# Empirical shake map for long-period (1-15 sec) ground motion in Japan

**Y. YUZAWA & H. NAGUMO**
*Tokyo Electric Power Services Co., LTD, Japan*

**K. KUDO**
*College of Industrial Technology, Nihon University, Japan*

**ABSTRACT:**
In order to provide an empirical shake map of long-period (1-15sec.) ground motion (LPGM), we first obtained a spectral predictive model of LPGM on hard rock (Vs>2.0 km/s) using the down-hole data registered by the KiK-net (NIED) rock sites from earthquakes of larger magnitudes than 5.7. Next, we estimated the shake-ability at all sites of whole Japan covered by the K-NET, KiK-net and JMA Intensity Network by taking spectral ratio of acceleration response spectra at sites to those estimated by the proposed empirical model on hard rock. A very strong spatial variation of shake-ability was found in and around large sedimentary basins. The shake-ability at thick sediment sites exceeding more than 10 times of rock sites is not rare and it also depends strongly on period. The obtained shake-ability may be useful for quickly assessing seismic safety of long-period structures.

*Keywords: Long period ground motion, Empirical predictive model, Shake map, Strong-motion records*

## 1. INTRODUCTION

Recent rapid increases of long period man-made structures such as tall buildings, base-isolated buildings, large storage tanks, and long-span bridges have brought essential issues for providing seismic safety of society from future large earthquakes. We, therefore, made efforts to assess the long-period ground motion (LPGM) using strong-motion records and to provide the shake-map for LPGM. We have experienced an important role of LPGM during the 1985 Mexico earthquake, the 2003 Tokachi-oki earthquake and others, however, these issues have not necessarily been accounted for the seismic safety of long-period structures. Very recently, some empirical predictive models for LPGM have been proposed by Kataoka et al. (2008), Sato et al. (2010), Yokota et al.(2011) by statistically analyzing the strong-motion records in Japan. The most important fact of LPGM is that LPGM is strongly biased by the site and path effects. To make clear the fact, as a first step, Yuzawa and Kudo (2008) proposed an empirical predictive model applicable to base rock sites (Vs> 2.0 km/s; average $V_S$ ~ 2.4 km/s) using the KiK-net (http://www.kyoshin.bosai.go.jp/kyoshin/) records. The predictive model was revised by Yuzawa and Kudo (2011) including recent strong-motion data and period range (1-15 seconds) of analyses. This is an extension of previous papers for understanding the LPGM, especially on variability with site- and path-properties. We used the acceleration response spectrum of 1 and 5 percent damping as a level of shaking severity, in the period range of 1-15 sec. ground motion on base-rocks. Next, we direct to assess the locality of shaking severity of LPGM by taking the spectral ratio of the response spectrum observed at a site to that of the seismic base-rock predicted using the empirical attenuation model proposed by Yuzawa and Kudo (2011a). We define the “shake-ability” at a site by the spectral ratio for the period rage of 1-15 sec. and evaluated them in whole land in Japan, using the strong-motion data from the K-NET, KiK-net, and JMA Seismic Intensity Observation Network. The shake-maps for an individual period were provided and the validity of our model was examined by comparing the maps with some typical observed records.

The shake-ability for LPGM at a site in Japan is successfully determined and the predicted shake map is similar to the distribution map of the observed ground motion. The areas that large LPGM should be expected are well corresponding to the large basins, such as Teshio-Ishikari-Yufutu, Tokachi plains in Hokkaido, Tsugaru, Shonai, Niigata, Kanto, Nobi, and Osaka plains in Honshu. However, due to the large standard deviation of shake-ability at a site, we are obliged to predict LPGM with large ambiguity. The large scattering of shake-ability dominates at deep sedimentary basins, especially in the Kanto basin. We investigated the reasons for the scattering of shake-ability at some sites in Kanto basin. We found two major reasons for the scatterings: the one is the earthquake source depth and the other is the location of earthquake source. They would implicitly be related to the excitation of surface waves and the velocity structures of the propagation path. We propose new factors, those are the sorting of source depth and location, to reduce the scattering of shake-ability at a site in predicting LPGM.

## 2. EMPIRICAL PREDICTIVE MODEL OF LPGM ON HARD ROCKS

We propose an empirical predictive model of LPGM on bedrock as a standard level of ground motion in Japan. This is an extended study of our previous papers (Yuzawa and Kudo, 2008; Yuzawa and Kudo, 2011a; Yuzawa and Kudo, 2011b;Yuzawa and Nagumo, 2012). The strong-motion records registered at 161 rock borehole sites among KiK-net [National Research Institute for Earth Science and Disaster Prevention (NIED)] stations were used. The observation sites that can be considered as bedrock were selected with the conditions that S-wave velocity at bore-hole exceeds 2.0 km/sec and amplification factor is smaller than 2 at the surface in the period range longer than 1 sec. These selected stations are 23 % among whole KiK-net sites. The average of the S-wave velocities of the selected sites is 2.4 km/sec. In addition, observation records with the condition of larger moment magnitudes ($M_w$) of 5.7, shallower earthquakes than 60 km determined by F-net (NIED) and focal distance of 500 km or less. After that, database of acceleration response spectra with 5 and 1 % damping was constructed to obtain empirical predictive model of LPGM at seismic bedrock corresponding to the periods of 1 to 15 sec, by regression analysis. Since the wave theory analysis has indicated the excitation of surface wave at LPGM, geometrical spreading factor on empirical predictive model is the theoretical surface wave (0.5). Also the factor that relates the focal depth and effect of surface wave was added into the prediction model. And finally, the adequacy of the proposed empirical predictive model was verified by comparing the predicted ground motions with strong motion records.

