Macro-spatial correlation model of seismic ground motions

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Keywords: macro-spatial correlation model; seismic ground motion; attenuation relation; logarithmic deviation; correlation length

ABSTRACT: It is very important to estimate a macro-spatial correlation of seismic ground motion intensities for earthquake damage predictions, building portfolio analyses etc., whereby damages in different locations have to be taken into account simultaneously. This study focuses on the spatial correlation of the logarithmic deviation between the observed and the predicted ground motion intensity by an empirical mean attenuation relation. The macro-spatial correlation model of the logarithmic deviation is proposed with an exponentially decaying function as well as an empirical mean attenuation relation, assuming that the logarithmic deviation constitutes a homogeneous two-dimensional stochastic field. The dense observation data of earthquakes which occurred in Japan in recent years are fully used for the analysis in this paper.

1 INTRODUCTION

Prediction of strong ground motion in wide area has played a very important role in earthquake disaster prevention and damage mitigation, as well as in seismic design and assessment of infrastructures spatially spread. Management of widely located building assets, so-called portfolio analysis, has become popular in the field of earthquake risk management in recent years, whereby simultaneous damages of assets in different locations are of major concern (Achiwa et al. 2001).

Mean attenuation characteristics of the ground motion induced from a seismic source can be conveniently predicted by using the mean attenuation relation. The spatial correlation structure of the uncertainty of the empirical ground motion attenuation relations also has to be adequately modeled on the basis of mean attenuation relations. Therefore, the ground motion intensity can be more accurately predicted with the past empirical attenuation relations and the macro-spatial correlation model proposed in this study. Either perfect correlation or perfect non-correlation of the uncertainty of attenuation relations has been intuitively assumed in the past researches (Ishikawa et al. 2000, Fukushima and Yashino 2002). However, this correlation could be, in fact, dependent upon many factors such as relative distance between two different sites, ground conditions of the sites, directivity of propagating waves etc. No past systematic research on quantifying the spatial correlation structures of ground motion intensity has been reported so far.

This study focuses on the spatial correlation structure of the logarithmic deviation (uncertainty) from its mean value. In this paper, high-density earthquake records of six recent earthquakes published on K-NET and KiK-NET deployed by National Institute for Earth Science and Disaster Prevention (NIED) in Japan are fully utilized to quantify the spatial correlation characteristics of the ground motions.

2 STOCHASTIC MODELLING OF SESMIC GROUND MOTION

2.1 Mean Attenuation characteristics of ground motion

The Annaka and Midorikawa-Ohtake attenuation relations based on the earthquake data of Japan are adopted to characterize the median of PGA and PGV. The Annaka relation (Annaka et al. 1997) is described as in Eq. (1).

\[ \log_{10} T = a_i M_j + a_i H - a_i \log_{10} (D + 0.334^{0.653M_j}) - a_i \]  

where \( T \) is PGA in gal on ground surface or PGV in kine on engineering bedrock, \( M_j \) is JMA (brief for Japan Meteorological Agency) magnitude, \( D \) is the closest distance to the fault plane in km, \( H \) is a source depth in km, \( a_i \) is a regression coefficient.
The Midorikawa-Ohtake relation (Midorikawa and Ohtake 2002) is described as in Eq. (2).
\[
\begin{align*}
\log_{10} T &= c - \log(D + m \cdot e^{0.35M}) - m_D (H \leq 30 km) \quad (2a) \\
\log_{10} T &= c + 0.6 \log(1.7H + m \cdot e^{0.35M}) \\
-1.6 \log(D + m \cdot e^{0.35M}) - m_D (H \leq 30 km) \quad (2b)
\end{align*}
\]
where \(c = m_M + m_H + \sum d_s - m_s\) (3)

\(M_w\) is a moment magnitude, the variable \(d=0, 0.05, 0.15\) for crustal, inter-plate and intra-plate type earthquake, \(s_i\) is a dummy variable, \(m_i\) is a regression coefficient.

Uncertainty associated with the attenuation relation can be generally decomposed into inter-earthquake and intra-earthquake uncertainties. These two kinds of uncertainties for PGA and PGV associated with two attenuation relations are listed in Table 1, respectively. In this paper, only the intra-earthquake uncertainty is comprehensively discussed.

