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Characteristics of Soil Liquefaction using H/V of Microtremors in Yuan-Lin area, Taiwan

Huey-Chu Huang[1,*] and Yung-Sheng Tseng[1]

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ABSTRACT

The characteristics of soil liquefaction were investigated using the H/V ratios of microtremors in the Yuan-Lin area. Liquefaction at Luen-Ya-Li, Yuan-Lin in central Taiwan was clearly observed with serious sand boils bringing about massive damages during the Chi-Chi earthquake. Based on the H/V ratios calculated from microtremor measurements at 42 points distributed in this area, the predominant frequencies appeared between 0.8-0.9 Hz for the liquefied area, with higher relative amplification factors compared to other areas. In the study, the ground vulnerability index (K_g) values (Nakamura 1996) in the liquefied areas were higher than those in the neighboring areas without liquefaction. This study shows supporting evidence for the first time that the H/V ratios of microtremors can be a good alternative indicator for an area's potential for liquefaction.

(Key words: Soil liquefaction, the Chi-Chi earthquake, H/V ratio, Microtremor measurement, Ground vulnerability index)

1. INTRODUCTION

Devastations caused by earthquakes directly reflect the local geological condition. Although the best approach for understanding these ground conditions is through direct observation, such studies are obviously restricted to areas with relatively high seismicity. Due to constraints such as high rates of seismicity and the availability of an adequate reference site, a wide range of different methods has been applied for site response studies. However, the use of microtremors is invaluable, as it requires no other geological information while estimating the effect of surface geology on seismic motion.

Recently, the H/V technique (Nakamura 1989) is becoming more popular with its data collection facilities and application allowance in areas with low or even zero seismicity. Previous studies had suggested that the vertical component of ambient noise not only maintains the

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[1] Institute of Seismology, National Chung Cheng University, Ming-Hsiung, Chia-Yi, Taiwan, ROC

[*] *Corresponding author address*: Prof. Huey-Chu Huang, Institute of Seismology, National Chung Cheng University, No.160 San-Hsing, Ming-Hsiung, Chia-Yi, 621, Taiwan, ROC
E-mail: seihuey@eq.ccu.edu.tw

characteristics of source to surface ground of sediments, but also is significantly influenced by Rayleigh waves on the sediments. Therefore, they can be used to remove both the source and the Rayleigh wave effects from the horizontal components. This technique is effective in identifying the fundamental resonant frequency of a sedimentary layer while providing amplification factors that are more realistic than those obtained from sediment to rock site ratios. Many researchers (Ohmachi et al. 1991; Lermo et al. 1992; Field and Jacob 1993,1995) have, in fact, shown how such H/V ratios of noise can be used to identify the fundamental resonant frequency and amplification factor of sediments.

Ohmachi et al. (1991) and Lermo and Chávez-García (1994) applied the H/V ratio method to analyze microtremor measurements. Lermo and Chavez-Garcia (1993) used it to assess the empirical transfer function of the intense S-wave, part of an earthquake record, obtained from three cities in Mexico. Their results clearly indicated that the H/V ratio could provide a robust estimate of the frequency and amplitude of the first resonant mode, albeit not of the higher modes. In the meantime, Field and Jacob (1993) and Field et al. (1995) considered the response of sedimentary layers to ambient seismic noise and claimed that the H/V ratio method was an effective and reliable tool to identify the fundamental resonant frequencies of a layered sedimentary basin. Further evidence was given by Suzuki et al. (1995) who used both microtremor and strong-motion data in Hokkaido, Japan, and ascertained that the peak frequency determined by the H/V ratio seemed to correspond with the predominant frequency estimated from the thickness of an alluvial layer. Based on numerical calculations, many other researchers (Lermo and Chavez-Garcia 1993, 1994; Lachet and Bard 1994; Dravinski et al. 1996) have shown that the H/V ratio method is obviously able to predict fundamental resonant frequency well.

The Chi-Chi earthquake (Mw=7.6) in central Taiwan occurred at 1:47 a.m. on September 21, 1999, was triggered by the reactivation of the pre-existing Che-Lung-Pu fault, and generated a rupture more than 105 km in length with a maximum offset of 11m (vertical) and 10m (horizontal). It caused the highest casualties and damages in Taiwan history. The central island experienced extremely high shaking intensities with extensive soil liquefaction in many areas, especially in Yuan-Lin, Wu-Feng and Nan-Tou. Soil liquefaction caused houses to collapse, bridge piers to move and sway, levees to slide and settle, retaining structures to tilt and overturn as well as roadways and farm fields to crack, spread laterally and subside. Su et al. (2000) recently performed a field reconnaissance and preliminary assessment of liquefaction in the Yuan-Lin area, while Ueng et al. (2000) reported the preliminary results of their field investigation, subsurface explorations, in-situ and laboratory tests along with their analyses of soil liquefaction in the same area during the Chi-Chi earthquake. Su and Wang (2000) have done another site investigation and subsequently estimated the liquefaction potential in Yuan-Lin using the SPT (Standard Penetration Test) and CPT (Cone Penetration Test) methods.

