17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

ANALYSIS OF DIRECTIONALITY CONSIDERING PERIODIC CHARACTERISTICS FOR OVSERVED STRONG GROUND MOTIONS

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Abstract

In this study, in order to establish seismic performance evaluation method induced by horizontal bi-directional input, it is necessary to analyze the characteristics of actual bi-directional ground motions in detail. Especially, the directionality of bi-directional response considering periodic characteristics of ground motions was examined based on observation records of strong ground motion in Japan. First, as measure of seismic intensity from two horizontal components of seismic ground motion, focus on RotD100, 50 and 00 which takes the maximum, median and minimum values which have different response direction due to bi-directional input. In addition, an omnidirectional display of bi-axial response spectrum was proposed in which the relationship between the intensity, directionality, and natural period of seismic response was visualized using polar coordinates and a color map. Next, the average of RotD100, 50, 00 and omnidirectional display based on bi-axial response spectrum is calculated in order to clarify the characteristics of the directionality considering the periodic characteristics of bi-directional ground motion for the typical strong inland earthquakes and subduction zone earthquakes in Japan.

As result, it is confirmed that the directionality of short-period side is stronger than that of the long period side in both the inland earthquake records and the subduction zone earthquake records. Comparing inland earthquakes and subduction earthquakes, it was confirmed that subduction earthquakes are more directional on short-period side and inland-type earthquakes are more directional on long-period side.

Keywords: bi-directional ground motion; directionality; periodic characteristic; seismic response;

1. Introduction

In the process of conventional seismic design of structure, seismic response analysis induced by uni-directional ground motion is adopted. Advances in numerical analysis technology have greatly contributed to the spread of seismic design based on three-dimensional seismic response analysis. On the other hand, setting of horizontal bi-directional input ground motions are not specified in design criteria of structures, for example bridge, buildings and so on. The purpose of this study is to examine the directionality of bi-directional ground motions taking into account the periodic characteristics of ground motions and seismic response.

The results of this research are expected to be helpful in setting new horizontal bi-directional seismic input in the evaluation of seismic performance of structures.

In this study, in order to establish seismic performance evaluation method induced by horizontal bi-directional seismic input, it is necessary to analyze the characteristics of actual bi-directional ground motions in detail. Especially, the directionality of bi-directional response considering periodic characteristics of ground motions was examined based on observation records of strong ground motion in Japan. First, as measure of seismic intensity from two horizontal components of seismic ground motion, focus on RotDnn [1] which takes the maximum, median and minimum values which have different response direction due to bi-directional input. In addition, an omnidirectional display of response spectrum was proposed in which the relationship between the intensity, directionality, and natural period of seismic response was visualized using polar coordinates and a color map. Next, the average of RotD100, 50, 00 and omnidirectional display of response spectrum are calculated in order to clarify the characteristics of the directionality considering the periodic characteristics of bi-directional ground motion for the typical strong inland earthquakes and subduction zone earthquakes in Japan.

2. Suggestion of omnidirectional display based on response spectrum

Bi-axial response spectrum [2] and RotDnn can express the characteristics of bi-directional ground motion with a single line (maximum response value-natural period relationship) such as the response spectrum of uni-directional ground motion. Bi-axial response spectrum (RotD100) shows the maximum response value to the omnidirectional component of bi-directional ground motion. However, since the direction of maximum response value depends on the natural period, it is necessary to evaluate the directionality for each natural period. Therefore, as a method of displaying the directionality of the bi-directional ground motion, the omnidirectional display of response spectrum using a color map was devised.

The calculation procedure of an omnidirectional display of response spectrum is as follows.

(1) Set an azimuth axis forming an azimuth angle θ in the counterclockwise direction.

(2) From the two orthogonal component accelerations $a_x(t)$ and $a_y(t)$, the acceleration $a_\theta(t)$ in the rotation angle θ direction is calculated by Eq. (1).

$$a_\theta(t) = a_x(t)\cos\theta + a_y(t)\sin\theta \quad (1)$$

where $a_x(t)$ and $a_y(t)$ are the horizontal component acceleration time histories. θ is the rotation angle.

The range of the azimuth angle θ is from 0 to 180°, and the $a_\theta(t)$ are calculated in 1° increments.

(3) The seisemic response analysis are performed for the SDOF oscillator with natural period T with $a_\theta(t)$ as inputs.

