ATTENUATION AND SITE AMPLIFICATION FOR LONG-PERIOD GROUND MOTIONS OBSERVED IN WESTERN JAPAN

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ABSTRACT :

This paper discusses ground motion attenuation and site amplification using a series of long-period earthquakes that occurred in 2004 near the epicenter of the 1944 Tonankai earthquake (M_{JMA} = 7.9). A comparison of the observed ground motions and the attenuation relationships indicates that peak ground acceleration (PGA) and peak ground velocity (PGV) of the long-period ground motions are smaller than the attenuation equations, whereas peak ground displacement shows good fits with the attenuation relationship. The long-period motions are less amplified than earthquakes of ordinary frequency characteristics. The tendency is confirmed by one dimensional wave propagation analysis. Relationships between site amplification factors and predominant periods of ground motion indicate that site amplification becomes smaller with longer period ground motions. Application of attenuation relationships and site amplification equations based on a database of seismic motions of ordinary frequency characteristics may lead to overestimation of ground motions.

KEYWORDS: Long-period ground motion, Attenuation relationship, Site amplification, One dimensional multi-reflection theory

1. INTRODUCTION

There is a 50% chance that a Nankai earthquake will occur within the next 30 years and is foreseen to engender serious damage in a wide area of western Japan. The earthquake is an inter-plate earthquake and it is of magnitude 8 or greater occurring periodically at every 100 to 150 years. Unfortunately, there is no recording that is observed in the vicinity of the source area of the previous Nankai earthquake occurred in 1946. According to personal testimonies, the 1946 Nankai earthquake consisted of very long-period ground motions.

A series of long-period earthquakes occurred in 2004 near the 1944 Tonankai earthquake. According to Yamanaka (2004), the 2004 earthquakes are intra-plate earthquakes whereas the 1944 earthquake was an inter-plate earthquake. The long-period ground motions were observed at K-NET and KiK-net sites (nationwide Japanese strong-motion observation system by NIED) in a large area of western Japan.

Attenuation relationships and site amplification equations are often used to predict the seismic intensity of the ground motion associated with regional disaster prevention. These empirical estimations reflect the database used when they were established. Long-period earthquakes are unique, hence, it is questionable whether the empirical relationships can represent the attenuation and site amplification for long-period earthquakes.

We analyze attenuation and site amplification of long-period ground motions, comparing the results with empirical relationships developed in the past. The results are also compared with theoretical results by one dimensional wave propagation theory.

Table 1 Parameters of long-period earthquakes used in this study

Event	1	2	3	4
Date Origin time	09/05/2004 19:07	09/05/2004 23:57	09/07/2004 8:29	09/08/2004 23:58
Epicenter	N 33.03 E 136.8	N 33.14 E 137.14	N 33.21 E 137.3	N 33.11 E 137.29
Depth(km)	38	44	41	36
M_{JMA} (M_W)	6.9 (7.3)	7.4 (7.4)	6.4 (6.6)	6.2 (6.5)
Note	foreshock	main shock	aftershock	aftershock

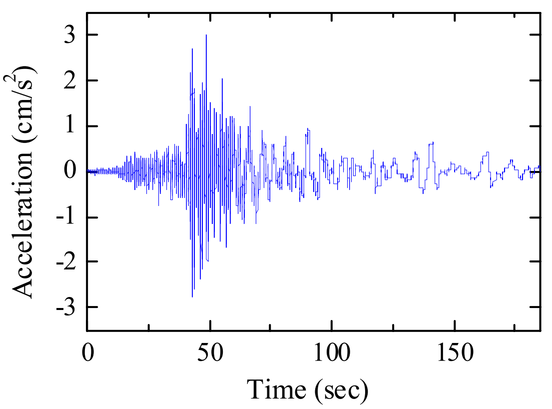


Figure 1 Acceleration time history observed at KiK-net Tokushima during the main shock

