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Water Level Fluctuations Induced by Ground Motions of Local and Teleseismic Earthquakes at Two Wells in Hualien, Eastern Taiwan

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ABSTRACT

Water level in wells often fluctuates in response to changes of volumetric strains caused by tectonic deformation or by passage of seismic waves. Continuous monitoring of water level fluctuations in two wells, coded HLC-05 and HLC-03, in the Hualien area of eastern Taiwan has been made since 2002 by digital recorders with high sampling rates at 1- and 6-second intervals. The data thus far show that water level fluctuations are often induced by earthquakes. The results can be summarized as follows: 1. Observable water level fluctuations can be induced by earthquakes of magnitude $M \geq 0.43 + 2.39\ \log_{10}D$, where D is the hypocenter distance from the well; 2. the peak water level fluctuation (PWL) is linearly proportional to either the peak ground velocity (PGV) or peak ground displacement (PGD) on logarithmic scales. However, no clear trends with peak ground acceleration (PGA) are found. The empirical relationships for local earthquakes between PWL and PGV, and between PWL and PGD, respectively, as obtained by regression are as follows:

For the HLC-05 well:

$$\ln(\mathrm{PWL}) = 0.83 \times \ln(\mathrm{PGV_H}) - 3.22 \quad ,$$
$$\ln(\mathrm{PWL}) = 0.97 \times \ln(\mathrm{PGV_V}) - 2.27 \quad ,$$
$$\ln(\mathrm{PWL}) = 0.80 \times \ln(\mathrm{PGD_H}) - 1.70 \quad ,$$
$$\ln(\mathrm{PWL}) = 0.91 \times \ln(\mathrm{PGD_V}) - 0.83 \quad ,$$

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For the HLC-03 well:

$$\ln(\mathrm{PWL}) = 0.73 \times \ln(\mathrm{PGV_H}) - 3.29 \quad ,$$
$$\ln(\mathrm{PWL}) = 0.73 \times \ln(\mathrm{PGV_V}) - 2.65 \quad ,$$
$$\ln(\mathrm{PWL}) = 0.53 \times \ln(\mathrm{PGD_H}) - 2.44 \quad ,$$
$$\ln(\mathrm{PWL}) = 0.57 \times \ln(\mathrm{PGD_V}) - 1.93 \quad ,$$

where the subscripts H and V denote the horizontal and the vertical component of ground motion, respectively.

Similar relationships for teleseismic earthquakes are as follows:

For the HLC-05 well:

$$\ln(\mathrm{PWL}) = 1.01 \times \ln(\mathrm{PGV}) + 2.04 \quad ,$$
$$\ln(\mathrm{PWL}) = 0.95 \times \ln(\mathrm{PGD}) + 0.50 \quad .$$

(Key words: Ground water level fluctuation, Earthquake-induced)

1. INTRODUCTION

Water level fluctuations are often induced by volumetric strain changes around the aquifer caused by various factors such as periodic earth tides, plate movement, seismic events or weather conditions. Seismically induced water level fluctuations are among the most significant (Liu et al. 1989; Roeloffs 1998; Montgomery and Manga 2003), because pore pressure changes may result from pre-, co-, or post-seismic ground deformation due to redistribution of stresses (Grecksch et al. 1999; Lee et al. 2002). Furthermore, passage of seismic waves may temporarily clog or unclog existing fractures in the aquifer of a water well, leading to water level fluctuations in the well (Brodsky et al. 2003). By using high-sampling-rate recorders installed in wells, water level fluctuations induced by seismic waves can be easily monitored.

In this study, we focus on water level fluctuations at two wells, HLC-05 and HLC-03, which are induced by the passage of seismic waves generated either by local earthquakes at distances out to a few hundred kilometers, or by teleseismic earthquakes at several thousand kilometers away from the wells. Since these wells are located in the highly seismic area of Hualien, eastern Taiwan, a total of 21 and 15 local earthquakes have been recorded since 2002 at the HLC-05 and HLC-03 wells, respectively. Water level fluctuations due to two great, teleseismic earthquakes on December 26, 2004 and March 28, 2005 off Sumatra Island, are also recorded.

In order to better fit our observational data we have refined the formula, which shows susceptibility of water level fluctuations in wells as a function of earthquake magnitude M and hypocenter distance D. Previous empirical susceptibility formulas were obtained based on data from wells in Japan by Matsumoto and Takahashi (1994) and Mogi et al. (1989).

