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Investigation for Strong Ground Shaking across the Taipei Basin during the M_W 7.0 Eastern Taiwan Offshore Earthquake of 31 March 2002

Yi-Ling Huang[1,*], Bor-Shouh Huang[2], Kuo-Liang Wen[3], Ya-Chuan Lai[2], and Yi-Ru Chen[2]

[1] Institute of Applied Geosciences, National Taiwan Ocean University, Keelung, Taiwan, ROC
[2] Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan, ROC
[3] Institute of Geophysics, National Central University, Jhongli, Taiwan, ROC

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ABSTRACT

According to reconstructed ground motion snapshots of the northern Taiwan area during the M_W 7.0 eastern Taiwan offshore earthquake of 31 March 2002, the composite effects indicated complicated wave propagation behavior in the ground motion of the Taipei basin. A major low frequency pulse arose after the S-wave with the duration of about 20 seconds was observed in northern Taiwan and dominated the radial direction. Observed waveforms of a low frequency pulse show amplification during the seismic wave across the Taipei basin from its eastern edge to western portion. This effect has been considered to be generated by an unusual source radiation, deep Moho reflection or basin bottom surface. In this study, recorded ground motions from a dense seismic network were analyzed using a frequency-wavenumber spectrum analysis for seismic wave propagation properties. We investigated temporal and spatial variations in strong shaking in different frequency bands. Results show that a simple pulse incident seismic wave strongly interacts with inside soft sediments and the surrounding topography of the Taipei basin which in turn extends its shaking duration. Evidence showed that seismic waves have been reflected back from its western boundary of basin with a dominant frequency near one Hz. Findings in this study have been rarely reported and may provide useful information to further constrain a three-dimensional numerical simulation for the basin response and velocity structure, and to predict ground motions of further large earthquakes.

Key words: Frequency-wavenumber spectrum analysis, Converted waves, Reflection, Topography effect

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1. INTRODUCTION

Many seismic disasters have been reported to have been induced by strong near source shakes (Archuleta and Hartzell 1981; Shin and Teng 2001). However, according to existing records in Taiwan, the Taipei urban area, locates in an alluvium basin, deserves more attention with regard to distant earthquakes. The strong ground shaking inside a basin from a distant earthquake can be caused by incident seismic waves interacting with a deep basin boundary, shallow soft layering soil and focused seismic energy during its propagation from the hypocenter (Frankel and Vidale 1992; Gao et al. 1996; Kawase 1996). The Eastern Taiwan Offshore Earthquake of 31 March 2002 (M_L 6.8, M_W 7.0) which is called the 331 earthquake caused minor damage near its epicenter but significant damage in Taipei, about 110 km far away from the epicenter. Back to the last event which had a similar location and magnitude as the 331 earthquake was the 14 November 1986, Hualien offshore earthquake. This earthquake caused the Hua-Yang market in Zhonghe city, Taipei County to collapse and damaged a number of buildings within the Taipei basin but with minor damage in the near source area of Hualien. It has been found that, no matter how shallow or deep an event, earthquakes located off the coast of Hualien usually induce more serious damage in the Taipei area than in the Hualien area. The under ground structure of the Taipei basin includes a very weak sediment which could make seismic energy more focused and magnified while seismic waves propagate through the soft structure which in turn induces a stronger shaking inside the basin than in other places with a harder site structure around the basin (Wen and Peng 1998).

* *Corresponding author*
E-mail: ylhuang@mail.ntou.edu.tw

However, when an earthquake located on the Ilan offshore area, there was minor damage in the Taipei basin instead. This discrepancy may indicate that as the seismic wave propagated through the complex deep structure of north Taiwan especially by following a path from Hualien offshore to Taipei; its focus and magnification may be one of the reasons to induce the strong shaking in the Taipei basin (Yeh et al. 1988). Reconstructed ground motion snapshots of the northern Taiwan area of the 331 earthquake display not only complicated wave propagation and complex direction of ground motion inside the Taipei basin, but also a long duration seismic pulse across the Taipei basin (Huang et al. 2003). In the 1995 Kobe earthquake, a similar pulse was reported (Wald 1996; Furumura and Koketsu 1998; Furumura and Koketsu 2000). Near the source and in the area of the highest concentration of damaged mid-rise buildings of Kobe's central business district, most collapses were evidently destroyed by a long-period velocity pulse which shook in a perpendicular direction to the fault (Wald 1996; Furumura and Koketsu 2000). Like the Kobe case, the simple pulse recorded in the 331 earthquake can be an origin of induced building damage.

