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SITE EFFECTS ESTIMATED FROM MICROTREMOR MEASUREMENTS AT SELECTED STRONG MOTION STATIONS IN TAIWAN

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ABSTRACT

Microtremor measurements are conducted using arrays of sensors at six strong motion stations in Taiwan where the peak ground accelerations over 400 cm/s^2 were recorded during the 1999 Chi-Chi earthquake. Shallow shear wave velocity profiles of these stations are estimated based on an inverse analysis of microtremor dispersion characteristics and H/V spectra. At Wufeng (TCU065) where building damage was the most extensive among others, a thick soft surface layer with a shear wave velocity less than or equal to about 200 m/s overlies a stiff layer with Vs greater than 400 m/s at a depth of about 30 m. At other stations, stiff layers with Vs greater than 300-400 m/s occur from the ground surface or at a depth less than 20 m. Linear and equivalent linear analyses are conducted using the estimated Vs profiles. The natural site periods computed from an equivalent linear analysis are generally consistent with the peak periods of the response acceleration spectra of the recorded strong motions, but they are considerably longer than those estimated from a linear analysis, regardless of the value of the shallow shear wave velocity. This suggests that local soil conditions including nonlinear soil behavior might have had significant effects on the ground surface motion and performance of buildings during the earthquake.

INTRODUCTION

The Chi-Chi earthquake (M_W =7.6) that occurred on September 21, 1999, with an epicenter near Chi-Chi in the central Taiwan (Fig. 1), caused extensive damage to various structures, claiming a death toll of about 2400. This earthquake provided the largest number of strong ground motion records that one event ever produced (Lee et al., 1999). Since the fault ruptured from the south to the north with large asperity on the north, the observed strong motion recordings are relatively long with predominantly short period motions on the south and relatively short with predominantly long period motions on the north. The damage distribution of buildings further indicates that not only the rapture mechanism of the fault but also local soil conditions might have had significant influence on the ground motion characteristics.

Field observation revealed that the structural damage caused by ground shaking was generally greater on the hanging wall side of the fault than on the lower block. At Wufeng (TCU065) on the lower block, however, many buildings collapsed with a peak acceleration of 774 cm/s^2. At Mingchien (TCU129) on the lower block, in contrast, significantly less structural damage was observed, in spite of a larger peak acceleration of 983 cm/s^2. The response spectra of the recorded strong motions in the period range less than 1s are completely different between the stations, claiming that the local site effects might have had strong influence on the ground motion as well as the observed damage distribution during the earthquake. It seems, however, that few data on the

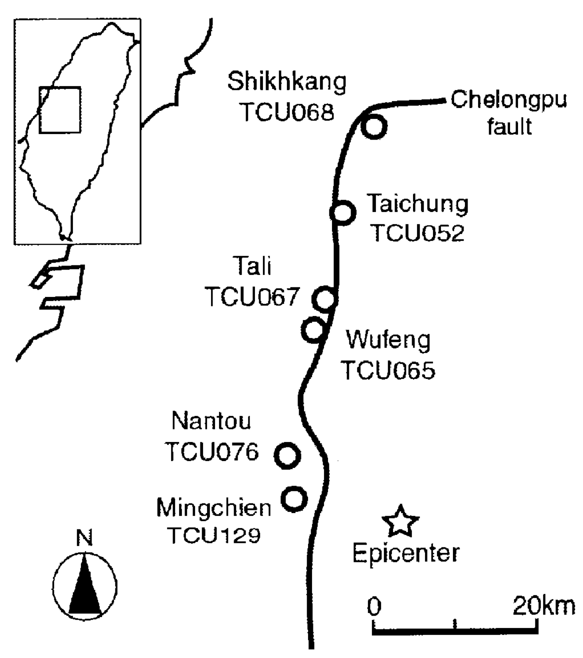

Fig. 1. Map showing selected strong motion stations where microtremor measurements were conducted

