PERFORMANCE EVALUATION OF GROUND MOTION PREDICTION EQUATIONS FOR ABSOLUTE VELOCITY RESPONSE SPECTRA (1-10 S) IN JAPAN FOR AN EARTHQUAKE EARLY WARNING

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ABSTRACT: In our previous study 1), we constructed ground motion prediction equations (GMPEs) for absolute velocity response spectra from the viewpoint of earthquake early warning of long-period ground motion intensities. In the present study, we evaluated the performance of the GMPEs for seven recent earthquakes having Mw ≥ 6.5 that occurred after the construction of the GMPEs. We found that the GMPEs generally performed well for the events. Finally, we explain a methodology for the revision of site factors in the GMPEs, and discuss some implications for future study.

Key Words: Long-period ground motion, absolute velocity response spectra, earthquake early warning, J-SHIS subsurface model, ground motion prediction equation

1. INTRODUCTION

In our previous study 1), we constructed ground motion prediction equations (GMPEs) for absolute velocity response spectra (AVRS) in the period range of 1 s to 10 s using data from events (Mw ≥ 6.5, focal depth ≤ 50 km) that occurred in different tectonic environments in and around Japan. We employed the JMA displacement-amplitude magnitude 2) and hypocentral distance in the GMPEs from the viewpoint of earthquake early warning (EEW) even for large magnitude earthquakes. The data set used in the GMPEs was from events that were recorded by K-NET and KiK-net 3) up to the end of 2012. The largest magnitude of inland earthquakes included in the GMPEs was Mw of 6.9. The 16th April, 2016, Mw 7.1 Kumamoto earthquake surpassed the magnitude range of the inland earthquakes used in the GMPEs, and occurred in a region lacking proximity to the past events used in the GMPEs. The JMA long-period ground motion intensity 4), 5) reached the maximum intensity of four at many sites
close to the source fault area of the Kumamoto earthquake, and reached intensity of two at Osaka basin located at about 450 km far from the epicenter of the earthquake. We show a table of intensity scale on long-period ground motions in Appendix 1. In addition to the Kumamoto earthquake, other several large magnitude earthquakes having $M \geq 6.5$ occurred off the Pacific coast of Japan after the construction of the GMPEs. It is, therefore, important to examine the performance of the GMPEs for recent events for reliability of the GMPEs for prediction of long-period ground motion intensities for an EEW.

In the present study, we compared the observed AVRS and JMA long-period ground motion intensity with predictions using the GMPEs\(^1\) for seven large earthquakes ($M \approx 6.5 \sim 7.1$) that occurred between 2012 and 2016. We found the previously determined site factors inappropriate at some sites having few recordings, and proposed a methodology for the revision of the site factors for an improved prediction of long-period ground motion intensities. Finally, we discussed some implications for future study.

2. **RECORD SELECTION AND PROCESSING**

We used recordings from seven events listed in Table 1. The table shows the magnitudes and hypocenter locations of the events in chronological order. The table also shows the used number of recordings for each event. The magnitudes of the new events are between $M \approx 6.5$ and 7.1, and $M \approx 6.7$ and 7.4. All events have focal depths $\leq 51$ km. The moment magnitudes of the events are taken from F-net\(^3\). The JMA magnitudes and hypocenters are taken from the JMA unified hypocenter catalog\(^6\).