Table 1. Uncertainties of the attenuation relations in natural logarithm

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Annake</th>
<th>Midorikawa-Ohtake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PGA</td>
<td>PGV</td>
</tr>
<tr>
<td>Inter-earthquake</td>
<td>0.37</td>
<td>0.37</td>
</tr>
<tr>
<td>Intra-earthquake</td>
<td>0.51</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Amplification factor (\(AVR\)) of motion is adopted to transform the PGV on the ground surface into that on the engineering bedrock. The shear-wave velocity average over the upper 30 m (\(V_{30}\)) is used as the variable to represent site effects. The empirical relation (Midorikawa et al. 1994) between \(AVR\) and \(V_{30}\) was proposed as in Eq. (4). The uncertainty associated with the site effect in Eq. (4) is suggested as 0.37.

\[
\log_{10} AVR = 1.83 - 0.66 \log(V_{30}) \quad (4)
\]

2.2 Separation of mean and logarithmic deviation of ground motion

The seismic ground motion intensity \(A(x)\) at location \(x\), can be separated into its trend component \(T(x)\) and deviation component \(\varepsilon(x)\) as given in Eq. (5):

\[
A(x) = \varepsilon(x)T(x) \quad (5)
\]

\(T(x)\) is predicted from the mean attenuation relation. The logarithmic deviation \(L(x)\) is now defined as in Eq. (6). In this paper, natural logarithms are used in the absence of special description.

\[
L(x) = \ln(A(x)/T(x)) \quad (6)
\]

Assuming that \(L(x)\) is a homogeneous two-dimensional stochastic field, it then follows that its auto-covariance function \(C_{LL}\) is described as in the Eq.(7).

\[
C_{LL}[x_1 - x_2] = E[(L(x_1) - \mu_L)(L(x_2) - \mu_L)] \quad (7)
\]

where \(E[\cdot]\) is an expectation, \(|x_1 - x_2|\) is a separation distance between the two locations \(x_1\) and \(x_2\), and \(\mu_L\) is the mean value of \(L(x)\). \(\mu_L = E[L(x)]\). \(\mu_L\) is not a function of location \(x\) due to the homogeneity assumption.

3 DATA ANALYSIS OF GROUND MOTION

3.1 Database of the seismic ground motion

The six earthquakes selected herein occurred during 2000 to 2004 including the latest one occurring on Oct. 23, 2004. The information on the hypocenter and the corresponding fault model used for the attenuation relations are listed on Tables 2 and 3. The data of the hypocenter in Japan adopted from the JMA report, and the fault model of earthquakes in Japan are taken from the Headquarters for Earthquake Research Promotion (HERP) or Geographical Survey Institute (GSI). The epicenters of the six earthquakes are shown in Fig. 1.

The accelerograms used in this paper are observed within 300 km of the closest distance to the fault plane. They are processed with a band-pass filter of 0.2-10 Hz for PGA (Midorikawa and Ohtake 2002, Si and Midorikawa 1999). PGV is obtained by integrating the accelerogram.

Table 2. Profile of earthquakes (JMA)

<table>
<thead>
<tr>
<th>Earthquakes</th>
<th>Date</th>
<th>(M_l)</th>
<th>(M_s)</th>
<th>Source Depth(km)</th>
<th>Fault Type</th>
<th>Number of Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tottori-ken Seibu</td>
<td>2000/10/06</td>
<td>7.3</td>
<td>6.8</td>
<td>9</td>
<td>Crustal</td>
<td>315</td>
</tr>
<tr>
<td>Geiyo</td>
<td>2001/03/24</td>
<td>6.7</td>
<td>6.7</td>
<td>46</td>
<td>Intraplate</td>
<td>370</td>
</tr>
<tr>
<td>Miyagi-ken-oki</td>
<td>2003/05/26</td>
<td>7.0</td>
<td>7.0</td>
<td>71</td>
<td>Intraplate</td>
<td>230</td>
</tr>
<tr>
<td>Miyagi-ken Hokubu</td>
<td>2003/07/26</td>
<td>6.2</td>
<td>6.2</td>
<td>12</td>
<td>Crustal</td>
<td>246</td>
</tr>
<tr>
<td>Tokachi-oki</td>
<td>2003/09/26</td>
<td>8.0</td>
<td>8.0</td>
<td>42</td>
<td>Intraplate</td>
<td>287</td>
</tr>
<tr>
<td>Mid Niigata-prefecture</td>
<td>2004/10/23</td>
<td>6.8</td>
<td>6.5</td>
<td>13</td>
<td>Crustal</td>
<td>374</td>
</tr>
</tbody>
</table>

