An Empirical Evaluation of Long-Period Earthquake Motion for Building Design

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SUMMARY:
We have made a proposal on method for evaluating the long-period earthquake motion time history with periods from 0.1 to 10 second using designated earthquake magnitude, shortest distance to the source area and location of hypocentre in view of establishing the generation scheme for design long-period motions for super high-rise buildings and applied it for the simulation of large subduction-zone earthquakes. The 2011 Off the Pacific coast of Tohoku earthquake has provided us with an opportunity to examine the method by comparing recorded motions with simulated ones. We had made revisions to this proposed method. We also made simulations for the Tohoku earthquake with the revised method. We have obtained better fit of the formula to the recorded motions. In addition, long-period ground motions were simulated for a three-events-connected source model expected to occur in the Nankai trough region.

Keywords: long-period ground motion, Site coefficient, Group delay time, Attenuation, the 2011 Off the Pacific coast of Tohoku earthquake

1. INTRODUCTION

A large earthquake is supposed to occur on subduction zones around Japan in near future. We have serious concerns on structural damage due to the long-period ground motions generated by the earthquake. We have developed a method to evaluate the long-period ground motion both in spectral and time-history formats (Satoh, 2010a), and are going to apply the method for constructing the input ground motion for the design of high-rise buildings and base-isolated buildings, concurrently performing earthquake response history analysis with the simulated motions to confirm the influences of those motions to building structures. The problem for the method was insufficiency of recorded motions especially for larger events.

During the 2011 off the Pacific coast of Tohoku Earthquake (hereinafter referred to as the Tohoku earthquake), the wide area in Japan suffered extremely large earthquake motions, the earthquake data for larger events including many aftershocks became available. It also caused a situation whether the proposed method can be applied to large event or not. During the earthquake, the high-rise buildings in large cities shook largely and some disorders with non-structural members were reported. For the expected huge earthquake in future, the long-period motions lasting long will be generated, and we confirmed that the effect on buildings with longer natural periods such as super high-rise buildings will be significant.

In this paper, we first revised our previously proposed formula for generating the long-period motions with large subduction-zone earthquakes, using the added recorded motions including records from the Tohoku earthquake. We have successfully revised the method. After confirming the better fit of the revised method to the recorded motions for larger earthquake, we additionally made some simulations for future large events. The advantage of the method we have proposed can be utilized easily to generate a long-period time history once the earthquake magnitude and hypocentre are fixed with small number of necessary parameters, and it will surely be an excellent reference values for judging the validity of the motions simulated with other various methods.

In this paper, for enhancing the applicability of our proposed method when it is applied for extremely large events, the formula for Sa with 5% damping is considered to include a first- and second-order polynomial, i.e., M_w and M_w^2. In addition, for both of spectrum and group delay time, the distance dependency is separately considered for events on either of the Pacific and the Philippine plates. The site factors for amplification and group delay time are also separately considered for the two plate events, in case the thickness of sediment under recording station above seismic bedrock is large enough with the travelling time of seismic wave of longer than 1 second. Although similar empirical formulas for the long-period response spectra involving site response factors have been proposed by other researchers, the considerations of the second-order term M_w^2 and the difference between the plates have not been applied yet. (Satoh et.al., 2012a)

2. EVALUATION OF LONG-PERIOD GROUND MOTION WITH SUBDUCTION-ZONE MEGA-EARTHQUAKE BASED ON THE EMPIRICAL METHOD

The research on the evaluation of long-period motions has widely been conducted using theoretical method such as the 3D-FDM. On the other hand, the researches with the empirical evaluation of the long-period motions are very few. (Kataoka, 2008) showed the attenuation formula for evaluating the response spectral properties. However, almost no research has targeted on the time history generation.
Considering the usefulness of the formula and expecting the data accumulation in future, the empirical method will become much more useful in engineering sense. In addition, the evaluated motion with the empirical method will be useful enough to judge the plausibility of the theoretical method.
We used nationwide many ground motion records to make an empirical model to predict the ground motion with 0.1 to 10 second period range. Furthermore, based on this formula, we investigated and proposed the method to construct the long-period ground motion time histories generated by hypothetical large future earthquakes. (Satoh, et.al., 2010a, Okawa, et.al., 2010)

We considered the problems to be solved as follows to make revision on our previous proposal. One point is that the total moment magnitude M_w of the Tohoku earthquake was large and each of the sub-events, even when being decomposed, was still larger than the database range in magnitude. Therefore, the evaluation is still an extrapolation, and in addition, the logarithm of response spectral value is related with only M_w term, then, the value is resulted in excess for larger magnitude. When the source spectrum is represented with the ω^{-2} model, the amplitude level in longer period will surely be overestimated.