<table>
<thead>
<tr>
<th>Event</th>
<th>Origin time (JST)</th>
<th>Latitude/Longitude</th>
<th>Depth</th>
<th>Mw/Mj</th>
<th>Stations used</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ev1</td>
<td>2014/07/12, 04:22</td>
<td>37.0500/142.3208</td>
<td>33</td>
<td>6.5/7.0</td>
<td>380</td>
<td>East off Fukushima Prefecture</td>
</tr>
<tr>
<td>Ev2</td>
<td>2015/02/17, 08:06</td>
<td>39.8723/143.1927</td>
<td>12</td>
<td>6.7/6.9</td>
<td>291</td>
<td>Far east off Sanriku</td>
</tr>
<tr>
<td>Ev3</td>
<td>2015/05/13, 06:12</td>
<td>38.8628/142.1502</td>
<td>46</td>
<td>6.8/6.8</td>
<td>457</td>
<td>East off Miyagi Prefecture</td>
</tr>
<tr>
<td>Ev4</td>
<td>2015/11/14, 05:51</td>
<td>30.9432/128.5900</td>
<td>17</td>
<td>6.8/7.1</td>
<td>63</td>
<td>Southwest off Kyushu</td>
</tr>
<tr>
<td>Ev5</td>
<td>2016/01/14, 12:25</td>
<td>41.9702/142.8012</td>
<td>51</td>
<td>6.7/6.7</td>
<td>413</td>
<td>South off Urakawa</td>
</tr>
<tr>
<td>Ev6</td>
<td>2016/04/16, 01:25</td>
<td>32.7533/130.7616</td>
<td>12</td>
<td>7.1/7.3</td>
<td>297</td>
<td>Kumamoto Prefecture</td>
</tr>
<tr>
<td>Ev7</td>
<td>2016/11/22, 05:59</td>
<td>37.3533/141.6033</td>
<td>25</td>
<td>7.0/7.4</td>
<td>515</td>
<td>East off Fukushima Prefecture</td>
</tr>
</tbody>
</table>

The data processing steps and method for the computation of AVRS in the present study are identical to those used in our previous paper\(^1\). We inspected the observed acceleration waveforms and their Fourier spectra for each recording. Recordings that contained spurious signals and low frequency noises were removed. Recordings in which the S-wave arrivals were identified were selected. We used JMA travel time table\(^7\) to confirm our visual inspection results for identification of S-wave arrivals. The number of recordings used in this study are listed in Table 1 for each event. Cosine tapering for five seconds was applied at the both ends of the waveforms, and acausal high-pass Butterworth filtering was applied with a corner frequency of 0.07 Hz before integration and computation of the response spectra. The AVRS were computed as the maximum value of vector sum of two horizontal component response time histories at individual natural period for 5% of critical damping.

3. **RESULTS AND COMPARISONS**

The GMPEs\(^1\) consist of magnitude, distance, and site terms. As stated above, the magnitude used in the GMPEs is JMA magnitude, and distance is hypocentral distance. Here we briefly introduce the site terms in the GMPEs. There are two types of site terms in the GMPEs. One type of site term is based on the deep and shallow subsurface velocity model. The intra-event residuals were regressed with the
depths of various sedimentary layers, and corrections based on minimum standard deviations were proposed. We used the subsurface velocity model provided by the Japan Seismic Hazard Information Station (J-SHIS)\textsuperscript{8,9}) for this purpose. The depth to the top of layer having an S-wave velocity (Vs) of 1.4 km/s yielded the smallest standard deviations at all periods. After correcting by the depth of Vs 1.4 km/s layer, the adjusted residuals were further regressed with the average S-wave velocity in the upper 30 m of the soil column (AVS30). For details on the construction of the GMPEs and the choice of parameters used therein, we refer to our previous paper\textsuperscript{1}) for interested readers. The second type of site term is based on only observed recordings. The site term is a constant value for an individual period, and is obtained as an arithmetic average of the intra-event residuals at each site over the available recordings at the site. We often abbreviate in the present report the site corrections based on depth of Vs 1.4 km/s layer and AVS30 as $d14vs30$ and those based on site factors as $sf$ in subsequent figures. In the following subsections, we describe the comparison of the AVRS at a period of 5 s and from the period band of 1.6 s to 7.8 s. We also describe the comparison of the observed and predicted intensities for selected events.

![Index map. Red filled circles denote the location of epicenters of earthquakes used in this study. The alphanumeric codes attached to the red circles correspond to the event numbers listed in Table 1. The grey colored large circles denote the epicenters of earthquakes, and the small circles and triangles the K-NET and KiK-net stations used in the GMPEs in our previous study\textsuperscript{1}). Pink arrows point towards major sedimentary basins in Honshu island.](image)

**3.1 Comparison of AVRS at a period of 5 s**

The observed AVRS at a period of 5 s are plotted as a function of hypocentral distance in Fig. 2 for all events listed in Table 1. Note that the amplitude and distance scales are different for the Kumamoto earthquake (event no. 6 in Table 1). All events are offshore events except the Kumamoto earthquake.
Fig. 2 A comparison between the observed and predicted AVRS for a period of 5 s. The solid lines denote median prediction values, and dashed lines denote one standard deviations. The black, red, and blue circles denote the observed values, observed values adjusted by site factors, and observed values adjusted by deep and shallow sediments, respectively. The event number and magnitude are written in each subplot. The circled area for the events Ev1, Ev3, and Ev7 indicate the data from deep sedimentary areas. See the text for further explanations.