Figure 1. Locations of earthquake epicenters in Japan
Table 3. Fault parameters of earthquakes (HERP, GSI)

<table>
<thead>
<tr>
<th>Earthquakes</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Depth (km)</th>
<th>Strike</th>
<th>Dip (°)</th>
<th>Width (km)</th>
<th>Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tottori-ken Seibu</td>
<td>35.35</td>
<td>133.3</td>
<td>1</td>
<td>152</td>
<td>86</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Geiyo</td>
<td>34.1</td>
<td>132.7</td>
<td>38.1</td>
<td>156</td>
<td>52</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Miyagi-ken-oki</td>
<td>38.94</td>
<td>141.81</td>
<td>52</td>
<td>192</td>
<td>68</td>
<td>19</td>
<td>17</td>
</tr>
<tr>
<td>Midorikawa-Ohtake</td>
<td>38.41</td>
<td>141.17</td>
<td>3.7</td>
<td>11</td>
<td>54</td>
<td>10.2</td>
<td>20.9</td>
</tr>
</tbody>
</table>

Table 4. Statistical values of logarithmic deviation $L(x)$ of PGA (intra-event uncertainty)

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>$\mu_L$</th>
<th>$\sigma_L$</th>
<th>$\mu_{\ln L}$</th>
<th>$\sigma_{\ln L}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tottori-ken Seibu</td>
<td>0.08</td>
<td>0.64</td>
<td>-0.41</td>
<td>0.07</td>
</tr>
<tr>
<td>Geiyo</td>
<td>0.59</td>
<td>0.75</td>
<td>-0.62</td>
<td>-0.13</td>
</tr>
<tr>
<td>Miyagi-ken-oki</td>
<td>0.83</td>
<td>0.90</td>
<td>-0.42</td>
<td>0.03</td>
</tr>
<tr>
<td>Hokubu</td>
<td>0.68</td>
<td>0.84</td>
<td>0.05</td>
<td>0.15</td>
</tr>
<tr>
<td>Tokachi-oki</td>
<td>-0.16</td>
<td>0.85</td>
<td>-0.51</td>
<td>-0.45</td>
</tr>
<tr>
<td>Mid Niigata-prefecture</td>
<td>0.03</td>
<td>0.76</td>
<td>-0.42</td>
<td>-0.19</td>
</tr>
</tbody>
</table>

3.2 Mean attenuation characteristic of ground motion

3.2.1 PGA

The attenuation characteristics of PGA observed in the Tottori-ken Seibu Earthquake and the Mid Niigata-prefecture Earthquake are shown in Fig. 2 as well as the two attenuation relations described in the above. The PGA given in the figure is the maximum value of EW and NS components of PGA.

![Figure 2. The attenuation characteristic of PGA](image)

(a) The Tottori-ken Seibu Earthquake

(b) The Mid Niigata-prefecture Earthquake

It is found that the empirical attenuation relation can capture the mean tendency of the observed data in a wider range, 300km. Two attenuation relations are similar in these two earthquakes of which the source depth is smaller than 30 km. Slight difference that the Midorikawa-Ohtake attenuation relation fits the observed data better than the Annaka relation can also be observed from the figure. This difference can be accounted for the considering the fault type in the Midorikawa-Ohtake relation when the source depth is within 30 km.