2.1 Additional Data for Revision of Attenuation Formula

For modification of the formula, the recorded data for 19 subduction-zone earthquakes occurring during the period that followed 33 subduction-zone earthquakes from 1988 to July, 2007 that was used for making the previous version of formulas. The totally 52 earthquake epicenters were plotted in Fig.1 (a). The 2009 Suruga Bay earthquake is from the Philippine plate among the added data. The off south-west Hokkaido earthquake occurring in the eastern fringe of Japan Sea was included in the group of the Pacific plate earthquake. The 2011.3.9 foreshock of the Tohoku earthquake and the 2011.3.11 off Iwate prefecture aftershock at 15:08 were characterized with moment magnitude M0 and fault plain analyzed by JMA. For the 2009 Suruga Bay earthquake, the M_0 and fault plain analyzed by Suzuki & Aoi was used. For other events, M_0 from F-net operated by NIED was used and the JMA hypocenters were used as point source. The Tohoku earthquake was not included in the database, since the earthquake should be modeled as a connected-sources event consisting several strong motion generation areas representing the earthquakes from the empirical formula representing

the period range between 0.1 to 10 second, however, the regression coefficients vary due to the selections of source model of the Mw=9 event that is not determined yet.
The data used here are from K-NET, KiK-net, JMA87 and JMA95 records for events prior to the 2009 Suruga Bay earthquake for Kanto, Nohbi and Osaka plains and the records from the 1st floor sensor at Kogakuin University in Shinjuku, Tokyo.
The selection criteria of Subduction-zone event records are as follows,

1) Subduction Type :Mj>6.5 for hypocentral distance<400km (Mj:JMA magnitude)
2) Recording station within the distance for which the PGA is equal to or greater than 2 cm/s^2 with the Fukushima-Tanaka attenuation formula (Fukushima et.al., 1992)
3) The motion is recorded from the S-wave arrival and reliable for period 0.1 to 10 second.

The recording stations are plotted in Fig.1 (b). The scatters of data for shortest distance to the fault and the moment magnitude are plotted in Fig.1(c). The smallest value for the shortest distance is 20 km. The largest M_w is 8.2 for 1994 Eastern Hokkaido earthquake and 2003 Tokachi-oki earthquake.

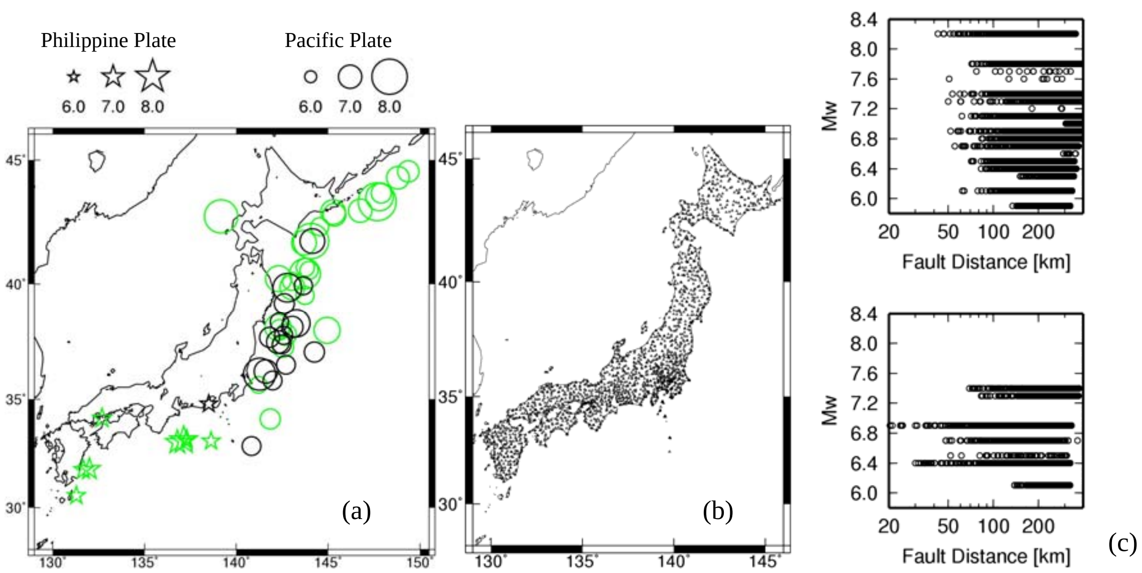


Figure 1. (a) Locations of epicenters, (b) Locations of recording stations, (c) Scatters of Mw, R of data

The analytical scheme is same as the previous study (Satoh, et.al., 2010a). The response spectra and the group delay times are evaluated from the data portions after the S-wave arrivals. The response spectrum stands for the geometrical average of the spectral values for two horizontal components and the mean and variance values for group delay time stands for those for the arithmetic mean values for two horizontal components. In addition, the mean and the variance values of the group delay time are calculated from time history data with time interval 0.02 second and total duration time of 1310.72 sec. with zero padding if necessary. The bandwidth for which the mean and the variance are computed is 0.049 Hz.

