THE INTERNATIONAL SYMPOSIUM FOR CISMID 25th ANIVERSARY
TECHNOLOGICAL ADVANCES AND LEARNED LESSONS FROM LAST GREAT EARTHQUAKES AND TSUNAMIS IN THE WORLD

Paper No. M-4

CHARACTERISTICS OF STRONG GROUND MOTION FROM THE 2011 GIGANTIC TOHOKU, JAPAN EARTHQUAKE

Saburoh MIDORIKAWA[1], Hiroyuki MIURA[2] and Tomohiro ATSUMI[3]

SUMMARY

The 2011 Tohoku earthquake (Mw9.0) produced many strong motion records, and provides an opportunity to examine the characteristics of strong ground motion from a gigantic earthquake. The ground motion characteristics such as attenuation, spectral shape and duration are analyzed using the observed records of the earthquake. The results are compared with those from the other gigantic earthquakes such as the 2001 Peru (Mw8.4) and the 2010 Chile (Mw8.8) earthquakes. The attenuation and spectral characteristics of the records from the Mw9.0 earthquake are similar to those from the other gigantic earthquakes. The duration of the records from the Mw9.0 earthquake, however, is much longer than that from the other gigantic earthquakes.

INTRODUCTION

The gigantic Mw 9.0 earthquake, the 2011 Off the Pacific Coast of Tohoku earthquake (hereafter the Tohoku earthquake), hit northeastern Japan. To understand the characteristics of strong ground motion from such a gigantic earthquake is of great help in preparing measures to reduce disaster from a similar event in the future. Few examinations have been done for the characteristics of ground motion from gigantic earthquakes, because such gigantic earthquakes rarely occur, .
Many strong motion records were obtained from the Tohoku earthquake. K-NET and KiK-net records by the National Research Institute for Earth Science and Disaster Prevention (NIED) were made available immediately after the earthquake. Records by the other institutions such as the Japan Meteorological Agency (JMA), Ministry of Land, Infrastructure and Transpot (MLIT), Building Reserch Institute (BRI) and Port and Airport Research Institute (PARI) have been also released. These records will provide valuable information to reveal ground motion characteristics of gigantic earthquakes. It will be also necessary to confirm whether the characteristics seen in these records are common to all such gigantic earthquakes. In this paper, we analyse attenuation characteristics of the observed records as well as the spectral shape and the duration, and compare these characteristics with those of records from other gigantic earthquakes.

----
1 Professor, Tokyo Institute of Technology, Yokohama, Japan. Email: smidorik@enveng.titech.ac.jp
2 Assistant Professor, ditto. Email: hmiura@enveng.titech.ac.jp
3 Graduate Student, ditto.