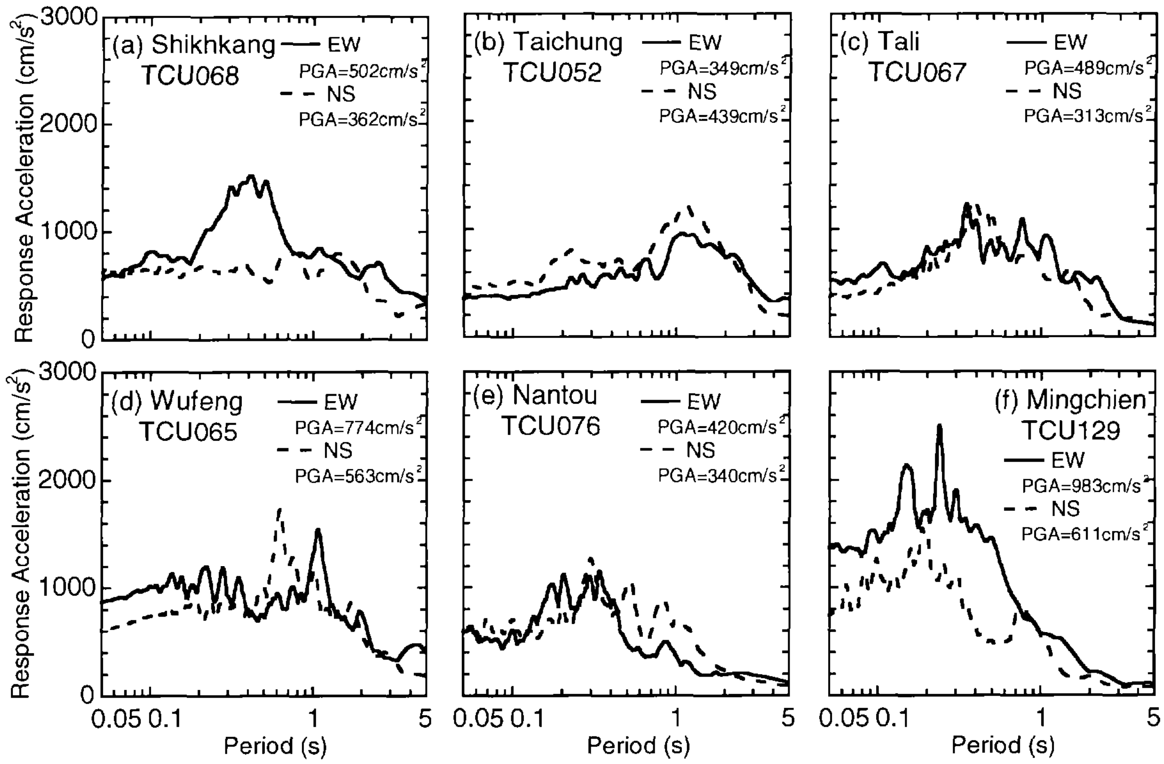

Fig. 2. Acceleration response spectra

shallow soil profiles are available to study the local site effects.

The objects of this study are to estimate shallow shear wave velocity profiles at selected strong motion stations based on microtremor measurements using array of sensors and to examine the effects of local site conditions on the ground motion characteristics and observed damage distribution during the 1999 Chi-Chi earthquake.

STRONG MOTION STATIONS SELECTED FOR MICROTREMOR MEASUREMENTS

Figure 1 also shows the location of the six strong motion stations where microtremor measurements were conducted. These stations include Shikhkang (TCU068), Taichung (TCU052), Tali (TCU067), Wufeng (TCU065), Nantou (TCU076), and Mingchien (TCU129). They are located along the fault from the north to the south. The recorded ground motions during the Chi-Chi earthquake at these stations had a peak horizontal acceleration greater than 400 m/s^2. Despite the large peak ground accelerations, the damage to buildings caused by ground shaking was not extensive except for the area near Wufeng (TCU065) (Midorikawa and Fujimoto, 1999; Miyakoshi et al., 2000).

Figure 2 shows the acceleration response spectra with a damping ratio of 5% for the two horizontal components at each station. The spectral shape and peak period as well as the peak ground acceleration vary from site to site. Of particularly noticeable are the large response accelerations in the period range of 0.6-1.0 s at Wufeng (TCU065), which contrasts well with those occurring at about 0.2 s at Mingchien (TCU129) where the peak ground acceleration exceeded 1 G. One of the reasons to cause this contrast is considered to be the difference in local soil conditions between the stations.

The high response accelerations in the period range of 0.6-1.0 s at Wufeng (TCU065) appear to correspond to the range of the natural periods of the buildings heavily damaged or collapsed nearby. Such a large acceleration response is not observed in the same period range at other stations with less structural damage. It is conceivable therefore that local soil conditions might have had significant effects on the performance of buildings at each station as well. There exists however few information available for examining local site effects in further details.

MICROTREMOR MEASUREMENTS AT STRONG MOTION STATIONS

Microtremor measurements using array of sensors have proven to be effective in exploring a shear wave velocity profile at a site (e.g., Horike, 1985; Okada and Matsushima, 1986; Tokimatsu et al., 1992) and have been frequently used to evaluate local site effects (e.g., Tokimatsu, 1995).