We assume a following form for a regression analysis applied to LPGM data,

$$\log F_{ij}(T) = a(T)M_w - (0.5\log X_{eq} + b(T)X_{eq}) + c(T) + d(T)H \qquad (1)$$

$$H = \log e^{(1-D/60)} = 0.434 - 0.0072D \quad (D \leq 60\ \text{km}) \qquad (2)$$

where, $F_{ij}(T)$ is acceleration response spectra at an undamped period of $T$ for $i$th site and $j$th earthquake. $M_w$ and $X_{eq}$ are a moment magnitude and an equivalent fault distance defined by Ohno et al. (1998), respectively. The regression coefficients, $a(T)$, $b(T)$, $c(T)$, and $d(T)$ are determined by two step regression analysis (Joyner and Boore, 1981). The factor $H$ is introduced to include the effects of source depth ($D$) to LPGM as equation (2). Computations of equivalent source distances were conducted assuming the fault geometry determined by source inversions techniques referring the published data. We applied 2,078 horizontal motions registered at hard rock borehole sites of the KiK-net from 23 earthquakes. We computed spectral responses of 70 periods in the range between 1 to 15 seconds with two damping constants of 1 and 5 percents. The attributes of the used data can be recognized as shown in Figure 1.

Thus obtained regression coefficients for representative periods from 1 to 15 sec. are shown in Table 1. The differences of coefficients between 1 and 5 percent damping are very small. In addition, we assume that acceleration response spectra of small damping approximates Fourier spectra.

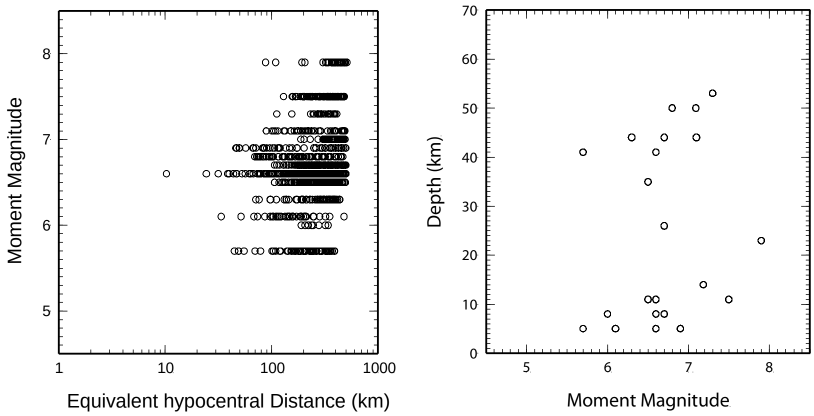



**Figure 1**. Attributes, such as magnitude vs. distance and focal depth of the strong-motion data used for regression analysis.

**Table 1.** Examples of the determined regression coefficients for the empirical predictive model of LPGM on hard rock sites.

| h=5% | | | | | h=1% | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Period(s) | a(T) | b(T) | c(T) | d(T) | Period(s) | a(T) | b(T) | c(T) | d(T) |
| 1 | 0.552 | 0.00228 | -1.4 | -0.403 | 1 | 0.553 | 0.00216 | -1.22 | -0.425 |
| 2 | 0.587 | 0.00171 | -2.2 | 0.158 | 2 | 0.607 | 0.00152 | -2.19 | 0.159 |
| 3 | 0.661 | 0.00165 | -3.08 | 0.612 | 3 | 0.678 | 0.00149 | -3.05 | 0.629 |
| 4 | 0.686 | 0.00161 | -3.38 | 0.82 | 4 | 0.702 | 0.00148 | -3.37 | 0.867 |
| 5 | 0.741 | 0.0015 | -3.94 | 1.07 | 5 | 0.762 | 0.00133 | -3.98 | 1.16 |
| 6 | 0.8 | 0.00142 | -4.48 | 1.239 | 6 | 0.841 | 0.00125 | -4.65 | 1.292 |
| 7 | 0.81 | 0.00137 | -4.71 | 1.504 | 7 | 0.838 | 0.00123 | -4.82 | 1.613 |
| 8 | 0.823 | 0.00135 | -4.93 | 1.671 | 8 | 0.851 | 0.00121 | -5.05 | 1.755 |
| 9 | 0.848 | 0.00133 | -5.22 | 1.821 | 9 | 0.897 | 0.00118 | -5.48 | 1.887 |
| 10 | 0.868 | 0.00132 | -5.46 | 1.892 | 10 | 0.902 | 0.0012 | -5.65 | 2.042 |
| 11 | 0.887 | 0.00123 | -5.64 | 1.812 | 11 | 0.926 | 0.00107 | -5.86 | 1.869 |
| 12 | 0.903 | 0.00115 | -5.82 | 1.761 | 12 | 0.945 | 0.00098 | -6.05 | 1.799 |
| 13 | 0.923 | 0.0011 | -6.01 | 1.753 | 13 | 0.962 | 0.00091 | -6.24 | 1.818 |
| 14 | 0.936 | 0.00109 | -6.13 | 1.69 | 14 | 0.975 | 0.00091 | -6.36 | 1.768 |
| 15 | 0.948 | 0.00106 | -6.24 | 1.595 | 15 | 0.994 | 0.00087 | -6.53 | 1.671 |