Furthermore, we have used the seismic records obtained at two nearby strong motion stations (HWA050 and HWA061) by the Central Weather Bureau (CWB), and at a broadband seismic station (NACB) by the Institute of Earth Sciences, Academia Sinica, to correlate water level fluctuations in the two water wells with seismic ground motions. Linear relations on a logarithmic scale between the peak water level fluctuations (PWL) and peak ground velocity (PGV), or peak ground displacement (PGD), are obtained by regression of the data from local and teleseismic earthquakes.

2. GEOLOGIC LOGS OF THE TWO GROUND WATER WELLS

The two ground water wells, shown as HLC-03 and HLC-05 in Fig. 1a, have been instrumented to monitor water level fluctuations since February 2002 and March 2002, respectively.

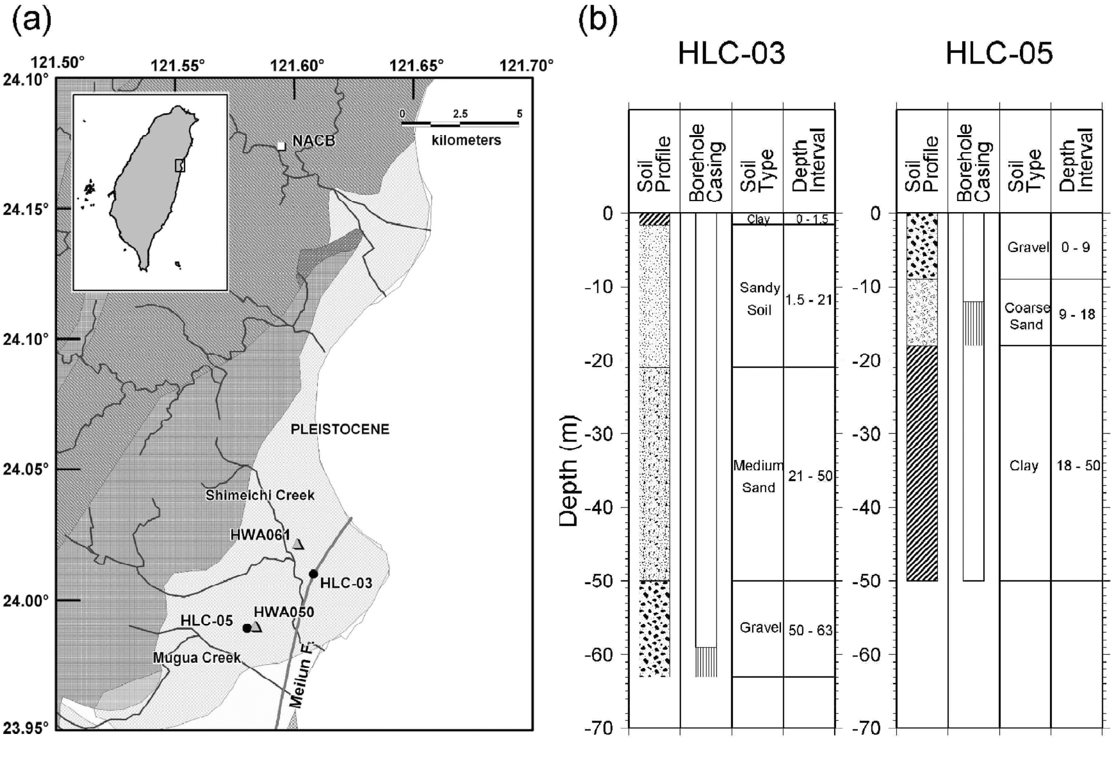


Fig. 1. (a) Locations of the HLC-03 and HLC-05 water wells, the HWA050 and HWA061 strong motion stations (CWB), and the NACB broadband seismic station (BATS) in the Hualien area of eastern Taiwan. (b) The geologic logs of the HLC-03 and HLC-05 wells.

Relevant information about the two wells is tabulated in Table 1. The screens are located at depths of 59 - 63 m in the HLC-03 well and at 12 - 18 m in the HLC-05 well, respectively. Geologic logs of the two wells are shown in Fig. 1b. The aquifer of the HLC-03 well near the Shimeichi Creek is overlain by three layers composed of 1.5 m of clay, 19.5 m of sandy soil, and 38 m of medium sand. Meanwhile, the aquifer of the HLC-05 well near the Mugua Creek is overlain by two layers composed of 9 m of gravel and 5 m of coarse sand. It is obvious that the aquifers of both wells are poorly confined, although the HLC-05 well may be slightly better confined by the thick underlying clay layer than the HLC-03 well. The water level is sampled at intervals of one second for the HLC-05 well, and six seconds for the HLC-03 well.