However, with only one strong-motion station (TCU110) deployed in the Yuan-Lin area, in order to investigate the site characteristics, it is necessary to conduct dense microtremor measurements covering 42 observation points distributed at Luen-Ya-Li and its vicinity. Based on the strong-motion data at TCU110 and the microtremor data at the 42 sites, we analyzed the site response using the H/V ratio method, and calculated K_g values to estimate the potential for soil liquefaction in the Yuan-Lin area.

2. TECHNIQUE

Site effects, usually considered empirical transfer functions of the surficial layers, are commonly studied by two techniques: the standard spectral ratio and the H/V ratio methods. The standard spectral ratio, S_T, is calculated by dividing the horizontal Fourier spectrum of the ground motions on an alluvium site, S_{HS}, by that recorded on a nearby rock site, S_{HB}. The latter station is taken as the reference station. Thus

$$S_T = \frac{S_{HS}}{S_{HB}}. \tag{1}$$

Following the work of Nakamura (1989), Lermo and Chavez-Garcia (1993) used a spectral ratio E_S to estimate the amplitude effect of the source

$$E_S = \frac{S_{VS}}{S_{VB}}, \tag{2}$$

where S_{VS} and S_{VB} are, respectively, the Fourier spectra of the vertical motions on the surface and those on the bedrock at a certain depth. Nakamura (1989) assumed that the vertical component of the microtremor spectrum was not amplified by low-velocity surface layers, and he estimated the effect of Rayleigh waves on the vertical components of the tremors by evaluating E_S. He proposed that if the effect of the Rayleigh waves was the same on the vertical and horizontal components, then E_S could be used to eliminate the effect of the Rayleigh waves on the transfer function. In applying this to compensate for the source effect (E_S), Lermo and Chávez-García (1993) introduced a modified site effect function (S_{TT}), namely

$$S_{TT} = \frac{S_T}{E_S}, \tag{3}$$

which is equivalent to

$$S_{TT} = \left(\frac{S_{HS}}{S_{VS}}\right) \Big/ \left(\frac{S_{HB}}{S_{VB}}\right). \tag{4}$$

Nakamura (1989) also pointed out that the ratio, $S_{HB} : S_{VB}$, was nearly 1 which he obtained by examining microtremor measurements in a borehole. Recently, Huang and Teng (1999) examined the ratio using microtremors and earthquake recordings at a bedrock site in Chiawan, Taiwan. With these empirical checks, it was assumed here that a reasonable estimate of the modified site effect function could be determined from

$$S_{TT} = \frac{S_{HS}}{S_{VS}}. \tag{5}$$

This suggests that the H/V ratio, as defined by this transfer function, can be obtained solely from the motions on the surface, which obviously makes it easier to estimate the characteristics of ground motion. By employing the H/V ratio, we were able to determine the predominant frequency (F_p) and the amplification factor (A_p) of the site. Nakamura (1996) also proposed the vulnerability index " K_g value" as a means to determine the extent of liquefaction. The K_g value is simply derived from strains of ground and structures (Nakamura 1996, 1997, 2000). It can be defined as

$$K_g = \frac{A_P^2}{F_P}. \tag{6}$$

In this study, we determined the site characteristics of the Yuan-Lin area using the H/V of microtremors and the K_g values to predict the potential for soil liquefaction at the site.

3. DATA AND SITES

A dense strong-motion observatory network consisting of 150 stations (coded as TCUxxx where xxx represents the station number) in central Taiwan was deployed by the Central Weather Bureau (CWB) some ten years ago. Among the 150 stations, only one (TCU110) locates in the Yuan-Lin area. The Chi-Chi earthquake (Mw=7.6) in the early morning of 21 September 1999 caused extensive damages and liquefaction with severe sand boils at several locations in the Yuan-Lin area of Chang-Hua county.

Many reliable strong motion data sets recorded during the Chi-Chi earthquake allowed us to compare site responses of the strong motion event with weak motion events recorded at TCU110 during 1993-1998 period. Figure 1 shows the epicenter of the Chi-Chi mainshock (marked with a star) and three weak-motion events (labeled 1, 2 and 3) recorded by TCU110 and TCU120. TCU120 was chosen as the reference site. In order to assess the site response, we extracted the intense S-waves with a cosine taper at a 20-sec length for the 921 mainshock and at a 10-sec length for all other ground motions. Furthermore, we applied the 0.25Hz Hanning smoothing technique for the H/V ratio calculations to avoid pseudopeaks caused by spectral holes.

To understand the characteristics of soil liquefaction in the Yuan-Lin area, we made dense microtremor measurements at 42 sites in Luen-Ya-Li and its neighboring area using the hand-type seismocorder system (SPC-51) and three-component velocity sensors (VSE-15D) with a sensitivity range of 0.1~70 Hz. Figure 2 shows the location distribution of the 42 measured points (Y01~Y42 where Y01 represents microtremor station YAN001, and so on) with the dark triangular symbols indicating the sites with obvious liquefaction. Sites Y01~Y04 located in Luen-Ya-Li have massive sand boils. Serious damages to buildings due to soil liquefaction were also observed at sites Y09 and Y10. The microtremor point Y24 is close to the strong-motion station TCU110.