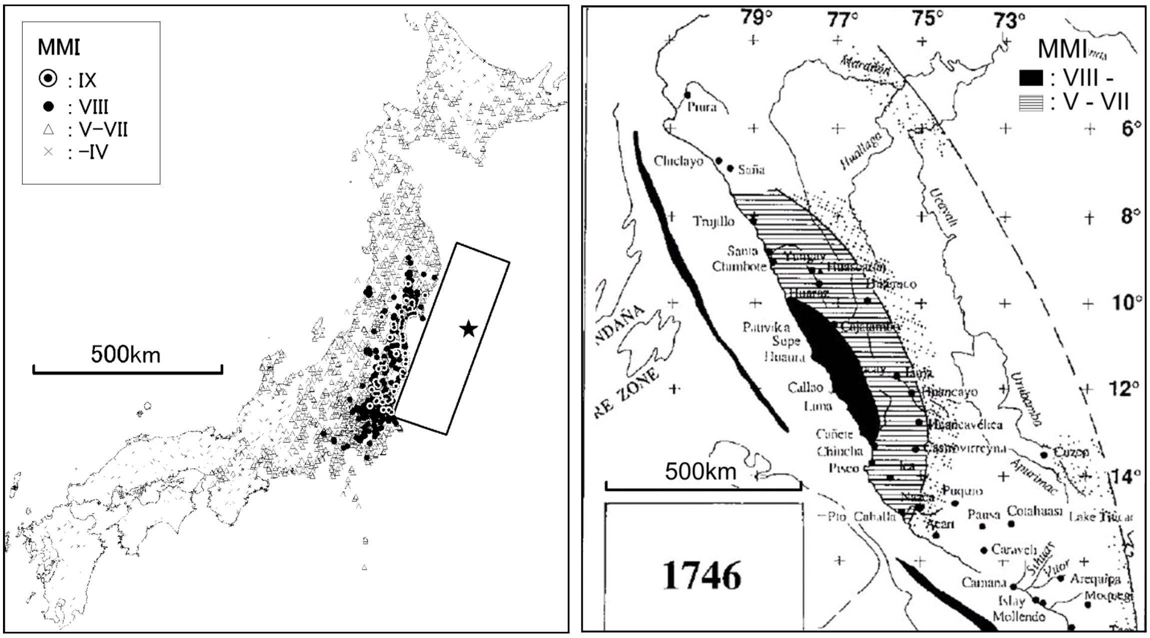
STRONG MOTION RECORDS FROM THE TOHOKU EARTHQUAKE

The Tohoku earthquake has a very large source area, 500 km in length and 150 km in width. As a result, the earthquake caused strong shaking in wide areas, and produced many strong motion records. About 1,200 K-NET and KiK-net records were made available soon after the earthquake [1]. JMA released about 400 records together with about 500 records from the Prefectures-network [2]. About 150 records from the MLIT network have been released [3]. BRI and PARI also released their records [4, 5]. We tentatively collected and compiled the records on ground from these networks. The total number of the compiled records is about 2,400. For soil classification of the strong motion sites, the average shear-wave velocity to 30m depth, V_{s30}, is estimated at all the sites from the PS logging data or geomorphological map.

The left side of Fig. 1 shows the seismic intensity distribution calculated from the strong motion records by using the relationship by Wald et al [6]. The area of the M.M. intensity VIII or greater is approximately 500 km in length. For comparison, the intensity map of the 1746 Peru earthquake of M 8.6 [7] is shown in the right side of the figure. The size of the high intensity area is almost same for both earthquakes, suggesting that both earthquakes have similar character.

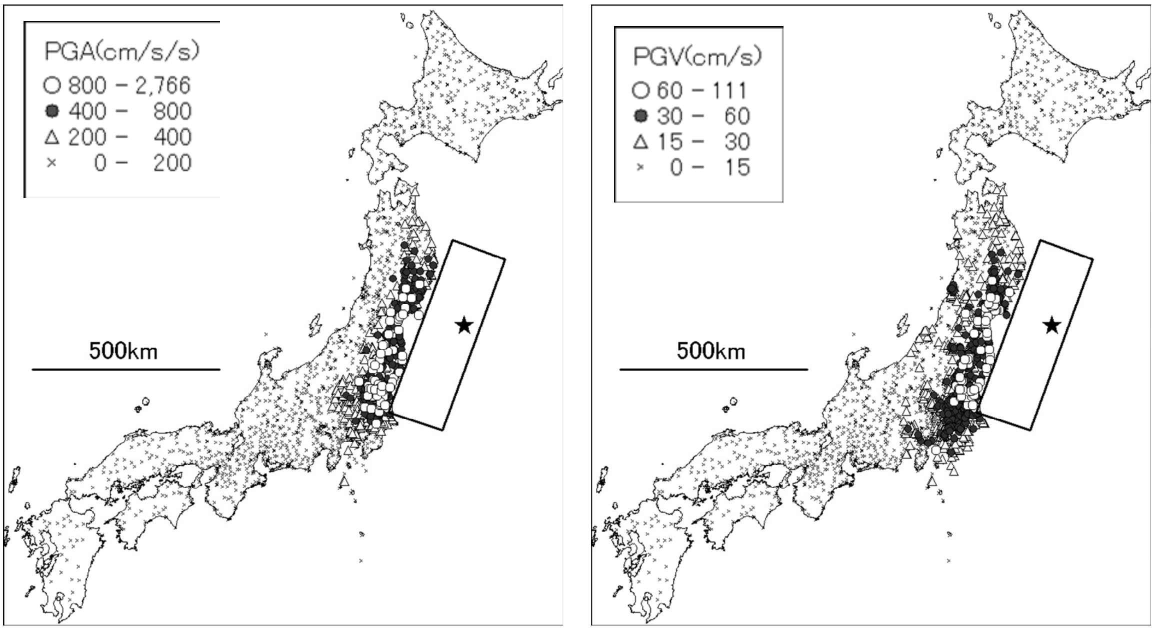
Figures 2 show distributions of peak horizontal acceleration and velocity, respectively. In this study, the larger of the two horizontal components is used. The highest peak acceleration observed is about 2.8 g at K-NET Tsukidate, which may be due to partial uplift of the instrument foundation as discussed by Motosaka and Tsamba [8].