The resolution of an estimated Vs profile depends on the quality of a microtremor dispersion curve used in an inverse analysis. Although the resolution of the inverted profile becomes low particularly at large depths, this technique appears attractive as it can readily be done on the ground surface without any borehole.

To enhance the reliability of the inverted Vs profile, Tokimatsu and Arai (1998) and Arai (1998) recently proposed a revised method in which not only a dispersion curve but also a horizontal-to-vertical spectral ratio (H/V) of microtremors is used in the inversion. The method requires only minor revisions and consists of the following three steps:

(1) Observation of microtremors using an array of sensors
(2) Determination of a Rayleigh wave dispersion curve in microtremors and their H/V spectral ratio using spectral analyses
(3) Determination of a shear wave velocity profile based on inverse analysis using both dispersion curve and H/V spectra

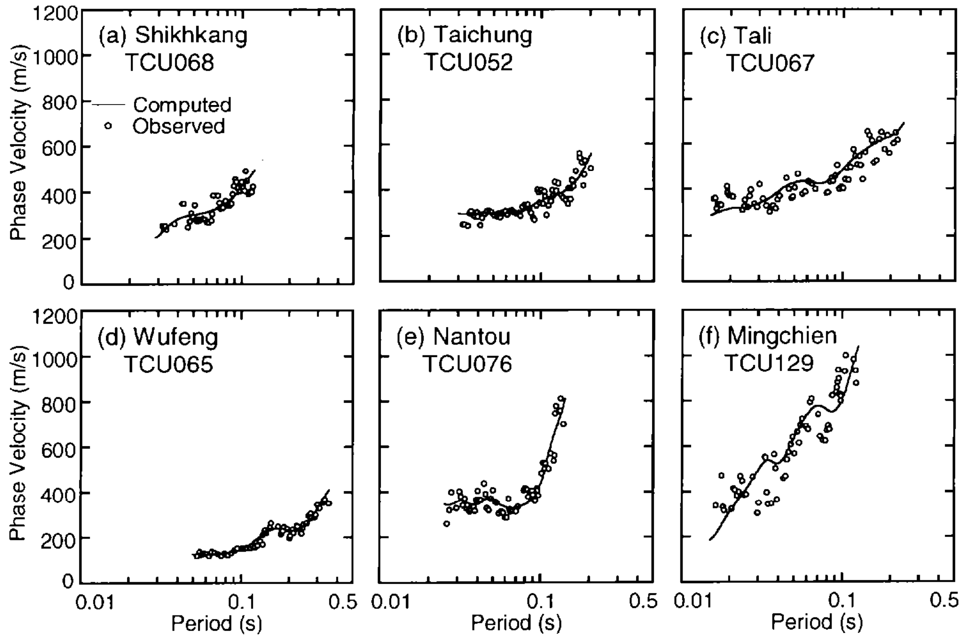

Fig. 3. Dispersion curves of microtremors

Based on the improved method, microtremor measurements were conducted at the six strong motion stations in Taiwan on November 3-6, 1999. As all stations were in the properties of elementary schools, the measurements were conducted on the playground. The instrument used in this study consists of amplifiers, lowpass filters, A/D converters, and a notebook computer, all built-in a portable case, as well as one three-component and five vertical velocity sensors. All the sensors have a natural period of 1 s.

Several circular arrays of different array radius were formed at each site, with the three-component sensor at the center and five vertical sensors on the circumference. Microtremors were then measured simultaneously with each array for several to about 10 minutes. The array radius used ranged from 2.5 m to 10-25 m. The sampling rate was varied from 100 to 1200 Hz, depending on the site geological condition as well as the array radius used. Sixteen sets of digitized microtremor data consisting of 2048 points each were obtained for each array and used in the following analyses. It took about one hour to complete the whole test including the placement and removal of the sensors at a site. The details of the test procedures have been described elsewhere (e.g., Tokimatsu et al, 1992).