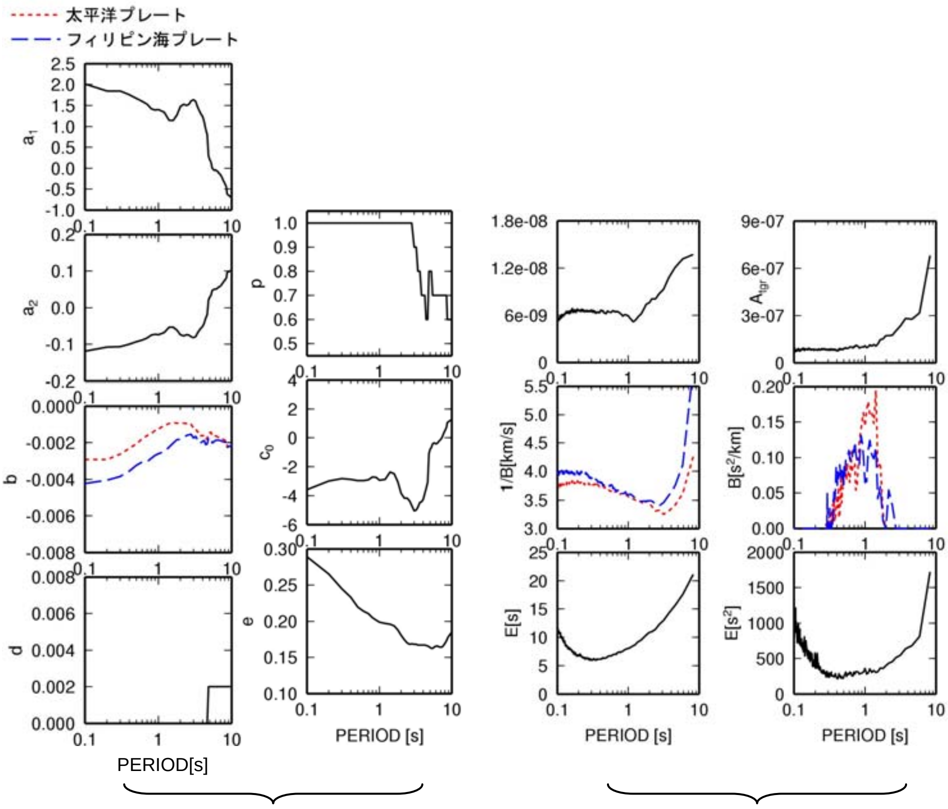
2.2 Revision of Attenuation Formula for Acc. Response Spectra with 5% damping in Longer Period

In the least square analysis, the 5% damping acceleration response spectra $S_a(T)$ is related with the moment magnitude and the shortest distance from recording station to the assigned source area of each recorded event. Our initial formula was Eqn. 2.1. (Satoh, et.al., 2010a) The second formula Eqn. 2.2 was used for revision with classified data. (Satoh, et.al., 2012a)

$$\log_{10} S_a(T) = a(T)M_w + b(T)R - \log_{10}(R^{p(T)} + d(T)10^{0.5M_w}) + c_0(T) + c_j(T) \quad (2.1)$$

$$\log_{10} Sa(T) = a_1(T)M_w + a_2(T){M_w}^2 + be(T)R + bw(T)R \\ -\log_{10}(R^{p(T)} + d(T)10^{0.5M_w}) + c_0(T) + c_j(T) + c_{wj}(T) \tag{2.2}$$