The offshore events have data from sites at hypocentral distance greater than 50 km whereas the Kumamoto earthquake consist of data beyond 12 km of hypocentral distance. The plots include the median prediction lines plus one upper and lower standard deviations of basic GMPE (i.e., GMPE with only the magnitude and distance terms). It can clearly be seen that the median prediction lines pass through the data for all events and at all distance ranges except for the Kumamoto earthquake beyond about 200 km. The plots also show the observed values adjusted by the abovementioned two site correction methods. The original observed and adjusted observed values are shown by distinct color circles. The deviation of the observed data becomes smaller after the site corrections. The corrections by site factors generally are more effective than the corrections based on subsurface velocity models in reducing the estimation errors. However, the both corrections are unable to bring
the corrected observed values within the range of one standard deviations at distances beyond about 200 km for the Kumamoto earthquake. We attributed the discrepancies of the observed response spectra from the GMPEs to the radiation pattern effects and propagation of long-period surface waves which were discussed in some detail in Dhakal et al. (2016)\(^5\). We also discuss the differences between the observed and predicted long-period ground motion intensities for the Kumamoto earthquake in Section 3.3. Some of the sites having large long-period site amplifications are indicated by large circles approximately in Fig. 2 for event numbers 1, 3, and 7; the sites are mostly from Kanto basin, and for the event no. 7, the sites are also from the Niigata and Shonai basins in Niigata and Yamagata Prefectures, respectively. At these sites, it can clearly be seen that the site factors are more effective to explain the site amplification effects compared with the corrections by the depth of sediments and AVS30.

3.2 Comparison of AVRS (1.6 s to 7.8 s) and intensities for off the Pacific coast events

One of our objectives of the construction of the GMPEs for AVRS was to provide an estimate of JMA long-period ground motion intensities for an EEW. The JMA long-period ground motion intensities are computed from the maximum value of the AVRS from the period band of 1.6 s to 7.8 s (see appendix 1 for the relationship between the AVRS and intensity scale). We show a comparison between the observed and predicted maximum response values of the period band of 1.6 s to 7.8 s using the two site correction methods mentioned above for the event no. 7 (Mj = 7.4) in Fig. 3. The event is the largest event in terms of the JMA magnitude in this study. The observed and predicted values generally match each other within a factor of two of the identical relation. The spatial distributions of observed and predicted JMA long-period ground motion intensities for the event are plotted in Fig. 4. It can clearly be seen that the observed spatial distributions of long-period ground motion intensities are reproduced well given the simple parameterizations in the GMPEs. At some of the sites where the observed and predicted intensities are different, the difference is simply due to the discrete intensity levels. The number of sites at which the intensities are equal (observed intensity – predicted intensity = 0), overestimated (observed intensity – predicted intensity < 0), and underestimated (observed intensity – predicted intensity > 0) are indicated as inset numbers in the spatial plots for predictions. From the inset numbers, we can see that the number of sites at which the observed and predicted intensities are equal is larger using the site factor method for the site corrections. However, when the difference of one level of intensity is allowed, the observed and predicted intensities are identical at 100% of the sites for the both site correction methods.

![Comparison of AVRS and Intensities](image)

Fig. 3 Comparison between the observed and predicted maximum values of the period band of 1.6 s to 7.8 s for the Mw 7.0 (Mj = 7.4) east of Fukushima earthquake (event no. 7 in Table 1). (a) Predictions using site factors at each site for site corrections. (b) Predictions using depth of Vs 1.4 km/s and AVS30 values at each site for site corrections. See the text for further explanations.
Fig. 4 Spatial distribution of observed (left panel), and predicted intensities using site corrections based on site factors (middle panel) and the depth of Vs 1.4 km/s layer and AVS30 (right panel), for the Mw 7.0 (Mj = 7.4) east off Fukushima Prefecture earthquake (event no. 7 in Table 1). A star denotes epicenter of the earthquake. The left and right numerals in the inset rectangles (middle and right panels) denote the differences between the observed and predicted intensities and the number of sites corresponding to the differences, respectively. The negative, zero, and positive numerals in the left indicate the overestimations, equal, and underestimations.