The peak horizontal accelerations higher than 500 cm/s^2 and 1000 cm/s^2 are observed at 210 sites and 34 sites, respectively. Higher accelerations are found in the areas along the central and southern part of the fault plane. The peak horizontal velocities higher than 50 cm/s and 100 cm/s are at 110 sites and 3 sites, respectively. Higher velocities are found not only in the areas along the central and southern part of the fault plane, but also in the Tokyo metropolitan area located south of the fault plane.



(a) The 2011 Tohoku Earthquake (M9.0) (b) The 1746 Peru Earthquake(M8.6) taken from [7]

Figs. 1 Comparison of Seismic Intensity Maps of Two Gigantic Earthquakes



(a) Peak Ground Acceleration (b) Peak Ground Velocity

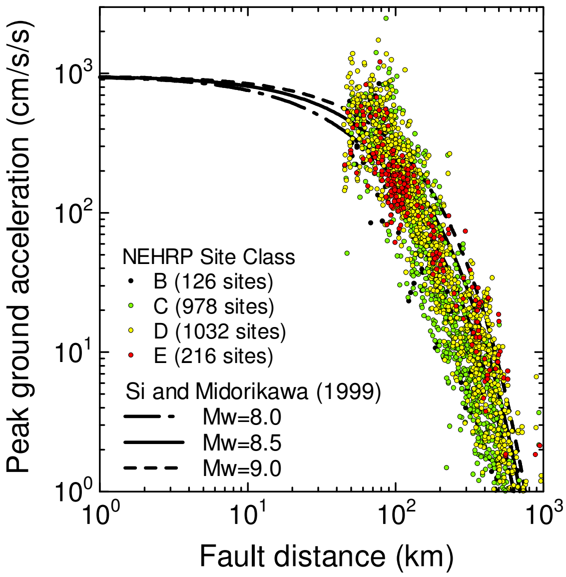
Figs. 2 Peak Ground Acceleration and Velocity of Observed Strong Motion Records