Where, T is period in second, and 55 values are selected for evaluation from 0.1 to 10 second. The M_w is the moment magnitude and R is the shortest distance from the recording site to the source area, and $a(T)$, $a_1(T)$, $a_2(T)$, $b(T)$, $be(T)$, $bw(T)$, $p(T)$, $d(T)$, $c_0(T)$, $c_j(T)$, $c_{wj}(T)$ are coefficients to be determined with the least squares analysis. $a_1(T)$, $a_2(T)$ are coefficients representing the source properties. $be(T)$, $bw(T)$ represent the property for propagation from the Pacific plate and the Philippine plate, respectively, and either coefficient is selected with the location of the event source. The coefficient $c_0(T)$ is assumed to be the site amplification factor for KiK-net FKSH19 station which is regarded as benchmark station on the seismic bedrock and, $c_j(T)$, $c_{wj}(T)$ are site coefficients for the j-th recoding station. $c_j(T)$ is used basically for each station. However, when recording site is on the Kanto plain, and event is from the Philippine plate and the seismic wave travelling time (Tz3.2) from the bedrock (the shear wave velocity Vs=3.2km/s) to the upper engineering base layer at site is greater than 1 sec., the coefficient $c_{wj}(T)$ is used instead of $c_j(T)$. The values for $10^{c_j(T)}$, $10^{c_{wj}(T)}$ are site amplification factors when T is larger than 1. The Tz3.2 can be evaluated using the deep sediment structure data disclosed by the Headquarters for Earthquake Research Promotion (HERP), MEXT. The site coefficients $c_j(T)$, $c_{wj}(T)$ are actually evaluated as the weighted average of the coefficients for the crustal earthquakes and Subduction-zone earthquakes, since the number of subduction earthquakes are very small.



(a) (b)

Figure 2, (a) Regression coefficients for formula Eqn. 2.2, (b) Regression coefficients for formula Eqn. 2.3, (b) left shows for μ_{tgr} and (b) right shows for σ^2_{tgr}

The coefficients for formula Eqn. 2.2 are shown in Fig.2(a). The two plots for coefficient b means that the red fine broken line is for be and blue dotted line is for bw. The plot e, additionally, indicates the regression error, i.e., corresponding to the standard deviation of logarithmic differences between recorded and predicted values. The following chapters refer the terms, mean (μ) and mean +standard deviation ($\mu + \sigma$) levels. The standard deviation corresponds to the regression error e that is shown here. The difference between be and bw indicates that the attenuation rate for distance differs for the two seismic source areas.

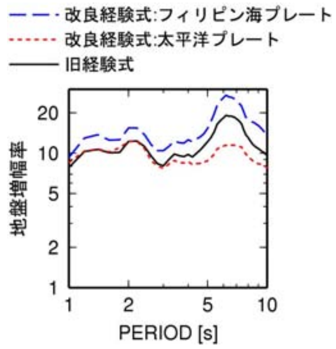


Figure 3. The difference of site amplification ratios of the K-NET site TKY018, in Tokyo. The black solid line is for the original formula Eqn. 2.1, the two dotted lines are for the revised formula Eqn.2.2. In addition, the blue dotted line is for events in the Philippine plate, whereas the red dotted line is for events in the Pacific plate.

We could find that the site amplification factors for events from the Philippine Sea plate indicates larger values than for events from the Pacific plates as shown in Fig.3 (for K-NET TKY018).

2.3 Revision of Empirical Formula for Frequency-dependent Mean and Variance of Narrow-band Group Delay Time

The mean value μ_{tgr} of the group delay time corresponds to the gravity center of arriving time of wave group in a narrowband. The standard deviation σ_{tgr} of the group delay time corresponds to the scatter of the arriving time that is the duration time of the wave group in the narrowband. Since the group delay time is the first derivative of the Fourier phase spectra, once the initial phase angle is fixed, the other phase angles are calculated recursively, assuming a normal distribution with the mean and standard deviation values within the narrowband. The method holds an advantage to realize the spectral non-stationarity of the wave seemingly caused by the dispersion of surface waves. The average values are corrected so that the rupture initiation time should be zero.

Since both of the average group delay time μ_{tgr}, and the variance $\sigma^2{}_{tgr}$ of group delay time can be related with the source property, the path effect and the site characteristic, both μ_{tgr} and $\sigma^2{}_{tgr}$ were eventually related with such parameters. We have evaluated both properties with the previous study. As was done for the spectral formula, we have also revised the formula considering the wave propagation from sources and site specific effect on the group delay times with the following formula.

$$\begin{aligned} \mu_{tgr}(f) &= A_{1tgr}(f)M_0^{1/3} + Be_1(f)X + Bw_1(f)X + C_{1j}(f) + Cw_{1j}(f) \\ \sigma^2{}_{tgr}(f) &= A_{2tgr}(f)M_0^{1/3} + Be_2(f)X + Bw_2(f)X + C_{2j}(f) + Cw_{2j}(f) \end{aligned} \qquad (2.3)$$