The possibility of disaster due to distant earthquakes ought to be viewed as an important issue, especially in a populous urban region like Taipei. In order to reduce the disaster that may be caused by distant earthquakes, investigation of the effects of wave propagation inside a basin is momentous. In this study, by analyzing the dense array strong motion data in different frequency bands, we obtained apparent velocities and incident directions of seismic waves across the Taipei basin which enabled us to study the topography and site effect of the Taipei basin with regard to the focus and magnifying characteristics of strong motion energy during wave propagation. Furthermore, it provided some evidence in that seismic waves are reflected after they propagated into the basin.

2. DATA AND METHOD

2.1 Data

The Taiwan Strong Motion Instrumentation Program (TSMIP) is conducted by the Central Weather Bureau and has been in operation since 1991 (Shin 1993). Over 600 digital free-field accelerographs are deployed around the Taiwan area; the spacing between two adjacent stations is on average 2 km within the Taipei basin. The 331 earthquake was well recorded by the strong motion instruments deployed in the Taipei area. The high quality records included invaluable information on the spatial variability of ground motions in the high seismic risk area and provided an opportunity to investigate the complex strong seismic shakes in this area. Among all the TSMIP records in the Taipei basin, we weeded out the unfit data that was compromised by man-made interference or system bugs, finally 43 station records were selected for analysis in this study (Fig. 1). Figure 2 is the vertical-, radial-, and transverse-component acceleration seismograms which were recorded at station TAP017 and is used as an example of all records. From Fig. 2 and other strong motion records, main strong shaking phases are the radial-component of long period later phases (named as later phase in this study) that come after the direct S arrivals and its amplitudes are larger than the amplitude of direct S arrivals. We corrected the P wave arrival time of the raw data by using the central Taiwan velocity structure model (Yeh and Tsai 1981). Figure 3 is a reduced travel time plot of corrected radial-component waveforms of all stations. Based on those high quality dense array data, it helps us to obtain well-documented and authentic results.

2.2 Analysis Method

The seismic array recorded seismic waves that passed through the Taipei basin in both time and space allowing a separation of seismic waves in wave field and provided an estimation of the apparent velocity of the wave and its approaching direction. In this study, the frequency-wavenumber spectrum analysis method was applied to obtain the incident direction and velocity of the seismic wave that passed through the basin in different frequency bands. The characteristics of seismic wave propagation were examined accordingly.

The time domain two-dimensional ground motion $V(x, y, t)$ can be presented by its frequency (ω) and wavenumber (k) components using a three dimensional Fourier transform as

$$V(\omega, k_x, k_y) = \iiint v(t, x, y) \exp[-i(\omega t - k_x x - k_y y)] dt dx dy \quad (1)$$

In this equation, k_x and k_y are two decomposed horizontal components of the wavenumber (k) and both can be represented as $k_x = |k| \sin\theta$ and $k_y = |k| \cos\theta$, respectively. Herein, θ is the angle of the azimuth. Two methods have been developed to estimate the ω-k spectra; one is the beamforming method (Lacoss et al. 1969), and the other is the maximum-likelihood method (Capon 1969). Huang and Yeh (1990) have a detailed discussion for the application of both methods in strong motion data. They concluded that the maximum-likelihood method is a suitable method to process two dimensional array data to achieve high resolution in the presence of multi-path interference. In this study, we employed a convenient and functional computer code, the Seismic Analysis Code (SAC), which provided for a complete analysis to estimate the ω-k spectra, to evaluate the temporal and spatial variation of strong ground motions (http://www.iris.washington.edu/manuals/sac/SAC_Home_Main.html).