STRONG MOTION CHARACTERISTICS OF THE TOHOKU EARTHQUAKE

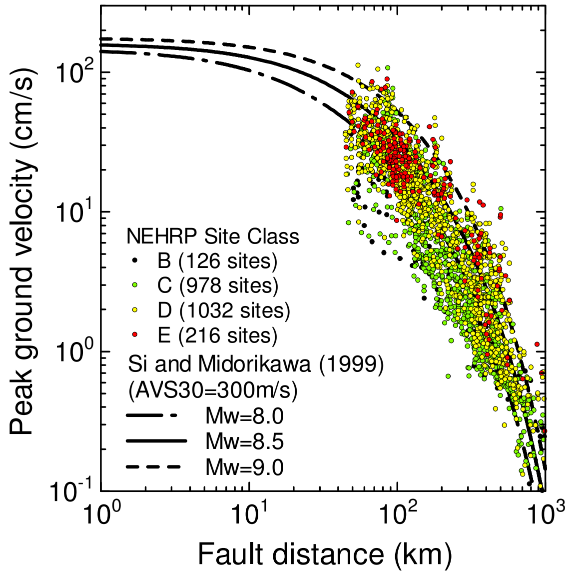
Figures 3 show attenuations of peak horizontal acceleration and velocity, respectively. In the figures, the data are classified into four site classes (NEHRP site class B, C, D and E). NEHRP site classes B, C, D and E correspond to V_{s30} of 760 to 1500 m/s, 360 to 760 m/s, 180 to 360 m/s and less than 180 m/s, respectively. For peak acceleration, some data show high acceleration over 1 g at site classes C, D and E, resulting deviation from majority of the data. Many of these data show spike-like acceleration pulses suggesting effects of cyclic mobility of sandy soils. In general, the data at site classes C, D and E (stiff to soft soil sites) show similar values each other, but rather larger values than those at site class B (rock site). For peak velocity, the data at site class with lower V_{s30} tend to show larger values, indicating stronger site effects.

The figure also shows attenuation curves obtained from an existing attenuation relationship (Si and Midorikawa [9]) for earthquakes with a magnitude of 8.0, 8.5 and 9.0, respectively. The inclination of attenuation of observed data is greater than the attenuation curves, but on the average, it appears to be smaller than the curve for Mw9.0 and be closer to the curve for Mw8.5.

In order to examine the spectral characteristics, two each records were chosen for soft soil sites, stiff soil sites and rock sites. Figure 4 shows the locations of the six sites. The velocity response spectra for the six sites are shown in Fig. 5. The spectra for rock sites are rather flat between the periods of 0.1 and 10 seconds, with comparatively small amplitudes of 20 to 40 cm/s. The spectral shape is similar to those from M8-class earthquakes in the past (Anderson and Quaas [10]). At stiff soil sites, the spectra differ in shape from each other. They do not have especially sharp peaks and their amplitudes are between 50 and 100 cm/s. At soft soil sites, on the other hand, the spectra have notable peaks, with the amplitudes at those peak periods reaching 300 to 400 cm/s. These results indicate that soil characteristics affect amplifications of seismic motion.



