Journal of Natural Disaster Science, Volume 24, Number 1, 2002, pp35-42

Instantaneous Instrumental Seismic Intensity and Evacuation

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(Received for 29. Jul., 2002)

ABSTRACT

The earthquake that occurred on October 6, 2000 in western Tottori, Japan is an interesting event because residents living in houses that completely collapsed had time to evacuate. The period which people had time to escape from collapsing buildings was due to the particular aspect of ground shaking. Escape time is another important variable besides building resistance, indoor environment, hour of the day, type of human activity at the time of the earthquake, that must be taken into account. To measure this new variable, a measure and a model that indicate the time available for evacuation are proposed. The measure of transitional characteristics of ground motion is presented as Instantaneous Instrumental Seismic Intensity (IISI). The duration of ground motion is modeled for several periods, which characterize human behavior and the surrounding situation. The evacuation time available defined as the period from when people start to feel the shaking until they cannot move at all, is measured by the IISI. An application that indicates the threshold of the time available to evacuate is examined together with the hypocentral distance and the earthquake's magnitude for practical future use.

1. INTRODUCTION

Seismic physical impacts on people are explained by a combination of ground failure factors (e.g., ground rupture, landslides, and liquefaction), structural damage factors (e.g., damage to residences, commercial buildings, and transportation systems), and functional factors (e.g., human occupancy, human activity, and the indoor environment). Past studies of earthquake-related casualties have mainly focused on physical damage factors, especially house collapse. The collapses of vulnerable houses do in fact cause a large number of human fatalities and injuries. After the 1995 Hyogoken nambu earthquake (M_{JMA}7.2, M_w6.9), which resulted in 6,432 fatalities, several detailed studies have been made of the classes and levels of damage suffered in order to clarify the relationship between house damage and casualties (e.g., Nishimura et al., 1996). Only a few studies, however, have focused on the characteristics of ground motion. Common parameters of ground motion used in earthquake-related casualty estimations are the peak ground acceleration, peak ground velocity, seismic intensity, and SI value. Some studies have investigated the correlation between the peak ground acceleration and number of casualties (Lu and Miyano, 1995) and between seismic intensity and human behavior. Okada (1996), focusing on the time history of ground motion, showed in detail changes in both household and human behavior.

Characteristics of ground motion greatly affect evacuation behavior and loss of human life during earthquakes. Previous case studies on earthquake-related casualties, such as the Hyogoken nambu (Imiya and Ohta, 2000) and Chi-Chi, Taiwan (Kuwata and Takada, 2001) earthquakes, have noted that human behavior and surrounding situation during ground shaking are crucial factors in the saving of human life. As background for our present paper, we report a site survey of casualties suffered during the 2000 Western Tottori, Japan earthquake. This is a particularly interesting case as no human lives were lost occurred despite the collapse of many houses. Overall damage was only slightly less than in the Hyogoken nambu earthquake, but this earthquake showed something novel. The intensity of ground motion changed in the short period of the earthquake, and this affected human behavior. All the case studies cited above provided precious descriptions based on interviews and questionnaire answers given by inhabitants, showing remarkable, although non-analytical, trends in cause and consequence.

Past studies of ground motion and casualties were done in one of two ways; analyses of peak ground acceleration or qualitative characterization of various causes. Advances in this type of research needs to take into account other parameters involved, from the peak point to the duration of ground motion. The transitional characteristics of ground motion need to be examined in order to assess human behavior and surrounding conditions more in detail. Two complicated problems must be tackled: how can the transitional characteristics of ground motion be measured quantitatively and how do ground characteristics affect human behavior. We here propose a new measure by which to express the transitional characteristics of ground motion and present a new index that assesses the time available for evacuation. The comprehensive discussion and analysis of human behavior during earthquakes need to take into account many factors, such as the structural response, indoor environment disruption, and the type of human activity at the time of an earthquake, as well as the characteristics of ground motion. The available evacuation time addressed in this paper therefore does not cover all the parameters related to human

KEY WORDS: Instantaneous Instrumental Seismic Intensity (IISI), human behavior, 2000 Western Tottori, Japan earthquake

evacuation behavior, rather it introduces as a relevant element the time available for evacuation based on the Instantaneous Instrumental Seismic Intensity.