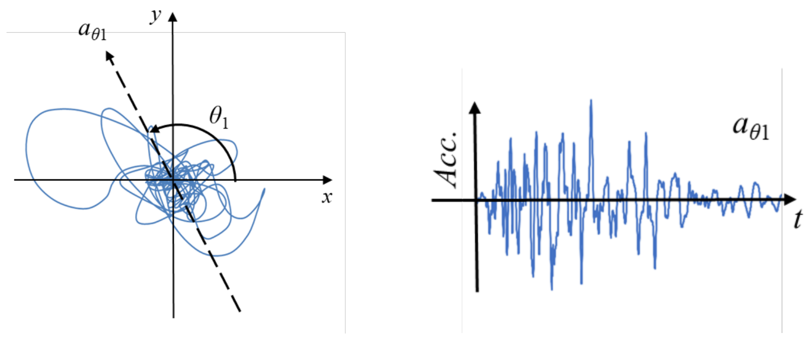
(4) As the results of seismic response analsysis, the maximum response value on the positive side and the maximum response value on the negative side (minimum value) are saved.

(5) At this time, the azimuth axis direction corresponding to the maximum response value on the negative side (minimum value) is updated to $\theta + 180°$.

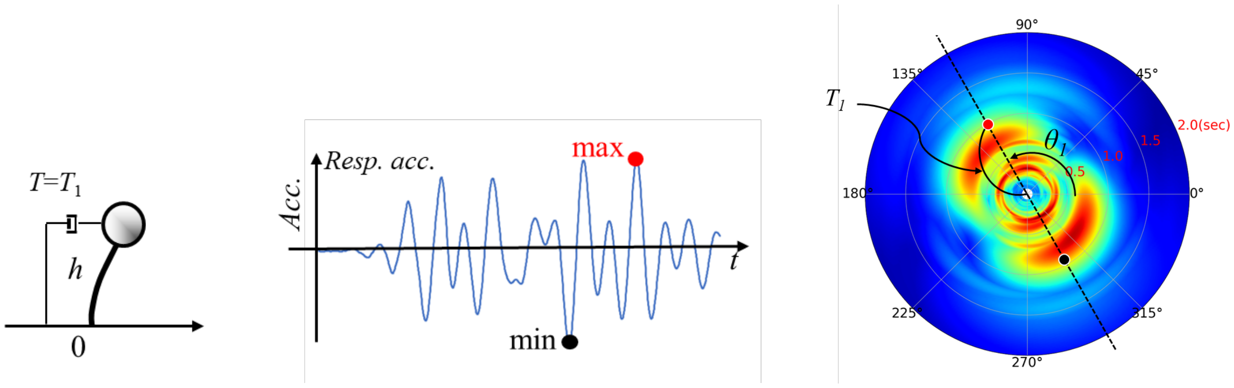
(6) In the plane polar coordinates system, the natural period T is represented by the radius and the azimuth θ is represented by the argument, the magnitude of the response value is represented by a color map.

In addition, the omnidirectional display of response spectrum shown in this study is drawn using matplotlib of Python3 [3].

A Conceptual diagram of calculation procedure of the omnidirectional display of response spectrum is shown in Fig. 1. The example of the omnidirectional display of response spectrum waves from the observed record at the Kobe Marine Observatory (JMA Kobe) of the 1995 Southern Hyogo Prefecture Earthquake wave and at Wakuya-town (JMA Wakuya) of the 2011 off the Pacific coast of Tohoku Earthquake are shown in Fig. 2.