(a) Peak Ground Acceleration



(b) Peak Ground Velocity

Figs. 3 Attenuation of Peak Ground Acceleration and Velocity

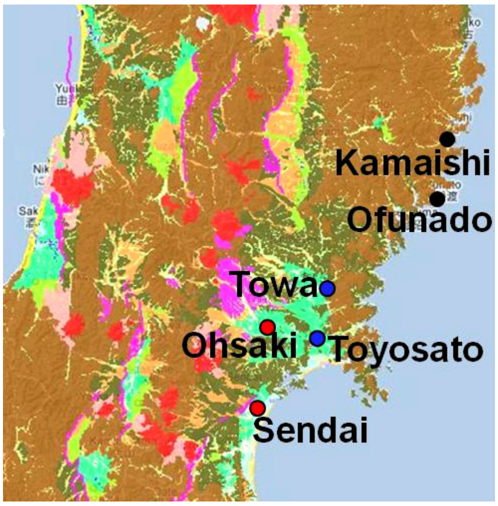


Fig. 4 Locations of Strong Motion Sites with Different Site Conditions

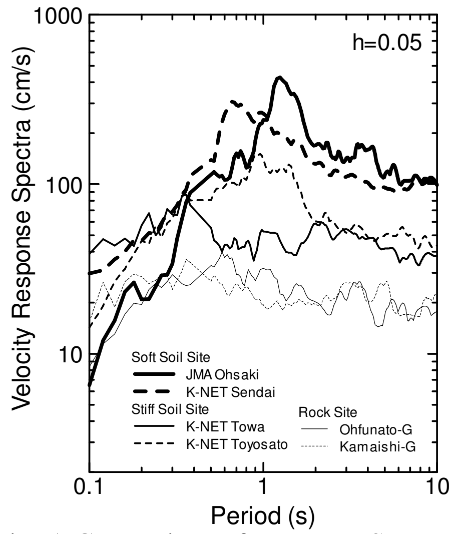


Fig. 5 Comparison of Response Spectra with Different Site Conditions

Figure 6 is for comparison of acceleration time histories at the six sites. Each record shows that large-amplitude ground motion continued for two minutes. The duration appears to be longer at soft soil sites than at rocks. The duration of strong ground motion, calculated as the time interval between 5 percent and 95 percent of the total power of acceleration (Trifunac and Brady, [11]), comes to approximately 120 seconds, 100 seconds and 70 seconds for soft soil, stiff soil and rock sites, respectively, as shown in Fig. 7. The duration is much longer than those in the past records.

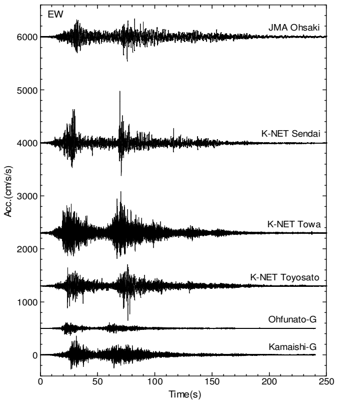


Fig. 6 Comparison of Time Histories

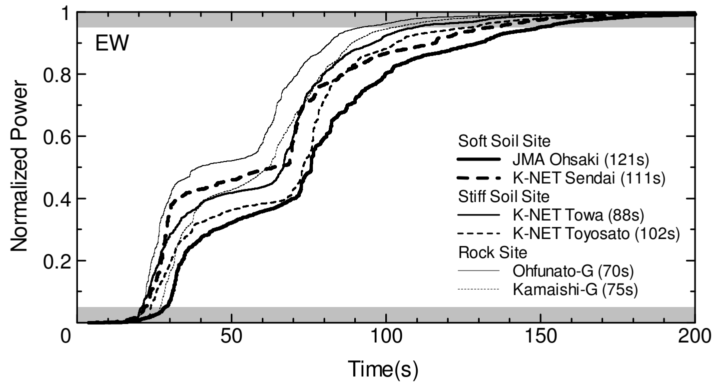
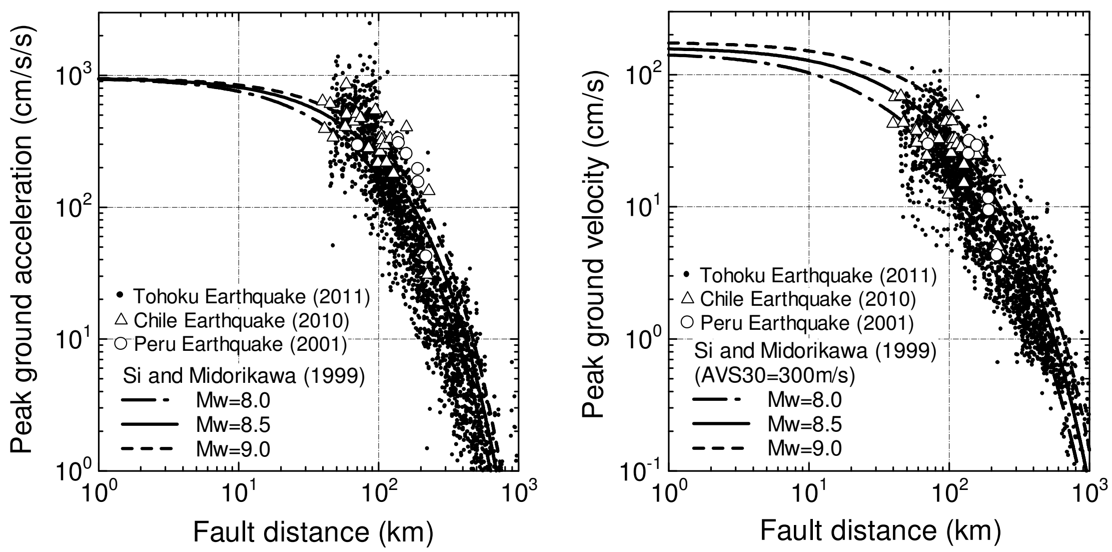