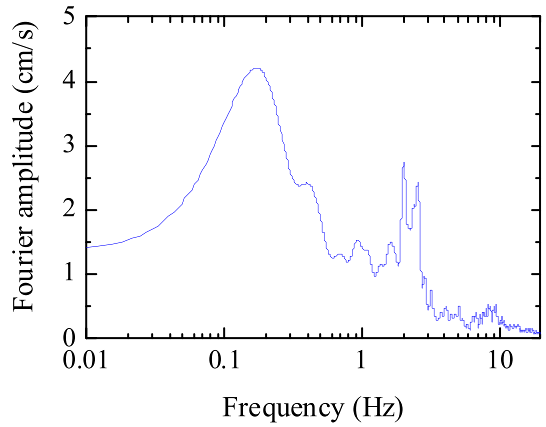


Figure 2 Fourier spectrum of the main shock (KiK-net Tokushima)

2. LONG-PERIOD GROUND MOTIONS OCCURRED AT OFF THE KII PENINSULA

Long-period earthquakes occurred in 2004 off the Kii Peninsula. The first one (M_{JMA} = 6.9) is considered to be a foreshock of the subsequent main shock (M_{JMA} = 7.4) followed by two aftershocks (M_{JMA} = 6.4, 6.2) which occurred in the following few days. The epicenters were located in the Nankai trough neighboring the source region of the 1944 Tonankai earthquake (M_{JMA} = 7.9). Table 1 lists the specifications of the earthquakes. As aforementioned, 2004 earthquakes are intra-plate earthquakes whereas 1944 earthquake was inter-plate one. Ground motions from these earthquakes have been observed at K-NET and KiK-net sites in a wide area of western Japan. Fig. 1 shows an acceleration time history of the main shock observed at 100 m deep at KiK-net Tokushima. The long-period wave train appears after the S-wave train. Fig. 2 shows the acceleration Fourier spectrum of the record. The predominant frequency is approximately estimated as 0.17 Hz which corresponds to a 5 to 6 second period.

KiK-net seismometers within soil are usually instrumented at GL-100m deep in which shear wave velocities range from 730 m/sec to 3500 m/sec. We used the recordings from 76 KiK-net sites for the analysis. Focal distances range from 80 km to 417 km.

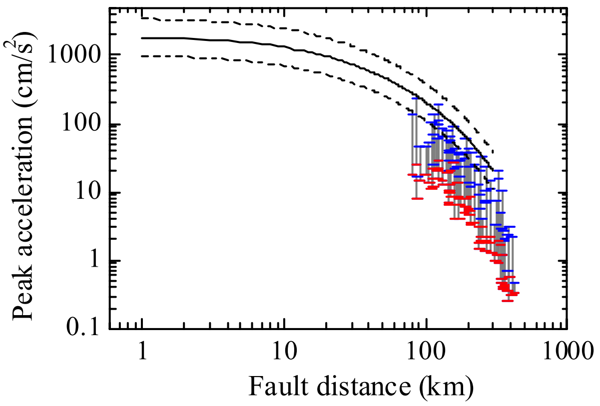


Figure 3 Observed PGAs (main shock) and attenuation relationship

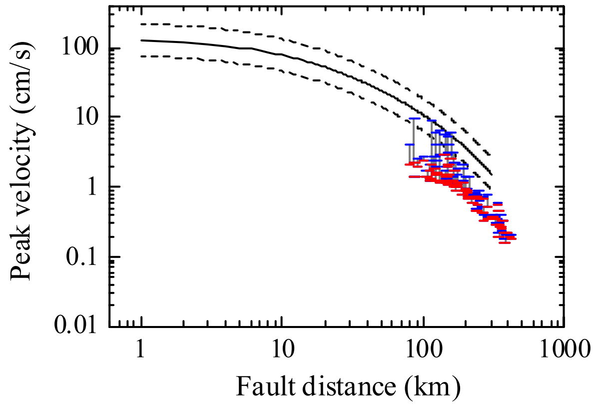


Figure 4 Observed PGVs (main shock) and attenuation relationship

3. ATTENUATION RELATIONSHIP OF GROUND MOTION

3.1 Attenuation Relationship

Si and Midorikawa (1999) developed attenuation relationships as shown in Eqns. 3.1 to 3.3 by regression analyses of recorded strong motion databases developed from data of 21 earthquakes which occurred in Japan from 1968 to 1997.