## 3. ASSESMENTS FOR SPATIAL VARIABILTY OF LPGM

### 3.1 Site Amplification Factors (Shake-ability)

It is well known fact that earthquake ground motions depend significantly on local geology irrespective to target periods. The local site amplification or shake-ability $S_i(T)$ at a site $i$ is defined by the equation (3), that is, the averaged ratio of observed spectra $O_{ij}(T)$ to those predicted, $F_{ij}(T)$, by equation (1) using $N$ events.

$$S_i(T) = \frac{1}{N}\sum_{j=1}^{N}(O_{ij}(T)/F_{ij}(T)) \,, \tag{3}$$

Used data for assessing the site dependent shake-ability of LPGM are K-NET, KiK-net of National Res. Inst. for Earth Sci. and Disaster Prevention, and JMA (Japan Meteorological Agency) intensity network data. For keeping a quality at long period range using acceleration records, we used the data from larger *Mw* of 5.7, shallower depth than 60 km and focal distances within 500 km, similar to Yuzawa and Kudo (2011a). The reason why we focused on shallow events is that surface waves dominate particularly in deep sedimentary basins. It is very limited but the data influenced by nonlinear behaviors of ground due to strong shaking (11 records) are excluded in the analyses, such as K-NET Ojiya (NIG019) from the 2004 Niigata Chuetsu earthquake, KiK-net Toyokoro (TKCH07, surface station) from the 2003 Tokachi-oki earthquake, KiK-net Hino (TTRH02) from the 2000 Tottori earthquake and others.

Examples of comparison between the spectral ratios of observed spectra to the predicted one at sites of hard rock are shown in Figure 2. The sites (a) IWT009 (Vs: 2.6 km/s) and (b) FKS19 (Vs: 3.06 km/s) are used as a standard by Kataoka et al. (2008) and by Sato et al. (2011), respectively. The site (c) WKYH05 (Vs: 1.94km/s) is one of a representative rock site in the western part of Japan. The ratios of three sites are widely scattered but the averages (red line) are approximately one with weekly dependent to periods.

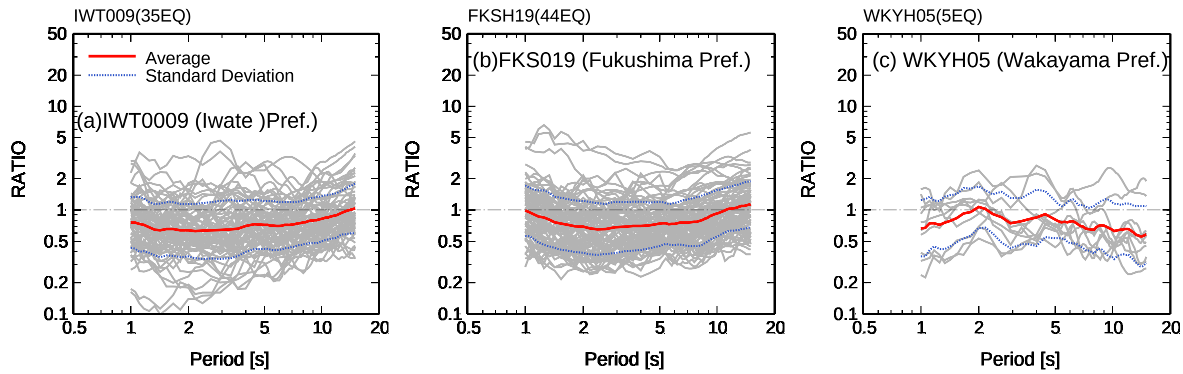



**Figure 2.** Examples of spectral ratios or shake-ability at hard rock sites to the standard spectra by the proposed predictive model. Gray lines show the ratios of individual events. Red and blue dotted lines show their averages and standard deviations, respectively.

On the other hands, very large ratios were obtained at sites located in thick sedimentary basins, such as Sendai (MYG013), Tokyo (TKY007), and Osaka (OSKH02). The ratios or amplification factors are very large at these sedimentary basins, especially at OSKH02 and depend strongly on period. The average of the ratios of TKY007 is almost 4 irrespective to period, but large peak at around 5-10 sec. for some ratios of individual events are found. This will be discussed in the later.

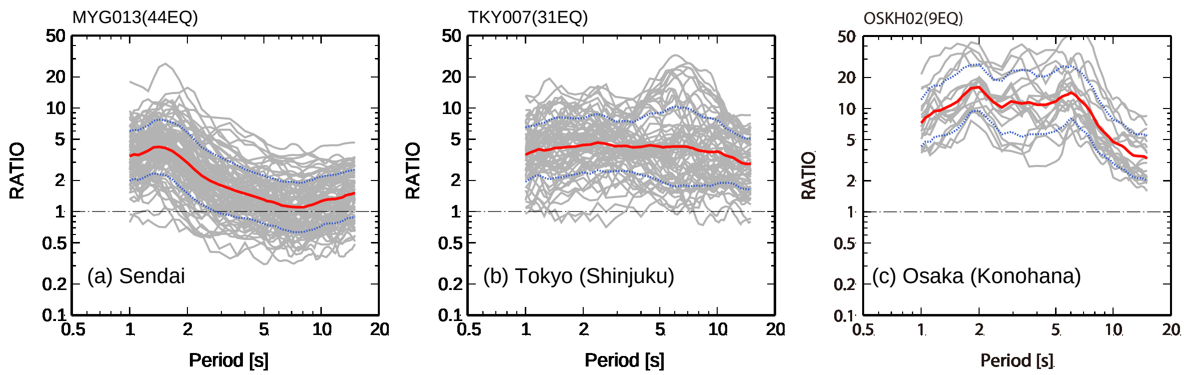



**Figure 3.** Examples of spectral ratios or shake-ability at sites in sedimentary basins to the standard spectra by the proposed predictive model. Gray lines show the ratios of individual events. Red and blue dotted lines show their averages and standard deviations, respectively.

