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A comparison between seismic hazard and The 2011 off the Pacific coast of Tohoku Earthquake

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ABSTRACT

In the evaluation of the seismic hazard of the Onagawa Nuclear Power Plant, the attenuation relation that was formulated based on the observation results of small to medium interplate earthquakes off the coast of Miyagi Prefecture was used, and the values calculated were based on the intensity distribution of the seven Miyagi-Oki earthquakes in the past to determine the variation in ground motion.

When the results of the seismic hazard analysis of the Onagawa Nuclear Power Plant and the observation results obtained in the 2011 Off the Pacific Coast of Tohoku Earthquake were compared, the probability is comparable to 10^{-3} of the uniform hazard spectrum in average, and it is consistent with the assumption that the 2011 Off the Pacific Coast of Tohoku Earthquake is an earthquake that occurs once every 1000 years statistically.

Although the spectrum in the NS direction exceeded 10^{-5} at around the 0.5-second cycle, it was confirmed that such a trend improves when the peculiarities in the observation record of the 2005 Miyagi-Oki Earthquake (M7.2), the largest one of its kind observed at the Onagawa site when the evaluation was conducted, was incorporated into the attenuation relation.

1. Introduction

Onagawa Nuclear Power Plant is located at the coast of Miyagi prefecture. Off the coast of Miyagi Prefecture, interplate earthquake (Miyagi-Oki earthquake) of about M7.5 ~ M8 has frequently at intervals of about 40 years. The probabilistic seismic hazard analysis at the Onagawa site are heavily influenced by such as the Miyagi-Oki earthquake. Prior to the 2011 off the Pacific coast of Tohoku Earthquake (the 2011 earthquake), we had evaluated the uniform hazard spectrum at the Onagawa site. This report is intended to describe the relationship of observed records of the 2011 earthquake and the results of the evaluation.

2. Characteristics of seismic hazard based on the probabilistic point of Onagawa

By evaluation of seismic hazard, the accuracy of the empirical ground motion model for response spectra has a much greater impact on the results. Also, the standard deviation of the ground motion model greatly affect the results of the evaluation the high probability to calculate of seismic hazard of the earthquakes which have very short interval such as the Miyagi-Oki earthquake.

Therefore, in the evaluation of seismic hazard at the Onagawa site, the ground motion model had developed on the basis of observation records due to small and medium-sized earthquakes at the Onagawa site.

In addition, the standard deviation had adopted the value that evaluated considering the intensity distribution of the seven Miyagi-Oki earthquakes that occurred in the past.

3. The ground motion model at the Onagawa site

Because of the tendency peculiar to the region that short cycle ground motion is predominant in the Miyagi-Oki interplate earthquakes, the attenuation relation that can appropriately handle such a tendency was formulated for the seismic motion evaluation of the Onagawa Nuclear Power Plant.

In formulating the attenuation relation, the observation data of the interplate earthquakes at the Onagawa site that satisfy the following conditions were used. Figure 1 shows distribution of epicenters and details of such earthquakes.

a. The ratio of response spectra observed on the free bedrock surface compared to those by Noda et al. (2002) with the cycle 0.1 seconds or less on the seismic bedrock is 2.0 or larger.
b. The earthquakes with magnitude M4.8 or larger, depth of the epicenter 60 km or less, and their seismic moment M_0 were estimated using F-net etc.

A short cycle level was obtained by conducting spectrum inversion of the epicenter using the records obtained at KiK-net observation points within and near the Onagawa site.

In formulating the attenuation relation, modifications to Noda et al. (2002) were applied depending on the magnitude of the short-cycle level of the earthquakes assumed. Specifically, the relative short period level (RSPL, Eq. (1)) normalized using the short period level M_0 of the observed earthquake was obtained and regression by the least squares method for the correction factor R(T) to Noda et al. (2002) was conducted using such RSPL. Equations (2), (3), and (4) were used in regression.

$$RSPL = A/M_0^{1/3} \quad \dots (1)$$

$$S(T) = S_T(T) \times R(T) \quad \dots (2)$$

$$\text{Horizontal direction: } \ln R(T) = a(T)\cdot \ln (\mathbf{RSPL}) + \mathbf{C_H}(T) \quad \dots (3)$$

$$\text{Vertical direction: } \ln R(T) = a(T)\cdot \ln (\mathbf{RSPL}) + \mathbf{C_V}(T) \quad \dots (4)$$