Where, M_0 is seismic moment in dyne-cm, X is the hypo-central distance in kilometer, f is frequency. A_{1tgr}, $Be_1(f)$, $Bw_1(f)$, $C_{1j}(f)$, $Cw_{1j}(f)$, A_{2tgr}, $Be_2(f)$, $Bw_2(f)$, $C_{2j}(f)$, $Cw_{2j}(f)$ are determined by the least squares analysis. $C_{1j}(f)$, $Cw_{1j}(f)$, $C_{2j}(f)$, $Cw_{2j}(f)$ are called site coefficients. These coefficients are shown in Fig.2(b). The coefficient for distance dependence is shown with 1/B. The Fig.2(b) left shows for μ_{tgr}, and the Fig.2(b) right shows for σ^2_{tgr}. The coefficents E that are presented in both cases indicate the regression errors in the similar manner for response spectrum formula. The value 1/B indicates the propagation velocity of seismic waves radiated from the seismic source. The values differ between cases for the Pacific plate and the Philippine plate. The revised formula indicates that the duration time is longer than the previous formula. There are still insufficient data with sufficient recording time. With this revision, the new data were added. These added data generally hold longer recording time. The aforementioned note will be owing to such situation with the current earthquake observations.

3. VALIDATION OF PROPOSED EMPIRICAL FORMULA WITH RECORDED MOTIONS

The empirical formulas for response spectrum and group delay time (tgr) were applied to the Tohoku earthquake, its foreshock and the largest aftershock. The moment magnitude and macroscopic fault model for the foreshock of March 9th were based on the JMA analysis (JMA, 2011a,b). However, the fault model for the largest aftershock at March 11th, at 15:15 JST was not announced by JMA yet. Therefore, its moment magnitude was taken the value from F-net operated by NIED, and the dip angle and rupture direction of the fault was assumed based on the Harvard CMT solution. The fault length, width and its area were calculated assuming static stress drop of 3MPa with square fault. In addition, the JMA hypocentre was placed at the middle of the fault plain as adopted as the point that initiates rupture. The values for the static stress drop 3MPa is close to the average for the world historical shallow earthquake faults database and even for the earthquakes occurring on the plate boundary. The value, 3Mpa is therefore used for source model with the three connected-earthquake for Tokai-Tonankai-Nankai established by the Central Disaster Management Council (CDMC), Cabinet Office (CAO, 2012).

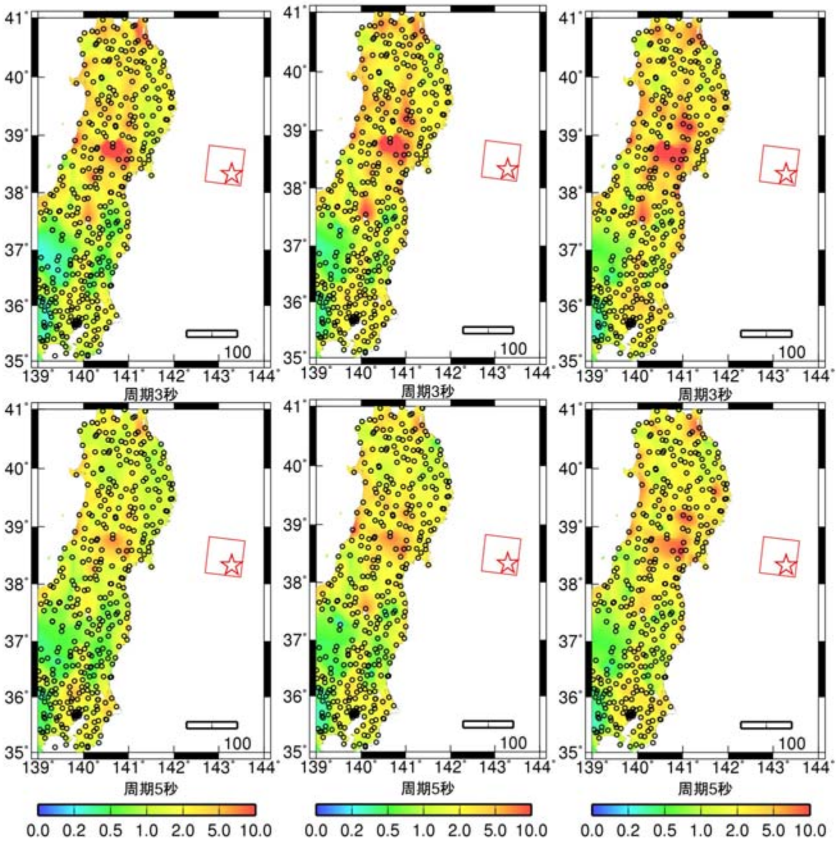


Figure 4. Distribution of pseudo velocity response spectrum for 2011March 9 foreshock for periods 3 and 5 seconds, (left) recorded, (middle) new proposal, (right) previous proposal