Fig. 7 Comparison of Ground Motion Duration

COMPARISON WITH RECORDS FROM OTHER GIGANTIC EARTHQUAKES

Strong motion records obtained from the Tohoku earthquake is the first ever available from a M-9 event, but there have been records from several gigantic earthquakes with a magnitude of greater than 8.0 in the world. For example, the 2010 Chile earthquake (Mw8.8) produced a considerable number of strong motion records (Boroschek et al. [12]). Records were also available, though limited in number, from the 2001 Peru earthquake (Mw8.4) (Rodriguez-Marek et al. [13]). Open triangles and open circles in Fig. 8 show attenuation of the 2010 Chile and the 2001 Peru earthquakes, respectively. The Chile earthquake's records almost match those of the Tohoku records. Records from the Peru earthquake show rather large accelerations, but considering that the sites were located in the direction of rupture propagation, making amplitudes larger due to directivity effects, the records can also be interpreted as having attenuation characteristics similar to those of the other earthquakes.



(a) Peak Ground Acceleration (b) Peak Ground Velocity

Fig. 8 Comparison of Attenuations between the Tohoku, Chile and Peru Earthquakes

Thus, attenuation characteristics of the Tohoku earthquake generally match those of records from Mw8.4 and Mw8.8 earthquakes. They are also largely in line with the attenuation curve not for Mw9.0, but for Mw8.5 obtained from an existing attenuation relationship. These suggest that attenuation curves begin to saturate when a moment magnitude surpasses 8.

To check the spectral characteristics of ground motions from three earthquakes, comparison of stiff soil records of the three earthquakes are shown in Fig. 9. For the 2010 Chile and 2001 Peru earthquakes, the records at Concepcion San Pedro and at Monquegua were used, respectively. In this figure, the spectral shapes of the three earthquakes show no prominent dominance of long-period components, and are generally similar to one another.

Figure 10 is comparison of acceleration time histories in records at stiff soil sites in these three earthquakes to examine durations, which tend to become longer as the magnitude becomes greater. The durations reflected differences in their magnitudes: close to 40 seconds for the 2001 Peru earthquakes; about 70 seconds for the 2010 Chile earthquake; and approximately 100 seconds in the Tohoku earthquake.

Figure 11 plots relationship between ground motion durations and magnitudes for the records. In this figure, the data from the 2003 Tokachi-oki, Japan earthquake (Mw8.3) are also plotted. It can be seen that duration is around 40 seconds for M8.4, and comes close to 100 seconds for M9. This confirms that duration becomes longer as magnitude becomes greater. Also shown in the figure is an empirical relationship between duration and magnitude obtained from earthquakes in California, with magnitudes of up to 7.6 (Dobry et al. [14]). The duration of a magnitude-5 quake is 2 seconds, compared with some 25 seconds for an earthquake with a magnitude of 7.5. The results from the analysis thus fall largely in line with an extension of the relationship by Dobry et al.[14], and the logarithm of duration and magnitude appear to be generally in a linear relationship across a broad range of magnitudes.