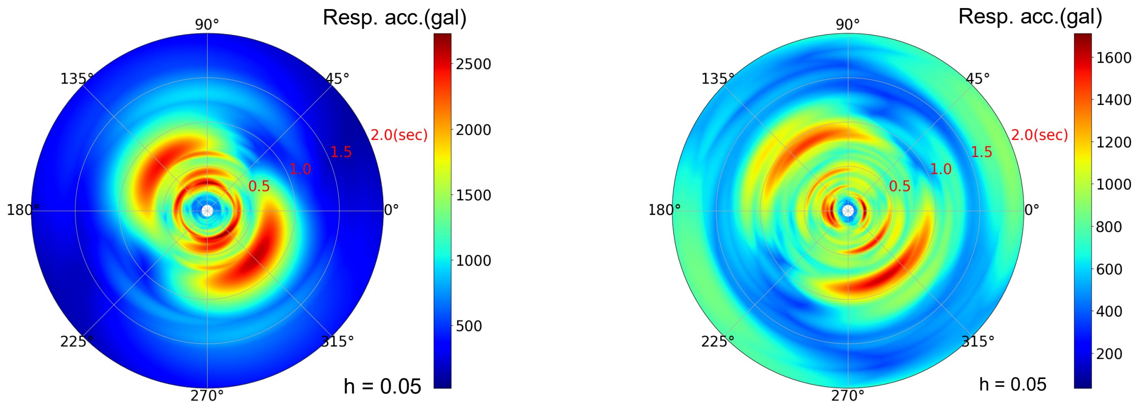


(a) Calucalation of the time histories of $a_\theta(t)$



(b) Plot SDOF seismic response values in polar coordinates

Fig. 1 – Conceptual diagram of calculation procedure of the omnidirectional display of response spectrum



(a) JMA Kobe (b) JMA Wakuya

Fig. 2 – Omnidirectional display of response spectrum

3. Analysis conditions for directionality of bi-directional ground motions

3.1 Observed ground motion in JAPAN

The purpose of this study is to analyze the direction of strong ground motions which is observed in Japan with the aim of considering the tendency of the horizontal two-directional characteristics of observation records in seismic design. Specifically, analysis target 37 ground motions are disclosed in "Strong Earthquake Observation Data"on the Japan Meteorological Agency(JMA) web page [4]. Among strong ground motions, 24 inland earthquakes and 13 in subduction zone earthquakes are analytically targeted. The seismic design of current structures are often classified and set as inland earthquakes and trench earthquakes. Therefore, these two types of earthquakes were analyzed.

3.2 RotDnn

In order to analyze the intensity variation with the direction of the ground motion, the distances of RotD100, RotD50, and RotD00 at the same natural period were analyzed. The calculation procedure is as follows

(1) Calculateion RotD100, RotD50, and RotD00 of analysis target seismic motion

(2) RotDnn are normalized to a value between 0 and 1.0 by dividing by the maximum value of RotD100 of each ground motion.

(3) Then, W_1 and W_2, which indicate the distance of RotDnn, are calculated by Eq. (2) and (3).

$$W_1 = \frac{\mathrm{RotD}100(T) - \mathrm{RotD}50(T)}{\mathrm{Max}(\mathrm{RotD}100(T))} \tag{2}$$

$$W_2 = \frac{\mathrm{RotD}100(T) - \mathrm{RotD}00(T)}{\mathrm{Max}(\mathrm{RotD}100(T))} \tag{3}$$

Fig. 3 shows a conceptual diagram of W_1 and W_2 in RotD100, RotD50 and RotD00 that are normalized. W_1 is the normalized distance between RotD100 and RotD50, and W_2 is the normalized distance between RotD100 and RotD00. The magnitudes of W_1 and W_2 indicate that the fluctuation of seismic response of SDOF system depending on the direction of ground motions. Fig. 4 respectively show the W_1 and W_2 of JMA Kobe wave and JMA Wakuya wave. The seismic response of SDOF system induced by JMA Kobe wave has the largest fluctuation at around the natural period of 0.8 sec, in case of JMA Wakuya wave at the natural period of around 0.9 sec.