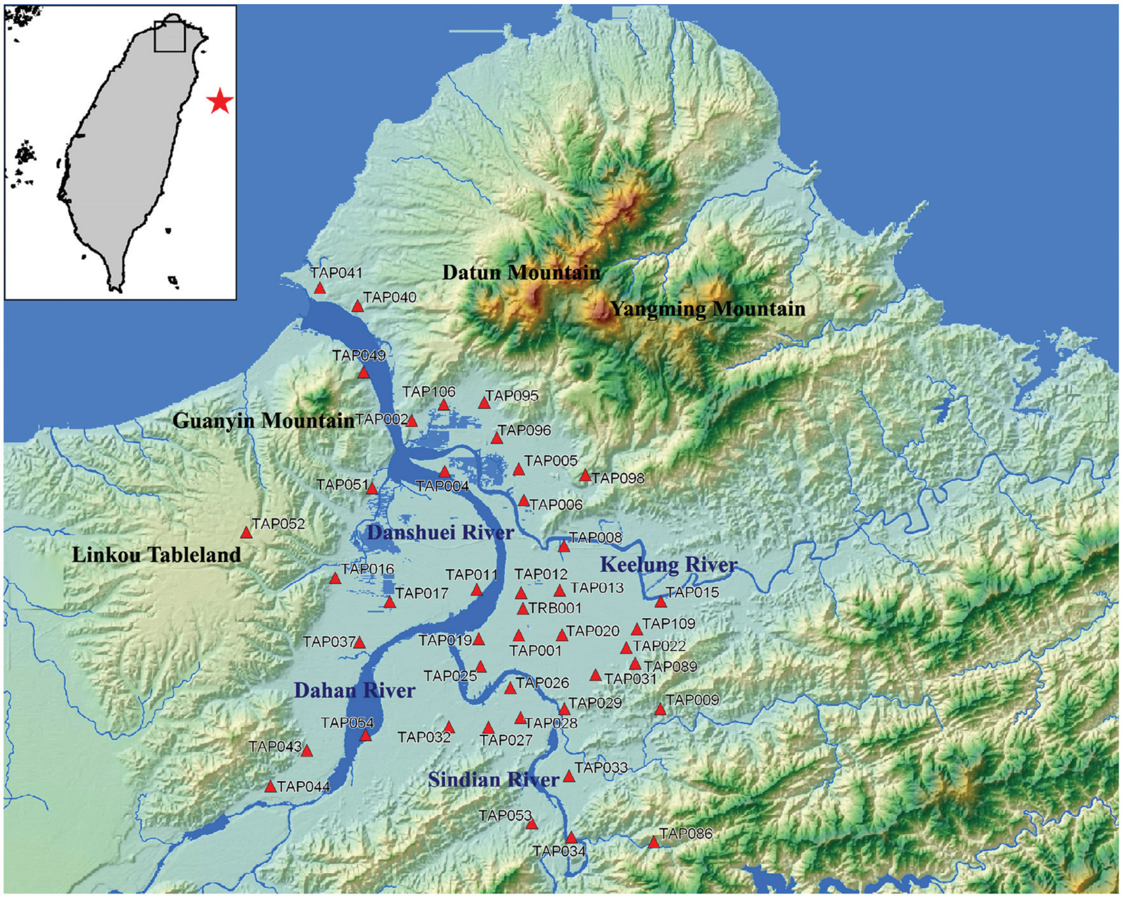

Fig. 1. The 43 free-field strong motion stations (solid red triangles) of the TSMIP network in the Taipei basin, whose data we used to analyze in this study. The index map in the upper left corner shows the relative location of the epicenter (solid star) and the study area (square).

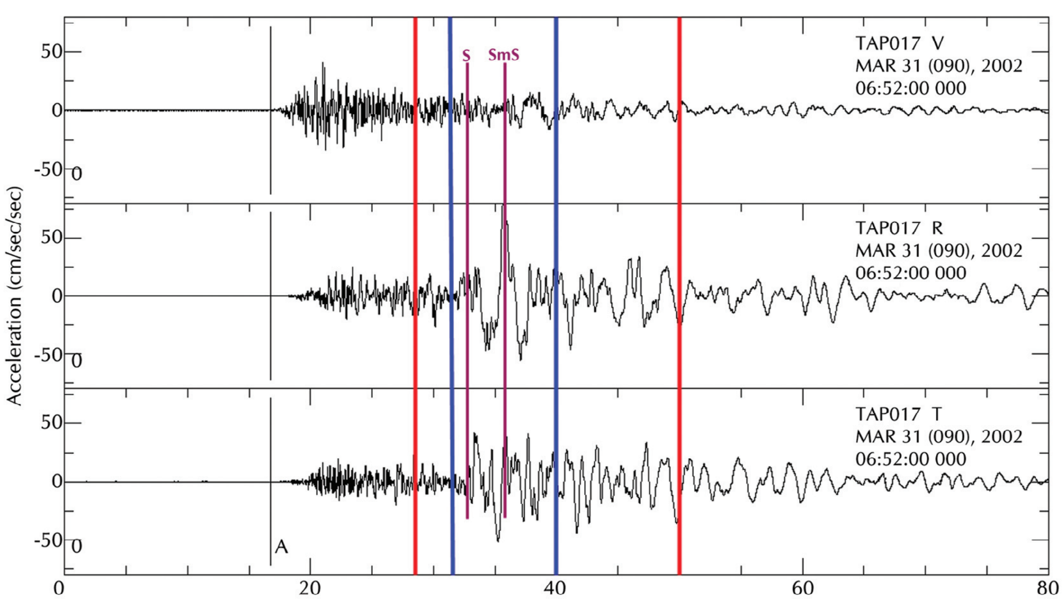

Fig. 2. An example of three-component acceleration seismograms (station TAP017) of the eastern Taiwan offshore earthquake of 31 March 2002. The first trace is the vertical (V) component. Both horizontal components have been rotated to its radial (R), and transverse (T) directions. Both vertical red lines and blue lines define a long time window (22 seconds) and a short time window (8 seconds), respectively. Two purple lines with S and SmS marks indicate the phases travel time in the traces.

