# Attenuation Relationship of Earthquake Motion at Dam Foundation in Consideration of The 2011 Tohoku Earthquake

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**ABSTRACT:**
*Estimation of input earthquake motion is very important aspects of the seismic design and seismic performance evaluation of dams. Generally, characteristics of earthquake motion at some geographical point are affected by three element combinations, which are earthquake source mechanisms, transmission path properties, and local site conditions. There are three basic approaches to estimate site-specific earthquake motions: theoretical, semi-empirical, and empirical methods. The hybrid method is a combination of theoretical and semi-empirical approaches. With enormous develop of computer simulation ability, the theoretical, semi-empirical, hybrid approaches are rapidly evolving. However their results should still be examined by empirical approach, that is, attenuation about seismic motions, from the viewpoint of accuracy checking.*
*We have presented several papers about attenuation equations of acceleration response spectra for the dam rock foundations in the past. In the first paper, attenuation equations were derived from the statistical analysis of horizontal-direction ground motions recorded at 91 dams sites for 63 earthquakes occurred in Japan from 1974 to 2000. After the publication of the first paper, we have proposed vertical-direction attenuation relationships, and made the brush-up and modification for these attenuation relationships.*
*In this paper, we propose the latest attenuation relationships derived from the statistical analysis of 794 horizontal-direction and 394 vertical-direction ground motions recorded at 239 dams sites for 91 earthquakes from 1974 to April, 2011 including The 2011 Tohoku Earthquake (March 11th, 2011 $M_w$[moment magnitude]9.0)*

***Keywords: Attenuation Equation, Acceleration Response Spectra, The 2011 Tohoku Earthquake***

## 1. INTRODUCTION

We have presented several papers about attenuation equations of acceleration response spectra for the dam rock foundations in the past. In the first paper [N. Matsumoto et al., 2003], attenuation equations were derived from the statistical analysis of 293 horizontal-direction ground motions recorded at 91 dams sites for 63 earthquakes from 1974 to 2000. After the publication of the first paper, we have proposed vertical-direction attenuation relationships, and made the brush-up and modification for these attenuation relationships [N. Matsumoto et al., 2006]. Recently, we have revised attenuation equations in 2008 as "the year 2008 formula" derived from the statistical analysis of 642 horizontal-directions and 318 vertical-direction ground motions recorded at 213 dams sites for 88 earthquakes from 1974 to 2008, then we have implemented the year 2008 formula as a principal method for setting up input motions for seismic performance evaluation of dams in Japan [S. Mitsuishi et al., 2009].

In this paper, we propose the latest attenuation relationships as "the year 2011 formula" in consideration of ground motions recorded at dams sites on The 2011 Tohoku Earthquake (March 11th, 2011 Mw9.0) and its aftershocks. In the development of the year 2011 formula, we reexamine usage of the magnitude from JMA-magnitude; $M_J$ (defined by Japan Meteorological Agency, and that has been used in the past attenuation equations) to moment-magnitude; $M_W$. Therefore, we can deal with huge earthquake scale in the attenuation equations consistently.

Attenuation equations are affected by characteristics and quantity of acceleration records at each earthquake. So first, we show an outline of data used for the year 2011 formula, and then, the year 2011 formula itself, that is regressed by factors such as magnitude, distance to epicenter and depth of fault. Furthermore, we compare response spectra estimated by the year 2008 formula and the year 2011 formula, and inspect conformity to observed records. Finally, we show validity of the year 2011 formula.

## 2. STRONG MOTION DATA SET

The strong motion data used obtained in earthquakes which magnitude ($M_J$) are larger than 5.0, distance from dam site to epicenter is less than 200km, and depth of fault is less than 100km is used for the analysis. A change of the number of data used for regression analysis concerning each attenuation equations is shown in Table 1.

**Table 1.** The number of data used for regression analysis

| | Subject to regression | | | Number of observed records | |
|---|---|---|---|---|---|
| | Period | Number of earthquakes | Number of dams | Horizontal-direction | Vertical-direction |
| 2001 formula | 1974-2000 | 63 | 91 | 293 | - |
| 2008 formula | 1974-2008 | 88 | 213 | 642 | 318 |
| 2011 formula | 1974-2011 | 91 | 239 | 794 | 394 |

In regression analysis concerning this paper, 794 horizontal-direction and 394 vertical-direction ground motions recorded at 239 dam sites for 91 earthquakes from 1974 to April 2011 are used.