Table 1. Well parameters.

	Well Code	
	HLC-03	HLC-05
Location	(24.01°N, 121.61°E)	(23.99°N, 121.58°E)
Elevation	10.72 m	19.36 m
Well depth	63.12 m	50.00 m
Slotted depth	59-63 m	12-18 m
Drainage	Shimeichi Creek	Mugua Creek
Well bore radius	3.2 cm	3.2 cm

3. EARTHQUAKE MAGNITUDE THRESHOLDS FOR INDUCING GROUND WATER LEVEL FLUCTUATIONS

Susceptibility of water level fluctuations in wells due to seismic ground motions is known to depend on earthquake magnitude and distance. In order to define the susceptibility range earthquakes above local magnitude (M_L) 3 are taken from the earthquake catalogs of the Central Weather Bureau (CWB) for the entire monitoring duration from February 2002 to March 2005.

In Fig. 2, locations of the two wells are shown by triangles. Events accompanied by water level fluctuations are denoted by red, blue and black solid circles, whereas all other earthquakes are shown by gray open circles. The red circles represent the earthquakes that have induced water level fluctuations in the HLC-05 well, the blue ones in the HLC-03 well, and the black ones in both wells. The figure shows that most earthquakes inducing water level fluctuations were located in the regions where the Philippine Sea Plate (PSP) collides with or subducts the Eurasian Continental Plate (ECP), with the exception of only one earthquake in the Central Range to the southwest of the wells.

Previously, Matsumoto and Takahashi (1994) observed water level fluctuations in a well in Japan and found susceptibility of water level fluctuations to be dependent on earthquake magnitude and distance from the well. They obtained the following empirical formula for the magnitude thresholds:

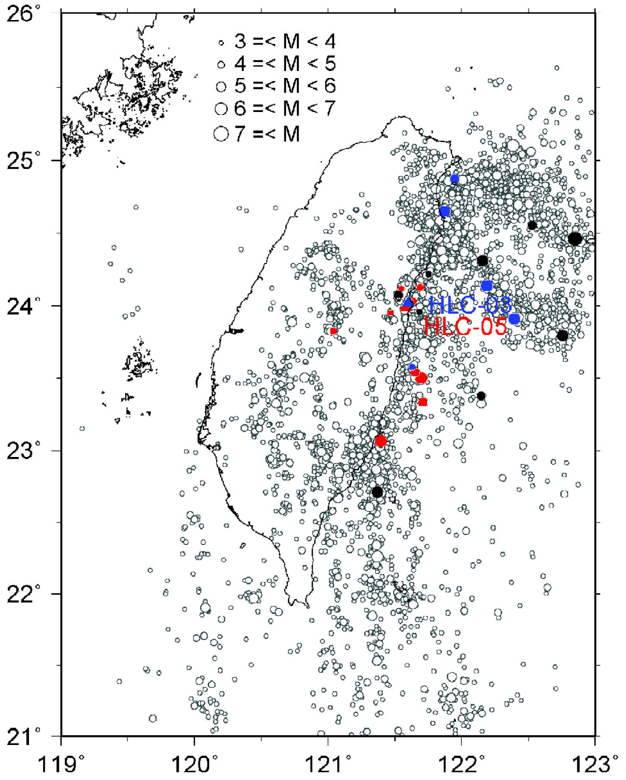


Fig. 2. Distribution of $M \geq 3$ earthquakes in Taiwan since 2002. The earthquakes that have induced water level fluctuations are marked in solid red circles for the HLC-05 well, in solid blue circles for the HLC-03 well, in solid black circles for both wells, and in open circles for all other earthquakes.

$$M \geq 0.69 + 2.45 \log_{10} D \quad , \tag{1}$$

where M and D are the earthquake magnitude and hypocenter distance, respectively. Mogi et al. (1989) also obtained a similar empirical formula based on their observations at the Usami Hot Spring:

$$M \geq 1.3 + 2.2 \log_{10} D \quad . \tag{2}$$

The above two curves are shown in Fig. 3 by the dashed and dotted lines, respectively. These curves show that at a hypocenter distance of 100 km water level fluctuations can be induced by earthquakes with magnitude greater than 5.6. They differ more at smaller distances. Furthermore, these observations also suggest that the susceptibility of water level fluctuations in wells may depend on local geologic conditions, too.