MICROTREMORS DISPERSION CHARACTERISTICS AND H/V SPECTRA

The high-resolution F-k spectral analysis (Capon, 1969) was performed with microtremor vertical motions measured with each array to determine dispersion characteristics at each site, assuming that the effective wavelength range is 2–6 times the array radius. The results are summarized with open circles in Fig. 3 in which the phase velocity is plotted against the period. The data show normally dispersive trends in which the phase velocity increases with increasing period at all sites. Both the

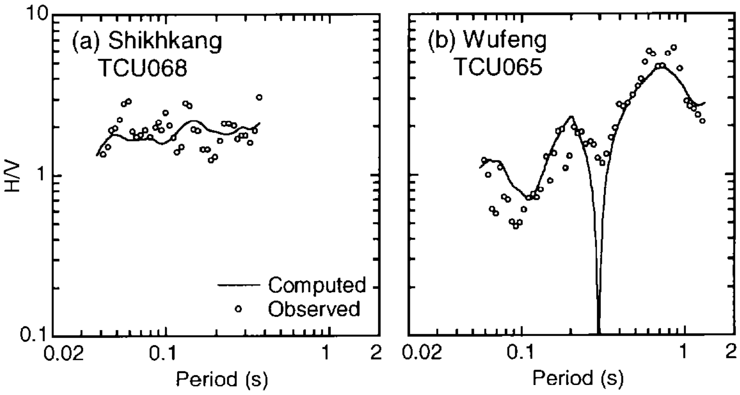

Fig. 4. Microtremor H/V spectra

phase velocity and period are however different significantly from site to site, despite the same array sizes used. The phase velocity varies from 100-400 m/s in the range from 0.05-0.4 s at Wufeng (TCU065), while it varies from 400-1000 m/s in the range of 0.02-0.1 s at Mingchien (TCU129). The large difference in the dispersion curve between the sites suggests that the Vs profiles are completely different with each other.

The microtremor H/V spectra were computed from the three-component motions observed in the center of the array and those at Shikhkang (TCU068) and Wufeng (TCU065) are shown with open circles in Fig. 4. The H/V spectra at Shikhkang (TCU068) do not show a prominent peak in the short period range. This suggests that it may be a rock site or a site with a low Vs contrast in shallow soils, i.e., the Vs increases gradually with depth. In contrast, the H/V spectra at Wufeng (TCU065) have a prominent peak at 0.7 s, indicating that it is a site with a high Vs contrast in shallow soils. The variation in H/V spectra and the shallow Vs profiles at other sites appear to fall in between the two.

SHEAR WAVE VELOCITY PROFILES FROM INVERSION OF MICROTREMOR DISPERSION CHARACTERISTICS AND H/V SPECTRA

Shear wave velocity profiles of the shallow soils at all the stations were estimated based on an inverse analysis (Arai, 1998) using both microtremor dispersion curves and H/V spectra. It was assumed that surface waves dominate in microtremors, i.e., Rayleigh waves in both the vertical and horizontal motions, and Love waves in the horizontal motions. The effects of higher modes of surface waves were taken into account.

It was also assumed that the shallow soil profile at each site consists of 2-4 horizontally stratified layers including the bottom half space, and their Vs and thickness were sought so that both the computed dispersion curve and H/V spectra match with the observed ones. The maximum depth of the Vs profile that can be estimated reliably by this method is about one third of the maximum effective wavelength, i.e., up to a depth of 20-50 m.

The solid lines in Figure 3 and 4 show the theoretical dispersion curves and H/V spectra for the inverted shear wave velocity profiles. The computed values are in fairly good agreement with the observed ones, suggesting that the inverted structures could be reasonably reliable.

Figure 5 shows the shear wave velocity profiles estimated for the six sites. At Shikhkang (TCU068), Taichung (TCU052), Tali (TCU067), Nantou (TCU076), and Mingchien (TCU129), where the damage caused by ground shaking was moderate despite the large accelerations, stiff layers with Vs greater than 300-400 m/s occur from the ground surface or at a depth less than 20 m. Particularly, at Mingchien (TCU129) where the peak acceleration exceeds 1 G, the shear wave velocity is as much as about 400 m/s near the ground surface and increases to over 600 m/s at a depth less than 10 m.

At Wufeng (TCU065) with severe structural damage, in contrast, a soft surface layer with Vs less than or equal to about 200 m/s overlies a stiff layer with Vs greater than 400 m/s at a depth of about 30 m. The soft thick surface layer might have amplified ground motions and affected the extensive damage to buildings in this area.

