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NOTES AND CORRESPONDENCE

Strong Ground Motions Generated by the February 11, 2014 Tatunshan Earthquake in the Taipei Metropolitan Area

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ABSTRACT

Strong-motion seismograms from the 11 February, 2014 Tatunshan earthquake were recorded at stations around the source area. These recordings were used to analyze the strong-motion characteristics in the area. The largest peak ground acceleration (PGA) values of 100.7, 93.4, and 66.6 cm sec^{-2} in the vertical, EW, and NS directions, respectively, were recorded at station TAP056, about 4.9 km to the northwest of the epicenter. The PGA decays fast with distance, indicating high attenuation in the Tatun volcanic area. The PGA ratio of vertical to horizontal ground motions decreases with increasing epicenter distance. The PGA values in the EW component are larger than those in the NS component. This might be associated with the focal mechanism of the earthquake. The spectral accelerations decrease rapidly with increasing period.

Key words: Strong-motion data, Spectra, Tatun volcano group

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1. INTRODUCTION

On 12 February, 2014 at 00:31 a.m. local time (16:31 11 February UTC), a M 4.0 earthquake occurred beneath the Tatun Volcano Group (TVG). It shook the Taipei Metropolitan Area (TMA) and caused minor damage to a water storage tank on the roof of a two-story building at the Pingdeng Elementary School. This earthquake was felt over a wide area in northern Taiwan. The largest Central Weather Bureau (CWB) intensity IV was observed in Taipei City with CWB intensity III in New Taipei City and Taoyuan County. The epicenter was located in the Shihlin District of Taipei City with a focal depth of 6.3 km (Fig. 1). The focal mechanism of this event is considered to be strike-slip faulting with a strike of 39°, a dip of 70°, and a rake of 3° (RMT 2014), which was inversed from a real-time moment tensor monitoring system (Lee et al. 2014). The largest peak ground accelerations (PGAs) were 100.7, 93.4, and 66.6 cm sec^{-2} in the vertical, EW, and NS directions, respectively. This was the largest earthquake in the TVG area since 1988.

The TMA, which is located on the Taipei Basin, is the political, economic and cultural center of Taiwan. Although seismicity, especially for moderate and large earthquakes, is usually lower in this area than other areas in Taiwan, numerous earthquakes occurred near the area (Hsu 1961; Hsu 1983a, b). Historical data shows that a large earthquake occurred in the area in 1694 resulting in an earthquake-induced lake and the destruction of numerous aboriginal houses. Hsu (1983b) evaluated the magnitude of this event as M 7. On April 15, 1909, an M 7.3 earthquake took place at a depth of about 80 km beneath the area (Wang et al. 2011). Casualties from this event included 9 dead, 51 injuries, 122 houses collapsed and 1054 houses damaged (Hsu 1961). On July 3, 1988, a M 5.3 occurred at Yangmingshan (25.16°N, 121.57°E), with a depth of 5 km beneath the TVG. This event caused 16 injuries. Kim et al. (2005) suggested that shallow seismicity in the TVG might result from subsurface hydrothermal or volcano-related activities.

Except for July 3, 1988 M 5.3 earthquake, seismicity

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in the TMA was low (Wang et al. 2006, 2012a, b). In 2005 three felt earthquakes (M_L = 3.8, 3.2, and 3.7) occurred near the eastern part of the basin, about 3 km to the south of Taipei 101, the tallest building in the world. Lin (2005) suggested that the felt earthquakes were triggered by the load of the massive skyscraper (Taipei 101) and an active blind normal fault was located just beneath the building. From the seismicity pattern and focal mechanisms of the three felt events, Chen et al. (2010) suggested the existence of a blind normal fault, whose surface project is along the river channel in the middle of the basin.

In the TMA, pre-1970 large distant earthquakes did not cause remarkable damage (Chen and Wang 1988; Wang 1998; Shin and Teng 2001; Chen 2003). Observations show that the predominant frequencies of seismic wave in the Taipei Basin generated by distant earthquakes are 0.5 - 1.0 Hz (Chen 2003). This would result in large damage to buildings with 10 - 20 floors. Before 1970, only buildings with few floors, usually less than 4, existed in the Taipei City area and, thus, the damage was small. Since 1970 a large number of high-rise buildings with 10 - 20 floors or more have been constructed. Earthquake-induced damage has thus increased due to an increase in the population, even though the quality of building construction has been substantially upgraded. A rapid transportation system has been in operation and two nuclear power plants located in the vicinity of the area have been operated for a long time. Hence, much attention to seismic risk mitigation must be paid to this area.