All foundations where the data were obtained in this study consist of rocks not including soils and gravels. The properties of rocks vary from site to site, and the average shear wave velocity of rock foundations ranges from 0.7 to 1.5km/s. The relationships between magnitude, depth of fault, horizontal-direction maximum acceleration and distance of the earthquakes used in the analysis are shown in Fig.1. Here, distance of the earthquakes is defined as the shortest distance from the site to fault-plane.

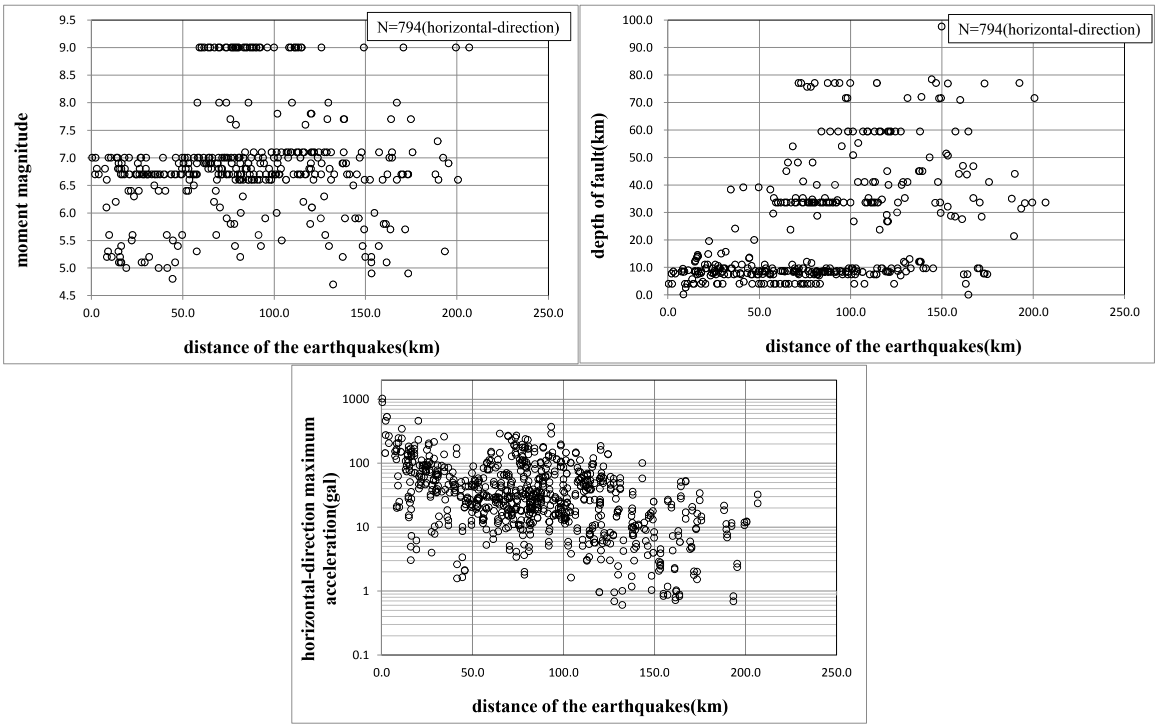



**Figure 1.** The relationships between magnitude, depth of fault, horizontal-direction maximum acceleration and distance of the earthquakes

## 3. MODIFICATION OF ATTENUATION EQUATIONS

### 3.1. Classification of earthquakes

Each earthquake-type; shallow crustal type, inter-plate type and intra-slab type (intra-plate type) that occur nearby Japanese Archipelago have characteristic on occurrence locations and mechanism. At compressional subduction zones, earthquakes occur in several settings ranging from very near surface to several hundred kilometers' depth. In this paper the earthquakes are classified into four types like shown in Table 2. And about the earthquakes at eastern margin of the Sea of Japan, individual attenuation equations are not prepared because of little and dispersion of these regression data.
Concerning intra-plate earthquakes, earthquake types are not divided by depth of fault. This point is different from the case of the year 2011 formula and the case of the year 2008 formula.

**Table 2.** Classification of earthquake type and number of acceleration records

| Type name | Classification of earthquake type | Number of | | |
|---|---|---|---|---|
| | | Earthquakes | Horizontal records | Vertical records |
| Type A | shallow crustal earthquakes | 37 | 456 | 226 |
| Type B | inter-plate earthquakes | 31 | 200 | 99 |
| Type $\alpha$ | Intra-plate earthquakes | 17 | 114 | 57 |
| Type E | earthquakes at eastern margin of the Sea of Japan | 6 | 24 | 12 |

### 3.2. Regression model

In case of regression analysis, first regression coefficients are estimated by using all observed records without classification of earthquake types. And then, geometric average and standard deviation of the ratio of the response spectra of observed records to the response spectra by regression equations are estimated in the respective earthquake types. Finally, correction factors are estimated in the respective earthquake types. That is to say, regression model proposed in this paper is estimated through two-step calculation processes.