$$\log A = b - \log(X + c) - kX \tag{3.1}$$

$$b = aM_w + hD + \sum d_i S_i + e + \varepsilon \tag{3.2}$$

$$c = c_1 10^{c_2 M_w} \tag{3.3}$$

where A is peak horizontal ground motion, X is fault distance in km, M_w is moment magnitude, D is focal depth in km, e is constant term, ε is standard deviation, S_i is fault type, and a, h, d_i, c and k are coefficients of regression analyses. We utilized Annaka's (2005) equation for the attenuation relationship for peak displacement.

3.2 Comparison of Observed PGA/PGV with the Attenuation Relationship

The abovementioned attenuation relationship defines PGA on the ground surface and PGV on a stiff ground. Since KiK-net sites are usually located on a stiff ground, we assumed that the PGA/PGV from attenuation comes in between motions at KiK-net surface and at KiK-net within ground. Thus, we showed PGA/PGV of KiK-net by a 2 point segment graph (bar chart).

Figs. 3 and 4 show observed PGAs and PGVs with respect to focal distances, shown together with the attenuation relationships. The observed PGAs/PGVs are lower than the attenuation relationships for long-period ground motions. Fig. 5 compares peak ground displacements. In this case, the observed data and attenuation coincides fairly good. This indicates that long-period components of the ground motions are predominant.

For reference, the PGA from another earthquake (shown in Fig. 6) which has a predominant frequency of approximately 1 Hz in the Shikoku area is compared with the attenuation relationship in Fig. 8. The data shows a good fit with the empirical estimation in this case.

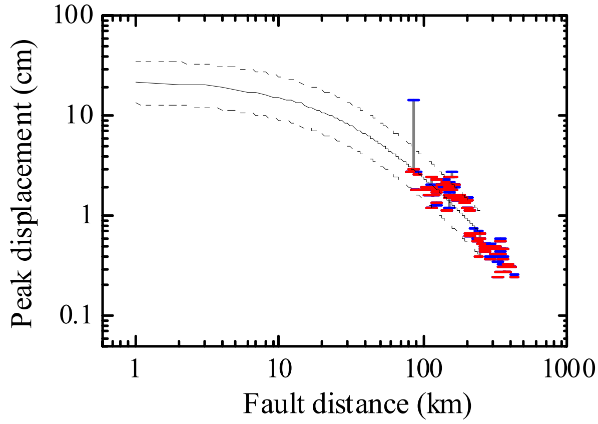


Figure 5 Observed peak ground displacements (main shock) and attenuation relationship

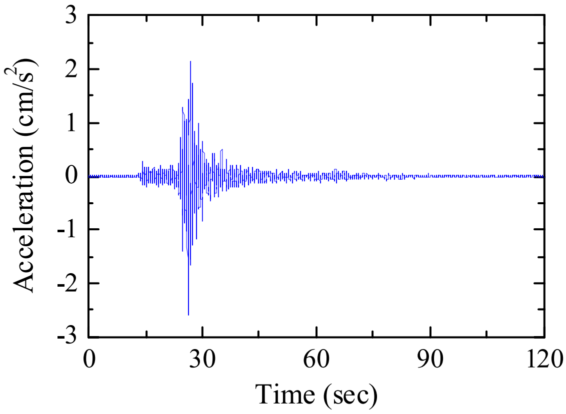


Figure 6 Acceleration time history observed at KiK-net Tokushima during an earthquake occurred at eastern Ehime

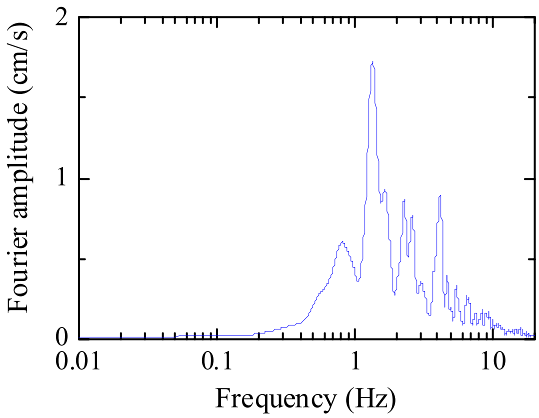


Figure 7 Fourier spectrum of the earthquake at eastern Ehime (KiK-net Tokushima)