2. SITE SURVEY OF THE 2000 WESTERN TOTTORI, JAPAN EARTHQUAKE

The 2000 Western Tottori, Japan earthquake that occurred in western Tottori Prefecture (35.3N, 133.4E, 10km) at 13:30 on October 6, 2000 had the magnitude $M_{JMA}7.3$, $M_w6.6$ (Figure 1). The damage survey published by Tottori Prefecture (2002) showed a total of 393 collapsed houses, 2,491 houses moderately damaged, and 141 people injured. High seismic intensity of 6+ on the Japan Meteorological Agency (hereafter JMA) scale occurred at Sakaiminato City and Hino Town in Tottori Prefecture. Hino Town (129 collapsed and 441 moderately damaged houses) is close to the epicenter, and Sakaiminato City (71 collapsed and 287 moderately damaged houses) is 30 km northwest of it. Most of the damage occurred in the mountainous area.

A site survey of the collapsed houses in Sakaiminato City was made immediately after the earthquake (Takada et al., 2000). The 16 collapsed houses reported on the third day after the earthquake by the Sakaiminato City Municipal office were surveyed. Table 1 lists them.

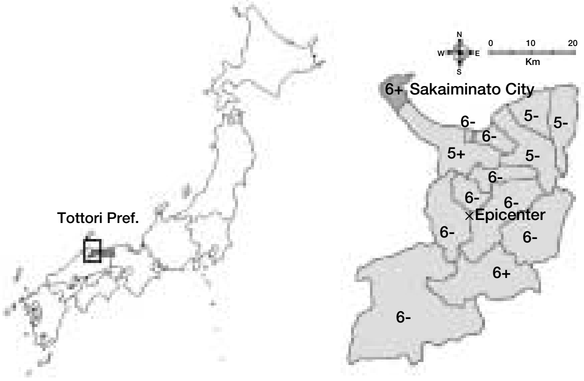


Fig. 1 Location of Sakaiminato City

With respect to overall features, they are wooden structures built more than 50 years ago. Their roofs were heavily tiled to withstand typhoons. In all cases, nearby newly constructed houses did not suffer damage to their main structural components. An interesting feature was that all the completely collapsed and tilted houses leaned to the east. People living near the damaged houses said that only furniture set on the north-south axis was dislocated. The peak ground acceleration recorded at the Sakaiminato Meteorological Observatory was 748 gal for the EW component, higher than the 299 gal for the NS component. This particular pattern of direct damage is due to the predominant direction of ground motion.

Evacuation behavior of those whose houses collapsed was reported. In case 3, Table 1, neighbor reported that an elderly woman was at home during the earthquake, but she did not suffer severe injuries although she was taken to the hospital. Her house was heavily tilted (Photo. 1). In case 6, an elderly woman was having an after-lunch nap. She became aware of the shaking and rushed to the front door. After she had run about 5 meters from her house, it completely collapsed with a loud noise (Photo. 2). In

Photo 1. Case 3

Photo 2. Case 6

Photo 3. Case 10

Photo 4. Case 14

Table 1. List of collapsed houses surveyed in Sakaiminato City

Case	Type	Age	Story	Direction for collapse	Collapse mode	Occupancy during earthquake
1	Dewlling	So old	One	East	Completely collapsed	Unkown
2	Dewlling		Two	East	Slightly tilted	Unkown
3	Dewlling		Two	East	Considerably tilted	1
4	Dewlling	So old	One	East	Completely collapsed	−
5	Dewlling	So old	One	East	Completely collapsed	0
6	Dewlling	>50 years	Two	East	Completely collapsed	1
7	Dewlling		One	East	Completely collapsed	−
8	Dewlling		Two	East	Considerably tilted	Unkown
9	Bush house	>100 years	One	East	Completely collapsed	0
10	Dewlling	>70 years	Two	East	Slightly tilted	0
11	Dewlling	>50 years	One	East	Completely collapsed	−
12	Dewlling	So old	Two	East	Completely collapsed	0
13	Dewlling	>100 years	Two	East	Considerably tilted	1
14	Dewlling	>50 years	Two	East	Completely collapsed	2
15	Dewlling	>70 years	Two	East	Considerably tilted	0
16	Dewlling		Two	East	Completely collapsed	0

case 13, an elderly man with a crippled leg felt the earthquake and crawled out of his house with help of his family. That house did not collapse completely (Photo. 3). In case 14, a young woman and her father who were on the first floor were frightened by the shaking ran out from the entrance. Just after they got out, the house collapsed (Photo 4), but they were not injured.