And in this paper, usage of the magnitude from $M_J$ to $M_W$ is reexamined to deal with huge earthquake scale in the attenuation equations consistently. $M_J$ is a JMA's original index to express magnitude estimated by earthquake waves which have several seconds' period, and can reflect damage of buildings. But it can't reflect energy scale appropriately in case of huge earthquake. On the other side, $M_W$ is also an index to express magnitude estimated by earthquake waves which have dozens of seconds' period, and has strong correlation with scale of fault movement. So it can reflect energy scale appropriately even in case of huge earthquake. The year 2011 formula is shown in equations (1) and (2) below. Equation (1) is the attenuation equations using distance of the earthquakes, and equation (2) is the attenuation equations using equivalent hypocentral distance.

$$logSA(T) = C_{m1}(T)M_W + C_h(T)H_C - \log(R + C_1(T) \cdot 10^{0.5M_W}) - (C_d(T) + C_{dh}(T)H_C)R + C_o(T) \quad (M_W \leq 5.0)$$
$$logSA(T) = C_{m1}(T)M_W + C_{m2}(T)(M_o - M_W)^2 + C_h(T)H_C - log(R + C_1(T) \cdot 10^{0.5M_W}) - (C_d(T) + C_{dh}(T)H_C)R + C_o(T) \quad (M_o = 5.0, M_W > 5.0) \quad (1)$$

Where *SA(T)* is response spectra (gal), *T* is period in second, $M_W$ is moment-magnitude, *R* is distance of the earthquakes (km), $H_C$ is depth of fault (km), *C(T)* are coefficients. In case of $H_C$ is over 100km, 100km is applied to $H_C$. R means the shortest distance from the site to fault-plane like introduced in chapter 2.

$$logSA(T) = C_{m1}(T)M_W + C_h(T)H_C - \log\left(X_{eq} + C(T)\right) - (C_d(T) + C_{dh}(T)H_C)X_{eq} + C_o(T) \quad (M_W \leq 5.0)$$
$$logSA(T) = C_{m1}(T)M_W + C_{m2}(T)(M_o - M_W)^2 + C_h(T)H_C - \log\left(X_{eq} + C(T)\right) - (C_d(T) + C_{dh}(T)H_C)X_{eq} + C_o(T) \quad (M_o = 5.0, M_W > 5.0) \quad (2)$$

Where $X_{eq}$ is equivalent hypocentral distance, and the other terms are the same as equation (1). $X_{eq}$ means one-line distance between the dam sites and virtual point epicenter that is equivalent to earthquake energy exploded from fault-plane. It is estimated by discretizing fault-plane into an array of many and small elements (Fig.2), and equation (3).

$$X_{eq}^{-2} = \sum_k M_{ok}^2 X_k^{-2} / \sum_k M_{ok}^2 \quad (3)$$

Where $M_{ok}$ is seismic moment at a small element k in fault-plane, and $X_k$ is distance from a small element k in fault-plane to dam sites.

The equation (3) is transformed into the equation (4) by postulating $M_{ok}$ equal over the whole fault-plane for convenience.

$$X_{eq}^{-2} = \frac{1}{N} \sum_k X_k^{-2} \quad (4)$$

Where $N$ is number of partitions into small elements concerning fault-plane.

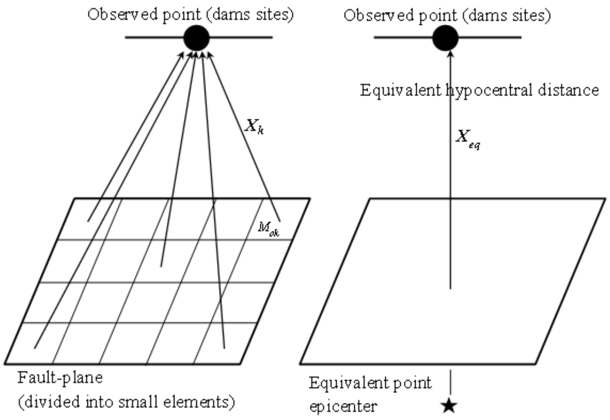



**Figure 2.** Schematic diagram of equivalent hypocentral distance

About the earthquakes that moment-magnitude is not estimated, transformation of $M_J$ into $M_W$ is depend on equation (5) in case of type A, that is used at The Headquarters for Earthquake Research Promotion (Ministry of Education, Culture, Sports, Science and Technology; Japanese Government) based on TAKEMURA's formula[M. Takemura, 1990]. And in case of other earthquakes types, $M_W$=$M_J$.