SITE AMPLIFICATION CHARACTERISTICS ESTIMATED FROM INVERTED Vs PROFILES

The amplification characteristics, defined as the spectral ratio of incident S waves between the ground surface and the top of the bottom layer of the soil profiles shown in Figure 5, were estimated based on one-dimensional dynamic response analyses. Both linear and equivalent linear analyses similar to those presented by Schnabel et al. (1972) and Sugito et al. (1993) were employed with the stronger component of the

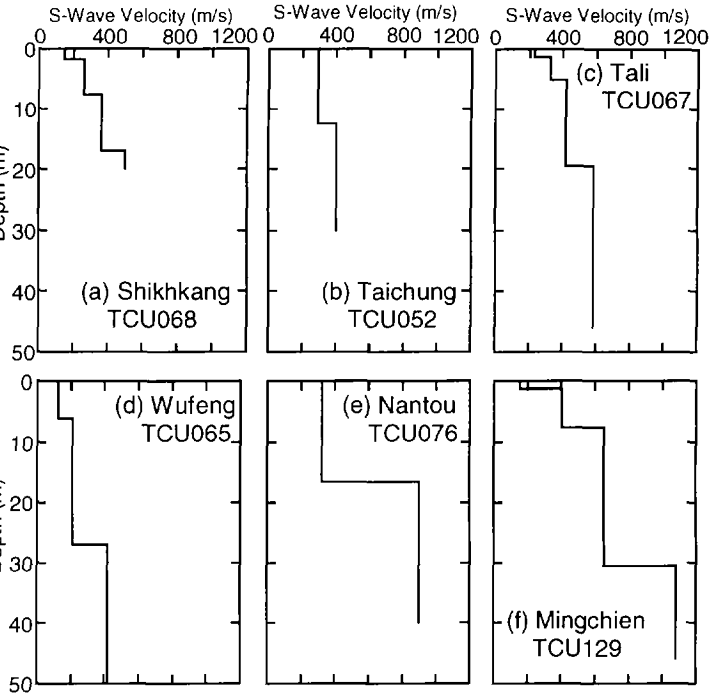

Fig. 5. Shear wave velocity profiles estimated from microtremor measurements

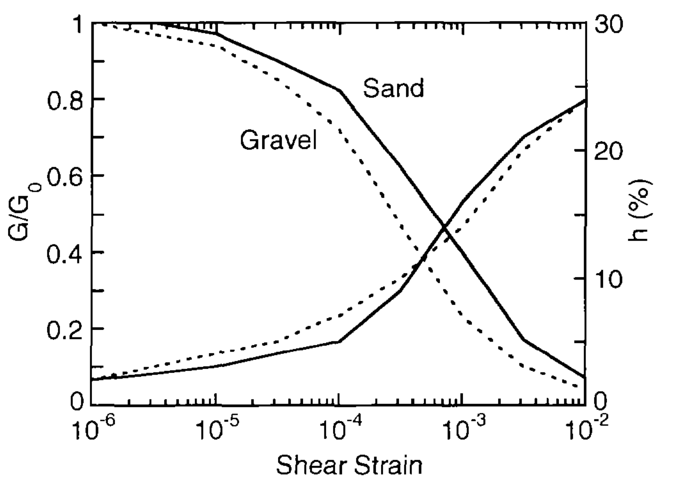

Fig. 6. Strain-dependent shear modulus and damping

strong motions recorded at each site during the 1999 event as the reference motion on the ground surface. The representative relations of shear modulus ratio and damping factor with shear strain for sand and gravel shown in Figure 6 were used for layers with Vs less than and greater than 250 m/s, respectively. The computed results are summarized in Figure 7.

The amplification peak period of 0.5 s from the linear analysis for Wufeng (TCU065) corresponds to the peak period of the microtremor H/V spectra shown in Fig. 4. The amplification peak period from the equivalent linear analysis for the same site is elongated to 1.0 s, which coincides with the spectral peak period of the stronger EW motion shown in Figure 2.