Where;
S(T): Response spectrum on the free bedrock surface
$S_T(T)$: Response spectrum of the seismic bedrock by Noda et al. (2002)
R(T): Correction factor of $S_T(T)$
a(T): Factor for RSPL obtained by regression
$C_H(T)$: Factor for horizontal component obtained by regression
$C_V(T)$: Factor for vertical component obtained by regression
A: Short period level
(Values obtained by observation were used in regression)
M_0: Seismic moment
(Values obtained by F-net or of Harvard University were used in regression)

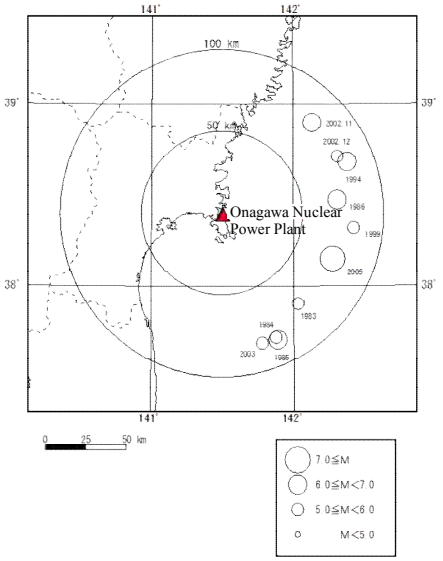
Factors obtained by regression using a least squares method are shown in Figure 2.

To verify the suitability of the formulated attenuation relation, a comparison was made applying the formula to the 2005 Miyagi-Oki Earthquake (M7.2), the largest earthquake of its kind observed at the Onagawa site before the 2011 Earthquake. Figure 3 shows the comparison between the waves observed at the top of the bedrock at the Onagawa Nuclear Power Plant in the 2005 Miyagi-Oki Earthquake removing the influence of reflected waves and the result of the ground motion evaluation using the formulated attenuation relation. M_0 and the short period level used in computing the RSPL were those in the 2005 Miyagi-Oki Earthquake.

The graph shows good correlation between the evaluation results using the attenuation relation and the observation results of the 2005 Miyagi-Oki Earthquake.

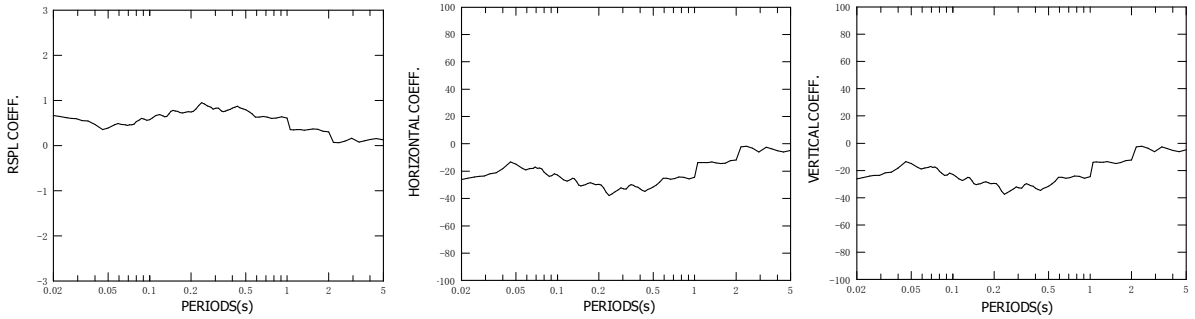
Figure 4 shows comparison between the ground motion evaluation results by the statistical Green's function method for the assumed inter-related Miyagi-Oki earthquakes and the evaluation results of ground motion by the formulated attenuation relation with M_0 and short period level of the fault model. Ground motion evaluations in both methods show similar results.

From the above, it is considered appropriate to apply the formulated attenuation relation in an evaluation of ground motion in the Miyagi-Oki earthquakes.