Instead of comparing the observed and predicted response spectrums for each event separately, we show the comparison of the maximum response values of the period band of 1.6 s to 7.8 s from five events together (event nos. 1, 2, 3, 5, and 7) to get an idea on the performance of the GMPEs for the prediction of long-period ground motion intensities in Fig. 5. The five events occurred off the Pacific coast of Japan. The observed maximum values and predicted maximum values using the site factors and subsurface models are compared in Figs. 5(a) and 5(b), respectively. The response spectra values ≥ 5 cm/s at periods between 1.6 s and 7.8 s correspond to the JMA long-period ground motion intensity levels ≥ 1. If we compare the observed and predicted maximum values using the site factors for a threshold of 5 cm/s (either of predicted or observed values), the true predictions occur at 68% of the sites, the predictions overestimate at 14% of the sites, and the predictions underestimate at 18% of the sites using the site factors for site corrections; see Fig. 5(a). The results are similar, but the percentage of overpredictions and underpredictions increases using the site corrections based on the depth of deep sediments and AVS30 as shown in Fig. 5(b).

3.3 Comparison of AVRS (1.6 s to 7.8 s) and intensities for the Kumamoto earthquake

The Kumamoto earthquake is the largest magnitude inland earthquake to occur in Japan after the nationwide installation of K-NET and KiK-net strong-motion networks. We show a comparison between the observed and predicted maximum values of the period band of 1.6 s to 7.8 s using the two site correction methods for the Kumamoto earthquake (event no. 6 in Table 1) in Fig. 6. One noticeable feature in the plot is that the observed values at around 10 cm/s, indicated approximately by large circles, are larger than the predicted values obtained by both site correction methods at many sites. We plot the spatial distribution of the observed and predicted long-period intensities in Fig. 7 to facilitate an understanding of the differences. The observed intensities, predicted intensities using the site factors, and predicted intensities using the depth of Vs and AVS30 for site corrections, are shown in left, middle, and right panels, respectively, of Fig. 7. The number of sites at which the intensities are
equal, overestimated, and underestimated are indicated as inset numbers in the spatial plots for corresponding predictions. The largest observed intensity was two in Osaka basin and intensity of one was observed at two other sites (hypocentral distance > 450 km). The predicted intensities are one at the Osaka basin sites using the site factors while the site corrections based on the depth of Vs and AVS30 produced null intensities. The plots in Figs. 2, 6, and 7 for the Kumamoto earthquake reveal that the observed data are systematically underestimated by the both site correction methods at distances beyond about 200 km in the northeast region of the epicenter. This systematic underestimated is attributed to the radiation pattern effect of the focal mechanism and generation and propagation of waves having characteristics of Lg waves and fundamental mode Love and Rayleigh waves in the region (e.g.,5)\(^1\),10,11\(^1\),12\(^1\). On the other hand, at short distances of the epicenter, the observed intensities are overestimated at some sites by using the site factors than those using the site corrections based on the depth of Vs 1.4 km/s and AVS30.

Fig. 5 Comparison between the observed and predicted maximum response values within the band of 1.6 s to 7.8 s from the five events (Ev1, Ev2, Ev3, Ev5, and Ev7) listed in Table 1. All these events occurred off the Pacific coast of Japan (see Fig. 1). (a) Predictions using site factors at each site for site corrections. (b) Predictions using depth of Vs 1.4 km/s and AVS30 values at each site for site corrections. The OP, TP, and UP are abbreviations for over prediction, true prediction, and under prediction, respectively, for a threshold of 5 cm/s. See the text for further explanations.