In this earthquake, those houses that completely collapsed did not cause death to the persons inside. The main reason for this is that something other than structural resistance (which was not sufficient to resist the earthquake) helped to reduce the number of casualties. Three factors: the hour of the day, indicative of low occupancy; the wide and multiple outlets from the houses; and the time available for evacuation, were involved.

1. **Low occupancy**: Most people were not at home and those who were resting on the first floor as the earthquake occurred at 13:30 in the early afternoon hours of a weekday. People were awake and at once perceived the shaking and moved. According to the statistics on hourly human behavior (NHK, 1990), the inhabitant occupancy (the percent at home) at 13:30 was 27 % and almost all were awake. In contrast, early in the morning when the Hyogoken nambu earthquake occurred 96 % occupancy was estimated. The number of those at home during the Tottori Western earthquake was much lower.
2. **Wide and multiple outlets**: There were more and wider entrance doors and windows in the houses in Sakaiminato City than in Kobe. Such multiple outlets can provide inhabitants many easy escape routes.
3. **Time available for evacuation**: Before houses collapsed, there was time enough for people to get out. The ability of elderly people to escape in earthquakes has been shown to be lower, as confirmed by a Taiwan earthquake case study (Kuwata and Takada, 2001), but the elderly people reported here were able to move and get out of their houses during the earthquake. In addition, some people said that they were able to turn off the gas in the kitchen before evacuating. In the case of Kobe, survivors said buildings suffered damage as soon as they felt the shaking, whereas in Tottori, most of the people interviewed said that their houses collapsed only after they had escaped.

The first two factors are functional ones related to the vulnerability component, and the last is related to the characteristic of input ground motion. Ground motion has been often assessed in terms of peak intensity and predominant frequency. Our case study indicates that there is a transitional characteristic during ground shaking, which allows people to move to safer locations. Consideration of the transitional characteristic of ground motion provides a chance to analyze human behavior in dynamic ways, but there is no available measure besides ground motion records with which to evaluate that instantaneous value.

3. TRANSITIONAL CHARACTERISTIC OF SEISMIC INTENSITY

3.1 Instantaneous Instrumental Seismic Intensity

A new measure is proposed related to the Instrumental Seismic Intensity (hereafter ISI) adopted by the JMA in 1996 (JMA, 1996). Whereas before the Hyogoken nambu earthquake only the two horizontal acceleration components were considered, after it the vertical component was added to the ISI. The new measure uses a calculation method which computes the ISI value as instant duration, and therefore is named Instantaneous Instrumental Seismic Intensity (hereafter IISI).

The IISI is calculated by three steps (Figure 2). The first is to compute the Fourier spectrum of acceleration in each component (2 horizontal and 1 vertical) and to multiply the spectrum by three kinds of filter functions (as follows), then to compute the filtered acceleration by its inverse Fourier transform.

$$F_1(\omega) = (1/\omega)^{1/2} \qquad (1)$$

$$F_2(\omega) = (1+0.694X^2 + 0.241X^4 + 0.0557X^6 + 0.009664X^8 + 0.00134X^{10} + 0.000155X^{12})^{1/2} \qquad (2)$$

subject to $X = \omega/\omega_c$

$$F_3(\omega) = (1-\exp(-(\omega/\omega_0)^3))^{1/2} \qquad (3)$$

where $F_1(\omega)$ is a filter corresponding to human sensitivity to shaking, $F_2(\omega)$ a high cut filter, $F_3(\omega)$ a low cut filter, ω the frequency, and ω_c and ω_0 are parameters of the high and low cut filters ($\omega_c = 10Hz$, $\omega_0 = 0.5Hz$).