To investigate strong earthquake ground motions it is necessary to first analyze the ground motion characteristics and site effects. Several authors (Wen et al. 1995a, b; Wen and Peng 1998; Sokolov et al. 2000, 2001; Sokolov and Jean 2002; Chen 2003; Fletcher and Wen 2005) did such studies in TMA. Wen and Peng (1998) showed that the spatial distribution of site amplifications depends on the incidence direction of waves into the Taipei Basin. They also stressed that two areas (one in east Taipei and the other in northwest Taipei) with high site amplifications at a low-frequency regime (0.2 - 1 Hz) are associated with the shape of the Tertiary basement and the top soft soils in the Sungshan formation. For a higher frequency band (1 - 3 Hz), the amplifications occur at places near the north, east and south basin edges. Examples that show the spatial distributions of vertical-component PGA generated from the 1999 Chi-Chi and 2003 offshore Hualien earthquakes will be given below. The above-mentioned differences can also be seen in those examples. Wang et al. (2004) reported that larger PGA is associated with lower S-wave velocity. For the M_w 7 Hualien offshore earthquake of 31 March 2002, which was about 110 km far away from Taipei, Chen (2003) observed that the PGA values in the Taipei Basin varied within a factor of 5. He suggested that the high PGA in the southeastern part

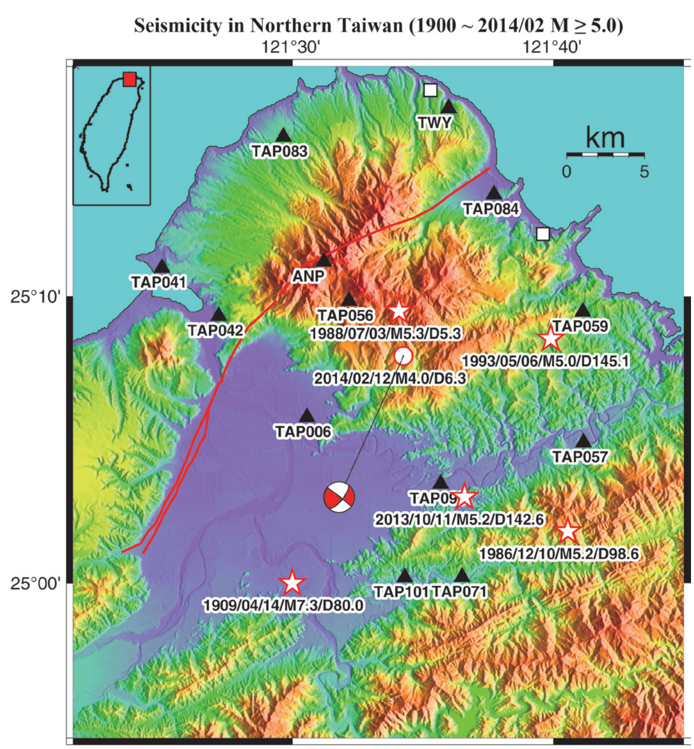

Fig. 1. Epicenter and focal mechanism of the 11 February 2014, Tatunshan earthquake (denoted by a circle). Also shown is seismicity of M ≥ 5 earthquakes in northern Taiwan during the period from 1900 to February 2014. (triangle for station used in this study; square for the location of nuclear power plant; and solid line showing the surface trace of active fault in the area).

of the basin can be interpreted as the PmP, SmP, and SmS phases, which are reflected from the Moho and amplified by soft sediments.

Lee et al. (2001) classified the 708 free-field strong-motion station sites in Taiwan from surficial geology on the basis of US's criteria. However, from the well-logging data, it is necessary to re-classify numerous sites. In the Taipei Basin, 13 station sites must be re-classified (Huang et al. 2009). Huang et al. (2009) also evaluated the frequency-dependent site amplifications at higher frequencies in the TMA. Results show that V_{30}, which is the average S-wave velocity in the topmost 30 m, is a significant factor in classifying the station sites, and the amplifications at all sites in study are larger than 1 and a function of frequency.

In this study, we examine the strong-motion seismograms of the 11 February, 2014 Tatunshan earthquake recorded at the stations around the source area. The PGAs and response spectra are statistically analyzed to investigate the characteristics of strong motions in the TMA, especially in the volcanic area.