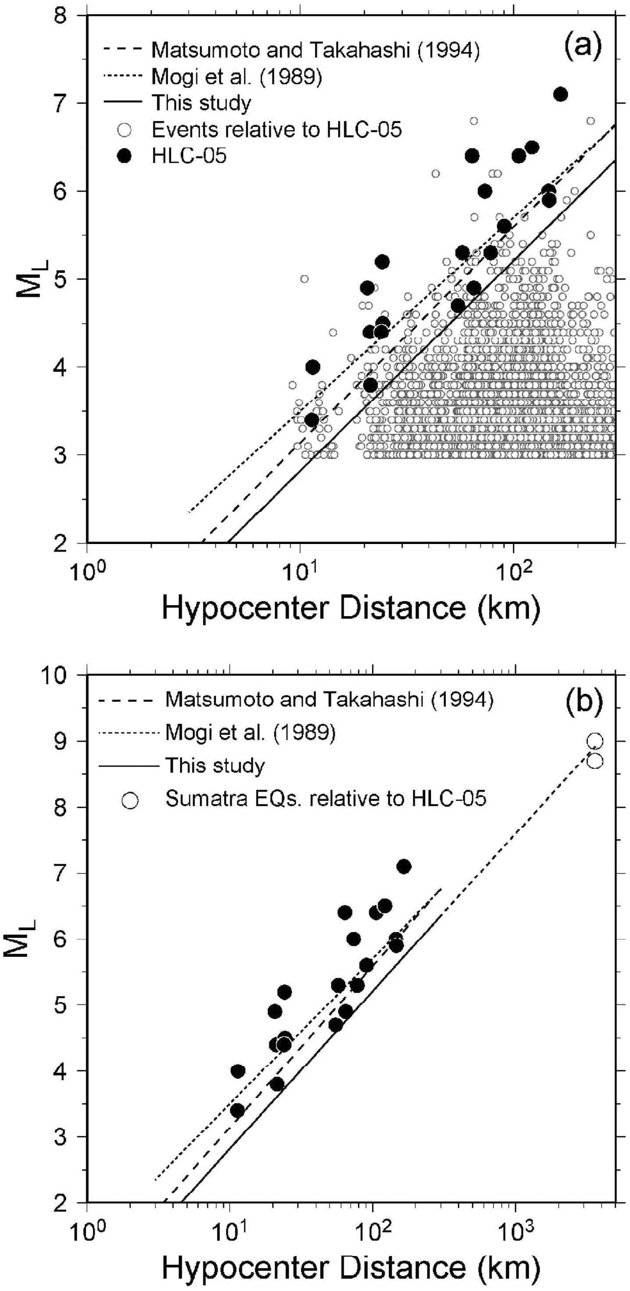


Fig. 3. (a) The magnitude and distance threshold curves for water level fluctuations induced by earthquakes in the HLC-05 well, and by other researchers. (b) Comparison of the revised magnitude and distance threshold curve with local and teleseismic earthquakes.

For the HLC-05 well the data points (solid circles) in Fig. 3a show that only larger earthquakes can induce water level fluctuations in wells at larger hypocenter distances. The results of this study generally agree with those of Matsumoto and Takahashi (1994) and Mogi et al. (1989) (solid circles in Fig. 3a and in Fig. 4). However, some of our earthquakes fall below their curves. From observations in both the HLC-03 and HLC-05 wells the earthquakes that have induced water level fluctuations appear to distribute in similar trends. So we opted to obtain a single susceptibility formula to fit all the data in this study.

We have applied a two-stage approach to find a new formula that fits the data. First, we use a least-squared method to obtain a linear curve passing through all data points. Then we shift the curve downward to ensure that all data points lie above it. The result is as follows:

$$M \geq 0.43 + 2.39 \log_{10} D \quad . \tag{3}$$

There are 148 earthquakes lying above Eq. 3, and only 21 earthquakes have induced water level fluctuations in the HLC-05 well. Meanwhile, there are 166 earthquakes lying above Eq. 3, and only 15 earthquakes have induced water level fluctuations in the HLC-03 well. In other words, the susceptibility rate is 12.7% for the HLC-05 well, and 9.0% for HLC-03. This suggests that only one out of every ten earthquakes above the magnitude threshold curve have actually induced observable water level fluctuations.