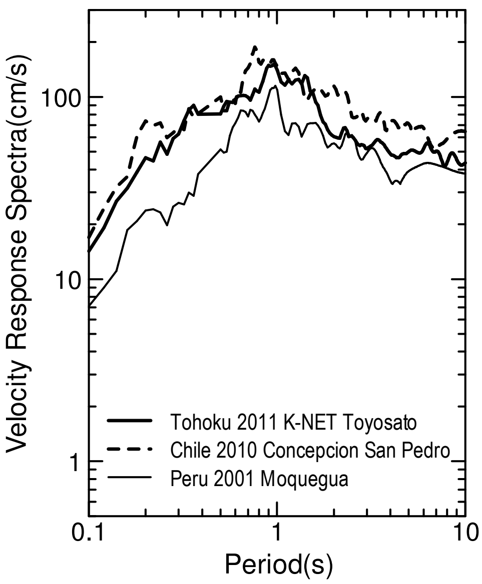


Fig. 9 Comparison of Response Spectra at Stiff Soil Sites from Three Earthquakes

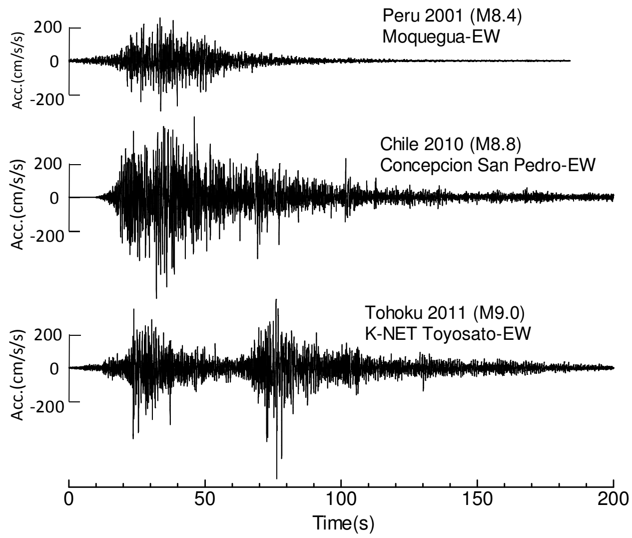


Fig. 10 Comparison of Time Hitories of Records from Three Earthquakes

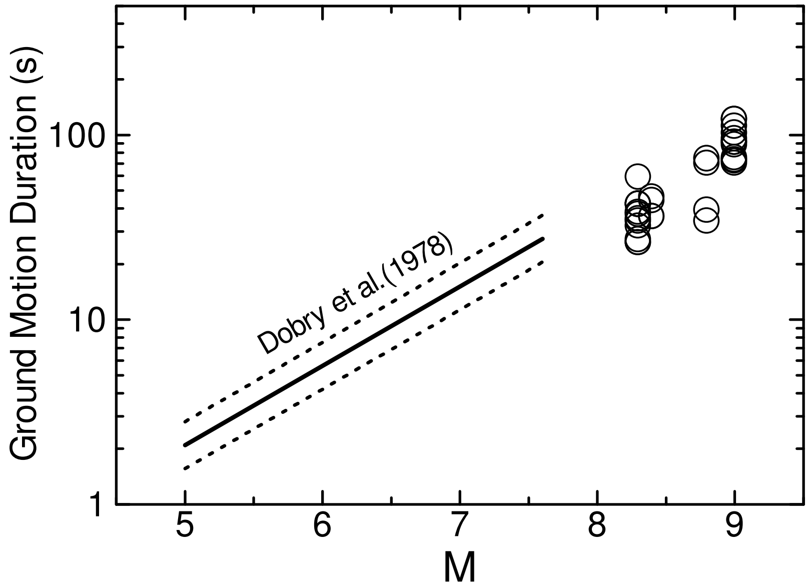


Fig. 11 Relationship between Ground Motion Duration and Earthquake Magnitude

CONCLUSIONS

Strong ground motion characteristics of gigantic earthquakes are examined by analysing the records from the 2011 Tohoku earthquake (Mw9.0) for its attenuation characteristics, spectral characteristics and duration and by comparing them with strong motion records from other gigantic earthquakes in Chile and Peru (Mw8.4 to 8.8). The examinations have found that attenuation characteristics and spectral characteristics of ground motions over a period range of up to 10 seconds were much the same for the Tohoku earthquake (Mw9.0) and the other events (Mw8.4 to 8.8). It has been also pointed out that duration, by contrast, tends to become longer as magnitude becomes greater even after it exceeds 8. Strong motion records from the Tohoku earthquake show that duration reached approximately 100 seconds. The logarithm of duration and magnitude are largely in linear relationship over a broad range of magnitudes.

ACKNOWLEDGEMENTS

Strong motion records used in this study are provided from NIED, JMA, MLIT, PARI, BRI, University of Chile, and Japan-Peru Center for Earthquake Engineering Research and Disaster Mitigation. Part of this research has been conducted in the SATREPS project “Enhancement of earthquake and tsunami disaster mitigation technology in Peru” (Principal Investigator: F. Yamazaki, Chiba University), the Global COE program of the MEXT, entitled “International Urban Earthquake Engineering Center for Mitigating Seismic Mega Risk” (Program leader: K. Tokimatsu, Tokyo Tech.) and the Grant-in-Aid for Scientific Research No. 23241054 from the MEXT, entitled “Construction of Next-Generation Ground Motion Prediction Equation” (Program leader: K. Koketsu, University of Tokyo).