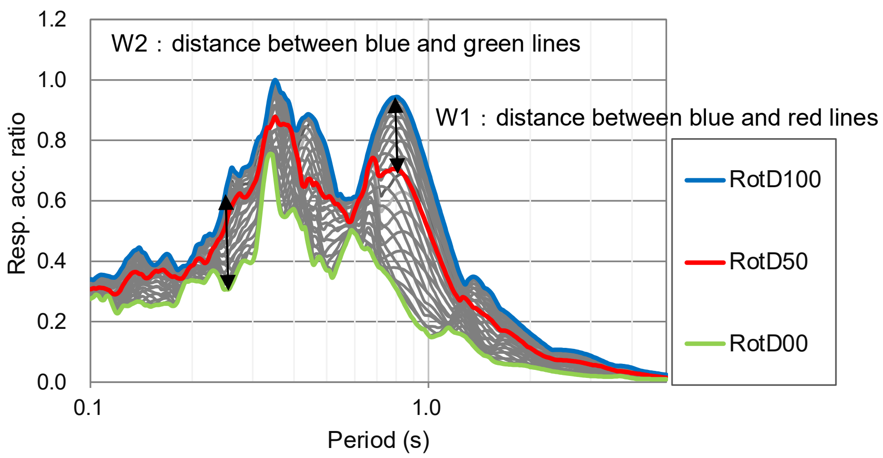
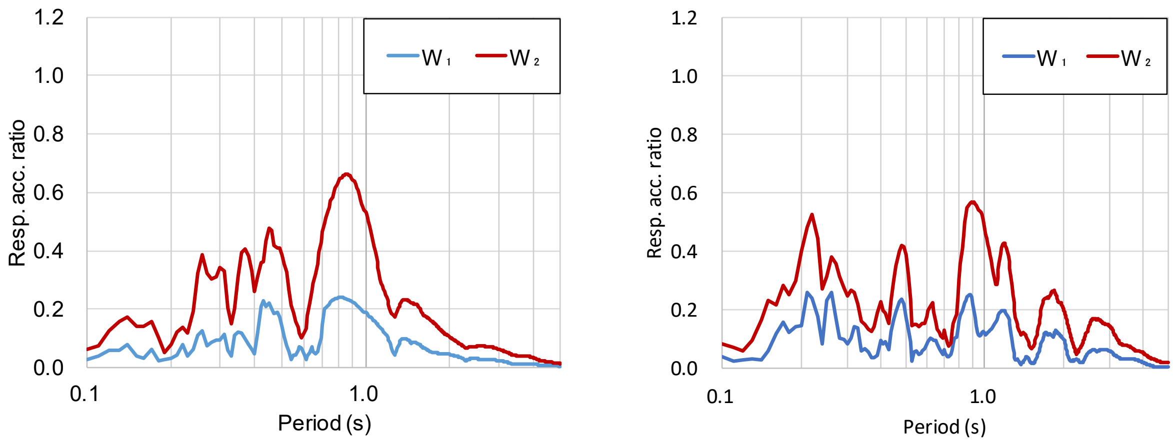


Fig. 3 – Normalization of RotDnn and W_1,W_2



(a) JMA Kobe (b) JMA Wakuya

Fig. 4 – W_1 and W_2 of observed strong ground motion

3.3 Omnidirectional display of response spectrum

In order to analyze the directionality of inland earthquakes and subduction zone earthquakes, the omnidirectional display of the response spectrum is used, and the average of each seismic type of the ground motion to be analyzed is calculated. The average of the omnidirectional display of response spectrum was calculated for each earthquake type to be analyzed. In calculating the average value of the omnidirectional display of the response spectrum, it is necessary to normalize in order to consider difference of the maximum response value and the maximum response direction of the SDOF system for each observed ground motion.

Specifically, conversion of the maximum response value to 0 to 1.0 and rotation of the maximum response direction in the 0° direction were performed on the omnidirectional display of the response spectrum of each observed ground motion.

The procedure for normalizing the omnidirectional display of the response spectrum of each earthquake motion and calculating the average value is shown below.

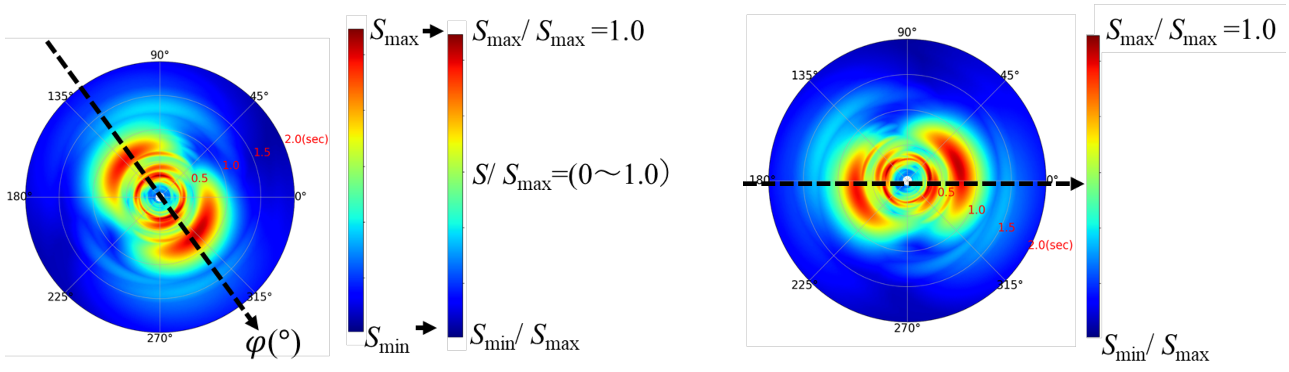
(1) Calculation the omnidirectional display of response spectrum of an observed ground motion.