### 3.2 Shake Map of LPGM in Japan

Spectral ratios or shake-ability were obtained similar to the previous section for all sites of K-NET, KiK-net and JMA Intensity Network, and they are plotted on the map of Japan for some representative period. The response spectra of 5 percent damping were used. They are shown in Figure 4. To draw maps, spatial interpolations by spline function in GMT (Wessel and Smith, 1998) were used. The mesh size was a 5 km x 5 km. A light green in the figure shows standards (average of rock motion) and a deep red indicates ten or more times large against the standards.

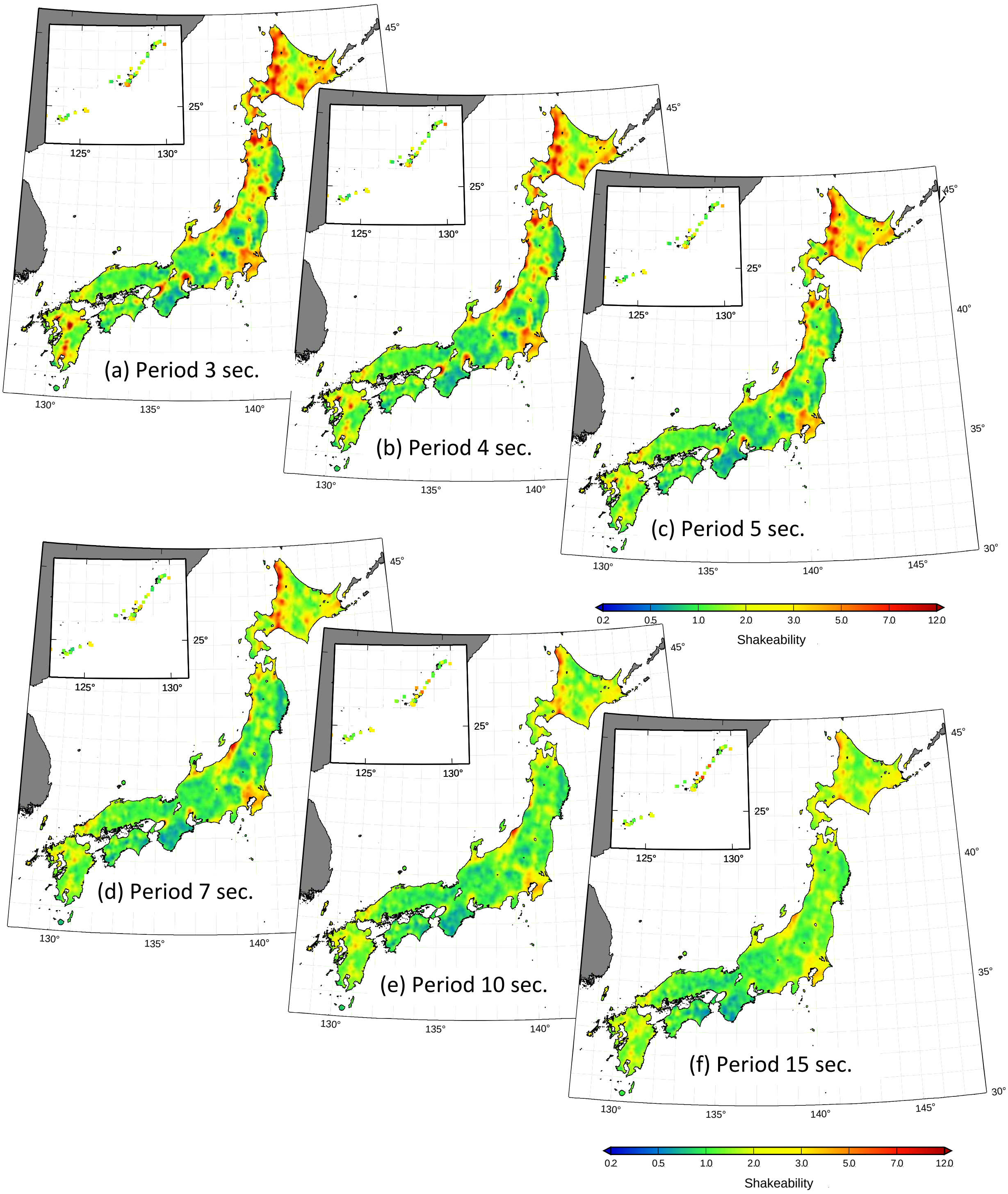



**Figure 4.** Shake map of LPGM as a function of period. Response spectra of 5 percent damping were used to obtain spectral ratios.