Velocity data were recorded at a rate of 200 samples per second on a permanent 16-bit, 16-channel data acquisition system. At each observation point, the microtremor measurements were continuously recorded for thirty minutes, and the records were divided into several 40-sec segments. We calculated the Fourier spectra for these segments and then smoothed the spectra by using a 0.25Hz Hanning window. In the next stage, the spectral ratios between the horizontal and vertical components were computed.

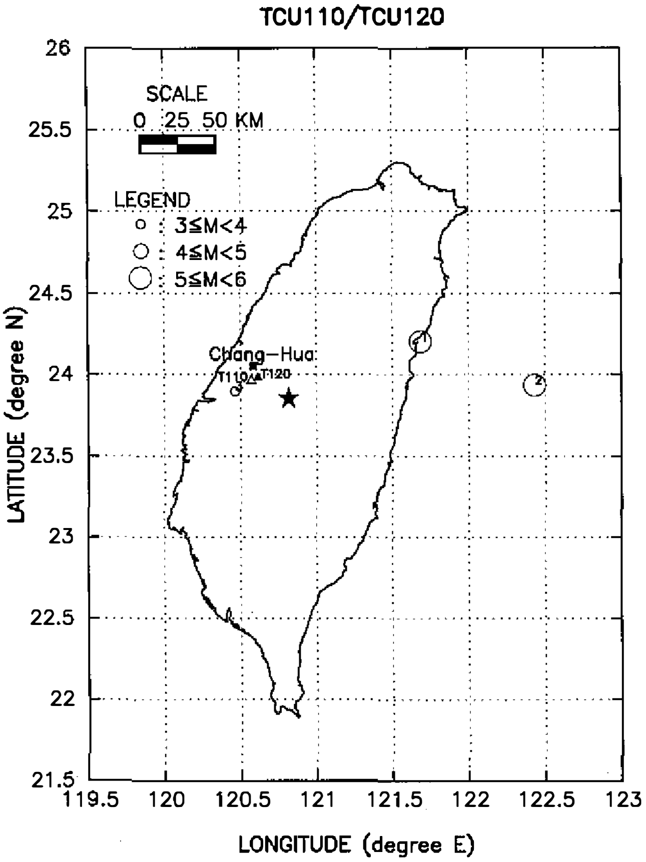


Fig. 1. Location of stations TCU110 (open triangular symbol), reference site TCU120 (dark triangular symbol), the epicenter of the 921 mainshock (Mw=7.6, marked with a star) and three weak-motion events (labeled 1, 2 and 3) recorded by TCU110 and TCU120.

Yuan-Lin locates at the alluvial fan of the Cho-Shui Stream (Fig. 3). According to borehole data by the Central Geological Survey (Chiang et al. 1999), the Yuan-Lin area is mostly on an alluvial structure chiefly composed of silt, mud, clay and sand (very coarse, coarse and medium), and the depth of basement gradually increases from east to west. The S-wave velocity at the depth of 0-30m is from 100 m/sec to 250 m/sec and increased to 600 m/sec at the 100m of depth. According to Ueng et al. (2000), the minimum SPT-N value may have dropped to 2 after the Chi-Chi earthquake. In general, the ground water levels are usually high with depths of 0.5m to 4.0m in this area (Su and Wang 2000).

4. RESULTS AND DISCUSSION

4.1 Comparison of Strong and Weak Motion Events

Based on the high-quality strong-motion recordings, the H/V ratio method was first examined by comparing it to the traditional spectral ratio method. The H/V ratio (thick line) at station TCU110 (a soil site) and the spectral ratio (TCU110/TCU120, thin line) are shown in Fig. 4. Station TCU120 was chosen as the reference site. These results were obtained using the S-wave windows for the three events shown in Fig. 1. Basically, the predominant frequency