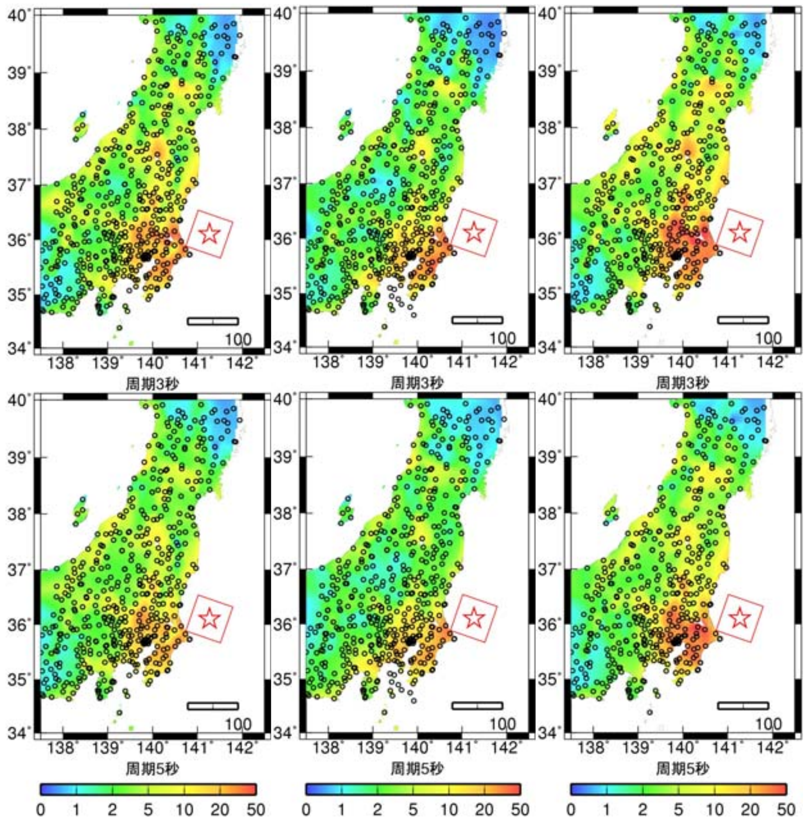


Figure 5. Distribution of pseudo velocity response spectrum for 2011 March 11, 15:15 largest aftershock for periods 3 and 5 seconds, (left) recorded, (middle) new proposal, (right) previous proposal

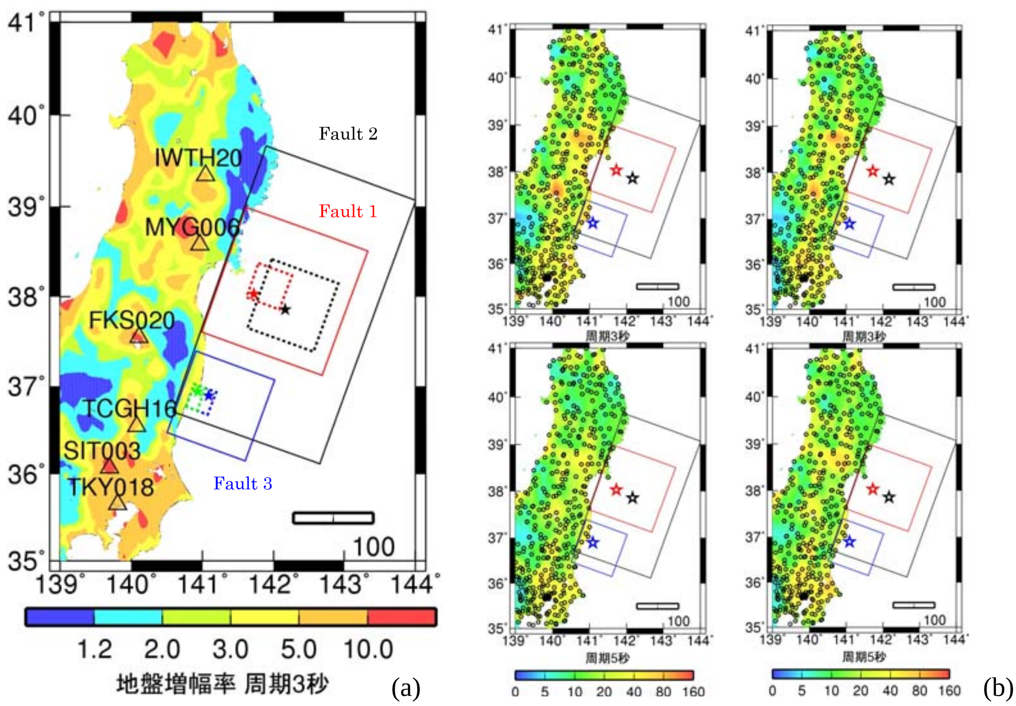


Figure 6. (a) The three macroscopic fault source models representing the 2011 Tohoku earthquake. The coloured contour shows the revised site amplification factor for Sa at 3 second of period. (b) left the pseudo velocity response spectra (pSv) at period 3 and 5 second with recorded motions for main shock, (b) right the pSv at 3 and 5 second for simulated motions with revised formula for main shock. (pSy are all with 5% damping)