Very high levels of LPGM shake-ability correlate well the large scale sedimentary basins or plains, such as Teshio, Ishikari, Yufutsu, Tokachi, Kushiro basins in Hokkaido, Tsugaru, Shonai, Echigo, Toyama basins along the coast of Japan Sea, large basins Kanto, Nobi, Osaka, Tsukushi basins and so on. In addition, the patterns of shake-ability depend strongly on periods. These features are qualitatively similar to recent results (Kataoka et al., 2008; Sato et al., 2010; Yokota et al., 2011). Variations of shake-ability tend to small associated with increasing period. However, we should note a large amplification exist at longer period than 10 sec. at Kanto and Niigata basins, where large oil storage tanks are densely constructed.

The reasons of very high level shake-ability will be attributed to the transmission of crustal surface waves into soft sedimentary basins with large amplification and/or induced surface waves due to sedimentary basins (e.g., Kawase, 1993). In the following, we will try to analyze the factors that might affect the scattering.

## 4. SCATTERING OF SHAKE-ABILITY

A statistical or empirical approach to predicting the LPGM is obliged to meet large scattering. Major reason will be that empirical modeling uses only very limited factors, nevertheless many factors influence the real or observed LPGM. For example, we have never taken into consideration of source radiation pattern, directivity effects, spatially heterogeneous rapture and so on. As indicated previous section, scattering of shake-ability or site factors is also very large (see Figure 3). We will try to analysis the factors of scattering or deviation in empirical site amplification factors. The major reason of the deviation will be attributed to complex 3-D structure of large basins; therefore, the deviation will be site-dependent. As an empirical approach to these issues, we discuss on the data retrieved in Kanto basin.

### 4.1 Effect of Source Depth

The effects of source depth on LPGM were already taken into the standard predictive model (Equation 1). However, looking at shake-ability at a site TKY007 (Shinjuku) in Kanto basin, as shown in Figure 5 (a), the source depth gives further effects on shake-ability; that is, the cases of shallower than 20 km shake-ability relatively large and dominate at 5-7 seconds (Figure 5 (b)), while the other cases show relatively low amplification and have no dominant period. The scattering is still large, but it is clearly reduced. In order to confirm the validity of counting the effects of source depth, we compared the observations from the very shallow earthquake and the deeper event than 20 km with the predicted spectra. They are shown in Figure 6. The validity to include the effects of source depth, at least dividing the depth at 20 km, is apparent especially in the period range from 5 to 10 seconds.