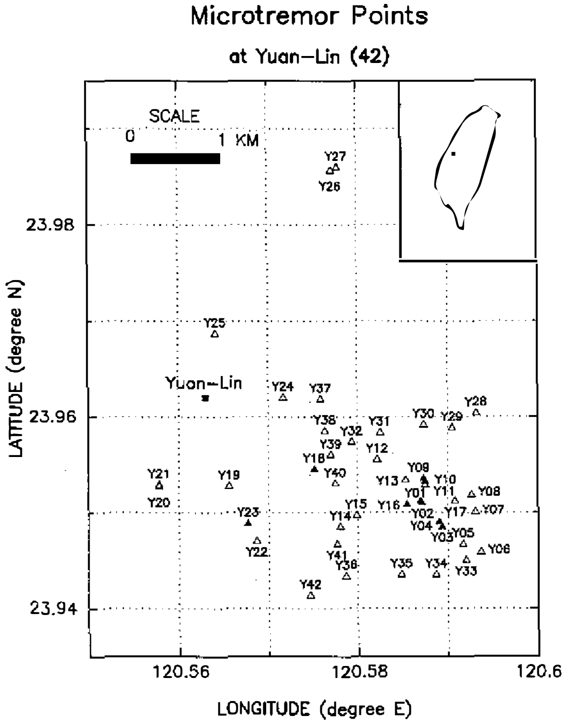


Fig. 2. Location distribution of 42 measured points (Y01~Y42) in the Luen-Ya-Li area of Yuan-Lin and its vicinity. The dark triangular symbols represent the sites with obvious liquefaction. Sites Y01~Y04 located in Luen-Ya-Li have massive sand boils. Serious damage to buildings due to soil liquefaction was also observed at sites Y09 and Y10.

estimated from both methods is close at about 0.8~0.9 Hz, and their trends are similar. On account of the Chi-Chi mainshock, the PGA values at most strong-motion stations are larger than those recorded during the earlier 1993-1998 period. The site responses between the strong and weak motions at station TCU110 were also compared. Figure 5 compares the averaged H/V ratios between the 921 mainshock (thin lines) and the weak-motion events (thick lines) at station TCU110. The PGA values triggered by the 921 event are larger than 0.18g. Apparently, the predominant frequency caused by the Chi-Chi mainshock (a strong event) shifts to a lower value when compared with that of weak-motion events. This phenomenon indicates that the site probably produced nonlinear behavior.

4.2 Microtremor Measurements

In order to investigate the characteristics of soil liquefaction, as mentioned earlier, we did dense microtremor measurements at the 42 sites distributed in Luen-Ya-Li and its neighboring area of Yuan-Lin (Fig. 2). According to Huang (2002), when compared, the predominant frequencies of the microtremor data and those of the earthquake recordings are similar at most stations although the amplification factors estimated from the microtremor data show lower values. Similar results appear at TCU stations. We compared the H/V ratios between the earthquake recording and the microtremor data at TCU110. In Fig. 6, the predominant frequency individually estimated from microtremors and earthquake data is respectively about 1 Hz and 0.85 Hz.

In order to understand the variations in the H/V ratios in this area, we selected 10 sites

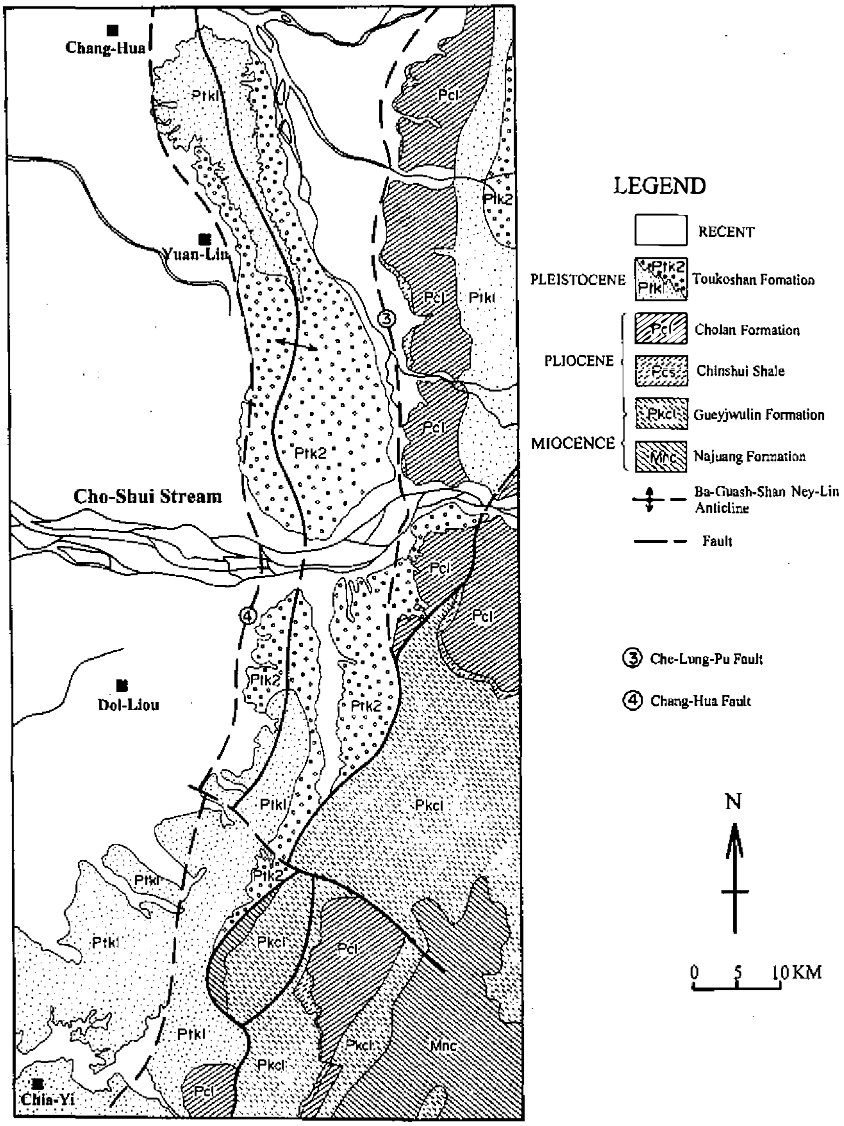


Fig. 3. Map sketching the geology of the middle reaches of the Cho-Shui Stream. The Yuan-Lin area is located at the alluvial fan of the Cho-Shui Stream (revised from Chiang et al. 1999).