The next step is to calculate the vector acceleration, $v(t)$, by summing the three components of the filtered accelerations. In the third step, the maximum amplitude, a_0, of vector acceleration that satisfies more than 0.3 second duration as in the ISI calculation is determined. The duration is defined as the sum of the time intervals between first and final peaks that exceed a threshold level of vector acceleration. In the calculation, the vector acceleration series ($v(k)$, $v(k+1)$,... $v(k+j)$) from the beginning, time k, is

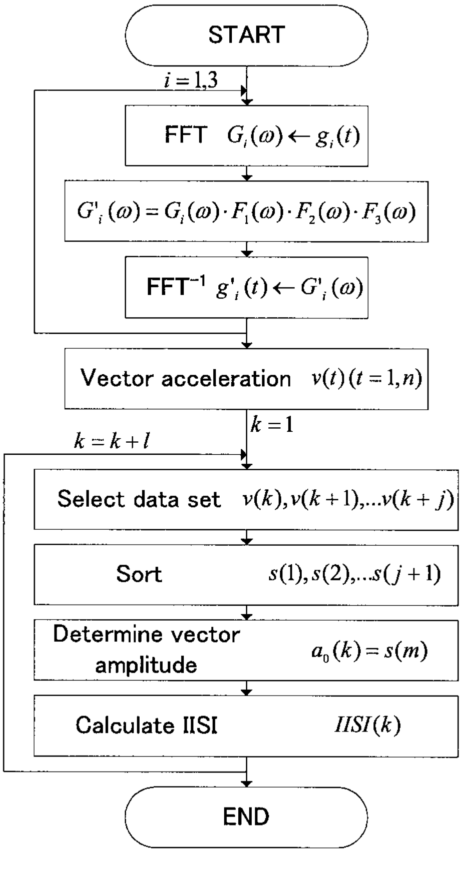


Fig. 2 IISI calculation method

selected based on a given time window. A vector acceleration series is sorted from the large to small amplitudes ($s(1)$, $s(2)$,... s ($j + 1$)), and the maximum amplitude is obtained based on the above condition. The *IISI* (k) at time k is computed by a formula which is related to the Kawasumi formula (Kawasumi, 1943).

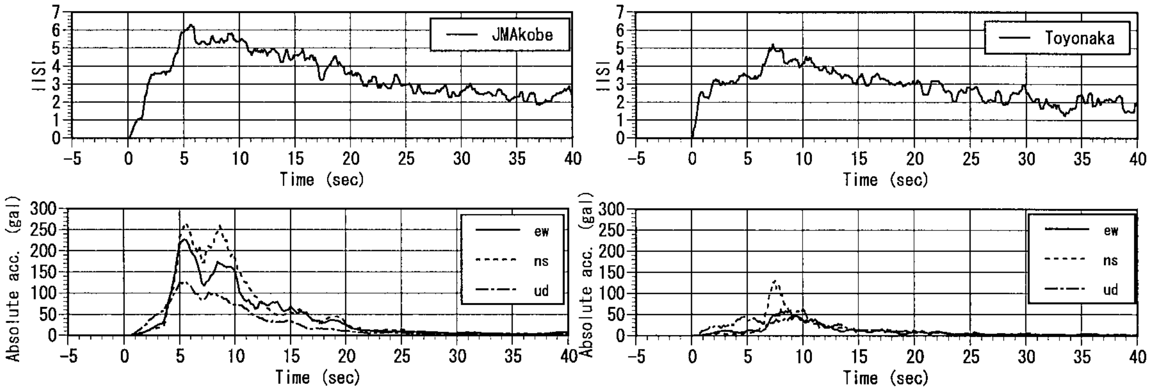
$$IISI\,(k) = 2 \cdot \log a_0\,(k) + K \tag{4}$$

where K is a parameter, equal to 0.94.

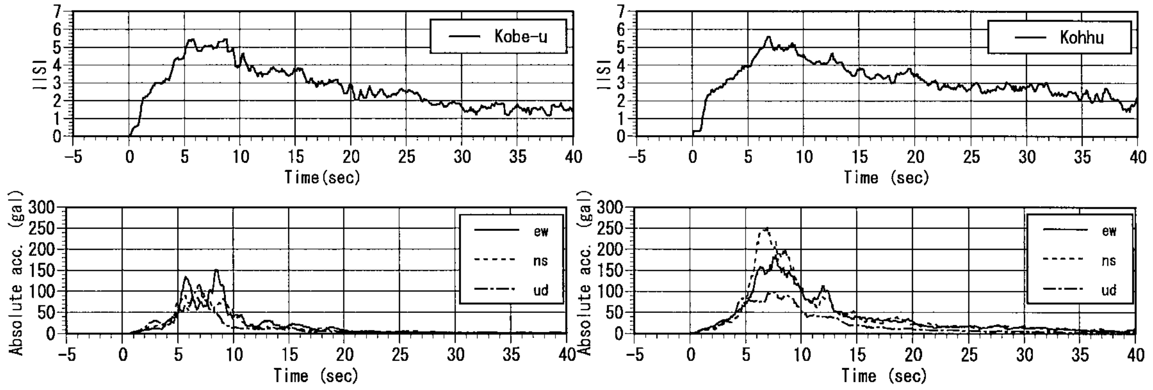
The IISI at another time can be calculated by shifting the time window of the vector acceleration series. Almost all the parameters and conditioning functions follow those in the ISI procedure. The IISI calculation procedure takes into account two additional parameters; the duration of the time window and the shift to the following time window. If the calculated value is less than 0.0, the IISI is regarded as equal to 0.0. The point at which the value of IISI exceeds 0.0 is defined as the beginning of the IISI.