2. GEOLOGICAL SETTING

The Taipei Basin is characterized with sedimentary layers (Wang-Lee and Lin 1987; CGS 1999; Wang et al. 2004). In the basin, Quaternary sediments lie on a Tertiary basement. The Quaternary sediments are composed of three formations, i.e., the Sungshan, Chingmei and Hsinchuang formations from top to bottom. Teng et al. (1994) divided the Hsinchuang formation into two, i.e., the Wuku and Banchiao formations. The topmost part of the Sungshan formation is a soft layer, composed of unconsolidated sand, silt and clay with a thickness varying from 50 m in the southeast to 120 m in northwest. The lower part of the formation is dominated by silt. The Chingmei formation is full of gravels. The Hsinchuang formation is composed of sand and silt. Wang et al. (2004) observed that the three layers of the Sungshan formation are specified with low V_s, i.e., 170, 230, and 340 m s^{-1}, respectively. The V_s values in the Chingmei, Wuku and Banchiao formations are, respectively, 450, 600, and, 880 m s^{-1}. The value of V_s of the Tertiary basement is about 1500 m s^{-1}.

Since the Piocene to the Pleistocene two main reverse faults have developed along the western boundary of the Western Foothills in the Taipei basin (Ho 1986). From NW to SE the two faults are the Hsinchuang fault and the Kangjiao fault, both trending in the NE - SW direction (Fig. 1). A segment of the Hsinchuang fault has been re-activated as a normal fault and is called the Sanchiao fault (Fig. 1). From the epicentral distributions, several authors (Tsai et al. 1973; Wang et al. 1983, 2006; Wang 1988; Chen and Yeh 1991; Chen et al. 1995; Chen et al. 2005; Kim et al. 2005; Konstantinou et al. 2007) showed lower seismicity in the TMA than other areas in northern Taiwan and a low correlation between seismicity and the recognized faults.

The Quaternary arc volcanism of TVG and several offshore volcanic islets are the volcanic arcs associated with Philippine Sea plate subduction beneath the Eurasian plate (Tsai et al. 1981; Suppe 1984). Lava flows with minor pyroclastic rocks are dominant in the TVG. Song et al. (2000) proposed a volcanic evolution model to interpret the characteristic features of regional volcanism in the TVG. Their model suggests that eruptions in the TVG commenced at about 2.8 - 2.5 Ma in a compressional tectonic environment during the accretion and oblique collision between the Luzon arc and the China continental margin. Volcanism was not significant for a long time period between 2.5 - 0.8 Ma. Northern Taiwan has experienced changes in the stress environment at about 0.8 Ma due to the opening of the Okinawa Trough or the post-collision extensional collapse. A large amount of andesitic lava erupted to form large volcanoes between 0.8 - 0.2 Ma. Currently, widely distributed hydrothermal activities and gas fumaroles and frequently observed clustered small magnitude earthquakes suggest that volcanic activity in the TVG may have persisted continuously since the last eruption at 0.2 Ma.

3. INSTRUMENTATION AND ACCELEROGRAMS

Since 1991, an island-wide strong-motion seismic array (known as the Taiwan Strong Motion Instrumentation Program, TSMIP) with more 600 stations in Taiwan has been operated by the CWB (Shin 1993; Kuo et al. 1995). Each station is equipped with a three-component, force-balance accelerometer with at least 16-bit resolution and a 96-db dynamic range (Shin 1993). The full scale of the recording system is 2g, and the sample rate is 200 samples per sec. The instrument response of each station is almost flat from DC to 50 Hz. Each recording system is operated in the trigger mode with a 20-sec pre-event memory.

The station density, including free-field and building stations, of TSMIP is high in the TMA. High-quality digital seismic data recorded by the array are available for seismological research and earthquake engineering applications. There are 135 strong-motion stations inside and around the TMA. For the purpose of comparison, the accelerograms recorded at 13 stations are taken into account. The station locations and station names are shown in Fig. 1. Also shown is seismicity of $M \geq 5$ earthquakes in northern Taiwan occurred during the period from 1900 to February 2014.

Figure 2 shows the three-component accelerograms for the 11 February 2014, Tatunshan earthquake recorded at four stations around the source area. The P-wave arrivals can be clearly indentified from the vertical component, while the S-wave arrivals can be indentified from two horizontal components. It is clear that the relatively low-frequency content of accelerogram recorded at TAP006 which is located at the unconsolidated sediments in the Taipei basin (Fig. 1). At TAP006, the site with soft sediments, the high-frequency signals attenuated strongly, and thus the ground motions are dominated by low-frequency waves. The total seismic wave duration was very short because the earthquake is quite small. However, the PGA values are very significant around the source area. The largest PGA values recorded at TAP056, which is about 4.9 km to the northwest the epicenter, are 100.7, 93.4, and 66.6 cm sec^{-2} in the vertical, EW and NS directions, respectively. Note that at this station the PGA value is larger on the vertical component than on the two horizontal components. For most stations, the PGA is larger on the EW component than on the NS component.