The site factors in the southwest Japan, especially in the Kyusyu region, were determined mostly from two or three recordings due to relatively small number of large earthquakes in the region (see Fig. 1 for the distribution of events in the region, and Fig. 11 for distribution of sites and recordings). The inset numbers in the middle panel of Fig. 7 indicate that the predicted intensities by the method of site factors are larger than the observed ones by two level of intensities at three sites. The three sites had only two recordings used in the determination of site factors, and the alternative site corrections based on the depth of Vs and AVS30 produced the observed intensities at those three sites; these results are shown in Dhakal et al. (2016)\(^5\). Our analysis suggested that the site factors are useful when at least three or more recordings are available at a site. At sites with small number of recordings, site corrections based on the depth of Vs 1.4 km/s layer and AVS30 are preferred. Nonetheless, the inset numbers in Fig. 7 suggest that a difference of two levels of intensities may occur at some sites; such difference may arise due to unaccounted site responses or source effects at specific directions or both in the GMPEs. Future studies should focus on reducing the differences for a reliable prediction of ground motions for an EEW. We describe a methodology for a revision of site factors in the following section.
Fig. 6 Comparison between the observed and predicted maximum values of the period band of 1.6 s to 7.8 s for the Mw 7.1 (Mj = 7.3) Kumamoto earthquake (event no. 6 in Table 1). (a) Predictions using site factors at each site for site corrections. (b) Predictions using depth of Vs 1.4 km/s and AVS30 values for site corrections. See the text for further explanations.

Fig. 7 Spatial distribution of observed (left panel), and predicted intensities using site corrections based on site factors (middle panel) and the depth of Vs 1.4 km/s layer and AVS30 (right panel), for the Mw 7.1 (Mj = 7.3) Kumamoto earthquake (event no. 6 in Table 1). The left and right numerals in the inset rectangles (middle and right panels) denote the differences between the observed and predicted intensities and the number of sites corresponding to the differences, respectively. The negative, zero, and positive numerals in the left indicate the overestimations, equal, and underestimations.

4. REVISION OF SITE FACTORS

4.1 Methodology

Site terms in GMPEs play a significant role to explain the observed variability of ground motions from site to site. Here we discuss a revision of previously determined site factors based on new data availability. The following recurrence relation\(^{(13)}\) may be used to obtain the new site factors.
where $\mu_{n+1}$ is an updated site factor at a site, $\mu_n$ is the previous site factor at the site, $n$ is the available number of recordings at the site, and $x_{n+1}$ is the intra-event residual for the new recording at the site. To determine the intra-event residuals, first we need to estimate the inter-event errors. The inter-event errors may be estimated using the following relation:

$$\eta_i = \frac{\tau^2 \sum_{j=1}^{n} (y_{ij} - \bar{y}_{ij})}{n \tau^2 + \sigma^2}$$

(2)

where $\eta_i$ is the inter-event error for $i^{th}$ earthquake, $\tau^2$ is variance of event-errors, $\sigma^2$ is variance of intra-event errors, $n_i$ is the number of recordings for the $i^{th}$ earthquake, $y_{ij}$ is the observed value from the $i^{th}$ earthquake at $j^{th}$ site, and $\bar{y}_{ij}$ is the predicted value. Note that the inter-event error is to be determined for each period in the above equation. The inter-event error may be interpreted to be a peculiarity of the event with respect to the average prediction. After determining the inter-event errors, they are added to the mean predictions at each site, and the sum is subtracted from the observed value to obtain the intra-event residual to be used in Eq. (1) for each period. This procedure is expected to minimize the event-errors propagating to site factors. From Eq. (2), it becomes clear that the values of variances used therein are not required to compute the inter-event errors when the number of recordings is sufficiently large. In the present study, we used the values of $\tau^2$ and $\sigma^2$ from our previous paper.

We plot the inter-event errors for the events listed in Table 1 in Fig. 8 together with the standard deviations of the inter-event errors from our previous study. The inter-event errors are consistent with the previous results at all periods except for three events (event nos. 3, 4, and 6) at periods longer than about 5 s. The inter-event errors may be used for further analysis of the GMPEs, and we discuss the implications of the event-errors shortly.