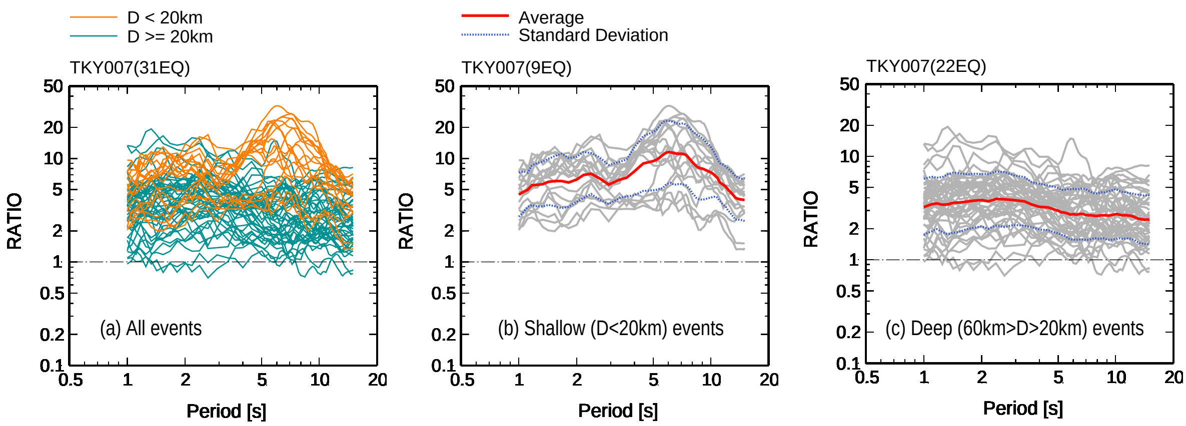



**Figure 5.** Effects of source depth on shake-ability at the site TKY007 (Shinjuku).

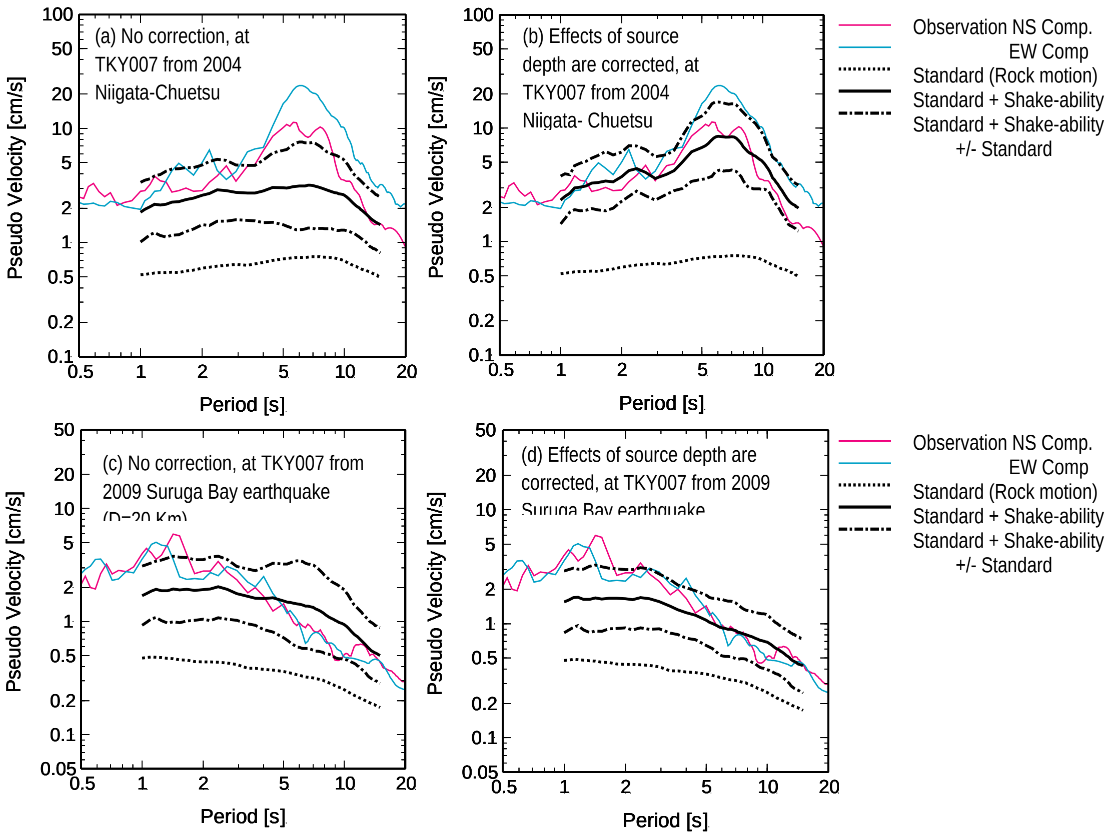



**Figure 6.** Comparisons of observations with predicted spectra (h=5%) considering the effects of source depth.

### 4.2 Effect of Earthquake Generation Area

We could understand that the basin response of LPGM depends on source depth, however, at the same time; we have to notice that the scattering is still large. We collected the records at three sites in the Kanto basin from very shallow events (D≤8km) as shown in Figure 7. Stars and triangles in the figure show epicenters and selected sites, respectively.

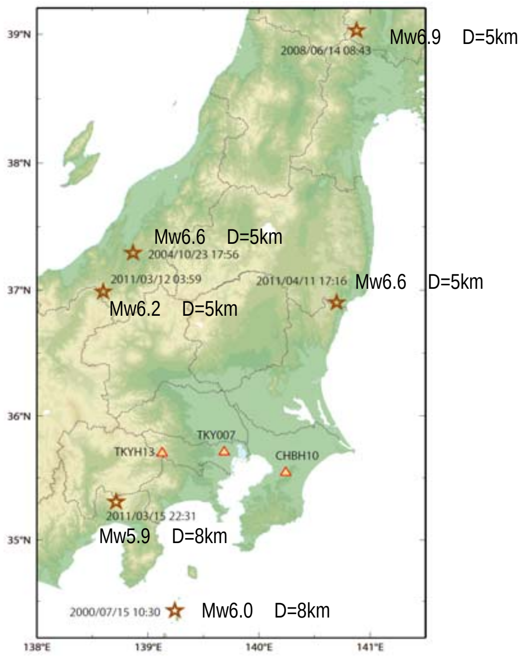



**Figure 7.** Epicenters and stations used for examine the basin responses from shallow events.

Aftershocks, with broad meaning, of the 2011 off the Pacific coast of Tohoku earthquake are included. The site TKYH13 is located at the west margin of Kanto basins belonging to the standard or rock site. TKY007 and CHBH10 are located inside of Kanto basin. Spectral ratios of observations from recent shallow events at each site to the standards (predicted spectra) are plotted and shown in Figure 8. The spectral ratios at the rock site TKYH13 show from 0.5 to 2 times irrespective to events and period. On the other hand, the spectral ratios are approximately 5-10 times and they scatter in the period range 4-10 sec for both cases of TKY007 and CHBH10. The differences of the ratio at the period range exceed 4 or 5 times. The reasons are not clarified at present, but complex 3D structure of Kanto basin, different path effects both from outside and inside of basin, and others would be plausible reasons.