Table 5. Statistical values of logarithmic deviation $L(x)$ of PGA (inter-event uncertainty)

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>$\mu_L$</th>
<th>$\sigma_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tottori-ken Seibu</td>
<td>0.41</td>
<td>0.22</td>
</tr>
<tr>
<td>Geiyo</td>
<td>0.59</td>
<td>0.22</td>
</tr>
<tr>
<td>Miyagi-ken-oki</td>
<td>0.41</td>
<td>0.22</td>
</tr>
<tr>
<td>Hokubu</td>
<td>0.41</td>
<td>0.22</td>
</tr>
<tr>
<td>Tokachi-oki</td>
<td>0.41</td>
<td>0.22</td>
</tr>
<tr>
<td>Mid Niigata-prefecture</td>
<td>0.41</td>
<td>0.22</td>
</tr>
</tbody>
</table>

The correlation coefficient of $L(x)$ to the fault distance $r_L$ represents the distance-dependency of $L(x)$, that is, the goodness of the fitness of the attenuation relation. It can be seen from Table 4, the absolute values of $r_L$ with the Midorikawa-Ohtake relation are smaller than those with the Annaka relation, and so do the uncertainties associated with the intra- and inter-earthquake. It shows that the Midorikawa-Ohtake relation can better describe the attenuation characteristic of PGA than the Annaka relation. More detail discussion about the homogeneity of $L(x)$ is left in the latter of this paper.

3.2.2 PGV

Fig. 3 shows the attenuation characteristics of PGV observed in the Miyagi-ken-oki Earthquake and the Tokachi-oki Earthquake as well as the past two attenuation relations. The statistical values of $L(x)$ for PGV, $\mu_L$, $\sigma_L$ and $r_L$ are also listed in Table 5.

Although two attenuation relations can basically capture the mean tendency of the ground motion, the Midorikawa-Ohtake relation has better accuracy of data fitting. The calculated inter-earthquake uncer-
tainty with the Midorikawa-Ohtake relation is 0.34 in a logarithmic standard deviation, and it is 0.37 for the Annaka relation.

Table 5. Statistical values of logarithmic deviation $L(x)$ of PGV (intra-event uncertainty)

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Annaka</th>
<th>Midorikawa-Ohtake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu_L$</td>
<td>$\sigma_L$</td>
</tr>
<tr>
<td>Tottori-ken-Seibu</td>
<td>0.46</td>
<td>0.51</td>
</tr>
<tr>
<td>Geiyo</td>
<td>-0.11</td>
<td>0.56</td>
</tr>
<tr>
<td>Miyagi-ken-oki</td>
<td>0.32</td>
<td>0.58</td>
</tr>
<tr>
<td>Miyagi-ken-Hokubu</td>
<td>0.14</td>
<td>0.58</td>
</tr>
<tr>
<td>Tokachi-oki</td>
<td>-0.48</td>
<td>0.64</td>
</tr>
<tr>
<td>Mid Niigata-prefecture</td>
<td>-0.48</td>
<td>0.58</td>
</tr>
</tbody>
</table>

(a) The Miyagi-ken-oki Earthquake

(b) The Tokachi-oki Earthquake

Figure 3. The attenuation characteristic of PGV

The intra-earthquake uncertainties of the attenuation relation $\sigma_L$ are computed in Table 5 in a logarithmic standard deviation from 0.51 to 0.64 for the Annaka relation, from 0.49 to 0.57 for the Midorikawa-Ohtake relation. They are close to the originally suggested values in Table 1. The absolute values of $\rho_L$ with the Midorikawa-Ohtake relation are smaller than those with the Annaka relation. These statistical characteristics show that the Midorikawa-Ohtake relation can better describe the attenuation characteristic of PGV than the Annaka relation which can be obviously seen from the Fig. 3. This difference is accounted for the considering the propagation effect besides the fault type in the Midorikawa-Ohtake relation when the source depth is beyond 30 km where the Moho is assumed and changes the wave propagation.

3.3 Homogeneity of logarithmic deviation

The logarithmic deviation $L(x)$ is assumed to constitute a homogeneous two-dimensional stochastic field in Eq. (7). The logarithmic deviation of the ground motion for attenuation relation is plotted along the distance to examine the homogeneity. Figures 4 and 5 give the plots of the logarithmic deviation of PGA and PGV respectively as well as the moving average of $L(x)$, $ML$. Its windows-width is 20 km. The mean value $ML$ and standard deviation of $L(x)$, $\sigma$, within the window are also calculated. Then the ranges of $ML$, $(ML \pm \sigma)$, are shown in the same figures.