No.	Date of Occurrence	M	Epicentral Distance (km)	Depth of Seismic Center (km)	Seismic Moment Mo (dyne·cm)	Short Period Level A (dyne·cm/s^2)	RSPL
1	24-May-83	5.8	73	42	1.74×10^{24}	3.37×10^{25}	2.80×10^{17}
2	27-Oct-84	5.4	83	47	1.16×10^{24}	1.77×10^{25}	1.68×10^{17}
3	12-Aug-85	6.4	85	52	5.75×10^{25}	1.35×10^{26}	3.50×10^{17}
4	2-Mar-86	6	72	33	6.56×10^{24}	1.05×10^{26}	5.61×10^{17}
5	14-Aug-94	6	83	42	7.91×10^{24}	2.91×10^{26}	1.46×10^{18}
6	15-Nov-99	5.7	82	46	2.89×10^{24}	4.44×10^{25}	3.12×10^{17}
7	3-Nov-02	6.3	78	46	3.87×10^{25}	1.41×10^{26}	4.17×10^{17}
8	5-Dec-02	5.3	79	40	8.89×10^{23}	2.73×10^{25}	2.84×10^{17}
9	3-Mar-03	5.9	83	41	4.17×10^{24}	7.89×10^{25}	4.90×10^{17}
10	16-Aug-05	7.2	73	42	5.43×10^{26}	1.08×10^{27}	1.32×10^{18}

Figure 1 Earthquakes Observed that were used in Formulation of the Attenuation relation applied in the Interplate Miyagi-Oki Earthquakes



a(T) $C_H(T)$ $C_V(T)$

Figure 2 Regression Results of Correction Factors

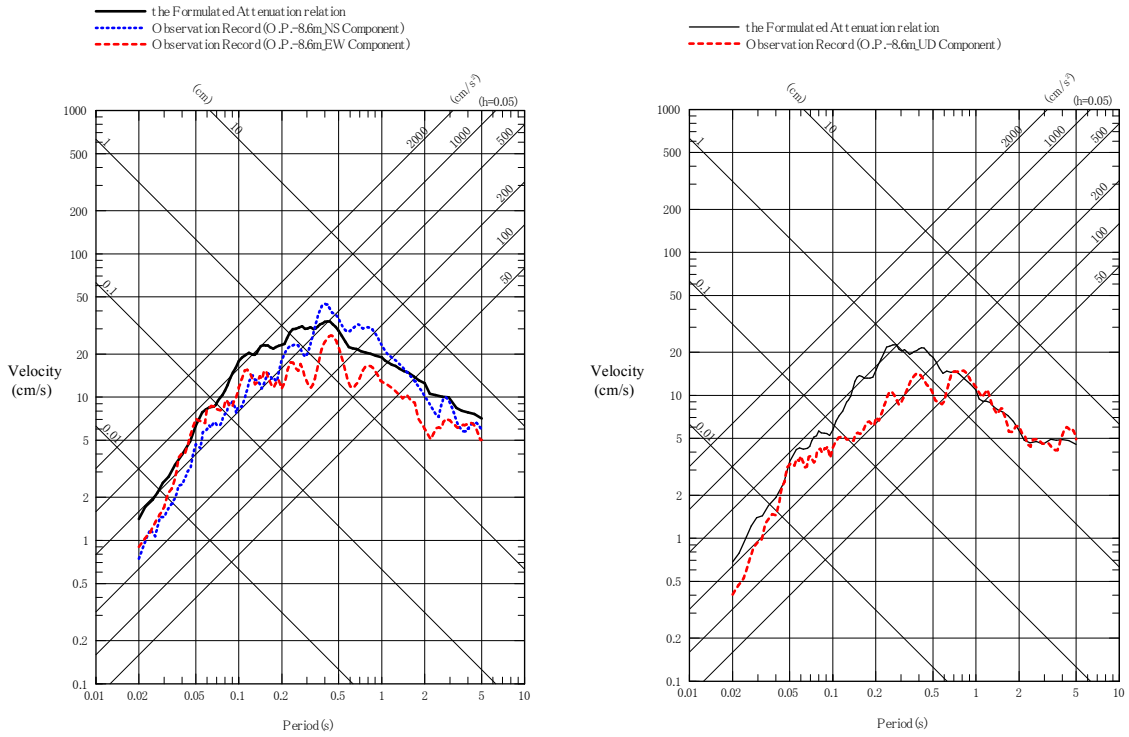


Figure 3 Applicability of the Formulated Attenuation relation to the Strong Motion Record (Waves removing Influence of Reflected Waves) in 2005 Miyagi-Oki Earthquake