4. STRONG MOTION ANALYSIS

4.1 Analysis of Peak Ground Accelerations

The 11 February, 2014 Tatunshan earthquake was felt over a wide area in northern Taiwan. Figure 3 shows the contour maps of PGA in the vertical, EW and NS directions. It is obvious that the most intense shaking area appeared in the TVG. The PGA spatial distribution patterns for the EW and NS components are broader than those for the vertical component. This observation reveals that the PGA is larger for the two horizontal components than for vertical component and attenuates faster for the vertical component than for the others. The PGA decreases dramatically from about 100 cm sec^{-2} at the source area to about 5 cm sec^{-2} at the epicenter distance of 15 km, suggesting relatively weak ground motions in the TMA.

A plot of PGA versus hypocentral distance for the EW and NS components is shown in Fig. 4. Also shown is the ground-motion attenuation curve for an M_w 3.95 earthquake based on an attenuation law suggested by Lin and Lee (2008). The PGA decreases rapidly with increasing hypocentral distance. The PGA is slightly higher for the EW component than for the NS component. All PGA values are below the estimated attenuation curve, suggesting high seismic attenuation in the TMA.

Figure 5 shows the PGA spatial distribution ratio in the EW component over that in the NS component. The largest PGA ratio is about 3.3 at the highest station, at 826 m above sea level, in the TVG. Since the PGA is a measure of acceleration caused by an earthquake on the ground surface,

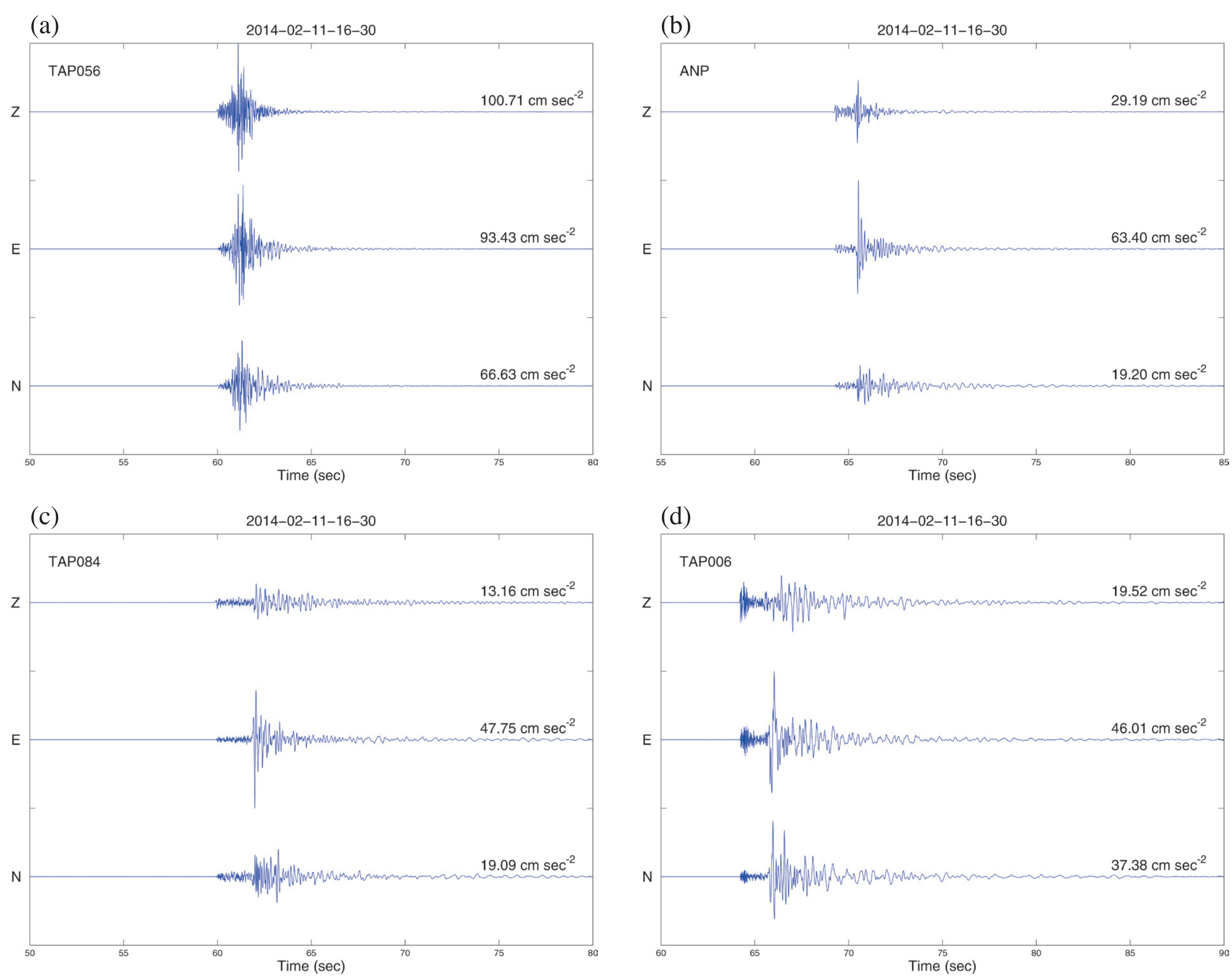

Fig. 2. Three-component accelerograms of the 11 February 2014, Tatunshan earthquake recorded at stations around the source area (a, b) and at the unconsolidated sediments (c, d).