$$M_W = 0.78M_J + 1.08 \quad (5)$$

Fig.3 gives the relationship between the regression coefficients and period in equations (1) and (2). These parameters correspond to the average of all earthquake types shown in section 3.2. H & V in explanatory notes means horizontal-direction and vertical-direction respectively.

Since each earthquake type has different characteristics of SA(T) attenuation, the regression coefficients are modified considering the spectral acceleration ratio of each earthquake type to the average (correction factor, see Fig.4). The response spectra in the respective earthquakes types can be estimated by multiplying the average response spectra calculated by regression coefficients shown in Fig.3 and correction factors shown in Fig.4. Correction factor here is estimated discretely with every period, About the earthquakes of at eastern margin of the Sea of Japan (type E), individual attenuation equations are not prepared and attenuation equations for inter-plate earthquakes (type B) are applied for the type B likewise the year 2008 formula.

For horizontal response spectra in Fig.4 (a), type A earthquakes (shallow crustal earthquakes) give smaller response acceleration than average, and the ratio of response to the average is approximately 80% to 100% along all period range. The ratio of type B earthquakes (inter-plate earthquakes) is approximately 90% to 110% along all period range. Type α earthquakes (intra-plate earthquakes) give largest response acceleration for all period range, resulting in the ratio of approximately 100% to 140%.

For vertical response spectra, similar relations between correction factor and period are found as shown in Fig.4 (b), and among them the ratio of type α earthquakes is approximately 110% to 150%.