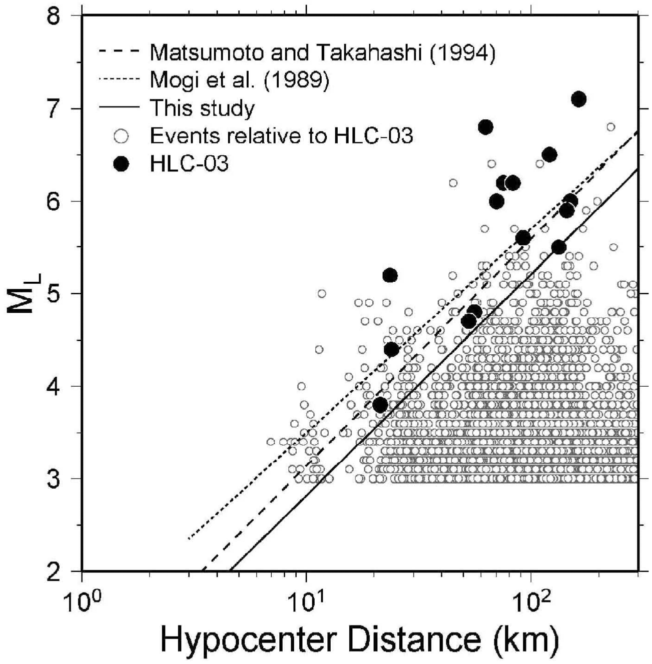


Fig. 4. The magnitude and distance threshold curves for water level fluctuations induced by earthquakes in the HLC-03 well.

Furthermore, the HLC-05 well is slightly more susceptible to earthquake-induced water level fluctuations than the HLC-03 well. As noticed previously, there are some differences in the geologic logs of these two wells. The HLC-05 well may have a better confined aquifer than the HLC-03 well. Previous studies of other wells (e.g., Yu and Mitchell 1988; Roeloffs 1998) have shown that a confined aquifer should be more susceptible to the changes of strains induced by earthquakes. The results of this study seem to agree with previous findings. One additional contributing factor could be the difference in sampling rates at the two wells. The HLC-05 well is recorded at one sample per second, while the HLC-03 well at one sample every six seconds. At a lower sampling rate detailed information of water level fluctuations induced by earthquakes may be missed.

Two teleseismic earthquakes (about 3600 km away from the two wells) with moment magnitude 9.3 and 8.7, respectively, on 26 December 2004 and 28 March 2005 occurred offshore of Sumatra, Indonesia. The former is the main shock, and the latter one is one of its biggest aftershocks. These two earthquakes generated large amplitudes of shear and surface waves that have caused water level fluctuations at the HLC-05 well. High correlation, both in phase and amplitude, between the ground shakings and water level fluctuations at this well is observed. The results will be discussed further in a latter section. As shown in Fig. 3b, the open circles, representing these two teleseismic events, fall right on the extension line of Eq. 3.

4. WATER LEVEL FLUCTUATIONS INDUCED BY SEISMIC GROUND MOTIONS

A. Local Earthquakes

Recorders with high sampling rates can monitor water level fluctuations in wells induced by the passage of seismic waves. As mentioned above, 21 local earthquakes have induced water level fluctuations in the HLC-05 well and 15 events in the HLC-03 well. Figure 5 shows sample records of water level fluctuations induced by an earthquake on 4 February 2004. In the figure, the amplitudes of both traces are normalized for the HLC-05 (red lines) and HLC-03 (blue lines) wells. All the water level records shown in this study have been subtracted by the background trend, which responds to long-term effects of earth tides and rainfalls.

A strong motion station HWA050, deployed by the CWB for monitoring ground shakings at free field, is situated in the vicinity of the two wells (in Fig. 1). The red lines show water level fluctuations and the black lines strong motion seismograms of the HWA050 station for the Z, NS, EW-components from top to bottom, respectively. In this study, the strong motion seismograms are integrated from acceleration records to get velocity and displacement time histories, with a band-pass filter over the frequency band of 0.1 - 5.0 Hz. Clearly, the water level fluctuation records do not resemble any of the seismograms. The *S*-waves of the local earthquake do not generate simultaneously water level fluctuations in the wells. In addition, the oscillatory duration of the water level in the HLC-05 well is almost the same as that of ground shaking lasting about 50 sec, but not in the HLC-03 well.