Figure 4. Homogeneity of $L(x)$ of PGA of the Tottori-ken Seibu Earthquake

(a) the Annaka attenuation relation

(b) the Midorikawa-Ohtake attenuation relation

Figure 5. Homogeneity of $L(x)$ of PGV of the Tottori-ken Seibu Earthquake

(a) the Annaka attenuation relation
shows that the moving standard deviation 

Tables 4 and 5. On the other hand, the plot of 

(b) the Midorikawa-Ohtake attenuation relation 

erages of the Midorikawa-Ohtake relation vary 

Figure 5. Homogeneity of 

way to understand the variation of the logarithmic 

can be referred to the correlation coefficient 

Due to the availability of dense observation in Ja-

former shows smaller distance-dependency which 

smaller than those of the Annaka relation. And the 

result, the assumption which the logarithmic deviation 

obviously show this distance-dependency. As a re-

L

The data observed from the each earthquake were 

fully grouped into several bins with the same sepa-

ration distance in the same bin is within 

shown in Fig. 6 in which the Mid Niigata-prefecture 

Earthquake is given as an illustration. Eq. (7) can 

then be rewritten into Eq. (8) with discrete expres-

\[ C_{ll}(h) = \frac{1}{N(h)} \sum_{i=1}^{N_{all}} (L(x_i) - \mu_l)(L(x_i) - \mu_l) \] (8) 

and 

\[ \mu_l = \frac{1}{N_{all}} \sum_{i=1}^{N_{all}} L(x_i) \] (9) 

where \( N_{all} \) is the total number of observation sites, 

\( N(h) \) is the number of pairs of sites \((x_a, x_b)\) that meet the condition \( h - \Delta h / 2 \leq |x_a - x_b| < h + \Delta h / 2 \), the interval \( \Delta h \) is set to 4 km in order to keep accuracy in the statistical analysis.

4 PROPOSAL OF NEW MACRO-SPATIAL CORRELATION MODEL

4.1 Macro-spatial correlation relation

The data observed from the six earthquakes are fully used to build up the macro correlation model. Following the model described above, the value of \( b \) can be obtained, and the results are listed in Tables 6, for the two attenuation relations. Figures 7 and 8 show part of the results PGA and PGV, respectively.

Figure 6. Histogram of separation distance \( h \) after the Mid Niigata-prefecture Earthquake

Due to the availability of dense observation in Japan, \( N(h) \) is found close to or more than 100 when \( h \) is larger than 10 km. By the statistical analysis above, the auto-covariance function \( C_{ll} \) can be estimated. Normalized auto-covariance function \( R_{ll} \) can be obtained by normalizing \( C_{ll} \) with the variation of \( L(x) \).

\[ R_{ll}(h) = \frac{C_{ll}(h)}{\sigma_L} \] (10)

Now the macro-spatial correlation model can be built up by modeling the discrete values of the normalized auto-covariance function \( R_{ll} \) with an exponential decaying function as:

\[ R_{ll}(h) = \exp \left( -\frac{h}{b} \right) \] (11)

where \( h \) is a separation distance between two observatories and \( b \) is so-called a correlation length, which can characterize the degree of correlation of ground motions between two locations. \( R_{ll} \) becomes \( 1/e (\approx 0.37) \) when the separation distance \( h \) between two sites equals \( b \). It can be seen from Eq. (11) that this exponential function satisfied two essential conditions: \( R_{ll}(0) = 1 \), and \( R_{ll}(\infty) = 0 \). Furthermore, this exponential function is in such a simple form, only with one parameter \( b \), that will greatly please the engineers in their analysis.

4.2 Results of analysis

The data observed from the six earthquakes are fully used to build up the macro correlation model. Following the model described above, the value of \( b \) can be obtained, and the results are listed in Tables 6, for the two attenuation relations. Figures 7 and 8 show part of the results PGA and PGV, respectively.