Furthermore, the source model for the main shock, the Tohoku earthquake, was set up based on the model by Satoh that utilized the empirical Green's function and the recipe for strong motion prediction by the HERP, MEXT (Satoh, 2012b). The moment magnitudes for three faults 1, 2, and 3 are, 8.4, 8.8, and 8.2, respectively. The three macroscopic fault plains and four sets of strong motion generation area on fault and the hypocentres are presented in Fig.4. In the figure, the distributions of the site amplification factors for 3 second period are also shown.

4. SIMULATION OF THREE-CONNECTED EARTHQUAKE MOTIONS IN NANKAI TROUGH

The long-period motions due to the mega-earthquake along the Nankai trough were simulated. The huge earthquake is assumed as three-connected earthquake for Nankai, Tonankai and Tokai earthquakes. The rectangular source model (Tsurugi, 2005) was used for Nankai and Tonankai earthquakes following CDMC (CDMC, 2003). We set up a rectangular source model for Tokai earthquake employing the HERP model used for the long-period earthquake motion map (HERP, 2009).

The method presented here generates each simulated motion as a sample of random process. The rupture sequences of faults also follow the assumption by CDMC as indicated in Fig. 5 with red arrows. There are variations among sample waves depending on the random numbers chosen for each simulation. The rectangular source shapes and locations are shown in Fig.5, together with the locations of the stations for which the long-period motions were generated. The moment magnitudes of sub-sources were 8.2 (Nankai-east) 8.4 (Nankai-west), 7.9 (Tonankai-east), 8.0 (Tonankai-west) and 8.0 (Tokai), and total moment magnitude amounts 8.7. The 21 sample motions were generated for ground surface at each station and one sample motion that is the closest to the average of them was taken and the pseudo velocity response spectra were computed.

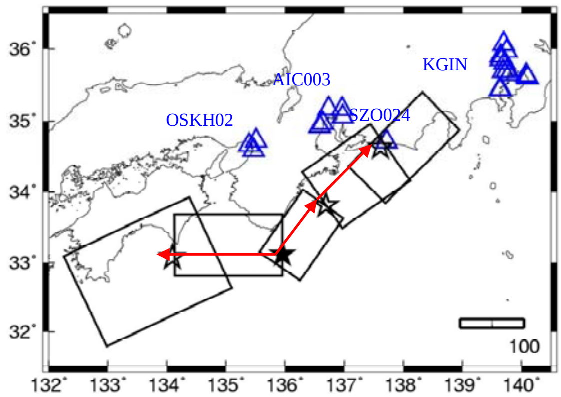


Figure 5. Three-connected earthquake model and the selected stations for evaluation of long-period motions.

The pSv spectral values were plotted in Fig. 6 for 4 recording station, named as OSKH02 (KiK-net) for Konohana on the Osaka bay, AIC003 (K-NET) for Tsushima, Aichi, SZO024 (K-NET) for Hamamatsu, Shizuoka, and KGIN for Kogakuin Univ. campus in Shinjuku, Tokyo. The blue solid line indicates the spectrum corresponds to the nearest one with the mean spectra in 21 simulated motions with different random numbers, the blue dotted line indicates that the spectra corresponds to the mean + standard deviation level spectra that was computed using the regression errors.

During the 2011 Tohoku earthquake, there are no recording sites where the pSv spectra with 5% damping above 5 second of period exceeded 80 cm/s, the level of the BSL notification at engineering bedrock. However, we have many recording sites exceeding the value for the periods less than 5 second. The K-NET site MYG006 in Miyagi prefecture exceeded the level 100 cm/s for 5% pSv in broad period range, 0.1 to 4 second. The amplitude is larger than the simulated motions at SZO024 for the three-connected earthquake motions.

The CDMC has recently released the new seismic source model for huge earthquake occurring along the Nankai trough region that renews the previous source model for the future Nankai-Tonankai-Tokai earthquake (Mw=8.7) and is almost double in earthquake size (Mw=9.0). They have also reported the estimated seismic intensity and tsunami height for wide areas influenced by this earthquake.
We will be also working for evaluating the long-period motions with this new earthquake sources for wide areas applying our revised new formulas.