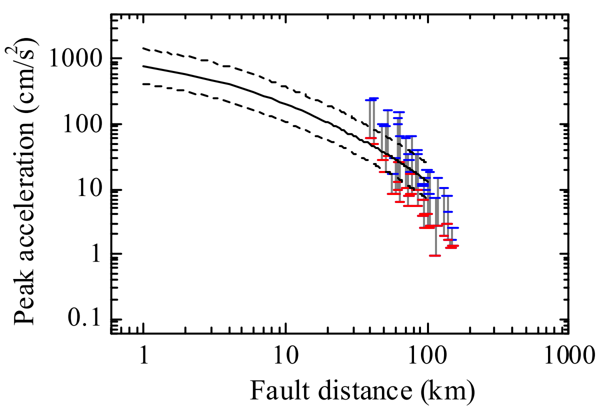


Figure 8 Observed PGAs with attenuation relationship (an earthquake at eastern Ehime)

Thus, we conclude that an attenuation relationship developed based on ground motions of ordinary frequency characteristics may lead to overestimation of PGA/PGV for long-period earthquakes.

4. SITE AMPLIFICATION EFFECT FOR LONG-PERIOD GROUND MOTIONS

4.1 Empirical Expression of Site Amplification

Midorikawa et al. (1994) developed the site amplification equation shown in Eqn. 4.1 by regression analyses of recorded strong motion databases compiled during the 1987 Chibaken-Toho-Oki, Japan earthquake.

$$\log \mathrm{ARV} = 1.83 - 0.66 \log \mathrm{AVS30} \pm 0.16 \qquad (4.1)$$
$$100 < \mathrm{AVS30} < 1500$$

where ARV is an amplification factor of peak velocity and AVS30 is the average shear-wave velocity from ground

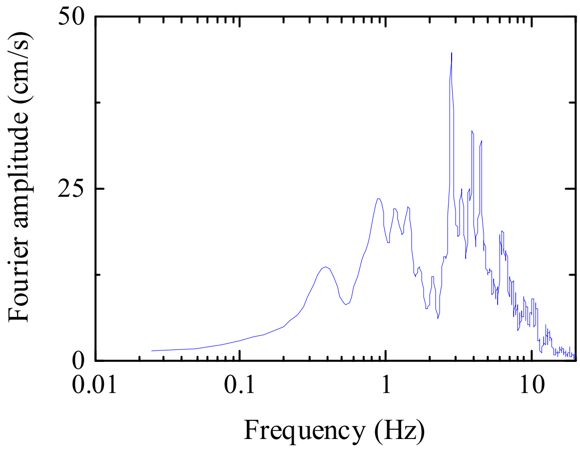


Figure 9 Fourier spectrum of a record observed at GL-40m (Chiba Experimental Station, Inst. Industrial Science, The University of Tokyo) during the 1987 Chibaken Toho-Oki earthquake

surface to a depth of 30 m in m/s.
Fig. 9 shows a Fourier spectrum of an acceleration record observed at GL-40m at the Chiba Experimental Station, Institute of Industrial Science, University of Tokyo during the 1987 Chibaken-Toho-Oki earthquake (Association for Earthquake Disaster Prevention, 1992). The predominant frequency is approximately estimated as 3 Hz which corresponds to a 0.3 to 0.4 second period.