3.2 Application to the Western Tottori and the Hyogoken nambu earthquakes

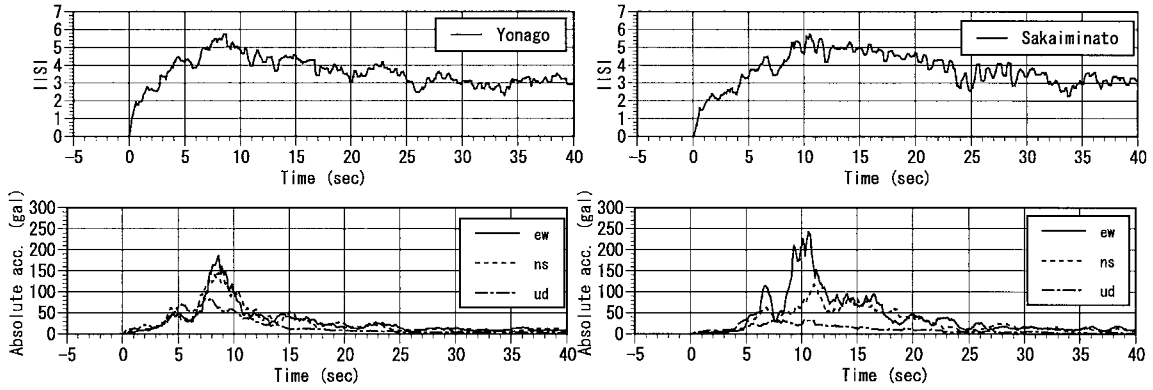
In this application of the new index, 0.5 second time windows, with 0.1 second shifts between, are used. Figure 3 shows the IISIs of several accelerograms during both earthquakes (JMA Kobe (JMA), Kobe University, Toyonaka (CEORKA, 1995), Kohhu, Yonago (NIED), and Sakaiminato (JMA)), for which the time axes



(a) JMA Kobe (HN) (b) Toyonaka (HN)



(c) Kobe University (HN) (d) Kohhu (WT)



(e) Yonago (WT) (b) Sakaiminato (WT)

Fig. 3 Instantaneous Instrumental Seismic Intensity and Smoothing Curve are set at the beginning of IISI. The peak IISI arrival time, defined as the time from the beginning of IISI to its maximum, was short (about 5 seconds) at JMA Kobe in the Hyogoken nambu earthquake. In contrast, values in the Western Tottori earthquake are relatively long, especially at Sakaiminato (about 10 seconds).

Figures below the IISI charts show the smoothing curves of absolute accelerations. The IISI peak point well corresponds to the horizontal acceleration peak. These peak characteristics are drawn by the envelope curves of ground motion as well as by the IISI. With respect to transitional characteristics up to the maximum IISI, for the Western Tottori earthquake the shapes of the smoothing curves until the peak points are similar for the three acceleration components, whereas for the Hyogoken Nambu earthquake, first vertical acceleration increases. Although the maximum IISI depends on the horizontal acceleration, the transitional duration characteristics from the beginning to the peak arrival mainly are determined by vertical acceleration.

Acceleration records at the JMA Kobe and Kohhu observatories show almost the same peak ground accelerations, 818 and 748 gal, whereas the calculated maximum IISIs differ 6.3 and 5.6. The maximum IISI slightly differs from that of the ISI due to the condition of the time window. The maximum IISI is almost equal to, or at most 0.3 less than, the ISI. The difference between the PGA and maximum IISI is due to the predominant frequency of acceleration. IISI calculation uses the filtering procedure to meet building damage and human perception. The IISI is reported to better fit building damage caused by earthquakes than the PGA (Kuwata et al., 2001). In fact, building damage at Kohhu was less than in Kobe.