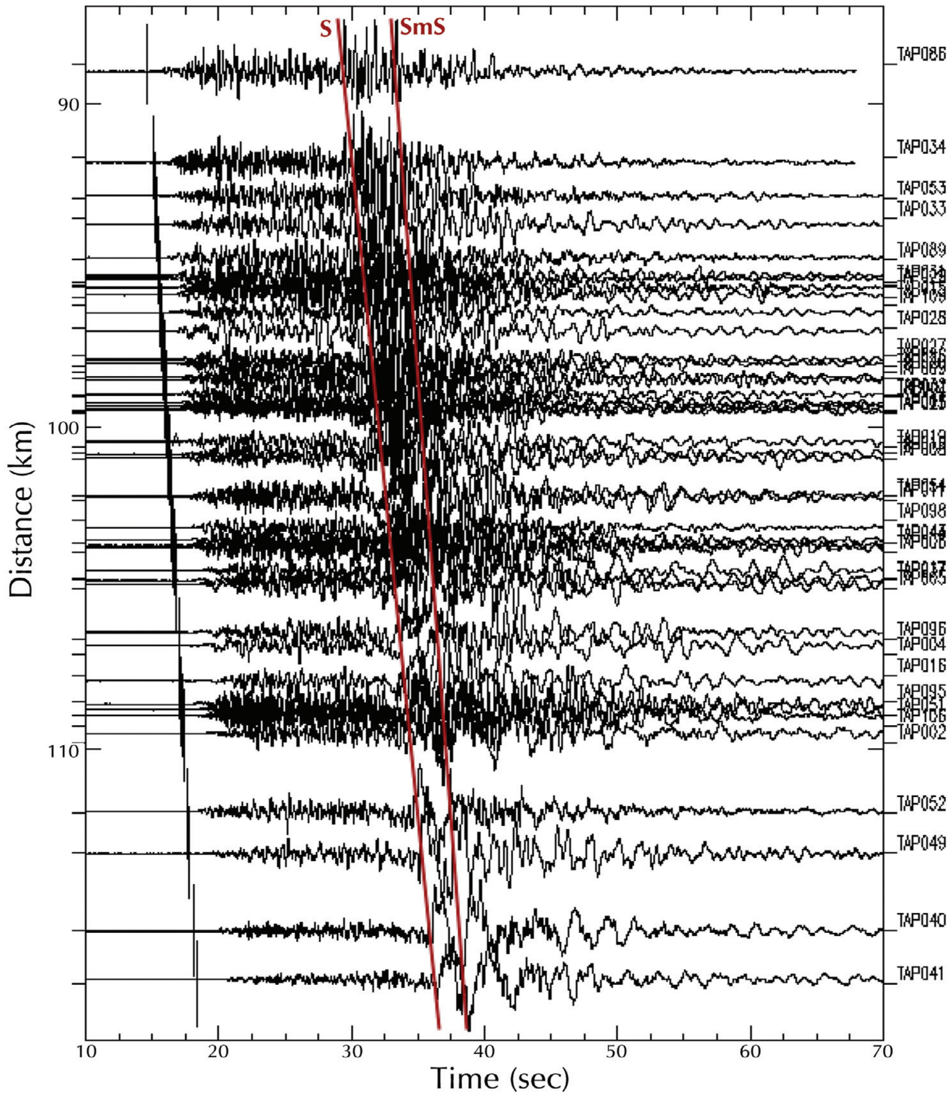

Fig. 3. A reduced travel time plot of radial-component waveforms for seismic stations at distances. Two dark-red lines with S and SmS marks indicate the phases travel time in the traces. This map shows that the later arrivals (later phase) arrive about 2 seconds later than direct S arrivals, and the amplitude of the later arrivals are larger than the direct S arrivals.

In order to make sure the geometrical distribution of this array is suitable for frequency-wavenumber analysis, we did the array response test firstly. Figure 4 is the array response for 43 stations we used in this study. It shows a very rapid collapse around the power peak and suppresses the side lobes which are caused by a finite array configuration. The response test verifies that the distribution of this seismic array is suitable for frequency-wavenumber analysis and provides a high spatial resolution to identify seismic wave propagation in different incident azimuths and speeds.

3. ANALYSIS AND RESULTS

It has been reported that the strongest ground-motion which was produced by the 331 earthquake occurs in the east margin of the Taipei basin (Wen 2002; Chen 2003; Huang et al. 2003). Furthermore, it shows seismic attenuation and slight dispersion as this later phase across Taipei basin. However, no detailed analysis and discussion for seismic wave scattering out of theoretical ray paths which may be induced by deep slab, shallow structure and surface topography. Chen (2003) indicated that the high amplitude later phases which followed the S waves were the critically reflected S waves (SmS phases) from the Moho discontinuity and arrived about 2 seconds later than direct S arrivals.