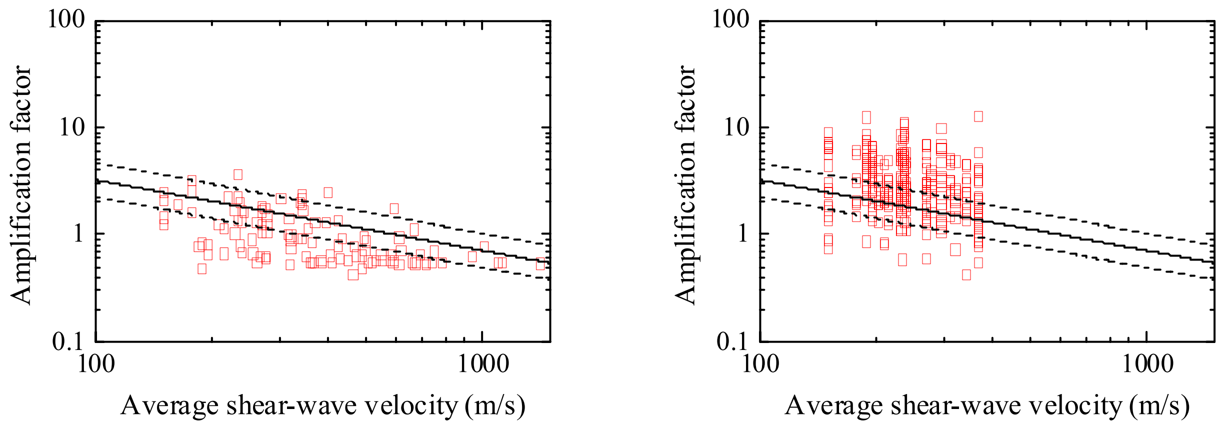
4.2 Comparison of Site Amplification Estimated from Recordings of Different Frequency Characteristics

Seismometers are installed at the surface for K-NET sites, and at both the surface and within the ground for KiK-net sites. The ratio of PGV observed near the surface at K-NET/KiK-net sites to PGV observed at the level of seismic instrumentation within the ground at the nearest KiK-net site is regarded as a site amplification factor in this study. Shear wave velocities of soil at the level of instrumentation within the ground are usually larger than the Vs of the base layer defined by Midoriwaka's equation (Vs = 600 m/sec). Thus, site amplification factors for PGV are modified so that the Vs of the instrumented ground becomes equivalent to 600 m/sec. If the Vs of the instrumented ground is larger than 1500 m/sec, it is assumed as 1500 m/sec referring to a study by Fujimoto and Midorikawa (2003). Results are shown in Fig. 10. Midorikawa's empirical equation is also shown in the Figure as a reference. Comparing (a) with (b), it is clear that long-period ground motions are less amplified compared with other ground motions.

In Table 2, site amplification factors are compared site by site for the 2004 off the Kii Peninsula earthquake (main shock) and two other earthquakes (M_{JMA} = 4.7, 5.3) that occurred during the last three years in western Japan. For every site, amplification factors are approximately 1.0 to 1.5 for the long-period earthquake, however, much larger for the other two earthquakes.

4.3 Comparison Site Amplification between Observed Records and Multi-Reflection Theory

Fig. 11 shows the comparison of site amplification factors from data with the calculated results for both long-period ground motions and other ground motions. Soil density is assumed to be 1.8 t/m^3 and damping ratio 0.05. In both cases, the theoretical results show high correlation with the data. Hence, it is understood that this phenomenon is not a unique one, but can be physically explained.



(a) Records observed during the 2004 off the Kii Peninsula earthquake

(b) Other ground motion records

Figure 10 Site amplification factors for peak velocity

Table 2 Site amplification factors and predominant periods site by site for 2004 off the Kii Peninsula earthquake (main shock) and two other earthquakes