(2) The maximum response value S_{max} in the omnidirectional display of the response spectrum is extracted, and all response values are divided by S_{max}. By this calculation, the omnidirectional display of response spectrum is converted to value of 0 to 1.0. (Fig. 5 (a)).

(3) Extract the azimuth direction φ of the maximum response value in the natural period of all calculations for each observed ground motion, and subtract φ from the stored omnidirectional data (rotate the color map clockwise by φ°). By this rotation, the maximum response value S_{max} exists in the 0° direction (Fig. 5 (b)).

(4) Perform steps (1) to (3) for all target observed ground motions.

(5) The average of the response values in the same direction and the same natural period is calculated for each type of earthquake.



(a) Nomarization (b) Rotation

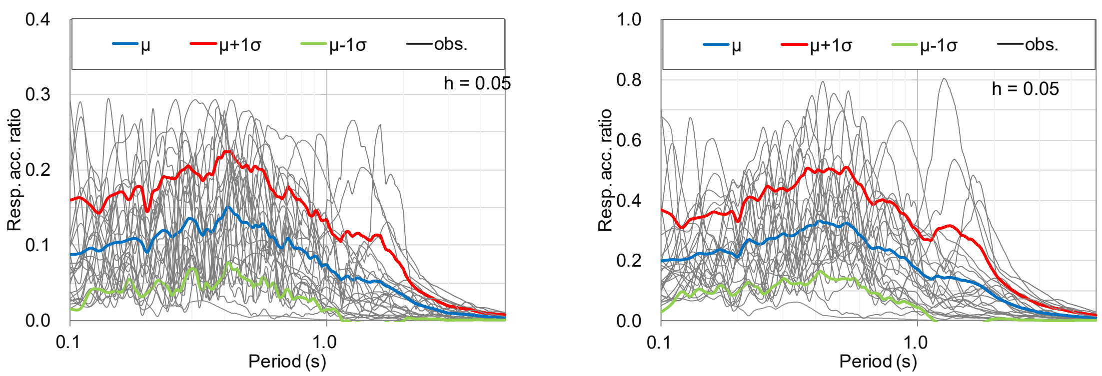
Fig. 5 – Normalization and rotation of omnidirectional display of response spectrum (Ex: JMA Kobe)

4. Analysis results for the directionality of bi-directional ground motions

4.1 RotDnn.

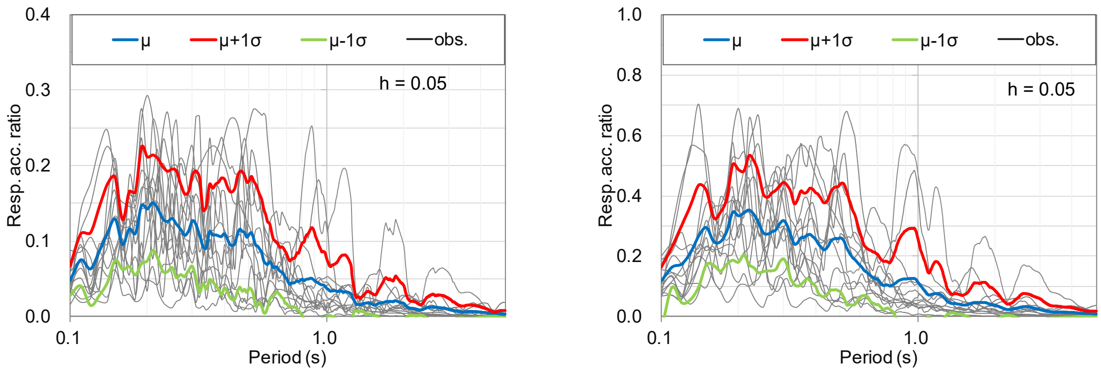
In order to characterize the directionality of the inland earthquake and the subduction zone earthquake, the average of W_1 and W_2 was calculated for each type of earthquake. Fig. 7 show W_1 of the analysis target ground motions for the inland earthquake and the subduction zone earthquake and Fig. 8 show the average of W_2. In addition, W_1 and W_2 of the analysis target ground motion are indicated by grey lines, the average μ of W_1 and W_2 in each natural period is indicated by a blue line, the standard deviation ($+ 1\sigma$) is indicated by a red line, and the standard deviation (-1σ) is indicated by a green line. Table 1 shows W_1 and W_2 of inland earthquakes and subduction zone earthquakes averaged in the representative natural period.