Two factors explain why inhabitants had the time to evacuate in Sakaiminato City: the peak arrival time was long, and the IISI was not high enough to correspond to PGA as it did in Kobe.

The advantage of utilizing the IISI is that the peak arrival time and transitional characteristics of three components can be treated as simple integrated value that agrees well with building damage and human perception. The weak point is that it involves complicated calculations. The IISI, however, can be used to assess past research on human behavior during earthquakes because these studies were done using the seismic intensity given on the JMA scale.

4. TIME AVAILABLE FOR EVACUATION

4.1 The human behavior period

If the IISI can be used as a new intensity measure, the problem is how can transitional characteristics used as a parameter of ground motion be used to evaluate the time available for evacuation. Our strategy in dealing with this problem was to divide the duration of ground motion into four characterized periods then to indicate the time available for evacuation when combined with a ground motion measure.

These four periods, based on human behavior and surrounding conditions for a certain intensity of ground motion are

period ① : people do not feel any ground motion,
period ② : people are aware of the earthquake and are able to evacuate,
period ③ : people cannot move, surrounding objects fall, but buildings do not completely collapse, and
period ④ : buildings completely collapse, surrounding objects fall on the people who are entrapped and cannot escape.

When a given ground motion intensity increases, the period proceeds from ① to ④, and physical factors increasingly become more important than human behavior. In period ④, the situation is completely determined by the physical damage done. Period progression depends on the transitional intensity of ground motion.

The most important factor affecting human loss is the time at which a building starts to collapse. This needs to be determined by adopting structural perspectives. An analysis of structural response and durability combined with the IISI has been published (Kuwata and Takada, 2002), but more investigation is required. Our paper deals mainly with the time available for evacuation. The following discussion therefore specifies the time available for evacuation in period ②.

Human perception depends not only on felt ground motion, but on buildings' responses to that motion. We propose a basic model that uses only observed acceleration records. Ground motion characteristics that are important in assessing a building's response will be considered in the future as added parameters.

A review of several studies on human behaviors during earthquakes shows there is a relationship between peak seismic intensity and human behavior. Okada and Kagami (1991) showed that 50% those surveyed felt they could not move at all at a level of 5.08 seismic intensity. Kosaka (1993) showed that the threshold for people's action, e.g., turning off fires, is a seismic intensity of 4.0. These intensities were derived from questionnaires distributed to people affected by earthquakes.

The explanation of the scale of seismic intensity used by the JMA (1996), completed after the 1996 revision of the JMA seismic intensity scale, shows the typical phenomena and damage experienced at each point on the seismic intensity scale. In that list, the situation, in which most people are very frightened and find it difficult to move around, corresponds to the ISI of 5.0, and most people in buildings can perceive an earthquake at the ISI of 1.5.

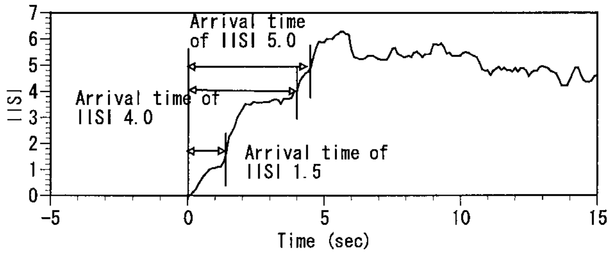


Fig.4 Arrival time of each IISI level

Table 2. Time available for evacuation

	Time available for evacuation (sec) IISI (level 1.5 to 4.0)	Time available for evacuation (sec) IISI (level 1.5 to 5.0)
(Hyogoken nambu earthquake)		
Jma Kobe	2.5	3.1
Kobe-u	2.9	4.1
Toyonaka	5.9	6.6
(Western Tottori earthquake)		
Kohhu	3.7	5.2
Sakaiminato	5.5	8.2
Yonago	3.4	6.1

4.2 Application

No study of the relationship between IISI and human behavior has been done published. Our research involves the above seismic intensities found based on answers given in a questionnaire and the ISI. We are convinced that even though questionnaire-derived intensities are not all that reliable from a scientific standpoint, they well fit findings for human behavior during earthquakes (Takada and Ueda, 1998).