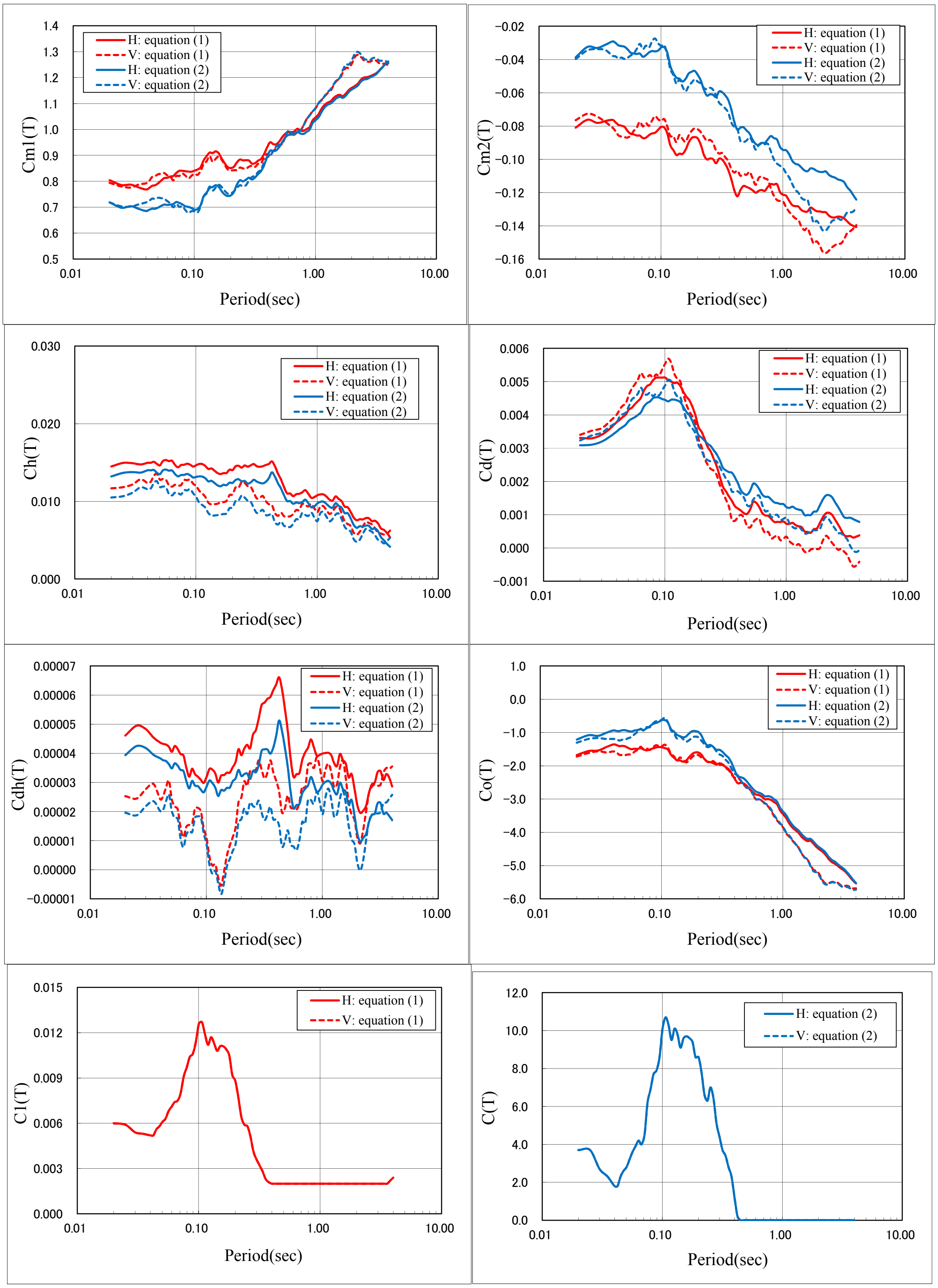
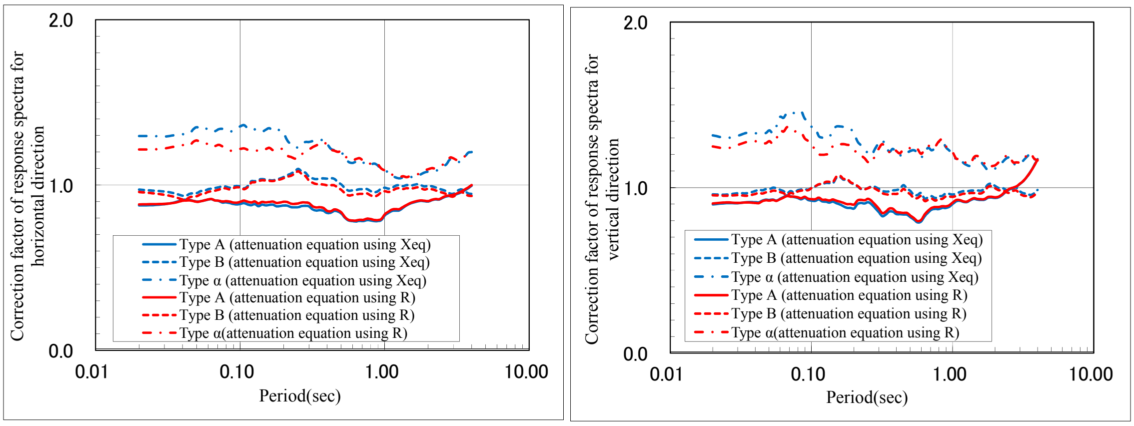



**Figure 3.** Regression coefficients on attenuation equations




(a) Horizontal direction (b) Vertical direction

**Figure 4.** Correction factors of response spectra

## 4. COMPARISON BETWEEN ESTIMATED VALUE BASED ON ATTENUATION EQUATIONS AND OBSERVED VALUE

The reliability of the year 2011 formula is checked through the comparison between response spectra calculated by the year 2011 formula proposed in this paper and observed records at dams sites.

To check the reliability of the year 2011 formula shown in this paper, the ratio of estimated values of response spectra at each dam for individual earthquake and observed values is calculated along all period. In the Fig.6 to Fig.11, conformity of estimated values based on attenuation equations and observed values for famous earthquakes (Table 3. and Fig.5) is shown. In Fig.6, both the graph indicated all ratio-data at each dam and the graph indicated average and average + S.D.(standard deviation) of ratio-data at each dam along period are shown. In Fig.7 to Fig.11, only the graph indicated average and average + S.D. of ratio-data at each dam along period is shown. In these figures, the ratio-data between observed data and estimated values by year 2008 formula is also shown.