Table 6. Correlation length for PGA and PGV with two attenuation relations (km)

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Annaka</th>
<th>Midorikawa-Ohtake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PGA</td>
<td>PGA</td>
</tr>
<tr>
<td>Tottori-ken Seibu</td>
<td>23.1</td>
<td>21.0</td>
</tr>
<tr>
<td>Geiyo</td>
<td>41.7</td>
<td>47.8</td>
</tr>
<tr>
<td>Miyagi-ken-oki</td>
<td>45.2</td>
<td>39.7</td>
</tr>
<tr>
<td>Miyagi-ken Hokubu</td>
<td>31.0</td>
<td>27.7</td>
</tr>
<tr>
<td>Tokachi-oki</td>
<td>59.1</td>
<td>44.5</td>
</tr>
<tr>
<td>Mid Niigata-prefecture</td>
<td>43.5</td>
<td>21.6</td>
</tr>
</tbody>
</table>
It can be seen from the Table 6 that the correlation length ranges for two attenuation relations are of the same order of magnitude, from 11 to 45 km for PGA, and from 21 to 35 km for PGV. This implies that the spatial correlation characteristic of seismic ground motions has approximately similar tendency regardless of the mean attenuation relations used as well as earthquake types or regions in Japan. The values of correlation length obtained from the Annaka relations are slightly larger than those obtained from the Midorikawa-Ohtake relation. Discussions accounting for the overestimation from the Annaka relation are mentioned later.

(b) The Tokachi-oki Earthquake

Figure 8. The spatial correlation model for PGV

Figures 7 and 8 show the exponential function adopted in the Eq. (11) can basically fit the data well except in the range of short separation distance. Note that in Figure 7a, there is a low correlation data plot in the closer range of separation distance of 2 km, and can be observed in some other earthquakes. This is mainly because the number of data pairs in this range is very small as shown in Fig. 6, attributed to the average separation distance, about 25 km, of K-NET stations. By further examination of the data pairs, it shows that the ground conditions easily affect the correlation result in the case of small number of data pairs. That is, if the ground conditions are quite different in the same bin, the correlation becomes small for the small number of data, which cannot lead to reliable result. This site effect will be dominant on the seismic ground motion in the range of short separation distance.

5 DISCUSSIONS

Although the attenuation relation plays a very important role in seismic engineering, the uncertainties associated with them range from 0.4 to 0.7 in natural logarithmic standard deviation (Abrahamason and Shedlock 1997). This study proposed a correlation model of the uncertainty inherent in the earthquake as an alternative to improve the prediction. The model is fully dependent on the homogeneity of the logarithmic deviation. The factors, such as source characteristic, wave propagation and site effect affecting the uncertainty of attenuation relation, may have effects on this model.

The fault type associated with the source characteristic is taken into account in term of parameter $d$ in Equation (3) in the Midorikawa-Ohtake relation. From the Fig. 2 in which the source depths are shallower than 30 km, the logarithmic deviation of the Midorikawa-Ohtake relation is more homogeneous than that of the Annaka relation, which leads to the smaller correlation length with the Midorikawa-Ohtake relation listed in Table 6. Fig. 9 is a com-
parison with Fig. 7a. Although the effect of rupture
directivity on ground motion was reported in the
literatures, the distance range of this effect is about a
quarter of the rupture length away from the rupture,
about 20 km (Somerville \textit{et al.} 1997, Ohno \textit{et al.}
1998, Midorikawa and Ohtake 2003). There are few
data in this range observed in the six earthquakes
adopted in this paper. In this sense, the directivity ef-
cfect can be ignored in the macro correlation analysis.

As is known, the Moho is the boundary between
the crust and the mantle in the earth where the seis-
ic wave changes its velocity. When the earthquake
occurs beneath this discontinuity, the wave propaga-
tion will be greatly changed. Equation (2b) in the
Midorikawa-Ohtake relation takes into account this
effect with coefficient of 1.6 when $H > 30$ km (as-
suming the depth of Moho is 30 km) rather than 1.0
in Equation (2a), while this propagation effect is not
considered in the Annaka relation. Fig. 5 shows this
difference in case that the source depths are deeper
than 30 km. The logarithmic deviation from the Mi-
dorikawa-Ohtake relation shows more homogeneous
than that from the Annaka relation which shows ob-
viously negative correlation with respect to distance.
Comparing the Fig. 8b and Fig. 10, the correlation
length for the Midorikawa-Ohtake relation is smaller
than those for the Annaka relation. Similar results
can be seen in Table 6.