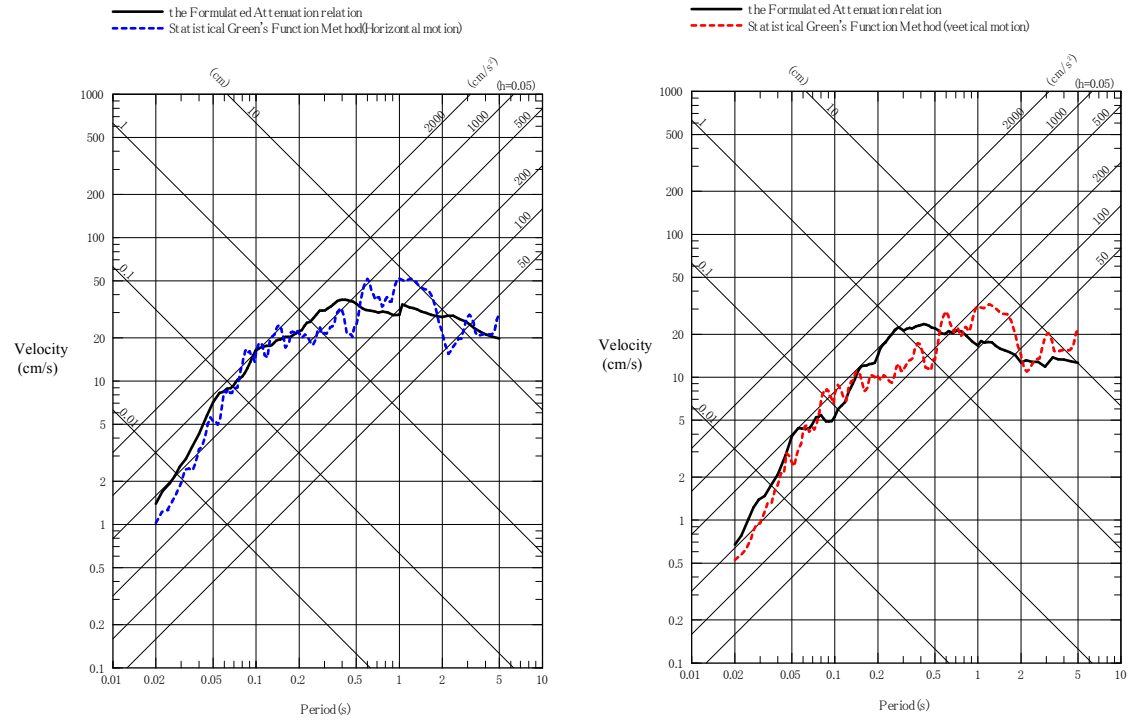


Figure 4 Applicability in Ground Motion Evaluation for the Assumed Inter-related Miyagi-Oki Earthquakes

4. The standard deviation of the Miyagi-Oki earthquake

When earthquakes occurring at high frequency are evaluated in the seismic hazard evaluation, the variation in ground motion significantly affects the evaluation results.

Miyagi-Oki earthquakes evaluated in this study are earthquakes that occur at about 40-year intervals, and the observation of seismic intensity is available. Seven large earthquakes that occurred off the coast of Miyagi Prefecture are known, including the one that occurred in 2005 and the other six, and the variation in ground motion was obtained from these seven earthquakes.

As shown in Figure 5, distribution of seismic intensity in these Miyagi-Oki earthquakes is similar, so these earthquakes were interpreted as the projection of a single earthquake, and the seven earthquakes were regarded as an earthquake that has a similar distribution of seismic intensity. By the method of Sasaki et al.(2008), the average difference in the degree of distribution of seismic intensity was evaluated as a variation in the characteristics of sources and the average projection of the Miyagi-Oki earthquakes, and the associated variations based on the distribution of seismic intensity were calculated.