among the 42 measured points that are aligned in the NW-SE direction. Figure 7 shows the RMS results of the H/V ratios at these 10 sites (Y06-Y24). Site names are simplified; for example, YAN001 in Fig. 7 is shown as Y01 in Fig. 2. Most of the predominant frequencies are between 0.8 and 1.0, while their amplification factors range from 2.5 to 3.3. Based on the results in Fig. 7, the predominant frequencies (F_p), amplification factors (A_p) and K_g values along the line are shown in Figs. 8(a), (b) and (c), respectively. It is evident that there are

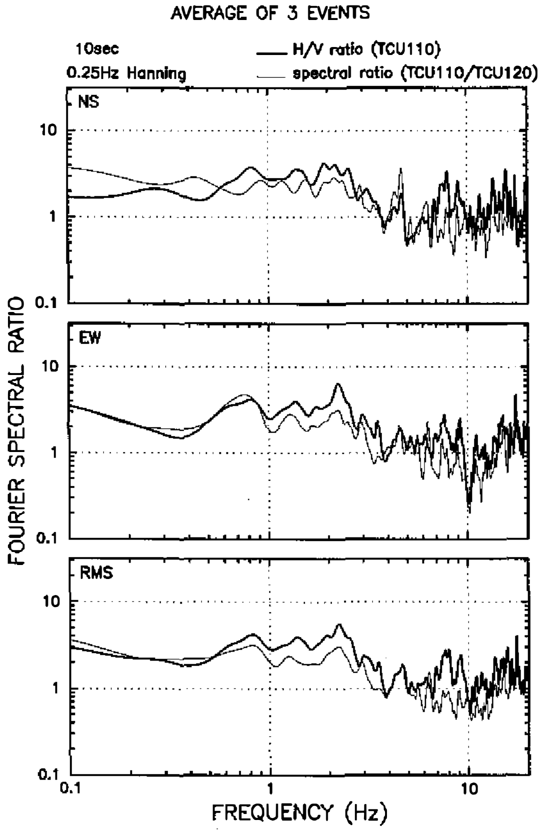


Fig. 4. Comparison of the averaged H/V ratios (thick lines) at TCU110 and the averaged spectral ratios (thin lines, TCU110/TCU120). TCU120 was selected as the reference station. The three panels represent the NS, EW components and their corresponding RMS results. The results of the two methods are similar.

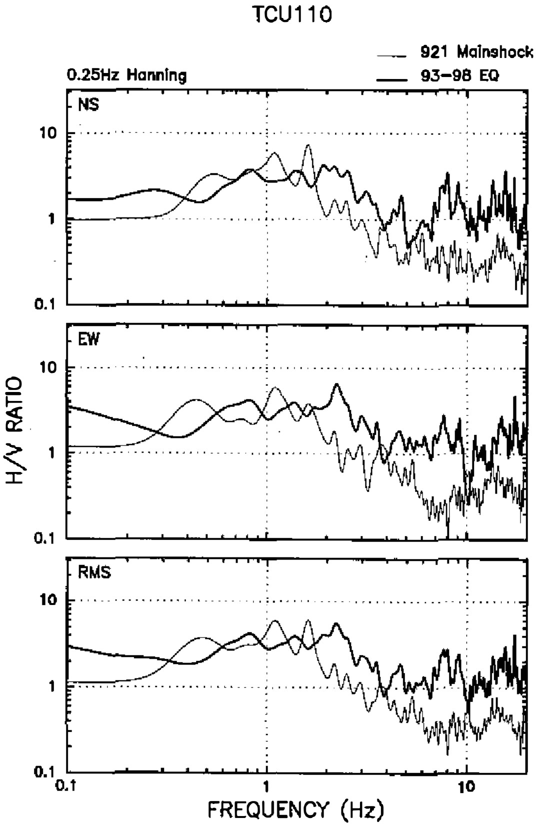


Fig. 5. Comparison of the averaged H/V ratios between the 921 mainshock (thin lines) and the weak-motion events (thick lines) at station TCU110. The three panels represent the NS, EW components and their corresponding RMS results. The predominant frequency caused by the Chi-Chi mainshock shifts to lower value when compared with that of weak motions.