**Table 3.** Examples of famous earthquakes in Japan

| Name | Earthquake type | Date of occurrence | Characteristic |
|---|---|---|---|
| The 2011 Tohoku Earthquake | Inter-plate (B) | March 11th, 2011 | hypocenter: off Sanriku, $M_W$: 9.0, seismic intensity: just over 7 (max), captured acceleration records at many dams, for example, Miharu Dam (gravity type, max acc. at foundation: 195gal) |
| The 2000 Tottori Earthquake | Shallow crustal (A) | October 6th, 2000 | hypocenter: Inland Tottori-Pref. Yonago-City, $M_W$: 6.8, seismic intensity: just over 6 (max), captured acceleration records at many dams, for example, Kasho Dam (gravity type, max acc. at foundation: 531gal) |
| The 2008 Iwate-Miyagi Earthquake | Shallow crustal (A) | June 14th, 2008 | hypocenter: Inland Iwate-Pref. Ichinoseki-City, $M_W$: 7.0, seismic intensity: just over 6 (max), captured acceleration records at many dams, for example, Aratozawa Dam (ECRD type, max acc. at foundation: 531gal) |

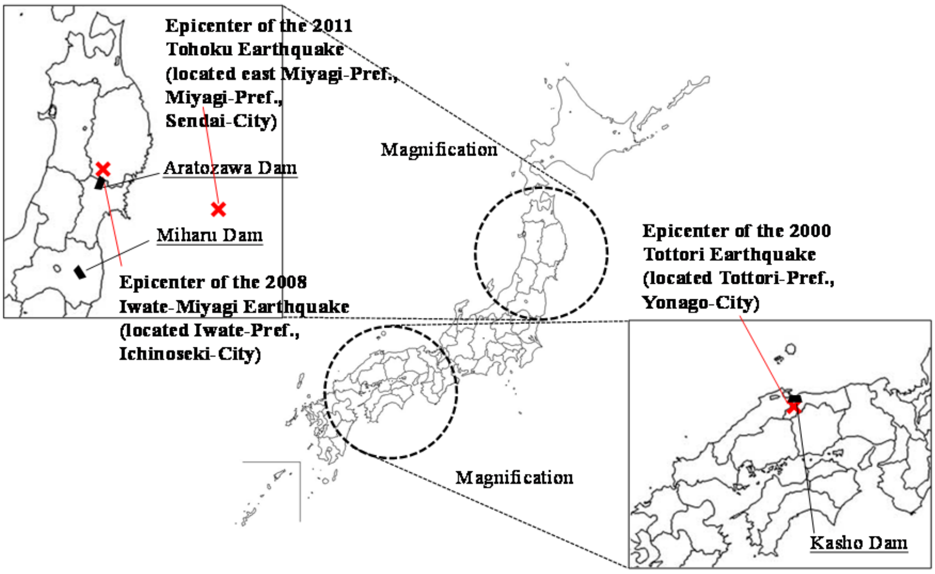



**Figure 5.** Location of hypocenter and dams on each earthquake

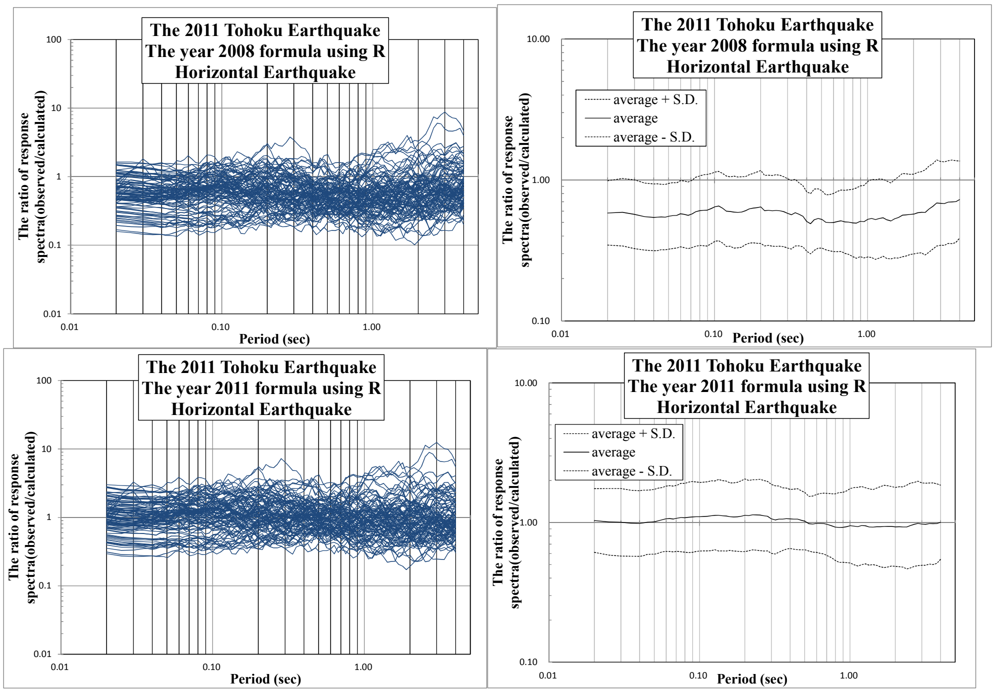



**Figure 6.** Checking conformity of attenuation equations using R to the 2011 Tohoku Earthquake

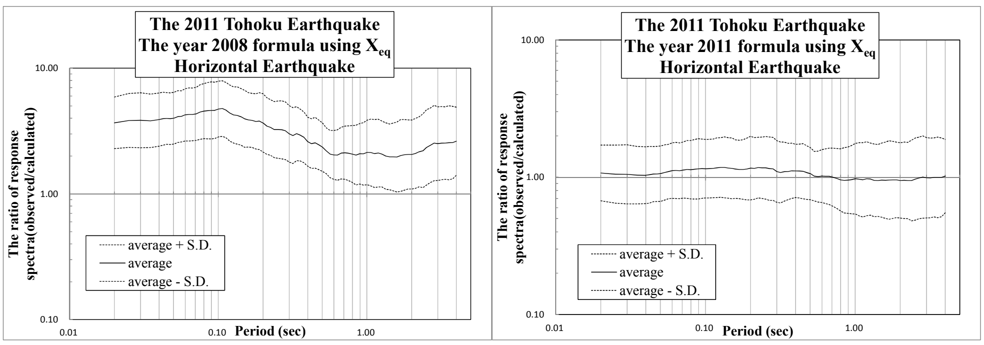