The following conditions were assumed in calculating the average projection of the earthquake and the associated variations.

(i) The location of the hypocenter is fixed at the point in A1 fault by the Headquarters for Earthquake Research Promotion (2005) where major short period components of the Miyagi-Oki earthquakes are produced. The difference in the actual locations of the hypocenter, scale of the earthquake, etc., was evaluated as the difference in characteristics of the source.

(ii) The seismic intensity recorded was the records at the same observation point and in the same observation condition.

Figure 6 shows the calculation flow of the average projection of the Miyagi-Oki earthquakes and the associated variations based on the distribution of seismic intensity.

Table 1 shows the calculation results of the residues in source characteristics from the initial model earthquake.

When the average projection of the Miyagi-Oki earthquakes (standard earthquake) was obtained from the residues in the calculated source characteristics, the mean of the residues in source characteristics for the initial model earthquake (M7.6) was "-0.14", and the magnitude of the standard earthquake became M7.5 from the relationship between seismic intensity and magnitude of the earthquake with an equivalent hypocenter distance fixed at 62 km.

The variation in ground motion became $\beta = 0.26$ in the natural logarithmic standard deviation when the residues in source characteristics in each earthquake were converted to acceleration according to the relationship between seismic intensity and acceleration in the calculation.

<<Standard Earthquake in Miyagi-Oki Earthquakes>>
Magnitude M7.5
Equivalent Distance of the Site from Hypocenter Xeq =62km
Relative Short Period Level RSPL = 4.48×10^{17}

<<Variation in seismic Motion>>
Natural Logarithmic Standard Deviation $\beta = 0.26$

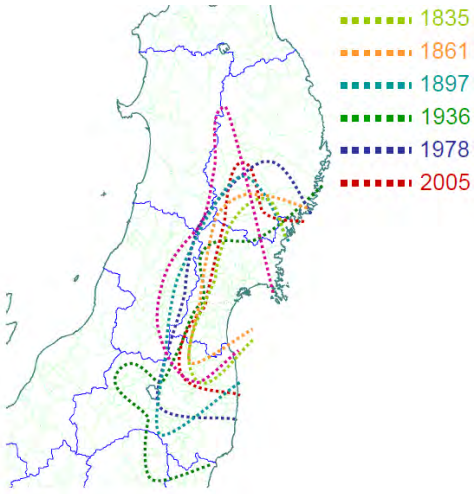


Figure 5 Distribution of Seismic Intensity Scale 5 or Larger in the Miyagi-Oki Earthquakes in the Past

(i) With the initial model earthquake (A1 fault by the Headquarters for Earthquake Research Promotion [M7.6]) established and the attenuation relation of Kanda and Takemura (2005) applied, seismic intensity at each point was estimated. [Seismic Intensity I = -4.7 Log(Xeq) + 1.2 M + 5.8]

↓

(ii) Gap between the seismic intensity at the observation point j in the Miyagi-Oki earthquake i and the seismic intensity of the initial model earthquake was computed. [K_{ij}]

↓

(iii) The average of the gaps in seismic intensity from the initial model earthquake for each earthquake was calculated [$P_i = (1/n)\sum K_{ij}$]
=> Gaps from the initial model earthquake in seven respective earthquakes occurred at Miyagi-Oki

↓

(iv) The average of the gaps in seismic center characteristics from the initial model earthquake in the seven earthquakes was calculated. [$\Delta P = (1/7)\sum P_i$]
=> Considering that ΔP (=-0.14) is the gap between the standard earthquake and the initial model earthquake, the magnitude of the standard earthquake (M7.5) was calculated.