To explore the possible variation of major seismic energy across the Taipei basin, a time window which included 22 second radial-component records (from 28 to 50 sec in Fig. 2) was chosen for analysis in this study. These 22 sec records contain complete S phases, SmS phases and some surface waves which converted by the effect of basin margin and complex propagating path. For recording the time window from 28 to 50 sec, Fig. 5 presents the frequency spectrum of radial-component data recorded at station TAP017 for instance. The frequency spectrum analysis results showed that most records have main energy distribution between 0.2 to 1.5 Hz, the blue curve in Fig. 5. To verify the seismic energy contribution within this time period, the frequency spectrum analysis results from the entire recording time is shown in Fig. 5, the red curve. It shows very similar results as the blue curve. Thus, we ascertained that the time window from 28 to 50 sec which we selected for analyzing was the time window that contained the main seismic energy. To compare results from seismic phases which were considered as critically reflected S waves (SmS phases) from the Moho discontinuity by Chen (2003), seismic data from a short time window (from 32 to 40 sec of Fig. 3) were also selected for future analysis. Figure 6 shows results of the frequency-wavenumber analysis and represents

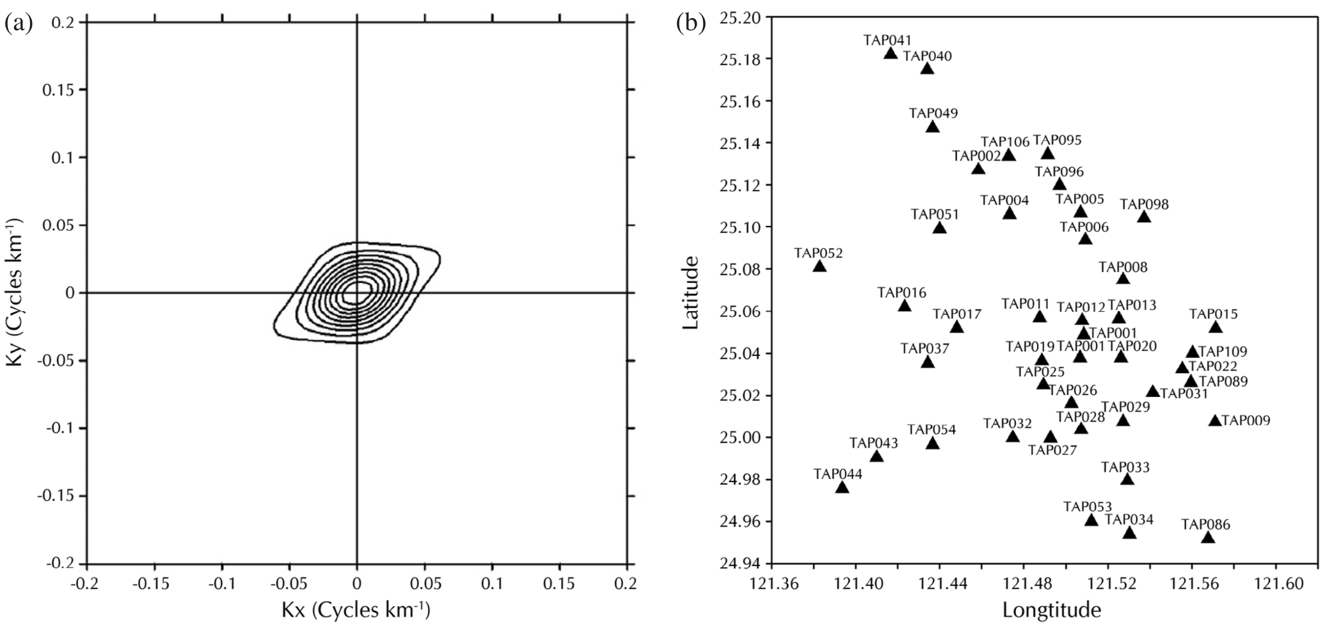

Fig. 4. The array response (a) of 43 TSMIP stations [the solid triangles in (b)] which are used in this study.