Taking into account more physical phenomena of
the earthquake, the Midorikawa-Ohtake relation can
describe the attenuation characteristics of the ground
motion than the Annaka relation, which can account
for the overestimation of the correlation model with
the Annaka relation.

Even though these effects are considered in the
Midorikawa-Ohtake relation, the correlation length $b$
calculated comprises uncertainties, such as inter-
earthquake uncertainty and site effect. The PGA and
PGV are defined on the ground surface and the en-
engineering bedrock, respectively. As we can see from
Table 6, the uncertainty of the correlation length for
PGV is smaller than that of PGA. The uncertainty of
site effect associated with Equation (4) is suggested
as 0.37 and can propagate to the uncertainty of the
correlation model.

The inter-earthquake uncertainty is magnitude-
dependence and usually relates with the different
propagation path in the difference area. It is sugg-
ested as 0.37 in natural logarithmic standard devia-
tion in two attenuation relations. Due to the tectonic
structures of the Japan islands, the abnormal Q struc-
ture in the subduction zone of Northeast Japan con-
tributes to the anomalous seismic ground motion and
the additional correction term, the distance between
the observatory to the trench axis, is suggested
(Morikawa \textit{et al.} 2003). These uncertainties can
propagate to the correlation length calculated, and
contribute to the slight difference of $b$-values of the
Northeast Japan from those of Southwest Japan
listed in Table 6.

As discussed above, there are many factors af-
flecting the correlation model. The source character-
istic, wave propagation and site effect are dominant.
The contribution of inter-earthquake uncertainty to
the variation of the correlation model is also appar-
ent. Incorporating this correlation model associated
with those physical phenomena not described in the
attenuation relation, the probabilistic seismic hazard
analysis can be greatly improved. Although the at-
tenuation relation can be improved by introducing
new parameters, the complicate attenuation relation
will increase the difficulty in the usage, and addi-
tional information is necessary, such as the correc-
tion term in the Northeast Japan which is difficult in
formulating yet. In Japan, the two attenuation rela-
tions adopted in the study are popularly used in the
prediction of ground motion. The Midorikawa-
Ohtake relation is better than the Annaka relation
from the analysis in this study. The parameters in
this relation can also be easily found from the web-
sites of the JMA, K-NET, KiK-NET and HERP.

6 CONCLUSIONS

Focusing on the logarithmic deviation between ob-
served data and those previously proposed mean at-
tenuation relations, the macro-spatial correlation of
residual value is proposed using records observed in the recent earthquakes in Japan.

From this study, the assumption that the logarithmic deviation \( L(x) \) constitutes a homogeneous two-dimensional stochastic field can be approximately satisfied with the Midorikawa-Ohtake attenuation relation. The proposed macro-spatial correlation model with a one-parameter exponential function can fit the data well. This simple correlation with the empirical attenuation relation can be applied in many fields with great ease, especially from the view of engineering. The correlation length \( b \) controlling the spatial correlation of ground motion can then be calculated and falls within the range about 20–40 km for PGV, and 10–45 km for PGA, although the correlation of ground motion is highly dependent on many factors such as, wave propagation, ground conditions, etc. The uncertainty of the correlation length can be attributed to these uncertainties. Due to lack of data from large earthquakes, and the data of which the separation distance is shorter than 10 km, the uncertainty of the correlation length is difficult to evaluate yet. Monte Carlo Simulation is expected to simulate the ground motion, then to quantify and evaluate the uncertainty of the macro-spatial correlation model in the future.

The proposed model along with the mean attenuation relation proposed in previous studies can be effectively utilized with great ease in various earthquake engineering fields. The spatial distribution of ground motion intensity, which is considered to be induced from a particular earthquake source, can be easily evaluated with emphasis on simultaneity of ground motion intensities at two different sites. The macro-spatial correlation model can easily be incorporated into the probabilistic seismic hazard assessment (Fukushima and Yashiro 2004, Wesson and Perkins 2001) for multiple sites.

Other possible application of this model is a stochastic prediction of ground motion at unobserved sites using the records observed near-by since the joint probability density function of ground motions at two arbitrary different sites has already been obtained by using this macro-correlation model (Field et al. 2003). These interesting applications will be further studied.

REFERENCES


National Research Institute for Earth Science and Disaster Prevention (Japan). http://www.bosai.go.jp