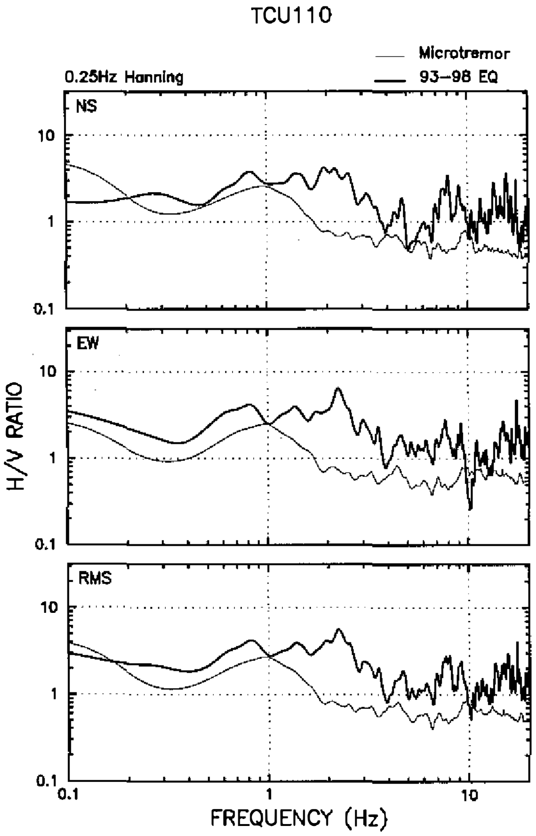


Fig. 6. Comparison of the averaged H/V ratios between the microtremor data (thin lines) and the weak-motion events (thick lines) at station TCU110. The three panels represent the NS, EW components and their corresponding RMS results.

higher amplification factors but relatively lower predominant frequencies at sites Y09 and Y01, which explains why larger K_g values appear at these two stations. In fact, serious liquefaction with sand boils was observed and caused houses to collapse at these sites during the Chi-Chi earthquake. However, site Y06 near the mountain area has the highest predominant frequency and the lowest amplification factor; thus, the K_g value is at its lowest at these sites. From these observations, it is reasonable to conclude that K_g is clearly a value which corresponds to the site and can be considered as vulnerability index of that site, an indicator which might be useful in selecting weak points of ground especially in liquefied areas.

The predominant frequencies and the relative amplification factors at the 42 measured points are shown in Figs. 9 and 10, respectively. Obviously, the liquefied areas have lower predominant frequencies (0.7~1.0Hz) and higher amplification factors (above 2.5). By contrast, the higher predominant frequencies (above 1.5Hz) and smaller amplification factors (near 2.0) appear at the eastern region or near the mountain area.

By employing the predominant frequencies and the amplification factors, we were able to calculate the K_g values as shown in Fig. 11. The higher K_g values (above 10) are concentrated in the liquefied area. Based on the estimations from the H/V ratio of microtremors in Fig. 11, a contour map of the Yuan-Lin area is shown in Fig. 12. Generally speaking, the results calculated from the H/V ratio method of microtremor data analysis and the results incorporating

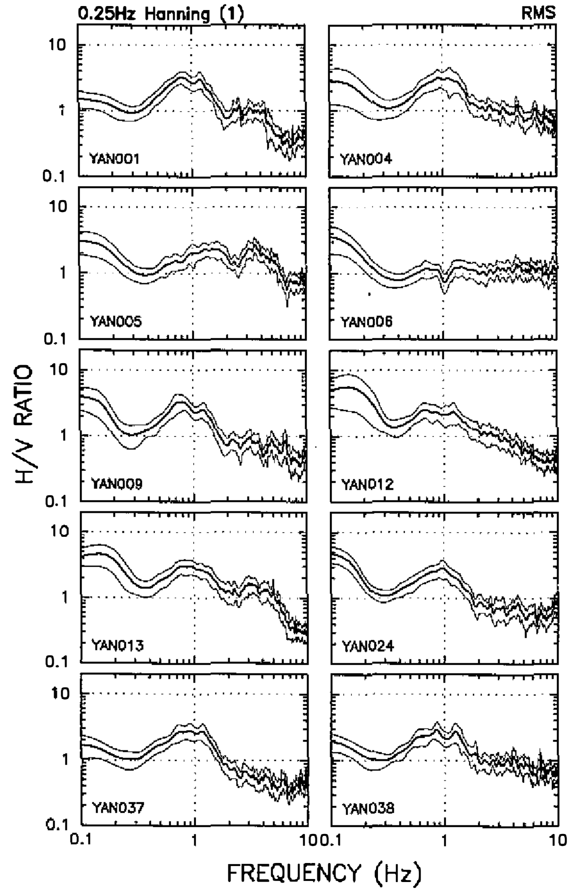


Fig. 7. Comparison of the RMS component of the averaged H/V ratios using microtremor data at 10 (Y06-Y24) of the 42 measured points. Except for YAN005 and YAN006, most of the predominant frequencies are between 0.8 and 1.0.

with the liquefaction potential index match well with liquefaction evidence from field investigations.