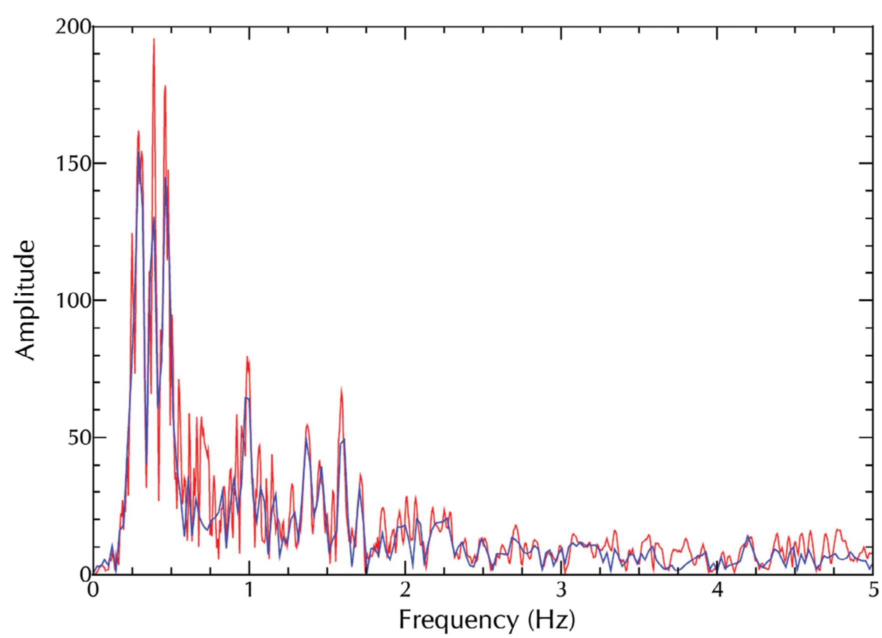

Fig. 5. Frequency spectrum of radial-component data recorded at station TAP017. The red curve shows frequency spectrum of entire recording time and the blue curve is computed by the time window from 28 to 50 sec after the earthquake occurred.

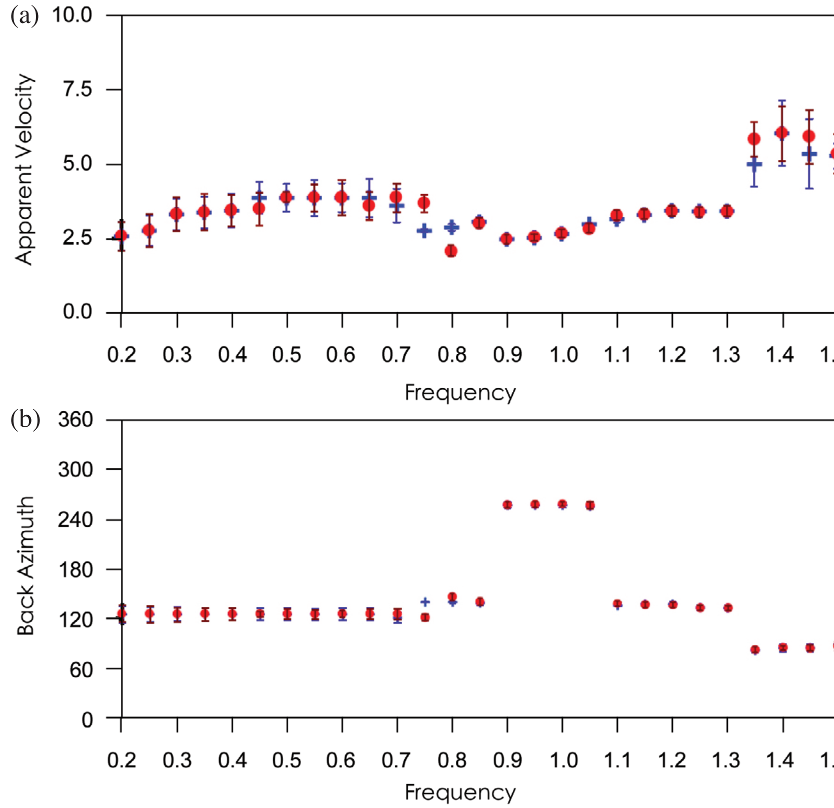

Fig. 6. (a) The apparent velocity as a function of the frequency. (b) The back-azimuth as a function of the frequency. Both (a) and (b) were obtained by the frequency-wavenumber spectrum analysis method at the 43 free-field strong motion stations in the Taipei basin. Red symbols indicate the results computed by the time window from 28 to 50 sec of radial-component strong motion data. Blue symbols indicate the results computed by the time window from 32 to 40 sec of radial-component strong motion data. The vertical bars are the errors estimated from the slowness spectrum in the range of their 0.85 peak values.