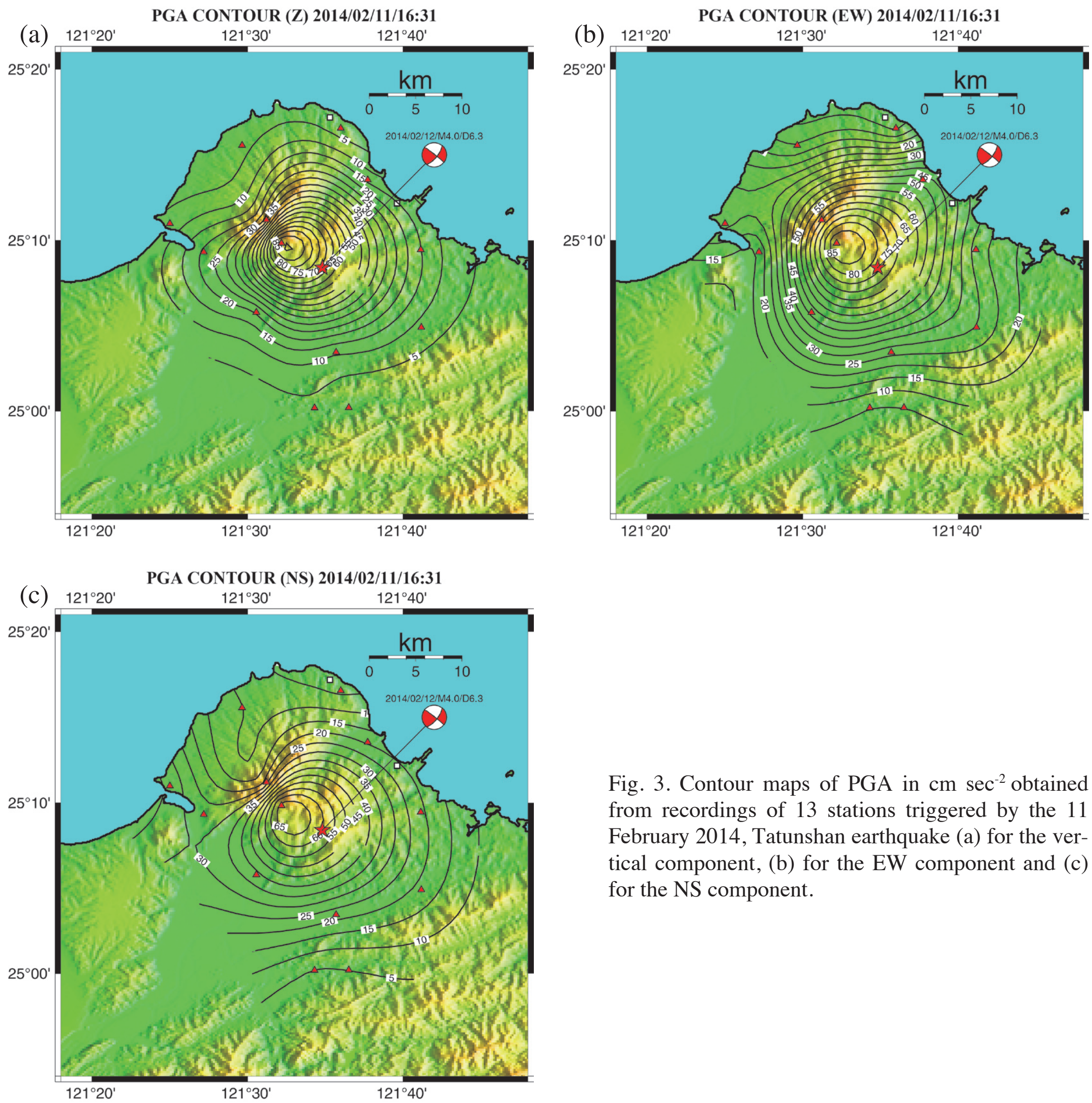

Fig. 3. Contour maps of PGA in cm sec^{-2} obtained from recordings of 13 stations triggered by the 11 February 2014, Tatunshan earthquake (a) for the vertical component, (b) for the EW component and (c) for the NS component.