↓

(v) The standard deviation of ground motion was calculated by converting the logarithmic number (seismic intensity) to the natural number (acceleration) based on P_i. ($\beta = 0.26$)

Figure 6 Calculation Flow of the Average Projection of Miyagi-Oki Earthquakes and the Associated Variations based on the Distribution of Seismic Intensity

Table 1 Past Miyagi-Oki Earthquakes used in the Study and the Variation Calculated

	Name of the Earthquake	Magnitude *1	Residues in Source Characteristics *2
1	2/17/1793 Earthquake of Rikuzen, Rikuchu, and Iwaki	M8.2 approx.	+0.25
2	7/20/1835 Earthquake of Sendai	M7.3 approx.	-0.39
3	10/21/1861 Earthquake of Rikuzen, Rikuchu, and Iwaki	M7.4 approx.	-0.05
4	2/20/1897 Earthquake of Off the Coast of Sendai	M7.4	-0.07
5	11/3/1936 Earthquake of Off the Coast of Kinkazan	M7.4	-0.28
6	6/12/1978 Earthquake of Off the Coast of Miyagi Pref.	M7.4	-0.17
7	8/16/2005 Earthquake of Off the Coast of Miyagi Pref.	M7.2	-0.29
Average in Residues in Source Characteristics			-0.14
Variation obtained based on Residues in Source Characteristics			0.26

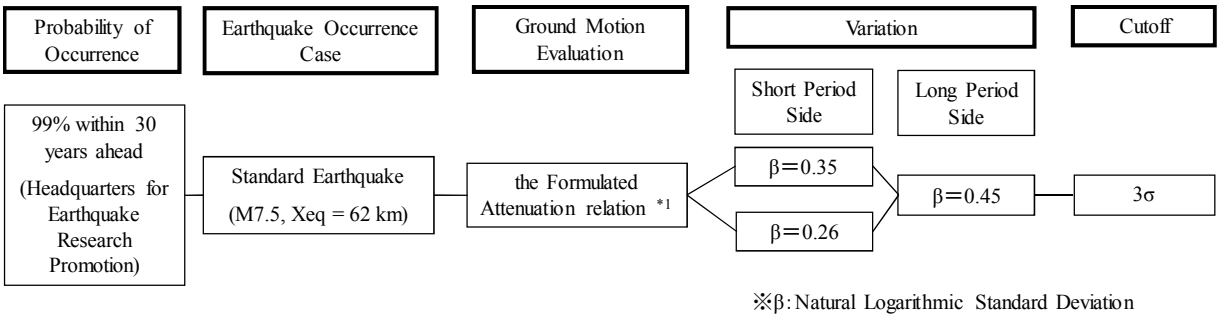
*1: The magnitude of each earthquake according to the Headquarters for Earthquake Research Promotion (2002) and the catalogue of the Japan Meteorological Agency
*2: A residues in source characteristics is the average of residues in seismic intensity at each observation point from the initial model earthquake.
*3: Equivalent distance to the hypocenter of the initial model earthquake from the site Xeq = 62 km

5. Logic tree of Seismic Hazard Evaluation for the Onagawa Nuclear Power Plant

The seismic hazard evaluation at the Onagawa Nuclear Power Plant was conducted using the annual exceedance frequency based on the average frequency of earthquakes assuming the Poisson process for earthquakes with the epicenter located within a 100 km radius from the site. Because Miyagi-Oki earthquakes significantly affect the results of a seismic hazard evaluation, the logic tree applied to Miyagi-Oki earthquakes is explained as follows. Figure 7 shows the logic tree for Miyagi-Oki earthquakes.

The probability of Miyagi-Oki earthquakes is estimated as 99% within 30 years from the time of assessment by the Headquarters for Earthquake Research Promotion in 2010 with the renewal process of BPT distribution applied. The frequency of Miyagi-Oki earthquakes was established so that the frequency was the same as shown above by obtaining the equivalent annual exceedance frequency from the exceedance frequency based on the average frequency of earthquakes.

The projection of the Miyagi-Oki earthquake assumed was selected as the standard earthquake obtained in the study in the foregoing section, and with respect to the variation in ground motion, the variation in the attenuation relation when the observation points and the areas where earthquakes occur are restricted was considered as a branch, in addition to the variation obtained by the foregoing distribution of seismic intensity of Miyagi-Oki earthquakes on the shorter period side, considering that the variation in recurring large earthquakes is smaller than the general variation obtained by small to medium earthquakes. ON the longer period side, the general variation of the attenuation relation was employed. The cutoff point in the variation was the range where it extends over three times the standard deviation.



* For spectrum configuration at the long period side was determined considering the seismic scale of the inter-related Miyagi-Oki earthquakes of magnitude M8 because the magnitude of the standard earthquake is M7.5.