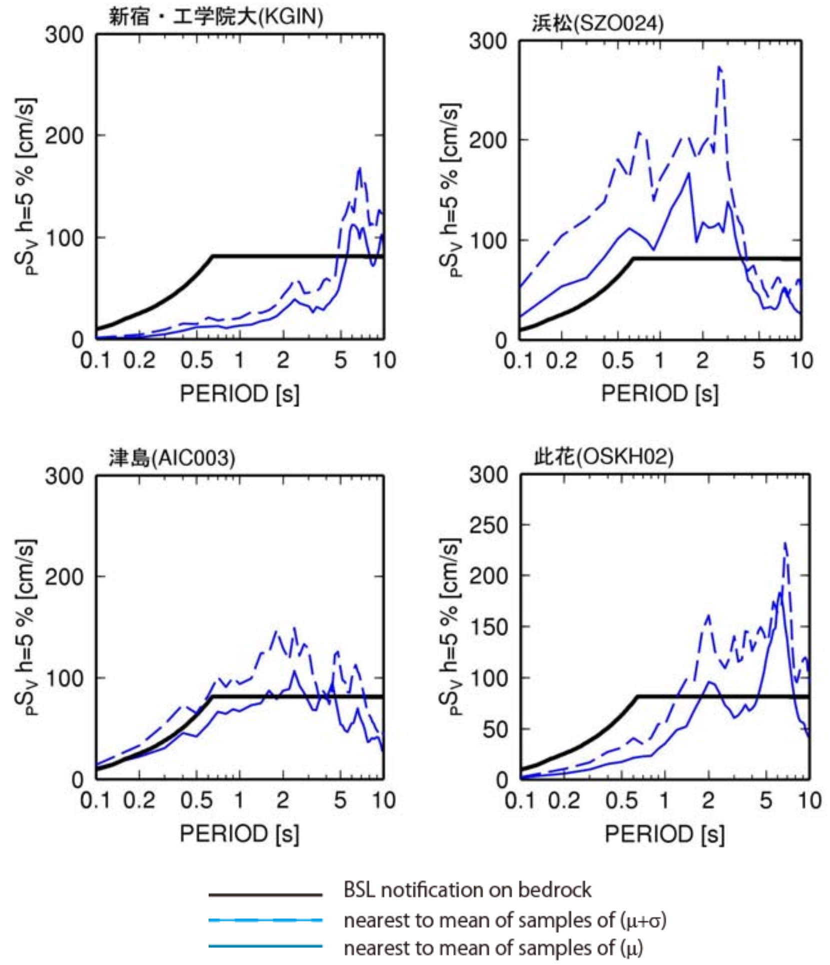


Figure 6. Pseudo velocity response spectra for simulated motions for three-connected earthquake for 4 stations

5. CONCLUSIONS

We have revised our proposed formula for evaluating the long-period earthquake motions using newly collected data with the 2011 Tohoku earthquakes and its aftershocks and have also successfully confirmed the validity of the formula. The long-period motion for the main shock of the Tohoku earthquake was simulated with three-connected earthquake model. We found that the application of the formula with some upper limit of magnitude was appropriate.

The attenuation properties were compared between earthquakes occurring on the Pacific plate and Philippine plate, and the difference was confirmed. The difference of site amplification and the site coefficients for properties on the group delay time was also large for Kanto area in case the predominant period between seismic bedrock and engineering bedrock (Tz3.2) is larger than 4.0 second. We have also confirmed that the site amplification is generally larger and the duration time of seismic motion is longer for the earthquakes in the Philippine plate than in the Pacific plate.

We applied the revised formula with parameters corresponding to the mean and the mean + standard deviation levels. For application to building design, we need to fix the parameter values appropriate for design considerations, i.e., the pertinent engineering parameters relevant to levels of earthquake motions, building responses and occurrence rate of these values.

As was mentioned previously, the new seismic source model for huge earthquakes occurring along the Philippine plate region was released from CDMC (2012, CAO). We are going to evaluate the long-period motions with these renewed conditions for wide areas applying our revised new formulas.

ACKNOWLEDGEMENT

We used the strong motion records from K-NET, KiK-net, the earthquake mechanism solution of F-net from NIED, the JMA 87 and 95 type strong motion records, and earthquake information from JMA, and the data of the Harvard University CMT solutions. We also acknowledge the usage of strong motions records from the campus building for Prof. Hisada, Kogakuin University, Shinjuku, Tokyo. In addition, the GMT was used for making maps (Wessel, 1998). This work was conducted in the task topic, “Study on the effect of long-period earthquake motions to the super-high-rise building,” in the 2011 Promotional Project for Upgrading the Building Standards under the auspices of the Ministry of Land, Infrastructure, Transport and Tourism. The authors express their sincere thanks to the members of the Committee for the Study of the Long-Period Earthquake Motions established in Ohsaki Research Institute, Inc. for their relevant ideas and fruitful discussions.

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