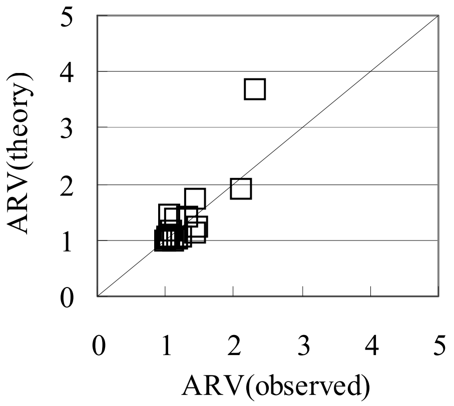
Name	ARV			Predominant period (sec)			AVS30 (m/s)	VS of base layer (m/s)
	2004 Kii Peninsula	2005 M_{JMA} =4.7	2007 M_{JMA} =5.3	2004 Kii Peninsula	2005 M_{JMA} =4.7	2007 M_{JMA} =5.3		
Tanbara	1.063	1.912		5.958	20.480		254	750
Ikata	1.163		2.651	6.302		1.057	267	2780
Ayakami	1.127	2.731		5.851	0.519		255	1287
Mino	1.435	3.162		5.554	0.958		185	1603
Ouchi	1.035	1.101	1.897	5.958	0.900	0.926	407	1760
Suzaki	1.027	1.433	1.968	6.068	0.993	0.592	385	1950
Tosashimizu	0.998	0.857	0.899	5.650	16.384	1.064	608	2050
Geisei	1.327	2.140	1.364	5.554	0.766	1.050	496	1870
Tokushima	1.215	2.041	1.567	5.851	54.613	0.745	475	1880
Kainan	1.462	1.845		5.749	1.018		380	1740

4.4 Relationship between Site Amplification Factors and Predominant Periods

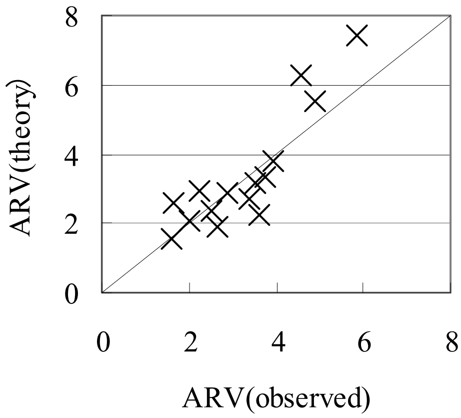
So far, we confirmed that long-period ground motions are less amplified compared with other ground motions, and the phenomenon was confirmed theoretically. However, we still do not clarify the relationships between site amplification and predominant period. Fig. 12 shows the results. In this case, the predominant period was calculated from the Fourier spectrum of velocity. The result indicates that site amplification becomes smaller for longer period ground motions and they are almost linear in relationship.

5. CONCLUDING REMARKS

This paper discussed ground motion attenuation and site amplification using a series of long-period earthquakes that occurred in 2004 near the epicenter of the 1944 Tonankai earthquake (M_{JMA} = 7.9). A comparison of the observed ground motions with attenuation relationships indicates that peak ground accelerations as well as peak



(a) Records observed during the main shock of 2004 off the Kii Peninsula earthquake



(b) Records observed during the 2005 and 2007 earthquakes

Figure 11 Comparisons of site amplification between observed records and multi-reflection theory

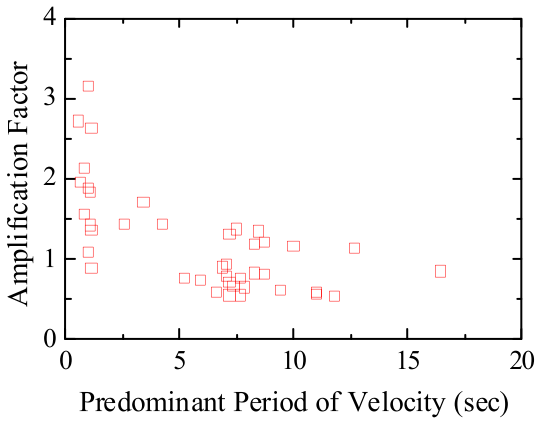


Figure 12 Relationship between site amplification factors and predominant periods

ground velocities of the long-period ground motions became smaller than the estimation by the attenuation equations, whereas peak ground displacements demonstrated good fits with the attenuation relationship.

For the site amplification, the long-period motions were less amplified compared with other earthquakes of ordinary frequency characteristics. The difference of the ground motion amplification due to different frequency characteristics of the ground motions was confirmed by using the one dimensional wave propagation theory.

Relationships between site amplification factors and predominant periods of the ground motion indicated that site amplifications became smaller as periods of ground motion became longer. Results indicate that application of attenuation relationships and site amplification equations developed based on a database of seismic motions of ordinary frequency characteristics may lead to overestimation of long-period ground motions.

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