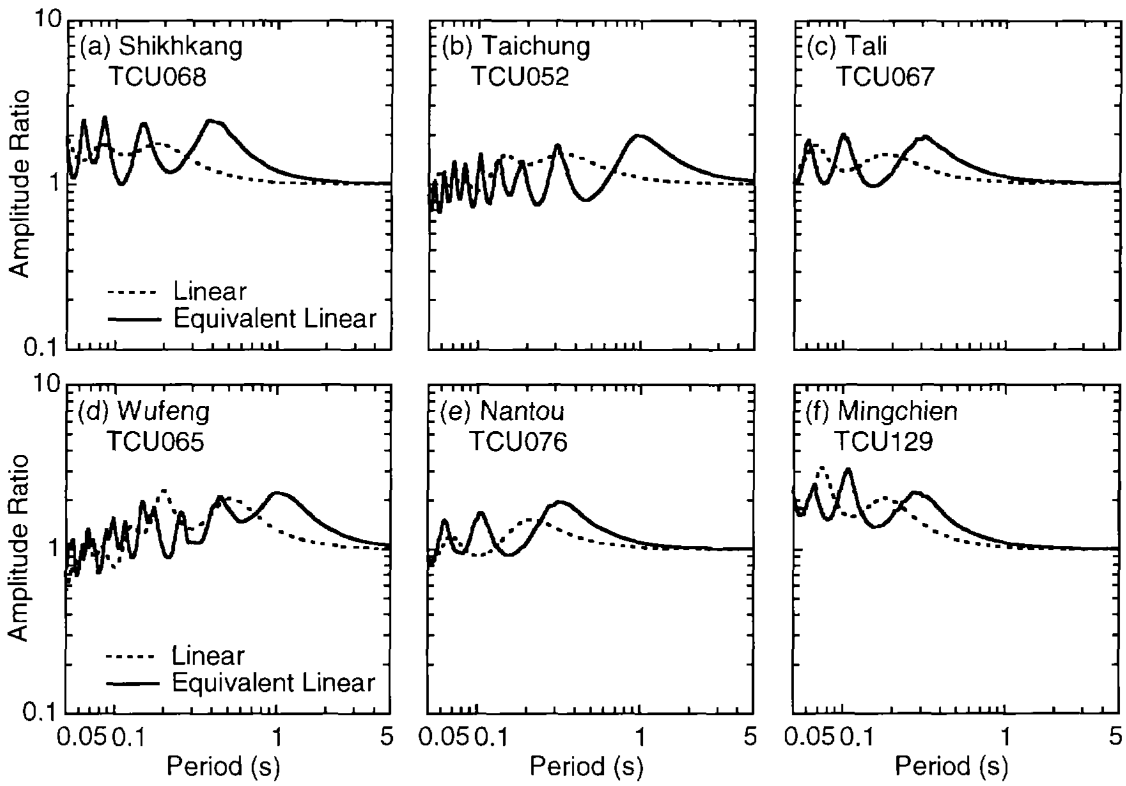

Fig. 7. Spectral ratios between the ground surface and the top of the bottom layer

The spectral peak period of the weaker NS motion falls in between the amplification peak periods from the linear and equivalent linear analyses. It seems therefore that the local site effects including non-linear soil behavior significantly affected the ground motions during the 1999 Chi-Chi earthquake.

The possible natural period range of the ground at Wufeng (TCU065) during the 1999 event appears to correspond to the natural period of the buildings damaged in the area, suggesting that local site effects might have had significant effects on the structural damage near the site as well.

The amplification peak periods from the equivalent linear analysis at other sites also show a fairly good agreement with the peak periods of the response spectra of the recorded motions at the same sites as shown in Fig. 2. The spectral peak periods of the recorded motions are much larger than those obtained from the linear analysis.

The above findings and discussions indicate that the local site effects including nonlinear soil behavior had a significant impact on the ground motion characteristics and the performance of buildings during the earthquake. In addition, the microtremor measurements using arrays of sensors used in this study appears very useful to estimate Vs profiles and local site effects in a rapid and yet reasonable manner.

CONCLUSIONS

The effects of site conditions on the recorded ground motions during the 1999 Chi-Chi earthquake were investigated, based on microtremor measurements using arrays of sensors and subsequent analyses. The shear wave velocity profiles at six strong motion stations have been determined from the inversion of both dispersion curves and H/V spectra of the microtremors. Based on the results and discussions, the following conclusions may be made:

(1) At Wufeng (TCU065) where building damage was the most extensive among others, a thick soft surface layer with Vs less than or equal to about 200 m/s overlies a stiff layer with Vs greater than 400 m/s at a depth of about 30 m. At other stations, stiff layers with Vs greater than 300-400 m/s occur from the ground surface or at a depth less than 20 m.

(2) The natural site periods computed from an equivalent linear analysis for the six stations are generally consistent with the spectral peak periods of the response acceleration of the recorded strong motions, but they are considerably longer than those estimated from a linear analysis, regardless of the Vs profile.

(3) The spectral peaks in the short period range of the recorded motions at the stations might have been induced by the amplification of the shallow soils subjected to strong shaking. The local site effects including nonlinear

soil behavior might have had a significant impact on the ground motion and the building damage during the earthquake.

(4) The microtremor techniques using arrays of sensors used in this study are effective in estimating Vs profiles and local site effects in a rapid and yet reasonable manner.

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