REFERENCES

1. NIED, http://www.kyoshin.bosai.go.jp/index_en.html, 2011.
2. Japan Meteorological Business Support Center, *Acceleration Time History Data 2011 DVD*, 2012.
3. MLIT, http://www.nilim.go.jp/lab/rdg/index.htm, 2011.
4. PARI, http://www.mlit.go.jp/kowan/kyosin/eq.htm, 2011.
5. BRI, http://smo.kenken.go.jp/smdb, 2011.
6. Wald, D. J. et al., "Relationships between Peak Ground Acceleration, Peak Ground Velocity, and Modified Mercalli Intensity in California," *Earthquake Spectra*, **15**, 557-564, 1999.
7. Dorbath, L. et al., "Assessment of the Size of Large and Great Historical Earthquakes in Peru," *Bull. Seism. Soc. Am.*, **80**, 551-576, 1990.
8. Motosaka, M. and Tsamba, T., "Investigation of High Acceleration Records at K-NET Tsukidate Station During the 2011 Off the Pacific Coast of Tohoku Earthquake," *Proceedings of the 8th Annual Meeting of Japan Association for Earthquake Engineering*, 24-25, 2011.
9. Si, H. and Midorikawa, S., "New Attenuation Relationships for Peak Ground Acceleration and Velocity Considering Effects of Fault Type and Site Condition," *Journal of Structural and Construction Engineering, A.I.J.*, 523, 63-70, 1999 (in Japanese).
10. Anderson, J.G. and Quaas, R., "The Mexico earthquake of September 19, 1985 – Effects of magnitude on the characteristics of strong ground motion: An example from the Gerrero, Mexico strong motion network," *Earthquake Spectra*, **4**, 635-646, 1988.
11. Trifunac, M.D. and Brady, A. G., "A Study on the Duration of Strong Earthquake Ground Motion," *Bull. Seism. Soc. Am.*, **65**, 581-626, 1975.
12. Boroschek, R. et al., *Maule Region Earthquake February 27, 2010 Mw=8.8,* INFORME RENADIC 10/05 Rev. 2, University of Chile, 2010.
13. Rodriguez-Marek, A. et al.. "Engineering analysis of ground motion records from the 2001 Mw8.4 Southern Peru earthquake," *Earthquake Spectra*, **26**, 499-524, 2010.
14. Dobry, R. et al., "Duration characteristics of horizontal components of strong motion earthquake records," *Bull. Seism. Soc. Am.*, **68**, 1487-1520, 1978.