The maximum values of W_1 and W_2 are about 0.4 sec for inland earthquakes and about 0.2 sec for subduction zone earthquakes, and the maximum values of W_1 and W_2 occur. In addition, the magnitude relationship of W_1 and W_2 between inland earthquake and the subduction zone earthquake is switched around. Table.1 shows W_1 and W_2 of inland earthquakes and subduction zone earthquakes averaged in the representative natural period. W_1 and W_2 of inland earthquakes are larger than those for subduction zone earthquakes. This result indicates that the response in each direction is larger for inland earthquakes than for subduction zone earthquakes.



(a) Inland earthquakes (b) Subduction zone earthquakes

Fig. 7 – Average of W_1



(a) Inland earthquakes (b) Subduction zone earthquakes

Fig. 8 – Average of W_2

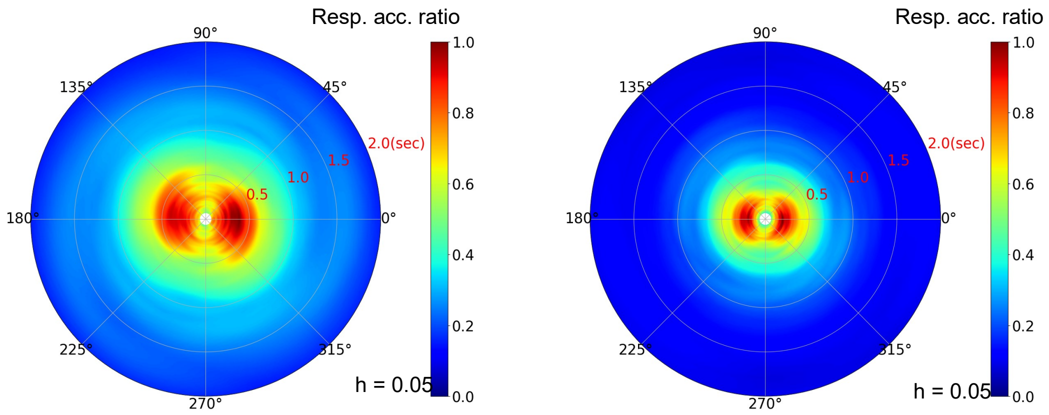
Table.1 – Value of W_1 and W_2 at the specific natural period

Period (s)	W_1		W_2	
	Inrand	Subduction zone	Inrand	Subduction zone
0.1～0.5	0.13	0.11	0.30	0.26
0.5～1.0	0.11	0.06	0.29	0.14
1.0～1.5	0.06	0.03	0.16	0.06
1.5～2.0	0.04	0.02	0.11	0.04
2.0～5.0	0.01	0.01	0.03	0.02