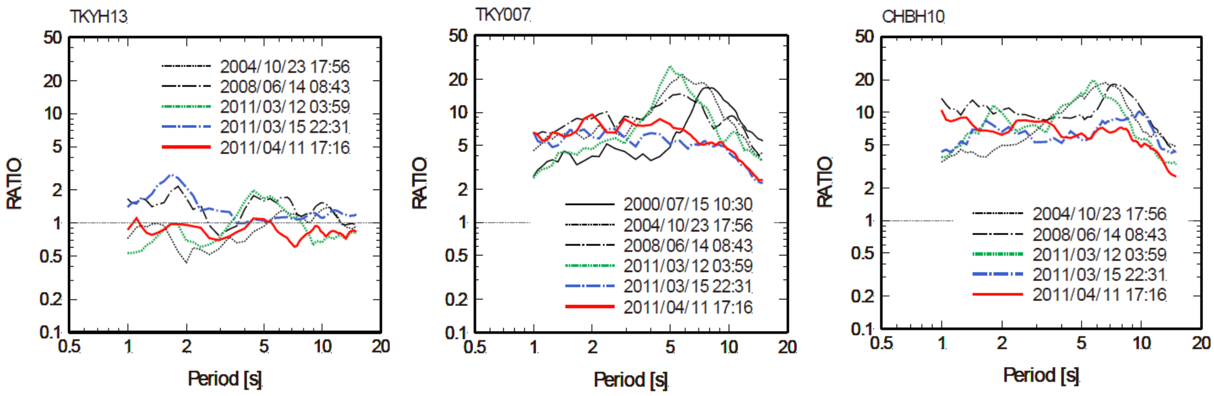
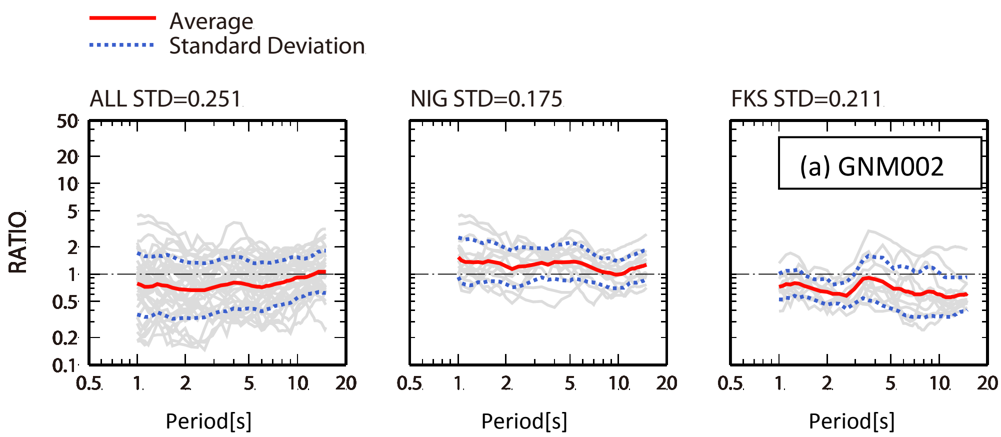



**Figure 8.** Spectral ratios of observations from recent shallow earthquakes at rock site (TKYH13), Shinjuku (TKY007), and Chiba (CHBH10) to the standards (predicted spectra).

### 4.3 Reduction of Deviation by Restricting Earthquake Generation Area

Next, we will examine to reduce deviation of shake-ability by restricting the location of earthquake sources. The problem is the limitation of data, but we have opportunity to use strong motion records from two areas where moderately large earthquakes (Mw>5.4 used) occurred in relatively concentrated locations; those are the Niigata-Chuetsu, Niigata-Joetsu and the east of Fukushima Prefecture (Hamadouri). Examples of the results are shown in Figure 9. Figure 9 (a) shows the spectral ratios of rock site (GNM002) at north margin of Kanto basin. The red line is the average spectral ratios and blue dotted lines show the standard deviation. The logarithmic standard deviation (STD in the figure) for using all data is 0.251, while the STDs are apparently reduced by separating data individually with Niigata and Fukushima areas. Figure 9 (b) shows the spectral ratios at TKY007 (Shinjuku) that diverge largely by using all data (left), but the deviations using the data restricting Niigata and Fukushima areas, respectively, are drastically reduced. Figure 9 (c) is an example that the deviations are clearly reduced by separating two datasets, but it is interesting the spectral shapes are similar to the others.