5. CONCLUSIONS

The intensity of shaking in the central part of Taiwan was very high during the Chi-Chi earthquake, and extensive liquefaction occurred in many areas. Especially hard hit were the towns of Yuan-Lin, Wu-Feng and Nan-Tou. The liquefaction potential using the SPT-N and the CPT methods has been analyzed and compared in many studies. This study proposed another convenient technique for the first time to examine liquefaction potential. We investigated the characteristics of soil liquefaction using the H/V of microtremors. The dense microtremor measurements made at the 42 points mainly distributed at Luen-Ya-Li, Yuan-Lin. From the H/V ratios of microtremors, the predominant frequencies of the liquefied areas are concentrated at about 0.8-0.9 Hz. The relative amplification factors are also higher than in other areas. Based on the predominant frequencies and their amplification factors, one important parameter, K_g, could further be determined to assess the occurrence of liquefaction. In this study, the K_g values in the liquefied areas are higher than those in neighboring areas without

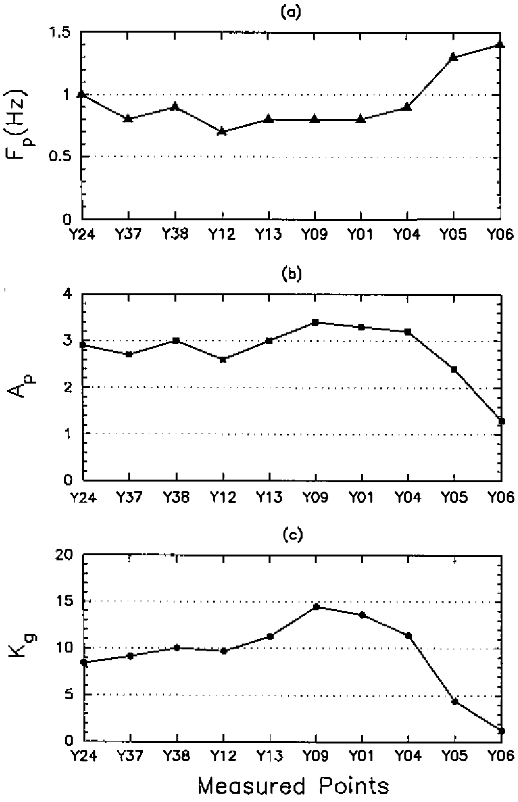


Fig. 8. Comparison of (a) predominant frequencies (F_p), (b) amplification factors (A_p) and (c) K_g values at the 10 measured stations (Y06-Y24). The maximum A_p and K_g values appear at station Y09, while the minimum A_p and K_g values are at station Y06.

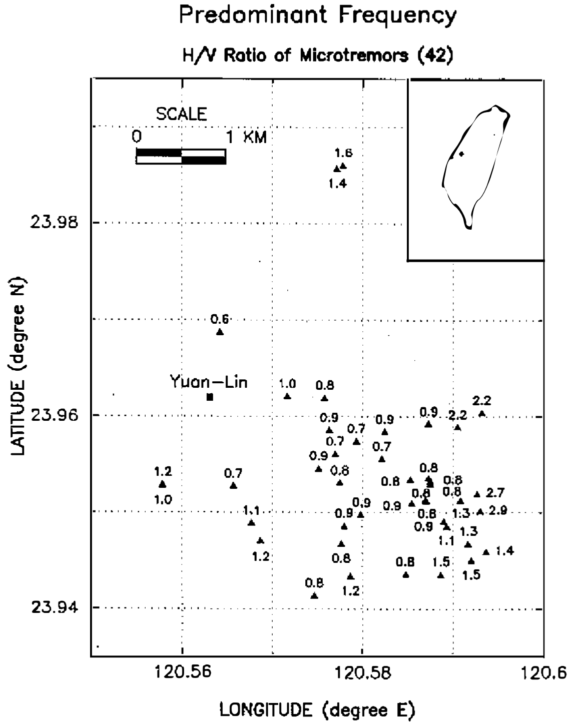


Fig. 9. Distribution map of the predominant frequencies estimated by the averaged H/V ratios of microtremors at the 42 measured points. Except for a few sites at the eastern side of the area, most of the predominant frequencies are between 0.7 and 0.9.