4.2 Omnidirectional display of response spectrum

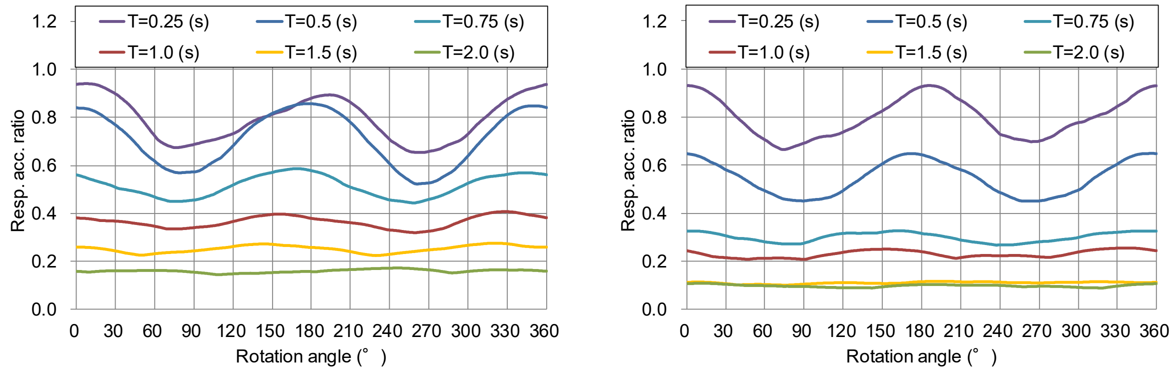
Fig. 9 show the omnidirectional average of the response spectra of the inland earthquake and the subduction earthquake. Fig.9 (a), (b) comparing the color fluctuations of inland earthquake and subduction earthquake with the same natural period, the color variation of inland earthquake is larger than that of subduction zone earthquake. This shows that inland earthquake has a larger variation in response depending on the direction at the same natural period than the subduction zone earthquake. In order to confirm the variation of seismic response depending on the directionality at the specific natural period and the response, the graph of the relationship between the response acceleration ratio and the rotation angle are drawn. The specific natural periods are 0.25, 0.50, 0.75, 1.0, 1.5, and 2.0 sec. Fig. 10 shows that for both the inland earthquake and subduction zone earthquake, the fluctuation of seismic response is larger on the short-period side.

Table 2 shows the response acceleration ratio corresponding to the rotation angle when the response acceleration ratio in the 0 ° direction is assumed to be 1.0 in the specific natural period. In the case of natural periods of 0.25 sec and 0.50 sec, the response acceleration ratio at 90 ° and 270 ° showed values of 0.63 to 0.75. On the other hand, the response acceleration ratio at 90 ° and 270 ° at the natural period of 1.0 sec and 2.0 sec showed values of 0.85 to 1.04. Focusing on the earthquake type, in the case of inland earthquake, the fluctuation of seismic response is the largest at a natural period of 0.50 sec, which is consistent with the results of W_1 and W_2. In the case of subduction zone earthquake, the fluctuation of seismic response is largest at a natural period of 0.25 sec, which is consistent with the results of W_1 and W_2.



(a) Inland earthquakes (b) Subduction zone earthquakes

Fig. 9 – Average of normalized omnidirectional display of response spectrum



(a) Inland earthquakes (b) Subduction zone earthquakes

Fig. 10 – Average normalized response acceleration ratio–Rotation angle diagram

Table. 2 – Average normalized response acceleration ratio – Rotation angle relationship

(a) Inland earthquakes

Rotation angle (°)	Period (s)			
	T=0.25	T=0.5	T=1.0	T=2.0
0	1.00	1.00	1.00	1.00
45	0.90	0.83	0.95	1.12
90	0.75	0.68	0.93	1.02
135	0.87	0.92	1.04	0.91
180	0.99	1.03	0.96	0.97
225	0.87	0.82	0.91	1.18
270	0.71	0.64	0.89	1.09
315	0.86	0.90	1.10	1.02

(b) Subduction zone earthquakes

Rotation angle (°)	Period (s)			
	T=0.25	T=0.5	T=1.0	T=2.0
0	1.00	1.00	1.00	1.00
45	0.82	0.83	0.85	0.93
90	0.74	0.70	0.85	0.88
135	0.84	0.85	1.02	0.83
180	1.00	0.99	0.98	0.96
225	0.87	0.84	0.91	0.94
270	0.75	0.70	0.89	0.89
315	0.86	0.86	1.03	0.82

5. Conclusions

In this study, the directionality of bi-directional ground motion considering periodic characteristics was examined as analysis target observed strong ground motions in Japan. The omnidirectional display of the response spectrum was proposed as a new evaluation method of the directionality of ground motion.

For both inland earthquakes and subduction zone earthquakes, the results showed that the SDOF seismic response fluctuated greatly depending on the direction of the ground motion in a short period.

It was also shown that inland earthquakes had larger fluctuations in seismic response in each direction than subduction zone earthquakes.

Acknowledgements

In this study, we used the strong motion observation records provided by the Japan Meteorological Agency. The research described in this paper was supported by Nagaoka University of Technology (NUT） grant for collaborative research with National Institute of Technology, Gunma College (NIT,GC).

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