In Fig. 6, from top to bottom, the black lines show the velocity spectral amplitudes of the Z, NS, EW-components without filtering at the HWA050 station. The scale of amplitude is given on the left hand side. The dotted and dashed curves display the displacement spectral

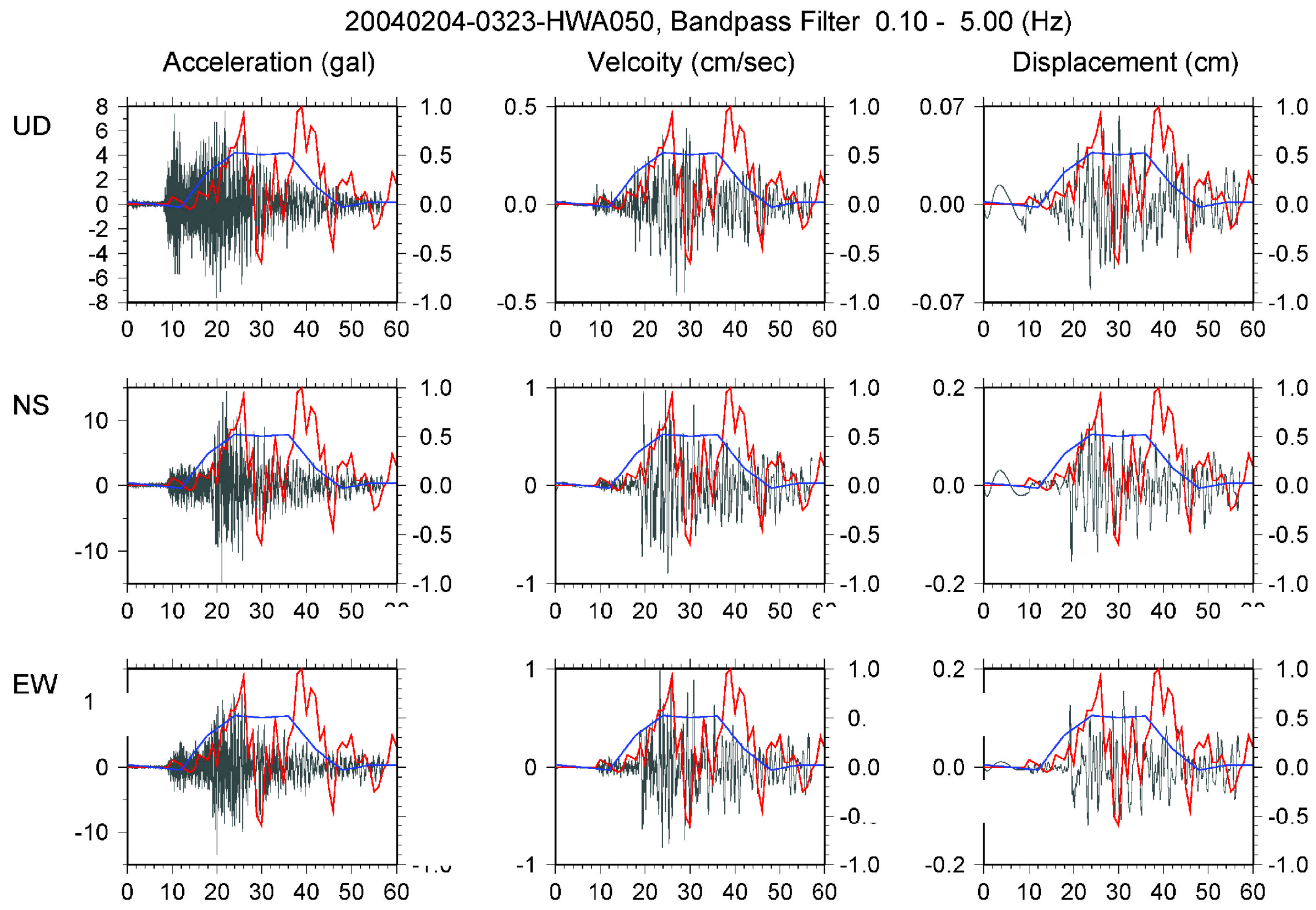


Fig. *5*. Comparison between the seismograms at HWA050 station with the record of normalized water level fluctuations at the HLC-05 well (red lines) and the HLC-03 well (blue lines). The amplitude scales on the left side are for seismograms and on the right side for water level fluctuations.