**Figure 7.** Checking conformity of attenuation equations using $X_{eq}$ to the 2011 Tohoku Earthquake

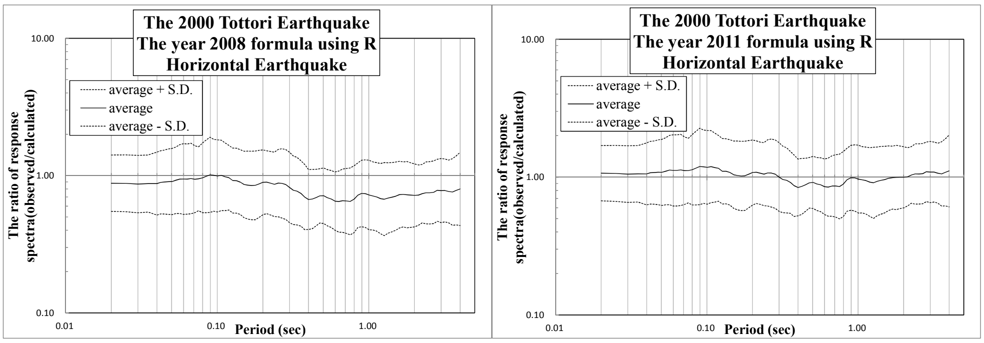



**Figure 8.** Checking conformity of attenuation equations using R to the 2000 Tottori Earthquake

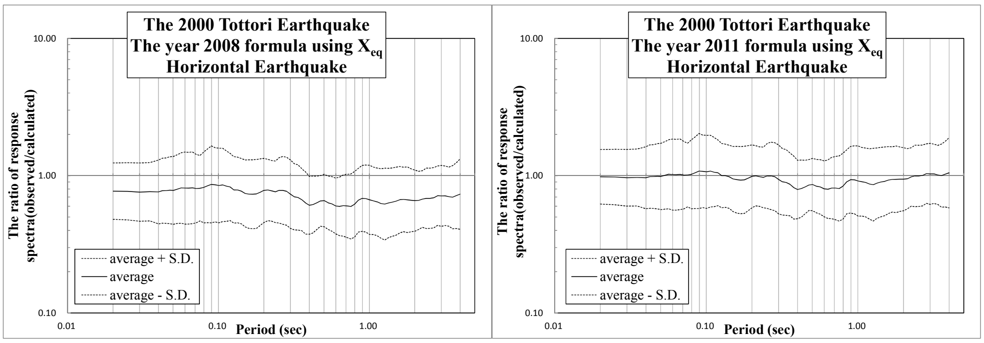



**Figure 9.** Checking conformity of attenuation equations using $X_{eq}$ to the 2000 Tottori Earthquake

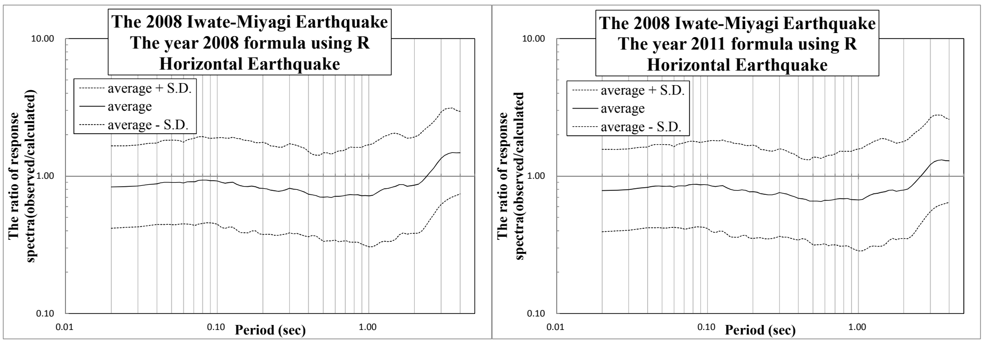



**Figure 10.** Checking conformity of attenuation equations using R to the 2008 Iwate-Miyagi Earthquake

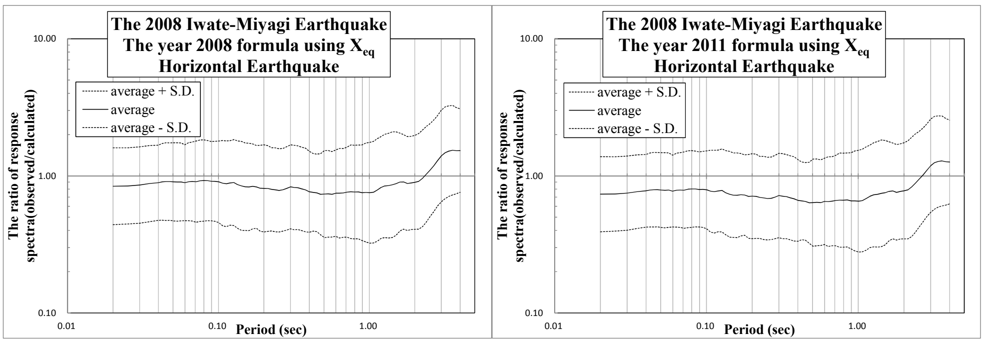



**Figure 11.** Checking conformity of attenuation equations using $X_{eq}$ to the 2008 Iwate-Miyagi Earthquake

Fig.6 shows it's apparent the year 2008 formula using R gives excessive values compared with observed values for the estimation of the earthquake motions concerning the 2011 Tohoku Earthquake. On the other side, Fig.7 shows the year 2008 formula using $X_{eq}$ gives too small values compared with observed values. But the year 2011 formula gives reasonable values in both equation forms. Similarly, Fig.8 and Fig.9 show the year 2011 formula gives reasonable values in both equation forms for the estimation of the earthquake motions concerning the 2000 Tottori Earthquake. Fig.10 and Fig.11 show the estimation of earthquake motions concerning the 2008 Iwate-Miyagi Earthquake. The year 2008 formula gives reasonable values in both equation forms, and this result is generally the same for the year 2011 formula. That is to say, the year 2011 formula never makes conformity to observed values worse concerning the 2008 Iwate-Miyagi Earthquake.

For the estimation of earthquake motions, the year 2011 formula gives better values than the past, and it's expected the year 2011 formula can contribute to advance in rational estimation of earthquake motions and reliability of the attenuation equations.

## 5. CONCLUSION

The knowledge in this paper is shown below;

• The year 2011 formula considering additional earthquake motions of the 2011 Tohoku Earthquake ($M_W$9.0) and its aftershocks is proposed as the latest attenuation equation at dams' rock foundation.
• Usage of the magnitude in the year 2011 formula is reexamined from $M_J$ to $M_W$ to deal with huge earthquake scale in the attenuation equations consistently.
• The earthquakes are classified into four types: shallow crustal, inter-plate, intra-plate and eastern margin of the Sea of Japan.
• The year 2011 formula can express the observed records on the 2011 Tohoku Earthquake ($M_W$9.0) and also on the other earthquakes accurately.

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