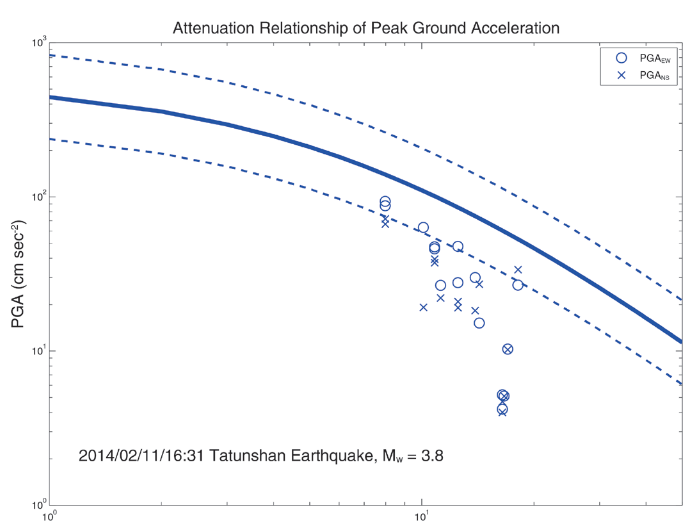

Fig. 4. A plot of the PGA values for the EW and NS components with respect to the hypocentral distance. Also shown is the ground-motion attenuation curve (in a solid line) and those with one standard deviation (in the dashed lines) for an M$_w$ 3.95 earthquake (Lin and Lee 2008).

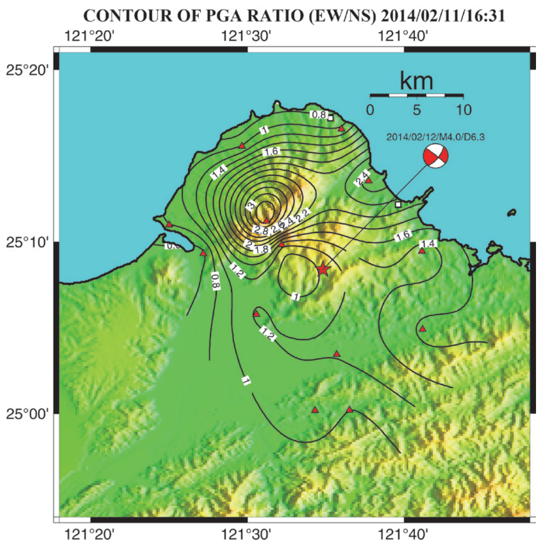

Fig. 5. Spatial distribution of the PGA ratio of EW component to NS component ground motions.

the acceleration, in physics, directly corresponds to the force exerted on the site, thus first speeds up it and then changes its position. Most the PGA ratios are larger than 1 except for two stations (TAP041 and TAP042) in the westernmost area, implying that the ground-shaking force is larger in the EW component than in the NS component. This observation might be associated with the focal mechanism of the Tatunshan earthquake. Wen (2002) reported similar observations from the 1999 Chi-Chi earthquake, that is, the ground motions on the EW component were slightly greater than those on the NS component due to the spatial distribution of displacements caused by thrust faulting of the Chelungpu fault.

The PGA ratio of vertical to horizontal component is taken to investigate the characteristics of near-source ground motions (see Fig. 6). The horizontal PGA is just the geometric mean of those in the two horizontal components. Most PGA ratios are smaller than 1.0, indicating that the PGA values are generally weaker on the vertical component than the horizontal. The PGA ratio is much larger near the source area and the ratio can reach 1.26 at the station close to the source, while the PGA ratio is relatively small at the sites far away from the source.

4.2 Analysis of Response Spectra

In order to investigate the frequency content for the strong motions generated by the Tatunshan earthquake, the 5%-damped response spectral accelerations with periods of 0.2 and 1 sec are calculated from the accelerograms recorded at each station. The horizontal response spectra are calculated from the geometric mean of the response spectral amplitudes of two horizontal components. Figure 7 shows the contour maps of vertical and horizontal response spectra, respectively. Obviously, the spectral accelerations are lower in the vertical component (Figs. 7a and c) than in the horizontal component (Figs. 7b and d). This suggests that the ground shaking is exerted by larger forces in the horizontal direction than in the vertical direction. At the period of 0.2 sec (Figs. 7a and b), the maximum vertical spectral accelerations are mainly distributed in the Taipei basin, while the maximum horizontal spectral accelerations mainly concentrated near the source area. At the period of 1 sec (Figs. 7c and d), both the maximum vertical and horizontal spectral accelerations appear in the Taipei basin. The maximum vertical spectral acceleration at the period of 0.2 sec is about 15 times larger than that at the period of 1.0 sec. The horizontal spectral accelerations at the period of 0.2 sec can be as high as 100 cm sec^{-2} near the source area, while the maximum spectral acceleration is only 10 cm sec^{-2} at the period of 1.0 sec. Comparison of spectral accelerations between the period of 0.2 sec and those at 1.0 sec suggests that the spectral accelerations decrease rapidly with increasing period.