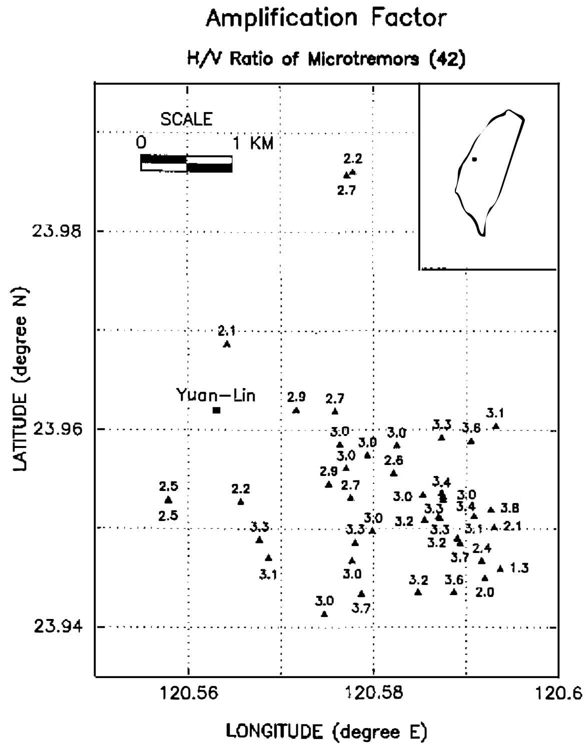


Fig. 10. Distribution map of the amplification factors of the predominant frequencies at the 42 measured points.

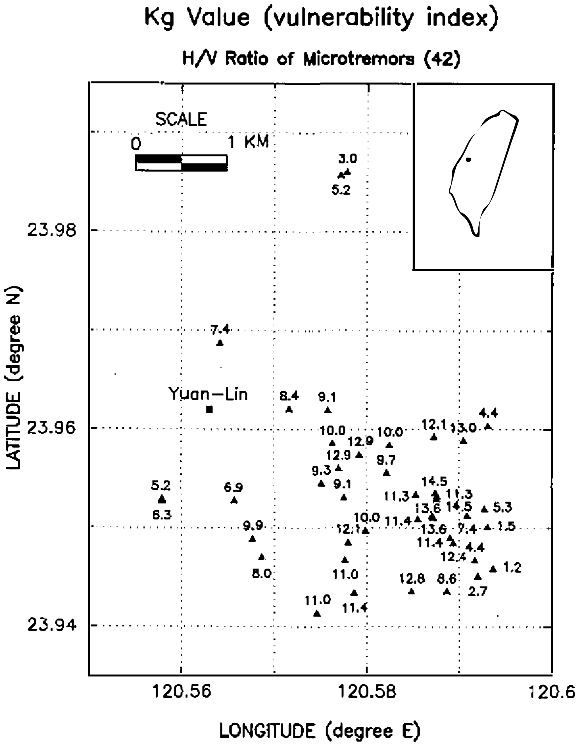
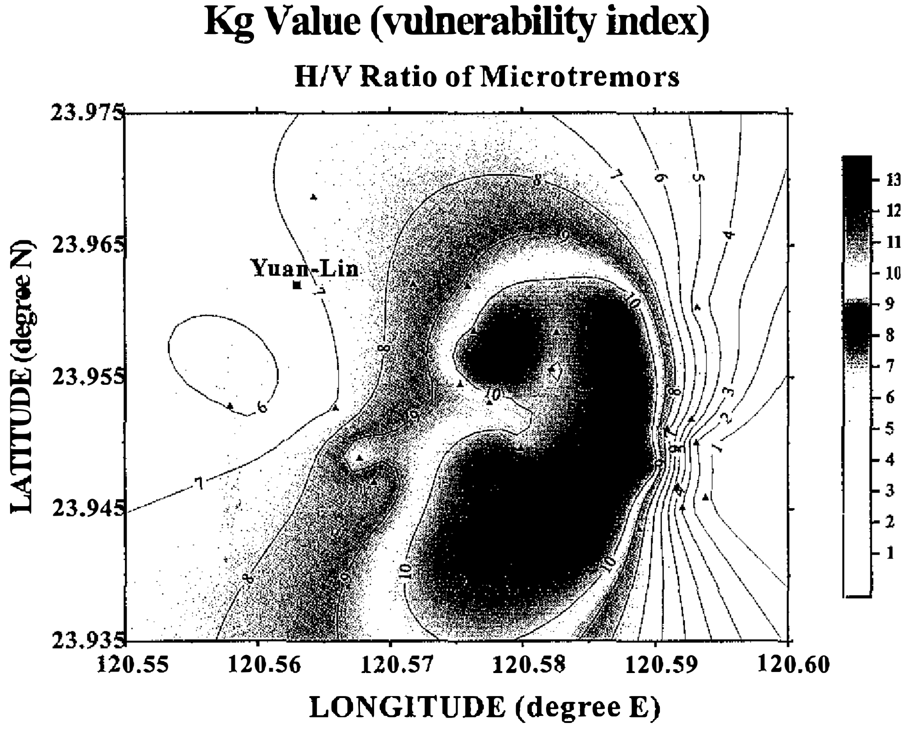


Fig. 11. Distribution map of the K_g values, a vulnerability index of a site, at the 42 measured points. The higher K_g values (above 10) are concentrated in liquefied areas.


Kg Value (vulnerability index)

H/V Ratio of Microtremors

Fig. 12. Contour map of the K_g values, based on the results of Fig. 11, in the Yuan-Lin area. The small dark triangular symbols represent the stations used. The higher K_g values appear in the Luen-Ya-Li area.

liquefaction. This indicates that the H/V of microtremors offers a good alternative for the estimation of an area's potential for liquefaction.

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