![Fig. 8 Inter-event errors plotted as a function of periods for events used in this study. The solid and dashed lines denote the mean and one standard deviations of the inter-event error terms in GMPEs, respectively. The legends correspond to the event identifications listed in Table 1.](image-url)
4.2 Example revision and verification

Firstly, we revised the site factors for sites located in the Kyushu region by adding the recordings from two events: event nos. 4 and 6, namely the southwest off Kyushu and Kumamoto earthquakes, respectively. It would be interesting to revise the site factors without using the recordings from the Kumamoto earthquake and test the results for the Kumamoto earthquake. However, due to only one event (event no. 4 in Table 1) other than the Kumamoto earthquake in the region, we used the recordings from the Kumamoto earthquake as well to enhance the dataset, and revised the site factors in the region. We showed a comparison between the observed intensities and predictions using the previous site factors and revised site factors for the Mw 6.6 (Mj 7.0), 2005, Fukuoka earthquake as a test event in Fig. 9. The observed intensities, predicted intensities using the previous site factors, and predicted intensities using the revised site factors, are shown in left, middle, and right panels, respectively, of Fig. 9. The number of sites at which the intensities are equal, overestimated, and underestimated are indicated as inset numbers in the spatial plots for the corresponding predictions. Compared to the results from the previous site factors, the observed and predicted intensities are equal at ten more sites, and the over- and under-estimations distribute more evenly using the revised site factors.

![Fig. 9 Spatial distribution of observed (left panel), and predicted intensities using site factors from our previous study (middle panel) and those revised in the present study (right panel), for the Mw 6.6 (Mj = 7.0), 2005, Fukuoka earthquake. A star denotes the epicenter of the earthquake. The left and right numerals in the inset rectangles (in the middle and right panels) denote the differences between the observed and predicted intensities and the number of sites corresponding to the differences, respectively. The negative, zero, and positive numerals in the left indicate the overestimations, equal, and underestimations.](image)

It is also interesting to see whether these revisions of the site factors affected the sites at distances beyond 200 km for the Kumamoto earthquake; at the sites, the differences were mainly due to the source and propagation path effects, and the results should not change after the revision of the site factors. We show the comparisons between the observed and predictions using the previous and revised site factors for the Kumamoto earthquake in Fig. 10. As expected, the predictions using the revised site factors are improved. The difference between the observed and predicted intensities is brought to within one level of intensity. The number of sites having equal intensities increases from 141 to 164, and the number of sites having differences of two level of intensities is reduced to zero (compare the inset numerals between the middle and right panels in Figure 10). It can also be seen that the two predictions before and after the revision of site factors are essentially the same at distances beyond about 200 km. These results suggest that a meaningful revision of site factors is possible without going for an entire process of regression analysis when the prediction errors are resolved into inter-event and intra-event errors.
Finally, we revised the site factors for the sites in the Honshu mainland and Hokkaido regions adding the recordings from the events located off the Pacific coast of Japan. Because of relatively large number of recordings used to derive the site factors in these regions, the change in previously derived site factors is negligible at most sites. We show the number of recordings used at each site in the derivation of site factors in Fig. 11. The sites are divided into four groups having number of recordings 2 or 3, 4 or 5, 6 to 10, and > 10, and are plotted in Figs. 11(a), 11(b), 11(c), and 11(d), respectively. It can clearly be seen that the number of recordings in south west Japan, Figs. 11(a) and 11(b), is limited to five or fewer at a site. On the other hand, in the north-east Japan, Figs. 11(c) and 11(d)), most sites have more than ten recordings. We provide the site factors to interested readers upon request, but suggest that the site factors ought to be used in relation to the GMPEs suggested in this report.

5. DISCUSSIONS

We employed the JMA magnitude and hypocentral distance in our GMPEs. By resolving the errors into inter-event and intra-event types, site correction terms were derived. Among the events listed in Table 1, we find that three events have relatively larger inter-event errors at periods longer than about 5 s (see Fig. 8), and it appears that the errors correlate with the depth of the events; the positive errors are associated with the relatively shallow earthquakes (event nos. 4 and 6, the southwest off Kyushu earthquake and Kumamoto earthquake, respectively), and the negative errors are associated with the relatively deeper subduction zone earthquake (event no. 3, east off Miyagi Prefecture earthquake, focal depth = 46 km). The event no. 5 (south off Urakawa earthquake) has a comparable focal depth of 51 km with that of event no. 3, but the absolute values of inter-event errors for the event are generally smaller than those of event no. 3. The difference between the two events (event no. 3 and 5) may be due to differences in spatial coverage of the recordings with respect to the event locations. However, further analysis is required to understand fully the reasons for the differences between the two events. Anyway, the plots of event errors in Fig. 8 point to the possible classification of events to reduce the variability of long-period ground motions in the GMPEs.