5. DISCUSSION

The strong motions generated by the 11 February, 2014 Tatunshan earthquake recorded at the stations around the source area provide high-quality seismic data for a comprehensive study of TMA ground motion characteristics, especially for the TVG. The duration of strong ground shaking during an earthquake is one of the key factors influencing the degree of damage to structures. Although the PGA values are very significant in the source area, the short duration of strong ground motions (Fig. 2) and the high seismic attenuation in the TVG (Figs. 3 and 4) only resulted in minor structural damage in the TMA.

The PGA decreases rapidly with increasing hypocentral distance and is below the estimated attenuation curve as shown in Fig. 3. However, the anomalously high PGA values appeared at station TAP041, which is located about 17 km to the western most of the epicenter. The site condition at TAP041 has been classified as class D (Lee et al. 2001; Lin and Lee 2008). The anomalously high PGA values at this station might be resulted from the amplification effect due to soils at the site. Nevertheless, further study is necessary to investigate the real reasons to cause anomalously high PGA values at this site.

The anomalously high PGA value has long been recorded at TAP056 since the installation of TAP056 and ANP in the TVG in 1992 (Wen et al. 1998). The two stations are about 3 km apart and located on the same geologic classification. Wen et al. (2008) reported that the PGA ratios between the two stations can be as high as 13.59, 27.66, and 19.20 in the vertical, EW, and NS directions, respectively. From the extensive seismic refraction survey results, Wen et al. (2008) suggested that the effects caused by local backfill or top soft soils controlled the local site amplification at

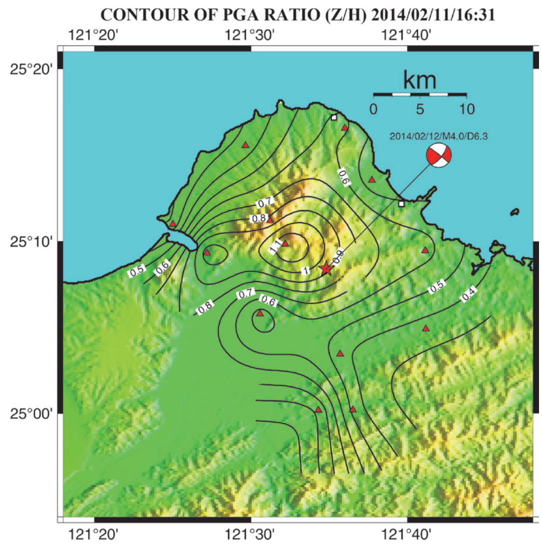

Fig. 6. Spatial distribution of the PGA ratio of vertical to horizontal component ground motions.