Based on the above reviews, the threshold between periods ① and ② is defined as the 1.5 IISI level, and that between periods ② and ③ the 4.0 to 5.0 IISI level. It is difficult to give a definite threshold between periods ② and ③ because they partially overlap and are influenced by many factors. The time available for evacuation therefore ranges from 1.5 to 4.0, or 5.0 (Figure 4), as calculated from the acceleration records in Figure 3. Results are shown in Table 2. Sakaiminato City had the longest available evacuation time. Results show that the time available in the Western Tottori earthquake was relatively longer than that in the Hyogoken nambu earthquake. The time available close to the epicenter was shorter, for example at JMA Kobe and Kohhu. The available time, however, does not always depend solely on ground motion characteristics, but on the location and distance from the epicenter as well.

5. FURTHER EXAMINATION AND FUTURE APPLICATIONS

The outlines of the new measure and model for evaluating the time available for evacuation have been given. In terms of their practical use, further analysis is needed to deal with various aspects. Above of all, prediction of the IISI can be used to estimate the time available for evacuation in order to reduce earthquake-related casualties. The advantage is that it takes into account the hazard uncertainty before an earthquake occurs, as in the hazard maps based on PGA and seismic intensity.

The entire shape of IISI history has been investigated successfully by means of some parameters focused on sites close to active faults for shallow earthquakes (e.g., Ozaki and Takada, 2001, 2002). That research succeeded in predicting a time history of ground motion based on the IISI.

The purpose of the following examinations is to determine the thresholds between periods in order to apply the proposed model to a given earthquake. For earthquakes with focal depths shallower than 20 km (NIED), the IISI arrival time is analyzed taking into account the hypocentral distance and two levels of earthquake magnitude. Acceleration records of 16 earthquakes, magnitudes of which were either 7.2 or 7.3 on the JMA scale, and of 17 earthquakes whose magnitudes ranged from 6.1 to 6.3 on the same scale were used. Figures 5 and 6 respective show IISI arrival times of levels 4.0 and 5.0. Only 6 of the 18 acceleration records, which had magnitudes 6.1 to 6.3, had arrivals of level 4.0. Both figures show that each arrival time is proportional to the hypocentral distance. Magnitude differences are not closely related to IISI arrival time 4.0. Here the arrival time is discussed mainly for near field earthquakes, but a generic chart will be made from results of future

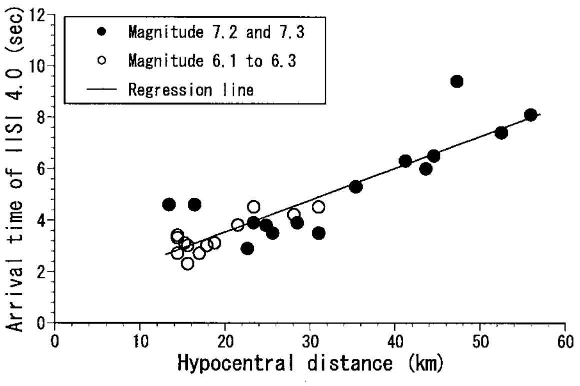


Fig.5 IISI arrival time related to hypocentral distance for IISI 4.0

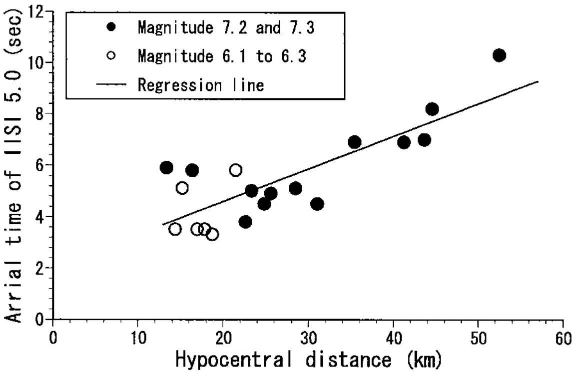


Fig.6 IISI arrival time related to hypocentral distance for IISI 5.0

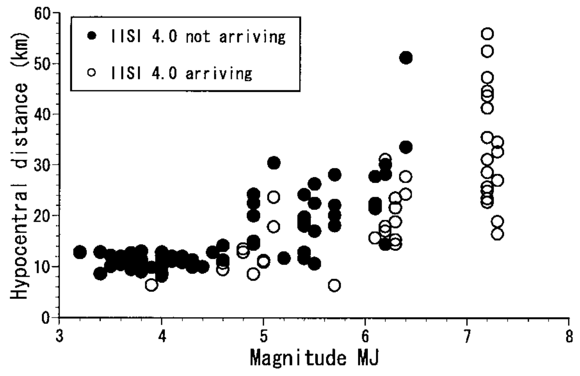


Fig.7 Maximum IISI related to magnitude and hypocentral distance for an IISI of 4.0