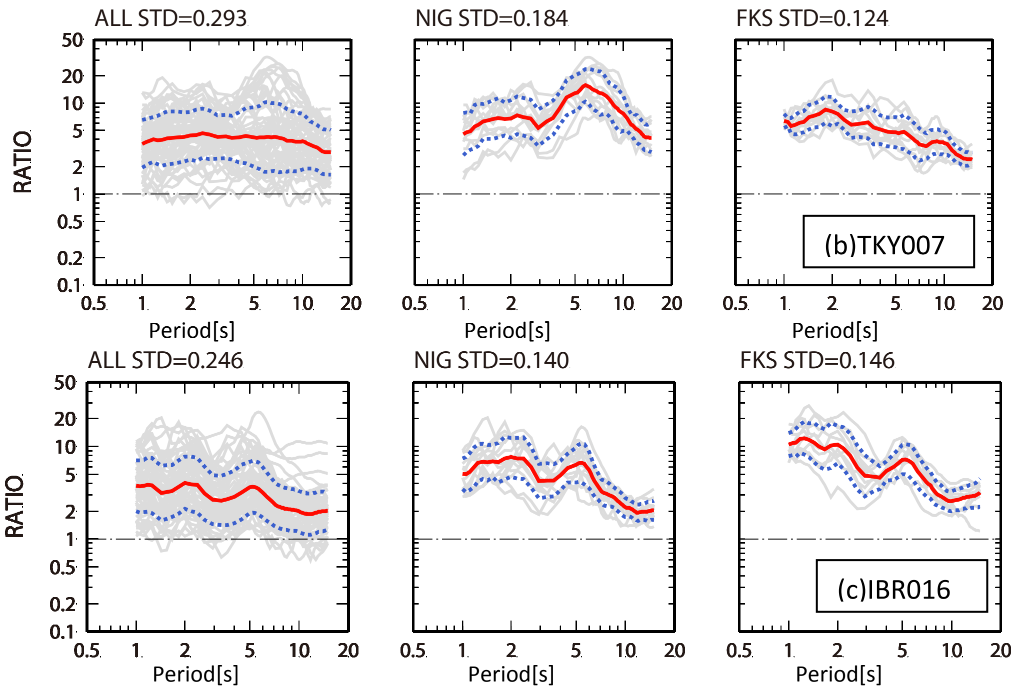


**Figure 9.** Examination of effectiveness to reduce the deviation of shake-ability by restricting source areas.

## 5. SUMMARY

We obtained empirical models of 5 % and 1% damped acceleration response spectrum for LPGM (long-period ground motion) on hard rocks. We only used the down-hole data of the KiK-net at 161 selected hard rock sites where the S-wave velocity exceeds 2.0km/s at depth of down-hole. We used the 2,078 records from larger magnitude than 5.7 and events shallower than 60 km. Considering the quality of data, the records of shorter distance than 500 km were used. In addition, we verified validity of our empirical predictive model by comparing with the observed individual strong ground motion records.

We defined the shake-ability at a site by the spectral ratio of the response spectrum observed at a site to the ones at seismic hard rock (average $V_S$ ~ 2.4 km/s) predicted using the empirical attenuation model proposed by Yuzawa and Kudo (2011). Shake maps for long-period (1-15 sec) ground motion in Japan were provided and they were examined using typical observed records that were retrieved by the K-NET, KiK-net, and JMA Seismic Intensity Observation Network.

We examined the factors affecting the scattering of shake-ability of LPGM in Kanto basin, aiming better accuracy of the prediction model. Generally speaking, the shake-ability at sedimentary basins depends on the location of earthquake source and focal depth. The factors affecting the variability in shakeability of LPGM were examined by comparing records and shake-ability As a result; the examination showed that the dominant factors affecting the variability in shake-ability in Kanto basin are the depth of sources and path of surface waves propagating Kanto basin. In addition, shake-ability corrected by restricting the source region reflects the observation with improved accuracy.

This paper proposed shake-ability of LPGM using the strong motion records in Japan. In addition, this paper developed the prediction method of response spectra at surface of LPGM easily, multiplying empirical predictive model on seismic bedrock and shakeability at each site.


## AKCNOWLEDGEMENT

The strong motion records of K-NET, KiK-net through Internet from the website provided by the National Research Institute for Earth Science and Disaster Prevention and the strong-motion data acquired by Seismic

Intensity Network by Japan Meteorological Agency were used throughout in this paper. We express our sincere thanks to them.

**REFERENCES**

Joyner, W. and D. Boore (1981) Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California, earthquake. *Bull. Seism. Soc. Am.*, **Vol.71, No.3,** pp.2011-2038,

Kataoka, S., S. Matsumoto, T. Kusakabe and N. Toyama (2008) Attenuation Relationships and Amplification Map for Ground Motion in Rather-Long Period Range, *Doboku Gakkai Ronbunshuu* A, **Vol.64, No. 4**, pp.721-738, (in Japanese with English abstract)

Kawase, H. (1993) Review: Amplification of Seismic Waves by Sedimentary Layers and Its Simulation, *Zisin*, **Vol.46,** pp.171–190. (in Japanese with English abstract)

Ohno, S., T. Ohta, T. Ikeura, and M. Takemura (1993) Revision of attenuation formula considering the effect of fault size to evaluate strong motion spectra in near field, *Tectonophys*, **218**, pp.69-81.

Sato, T., I. Okawa, T. Nishikawa, T. Sato and M. Seki (2010) Prediction of Waveforms of Long-Period Ground Motions for Hypothetical Earthquakes using Empirical Regression Relations of Response Spectra and Phase Spectra, *J. Struct. Contr. Eng. AIJ*, **Vol.75, No.649**, pp.521–530, (in Japanese with English abstract)

Wessel, P. and W. H. F. Smith (1998) New improved version of Generic Mapping Tools released, *EOS Trans. Am. Geophys. Union*, **79**, 579

Yokota, T., K. Ikeuchi, T. Yahagi, Y. Kaida and H. Suzuki (2011) Attenuation and Amplification of Long-Period Component of Ground motion, *J. Japan Assoc. Earthquake Eng.*, **Vol.11**, No.1, pp.81-101 (in Japanese with English abstract)

Yuzawa, Y. and K. Kudo (2008) Empirical Estimation of Long-Period (1-10 Sec.) Earthquake Ground Motion on Hard Rocks, *14th World Conf. Earthquake Eng., October 12-17, Beijing, China*, **S10-057.**

Yuzawa, Y. and K. Kudo (2011a) Empirical Predictive Model for Long-Period (1-15 sec) Ground Motion on Hard Rocks, *J. Struct. Contr. Eng. AIJ*, **Vol.76, No.661**, pp.519–526. (in Japanese with English abstract)

Yuzawa, Y. and K. Kudo (2011b) Shakeability Distribution for Long-period (1-15 sec) Ground Motion in Japan, *J. Japan Assoc. Earthquake Eng.*, **Vol.11**, No.3, pp.21-39.

Yuzawa, Y. and H. Nagumo (2012) Factors of Variability and Measures for the Shakeability of Long-Period Ground Motion - Kanto Basin as an Example -, *J. Japan Assoc. Earthquake Eng.*, **Vol.12, No.2**, pp.41-59. (in Japanese with English abstract)