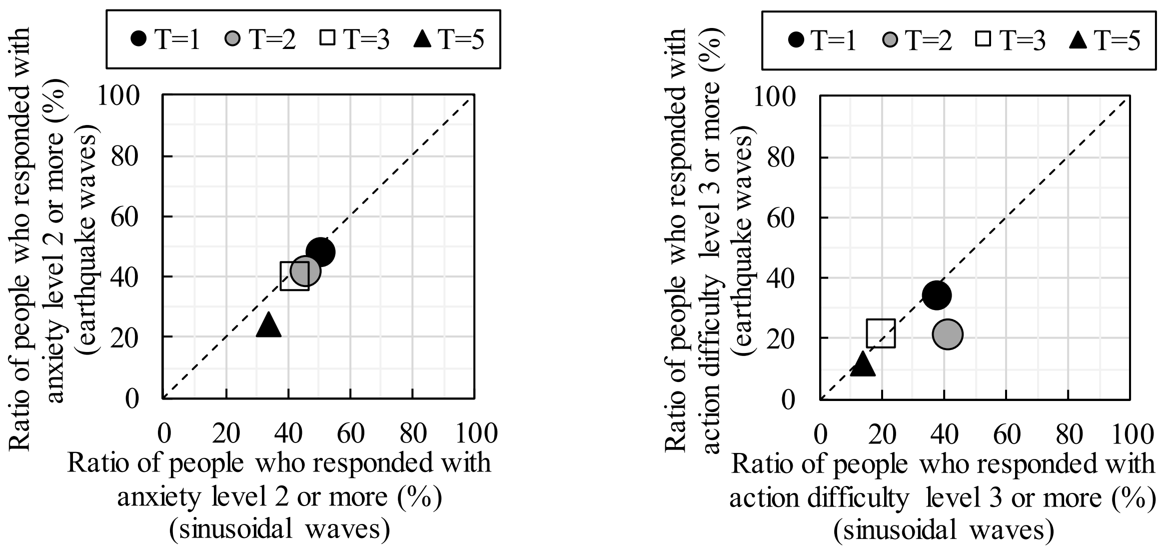


(a) Anxiety – earthquake waves (a) Action difficulty – earthquake waves

Fig. 9 – Effect of direction of motion

4.3 Type of motions

Figure 10 compares the anxiety and action difficulty responses to sinusoidal and earthquake waveforms with the same duration. Both anxiety and action difficulty are slightly higher with the sinusoidal waves than the earthquake waves. This may be because the sinusoidal waveform maintains maximum acceleration and maximum velocity for some length, while the earthquake waveform has an instantaneous maximum acceleration and maximum velocity. Since the evaluation curves are developed using the results for sinusoidal waveforms, it is necessary to consider how to use the evaluation curves to evaluate responses to actual earthquake waveforms.



(a) Anxiety (a) Action difficulty

Fig. 10 – Effect of type of motion

5. Conclusions

The attributes of subjects were found to be biased in previous experiments used to develop evaluation curves for human sensitivity to earthquake motion, so in this study new experiments were conducted with an expanded range of subjects. Experiments of two types were undertaken to bring the evaluation curves closer to the result of questionnaires about actual earthquake responses: basal condition experiments and experiments with different characteristics of vibration. The findings obtained are described below.

- In previous experiments using research engineers with expert knowledge of earthquakes as subjects, anxiety levels generally changed according to seismic intensity (SI). However, when the subjects are not researchers, levels of anxiety are very different, especially in the range of $A \geqq 200$ (cm/s^2), T <1.5s. For subjects with little knowledge of earthquakes, anxiety is found to increase with acceleration. Therefore, the evaluation curves were reconstructed to take into account acceleration using the experimental results obtained with non-researcher subjects.
- In the experiments, the duration of motion had almost no effect on anxiety and difficulty in taking action. However, in questionnaires about past earthquakes, some responses suggested anxiety resulting from not knowing how long the motion would last, so the duration of motion seems to affect at least anxiety.Thus there needs to be more analysis on the impact of earthquake duration on levels of anxiety.
- Results from experiments in which the direction of motion was varied indicate that there is a particular effect on anxiety when the wave period is about 2s. The modified evaluation curve developed in this work is for motion in the left-right direction, so it is necessary to adjust it for the influence of back-and-forth motion according to the wave period.
- In the case of actual earthquakes, the motion reaches maximum acceleration and maximum velocity only instantaneously, and anxiety and action difficulty are found to be lower than with sinusoidal waves. Since the evaluation curves are developed from the sinusoidal wave results, it is necessary to consider how to incorporate actual earthquake motion into the evaluation curves.

5. References

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