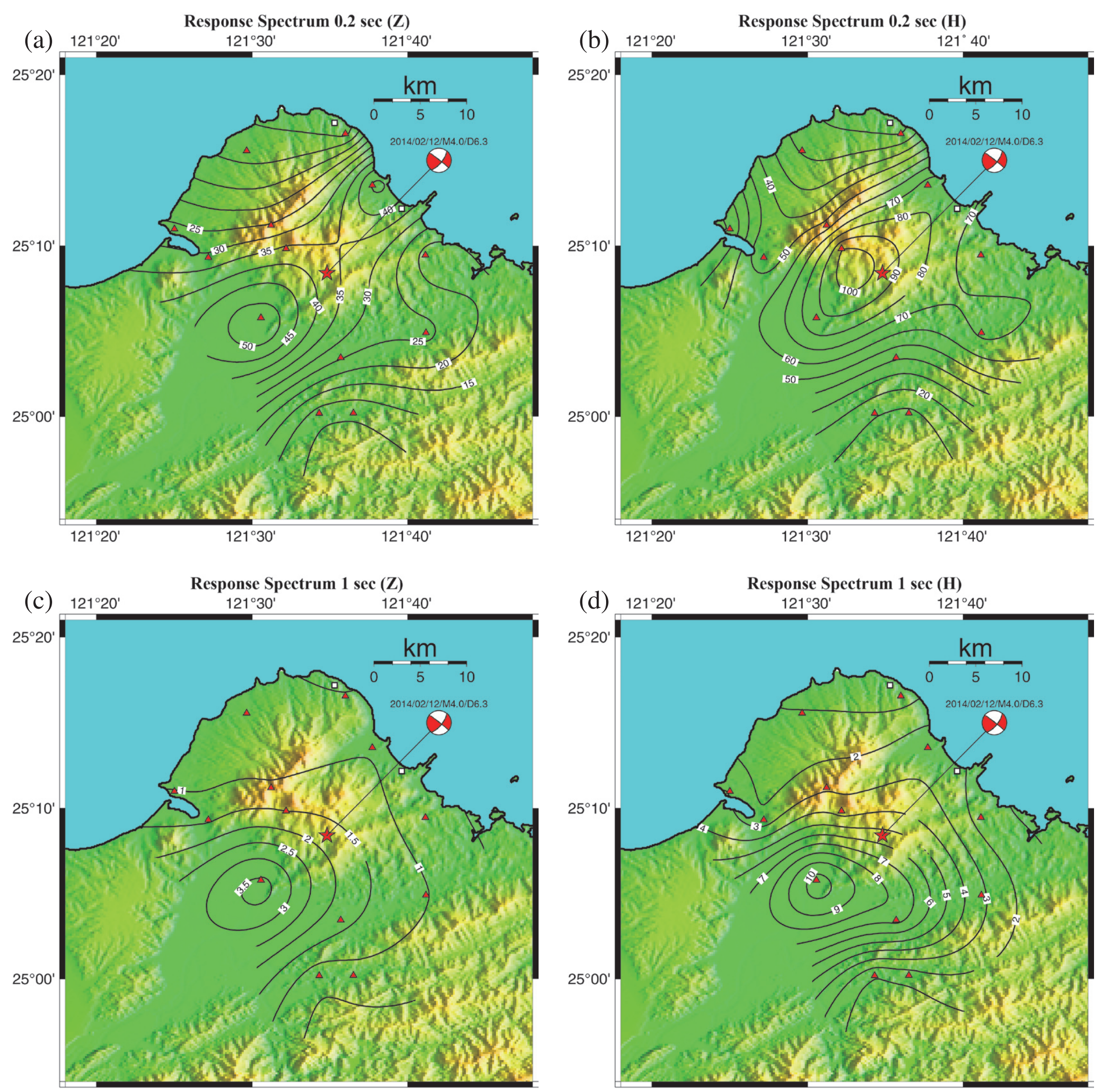

Fig. 7. Contour maps of the vertical (upper panel) and horizontal (lower panel) response spectral accelerations: (a) and (b) for the period of 0.2 sec, (c) and (d) for the period of 1 sec.

station TAP056. Hence, they recommended a new optimal site to re-install the instrument. Station TAP056 was re-installed at the current site, about 20 meters away from the original observation station, in September 2005. The PGA values at TAP056 from this earthquake are quit reasonable based on the plot of PGA versus hypocentral distance as displayed in Fig. 4.

The PGA ratio of vertical to horizontal component is quite high near the source area and it can reach 1.26 at the station close to the source (Fig. 6). Previous studies for ground motions near the earthquake sources reveal that the vertical PGA is larger than the horizontal PGA. Niazi and Bozorgnia (1991) analyzed near-source peak horizontal and vertical ground motions over SMART-1 array in Taiwan and suggested that the PGA ratio becomes larger when the site is close to the source area. Large vertical ground motions in the near-fault zone were observed in the 1989 Loma Prieta (Bozorgnia and Niazi 1993) and 1994 Northridge (Bozorgnia et al. 1995). Significant damage on civil structures due to vertical excitation was also observed in numerous earthquakes (Papazoglou and Elnashai 1996) and the 1999 Chi-Chi earthquake (Chen et al. 2000). Papazoglou and Elnashai (1996) suggested that the vertical motions might lead to both shear and flexure failures. The vertical motions in earthquake resistant design for civil structures in the near-source areas should be taken into consideration in the seismically active areas.

6. CONCLUSIONS

The observed PGA values are generally larger in the EW direction than the NS direction. This might be associated with the focal mechanism of the Tatunshan earthquake. The PGA values decrease rapidly with increasing hypocentral distance and the values are below the estimated attenuation curve, indicating high seismic attenuation in the TVG. Comparison of spectral accelerations between the period of 0.2 sec and that of 1.0 sec suggests that the spectral accelerations decrease rapidly with increasing period. The PGA value is larger in the vertical component than in two horizontal components for the near-source records and the spatial distribution of the PGA ratio becomes larger when the site is close to the source area. Near-source vertical ground motions should be taken into consideration for earthquake resistant design of structures based on ground-motion prediction and seismic hazard evaluations.

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