Figure 7 Logic Tree for Miyagi-Oki Earthquakes

6. The relationship between seismic hazard and observation records of 2011 Earthquake

Figure 7 shows relation between the calculated seismic hazard (uniform hazard spectrum) at Onagawa Nuclear Power Plant and the observation records in 2011 Earthquake.

Comparing the observed response spectrum with a damping factor of 5% of EW and vertical components due to the 2011 earthquake and the uniform hazard spectrum of the horizontal and vertical components at the Onagawa site, the observed response spectra was about the same level as the uniform hazard spectra at annual exceedance probabilities of 10^{-3} on average. (fig-8).

It is reasonable the last event of this aria is the 869 Jogan Earthquake, assumed that the previous event one temporarily, earthquakes linked interval is about 1000 years and earthquakes in seismic hazard evaluation result is what I will be consistent with this.

However, that of NS component is greater than the uniform hazard spectra at annual exceedance probabilities of 10^{-5} around the period of 0.5 second. The reason of this difference is considered that the site factor of ground motion based on the observed records at the Onagawa site, underestimates the response spectra around the present period.

The peaks at the period around 0.5 seconds in the horizontal directions were identified in the observation record of the 2005 Miyagi-Oki Earthquake (M7.2), which was the largest earthquake observed at the Onagawa site, and we tried to improve the spectrum configuration by incorporating this characteristics in the attenuation relation.

In the calculation, the Miyagi-Oki earthquakes that significantly affected the hazard evaluation were selected and studied.

In order to improve the spectrum configuration, the site correction factor around the period of 0.5 seconds was reviewed considering the attenuation relation of Noda et al. (2002) and the difference in the site correction factors for the residual of observation records for 2005 Miyagi-Oki Earthquake and for the difference between RSPL in the standard earthquake and RSPL observed in 2005 Miyagi-Oki Earthquake.

Figure 8 shows the comparison of the results with the observation record of the 2011 Earthquake after a review of the site correction factor.

As shown in Figure 8, the configuration of the uniform hazard spectrum around the period of 0.5 seconds is consistent with the observation records for the 2011 Earthquake, and the annual exceedance probability is generally at 10^{-3}.

As explained above, the feasibility of improving the seismic hazard evaluation by taking the spectrum configuration of large earthquakes into account in the attenuation relation as the site correction factor was confirmed.