its apparent velocity and back-azimuth as a function of frequency, which were obtained from 43 free-field strong motion records in the Taipei basin. The red symbols show the results which were computed by using the radial-component strong motion data of the time window from 28 to 50 sec. In Fig. 6a, the apparent velocity values were distributed between 2.5 and 4 km sec^{-1}. According to the calculation of apparent velocity by using theoretical model (Yeh and Tsai 1981), the incident velocity in the Taipei basin should be 5.19 km sec^{-1} or so. The apparent velocities from observations are lower than the result from the theoretical model calculation. Figure 6b shows that the incident direction of the seismic wave is consistently from the source direction, except the seismic energy between 0.9 and 1.05 Hz was obviously different to the incident directions in other frequencies. Within this frequency band, the incident wave was away from the source direction and changed its horizontal incident direction from southwest with back-azimuth of 257°. To verify the seismic energy contribution from the simple pulse, we selected a short time window (from 32 to 40 sec, in which, the main phases are the SmS phase) and recomputed its apparent velocity and back-azimuth and shown as the blue symbols in Fig. 6. It clearly shows that the results of using short time window (from 32 to 40 sec) are nearly the same as that from the time window between 28 to 50 sec, which includes S waves, SmS phases, and the surface waves due to the wave reflection and refraction from basin edge and travel through complex path.

Using a moving window analysis, we tried to find a time window in which the signals are incident from azimuth of 257°. We selected 4 windows (from 32 to 40 sec of Fig. 3 and filtered each signal within 0.9 and 1.05 Hz) to verify its temporal variation as shown in Fig. 7. A clear incident angle from azimuth of 257° was displayed on Fig. 7c. It indicated that the signal changed its incident azimuth within 35 and 39 sec after the earthquake. Further analysis verified that this time window was located at the later portion of its major energy pulse.

4. DISCUSSION

Figures 6a and b evidently show that using the data which contains only the short time window [thus, SmS phases proposed by Chen (2003)] provided the same result with that using the data from a long time window which contains S waves, later phases, and surface waves which

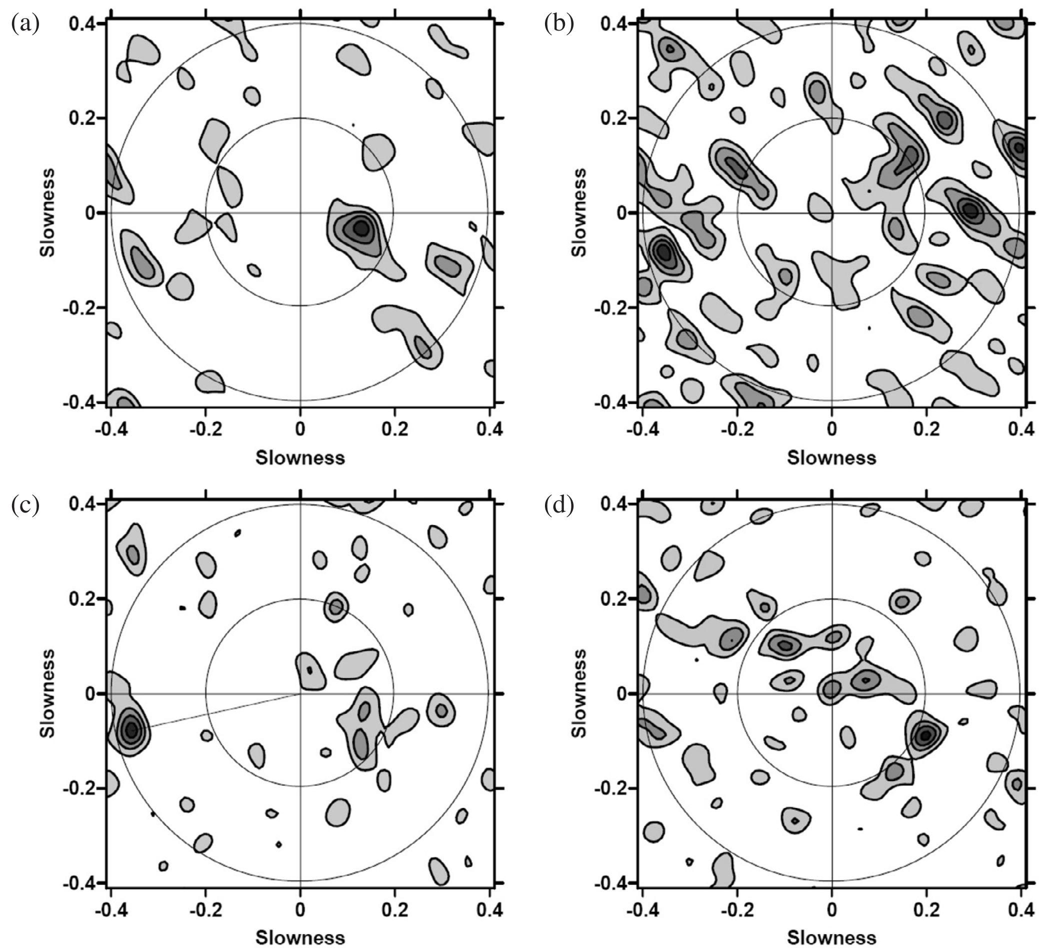

Fig. 7. Slowness spectrum diagrams of the 43 free-field strong motion stations in the Taipei basin. (a) to (d) represent the slowness spectrum diagrams on different travel time windows: (a) 33 ~ 37 sec; (b) 34 ~ 38 sec; (c) 35 ~ 39 sec; (d) 36 ~ 40 sec. A band pass filter of the frequency band between 0.9 and 1.05 Hz was previously applied to each seismogram.