The recent implementation of the DONET\(^{15}\) in the Nankai Trough area and S-net\(^{16}\) in the Japan Trench area is expected to contribute to a higher resolution of focal depths of offshore events. We
investigate the effects of focal depths and earthquake types on long-period ground motion intensities in our future study. Moreover, the effects of finite faults and fault geometry are not explained in our GMPEs because the fault geometry and extent of fault ruptures are not known in a brief time for an EEW. Nonetheless, they play a significant role in ground motion variability, and are also the topics of future research for the improved prediction of long-period ground motion intensities for an EEW.

Fig. 11 Distribution of sites by number of recordings used to derive the site factors at the sites. (a) Sites having number of recordings 2 or 3. (b) Sites having number of recordings 4 or 5. (c) Sites having number of recordings 6 to 10. (d) Sites having number of recordings > 10. The total number of sites in each group is indicated inside each frame. The K-NET and KiK-net sites are denoted by circles and triangles, respectively.

6. CONCLUSIONS

We compared the observed long-period AVRS with the predictions using the GMPEs\(^1\) for recent large
seven events that occurred after the construction of the GMPEs. We found that the GMPEs generally
described well the observed data except for the Mw 7.1 Kumamoto earthquake at distances beyond
about 200 km. The observed large values at sedimentary sites were generally explained better by the
site factors in comparison to the site corrections based on the depth of Vs 1.4 km/s and AVS30. These
results based on the recently acquired data confirm the results reported in our previous study. We
revised the site factors reported in our previous study at sites in the Kyushu region and adjoining areas
based on the new recordings from two events that occurred near the areas. The results indicated that
the revised site factors improved the accuracy of prediction at several sites for a test event. Also, we
showed that the methodology used to revise the site factors is almost free from contamination of
source effects into the revised site factors. Thus, we may conclude that the site factors need to be
updated when new recordings become available, especially in the region of few recordings. We
updated the previously derived site factors in the Honshu mainland and Hokkaido regions as well. The
change is negligible at most sites in these regions due to relatively large number of recordings used to
derive them. An analysis of inter-event errors for the new events employed in the present study
suggested a correlation between the errors and focal depths. In our future study, we examine the
effects of focal depths and earthquake types on the long-period ground motion intensities for an EEW.
We provide the site factors derived in this study to interested readers upon request, but suggest that the
site factors ought to be used in relation to the GMPEs suggested in this report.

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that helped to improve the quality of the report significantly.

APPENDIX 1

Intensity scale on long-period ground motions4,18). The values with the unit of velocity (first column)
denote the range of the maximum AVRS from the period band of 1.6 to 7.8 s.

<table>
<thead>
<tr>
<th>Intensity scale on long-period ground motions</th>
<th>Effects on people</th>
<th>Indoor situations</th>
<th>Effects on non-structural elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>I 5 - 15 cm/s</td>
<td>Felt by most people in buildings. Some are startled.</td>
<td>Hanging items such as lamps and blinds swing significantly.</td>
<td></td>
</tr>
<tr>
<td>II 15 - 50 cm/s</td>
<td>Many people find it difficult to walk without holding onto something stable</td>
<td>Furniture with casters move slightly. Dishes in cupboards and items on bookshelves may fall.</td>
<td></td>
</tr>
<tr>
<td>III 50 - 100 cm/s</td>
<td>It is difficult to remain standing</td>
<td>Furniture with casters move significantly. Unsecured furniture may topple over.</td>
<td>Partition walls may crack.</td>
</tr>
<tr>
<td>IV &gt; 100 cm/s</td>
<td>It is impossible to remain standing or to move without crawling</td>
<td>Furniture with casters move significantly and may topple over. Many unsecured furniture move and may topple over.</td>
<td>Many partition walls may crack.</td>
</tr>
</tbody>
</table>

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