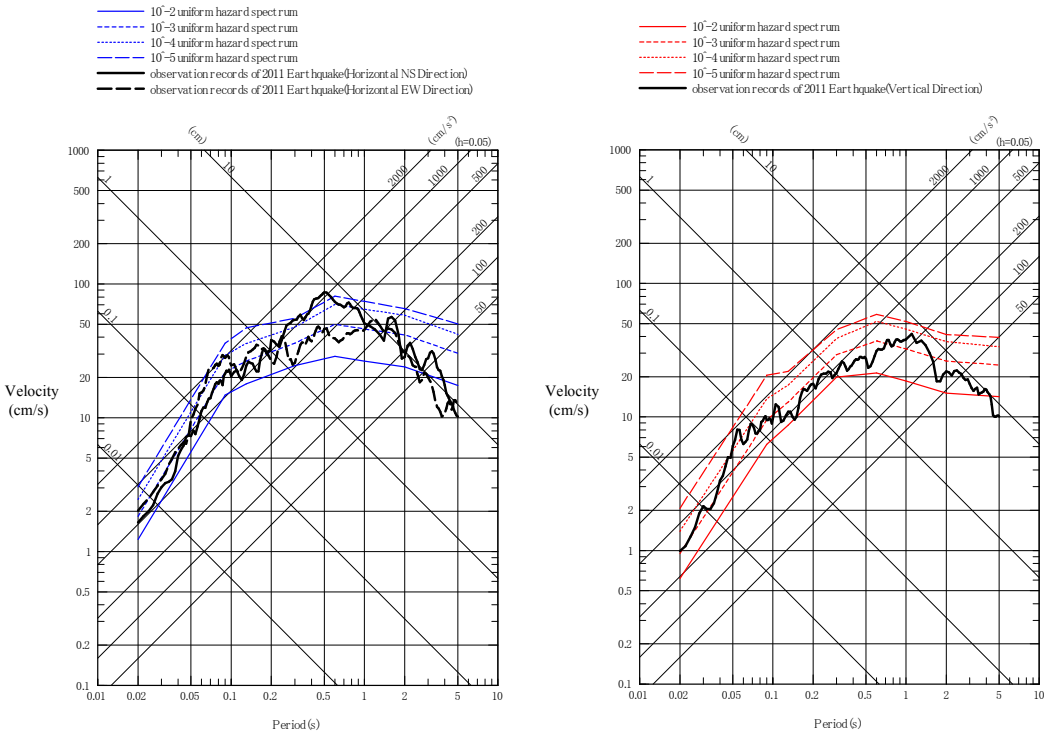


Figure 8 Comparison between the observed response spectra with a damping factor of 5% of observation records of the 2011 earthquake and the uniform hazard spectrum at the Onagawa site

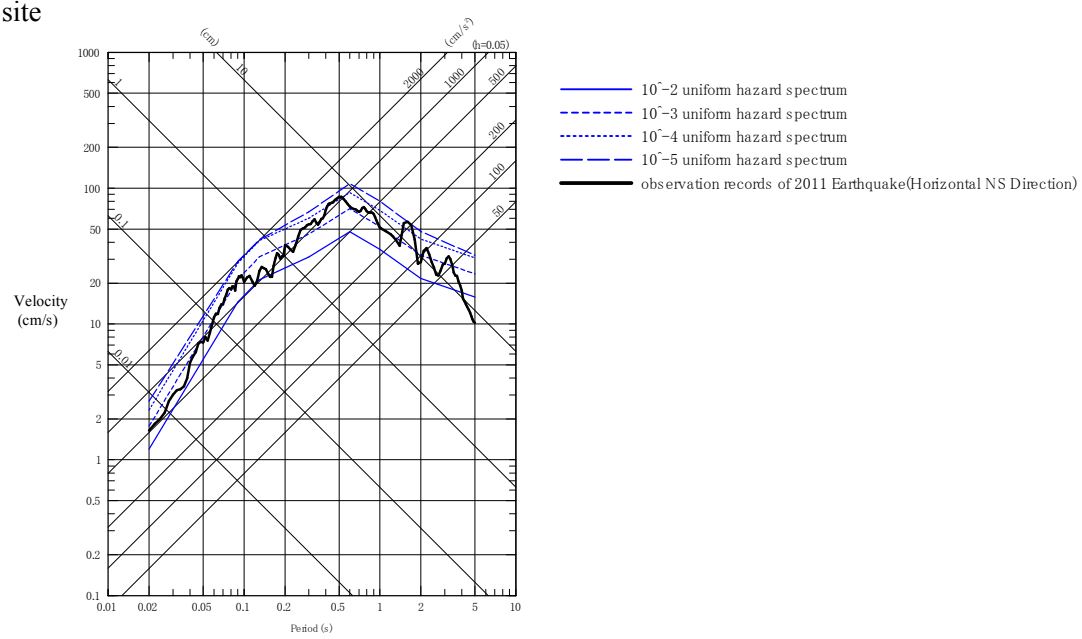


Figure 9 Comparison between the observed response spectra with a damping factor of 5% of horizontal motion due to the 2011 earthquake and the uniform hazard spectrum reviewed a correction factor at the Onagawa site

CONCLUSION

Seismic hazard evaluation results of the Onagawa Nuclear Power Plant was compared with the observation records from the 2011 Earthquake, and it was confirmed that the level was generally in good agreement with the 10^{-3} uniform hazard spectrum.

The seismic hazard evaluation result of the Onagawa Nuclear Power Plant is consistent with the observation results when the 2011 Earthquake is considered as the earthquake occurring at about a 1000-year interval.

Although the spectrum in the NS direction exceeds 10^{-5} at around the 0.5-second cycle, it was confirmed that such a trend improves when the peculiarities in the observation record of the 2005 Miyagi-Oki Earthquake (M7.2), the largest one of its kind observed at the Onagawa site when the evaluation was conducted, was incorporated in the attenuation relation.

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