was induced by the waves' reflection and refraction from basin edge and travel through complex paths. If we agree with the conclusion offered by Chen (2003) to consider the later phase as the SmS wave, it indicated that SmS phase was the main phase which caused the strong ground motion during the 331 earthquake in the Taipei basin. Actually, some researchers support idea that the deep structure under northern Taiwan is the main cause which induces more serious damage in the Taipei basin than in Hualien city when an earthquake occurs in an offshore area near Hualien (Chen and Wang 1988; Yeh et al. 1988; Chen 2003). The path effect of wave propagation from various underground structures might be the cause to bring seismic wave focus and magnification. In this study, we further verified that most of the deep reflection waves along the same azimuth of the main path, no clear scattering out of the plane was found. However, the apparent velocities in the Taipei basin which were estimated from observational data are between 2.5 to 4 km sec^{-1}. Its values are smaller than that estimated using the theoretical model of Yeh and Tsai (1981) as 5.19 km sec^{-1}. One possible reason for the difference between apparent velocities which estimates from observational data and from theoretical model (Yeh and Tsai 1981) is that observational data contains the effects from the thin sedimentary layer of the Taipei basin. Actually, the Taipei basin is a triangular-shaped alluvium basin filled with Quaternary unconsolidated sediments which overlays the Tertiary basement. The sediments thicken northwestward to about 700 m from a thin margin in the southeast of the basin (Wang et al. 1994, 1995, 1996, 2004). P wave velocity is between 1.5 to 2.2 km sec^{-1} and S wave velocity is between 0.2 to 0.6 km sec^{-1} in the sediments (Wen and Peng 1998). The thin sedimentary layer may cause an obvious effect that decreases about 20% of the apparent velocity and the same as alters the SmS pulse waveforms.

Figure 6b shows that the incident directions of seismic energy between 0.9 to 1.05 Hz changed its incident azimuth from southeast to southwest with incident azimuth of 257°. According to the amplitude spectrum (Fig. 5) of the strong motion record, the seismic wave near one Hz has amplitude about one third of its peak amplitude. It indicated that the southwest incident seismic wave has a significant contribution to this long period pulse. To look at arrival time from Fig. 7, it indicated that this phase is a later arriving phase which may be a reflection wave from the basin boundary. Comparing the direction with the topography in Fig. 1, the Linkou tableland could be a boundary to reflect the seismic energy. Furthermore, the direction of a back-azimuth 257° can be well interpreted as reflection from an oblique incident wave from source direction.

Although we have assumed the simple pulse which propagates into the Taipei basin is a SmS phase (Chen 2003), we can not rule it out from a unique source radiation. However, in the case of the Taipei basin, this long period pulse was observed far from the source area. The origin of building damage may be different from the Kobe earthquake. Actually, analysis of this study reveals that the effects due to the shape and sedimentary structure of the Taipei basin are extremely complex, and some one-dimensional or two-dimensional velocity models which are used widely these days do not satisfy the requirement of wave propagation simulation of the Taipei basin. The results in this study may provide a useful constraint in further three-dimensional numerical simulations for basin response and basin velocity structure.

5. CONCLUSION

By inspecting the data of the 331 earthquake, which was recorded by the array distributes over the Taipei basin, it has been affirmed that the simple pulse which propagated into the Taipei basin was observed. The dominant ground motions were the radial component S wave and its early later phases. Applying frequency-wavenumber spectrum analysis and moving-window techniques to analyze array seismograms revealed that this strong shake further interacted with the thick soft sediment of the Taipei basin and showed complex waveforms, extended durations and multiple propagation directions. Based upon the forgoing inspection and analysis, we believe that the complex effects of ground motion during the 331 earthquake in the Taipei basin was caused by three possible causes. First of all, a simple pulse like seismic wave (thus, SmS phase) was the main phase which caused the strong ground shaking during the 331 earthquake in the Taipei basin. Second, the shallow alluvium of the basin had a great effect in reducing the apparent velocity and modifying the incident seismic waves. Finally, the western edge of the Linkou tableland northwest of the Taipei basin might reflect the seismic energy and complex the wave propagation inside the basin.

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