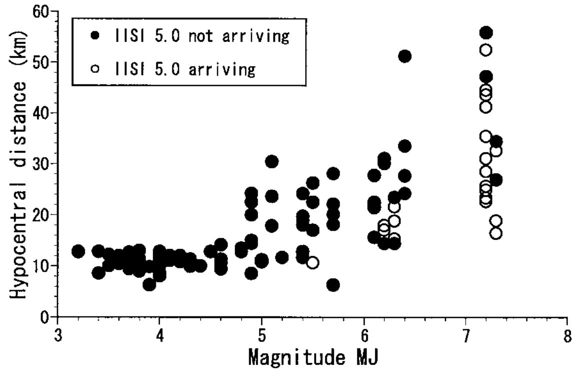


Fig.8 Maximum IISI related to magnitude and hypocentral distance for an IISI of 5.0

examinations of earthquakes of various magnitudes and focal depths and those of large magnitudes in oceanic plates.

Figures 7 and 8 show the arrival times of 112 earthquakes with focal depths shallower than 20 km in relation to magnitude and hypocentral distance. In Figure 7, a closed circle indicates that the maximum IISI reaches level 5.0, an open circle that it does not. Figure 8 likewise shows the case for an IISI of 4.0. The maximum IISI appears to be affected by the site ground and other local conditions, therefore, the threshold is not clear. The hypocentral distance reached at IISI 5.0 could be identified for a given earthquake magnitude based on Figure 8. This chart can be used to obtain the corresponding arrival time on the IISI scale by combining the magnitude level and hypocentral distance. For example, given an earthquake of magnitude 6, the target IISI arrival time of 4.0 is obtained, which corresponds to a hypocentral distance of less than 30 km.

Results of this research on the IISI provide researchers with beneficial information and a different view of ground motion parameters one that specifically addresses human casualties caused by earthquakes. The simpler and more easily understandable charts that show threshold lines in Figures 5 and 6, and hazard maps that show the time available for evacuation can help residents become more aware of earthquake threats. For a comprehensive human behavior model, however, several parameters besides the IISI must be considered.

CONCLUDING REMARKS

By reviewing the case of Sakaiminato City during the Western Tottori earthquake, the need for the transitional characteristic of ground motions was brought out in studies of earthquake-related casualties. A new measure of ground motion combined with a model indicating the time available for evacuation is proposed, and applications of the proposed model are shown. The following conclusions were obtained:

1. As a measure of the transitional characteristic of ground motion, Instantaneous Instrumental Seismic Intensity is proposed. It explains not only the peak intensity and time to reach that intensity but the transitional characteristics up to the peak intensity. This measure is more useful than the envelope curve of ground motion because as a simple measure it can treat complex characteristics that involve the vertical components.
2. To indicate the time available for evacuation, a transitional model characterizing human behavior and surrounding conditions is introduced. The duration of ground motion is divided into four characterized periods, and the time available for evacuation presented with the associated period sets.
3. The proposed measure and model were applied to the Western Tottori and Hyogoken nambu earthquakes. The time available for evacuation in Sakaiminato City was shown to be longer than that in Kobe. This longer period is supposed to have been an important factor for facilitating peoples’s escapes.
4. Practical applications of the proposed measure and model are shown. The relationship between the IISI arrival time and hypocentral distance for two levels of earthquake magnitude show that the time available for evacuation depends on the hypocentral distance. Although analyses of other earthquakes are needed, clearly the threshold for evacuation activity is limited by the closeness to the earthquakeÅfs source, when the event is of large magnitude.
5. For a comprehensive model of human evacuation, more investigation is needed related to factors such as building resistance, disruption of surrounding indoor objects, and human perception meeting with the IISI.

ACKNOWLEDGMENT

First author thanks the Japanese Society for the Promotion of Science (Grant-in-Aid for Scientific Research, DC1, No. 09368) for its support of this research.

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