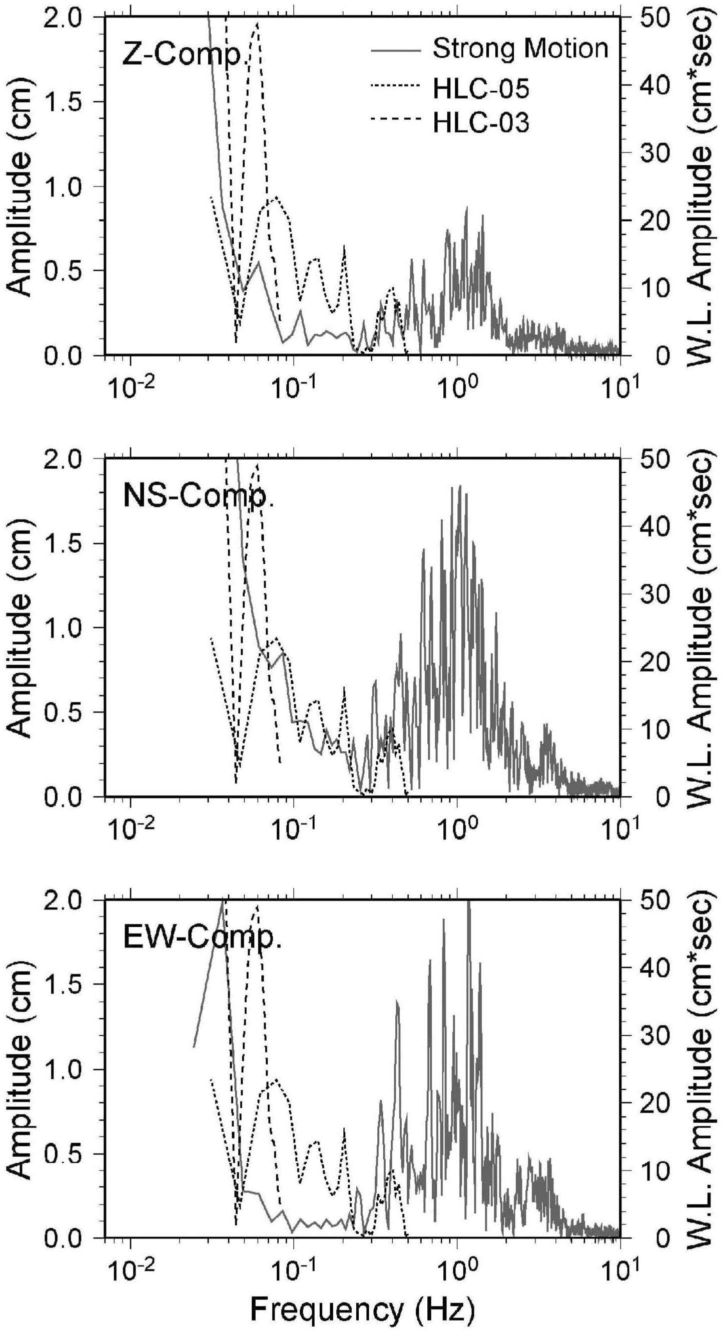


Fig. 6. Comparison of the spectral amplitudes of strong motions at the HWA050 station (black curves), of water level fluctuations at the HLC-05 well (dotted curves) and at the HLC-03 well (dashed curves).

amplitudes of the HLC-05 and HLC-03 wells, respectively, and the scale is given on the right-hand side. The predominant amplitudes of the seismograms are in the frequency range of 0.1 - 5 Hz. We set 0.1 Hz to be the low cut-off frequency of the designed filter because the spectral amplitudes at frequency less than 0.1 Hz tend to lead the waveform to deviate from the base line. The frequencies of predominant water level fluctuations range from 0.03 to 0.5 Hz for the HLC-05 well and from 0.03 to 0.08 Hz for the HLC-03 well. The overlap of significant spectral amplitudes occurs only over a narrow frequency range of 0.03 - 0.5 Hz between the seismograms and the water level fluctuations in the HLC-05 well.

Nevertheless, peak water level fluctuation appears to correlate with peak ground motion. The HWA050 and HWA061 stations, which are equipped with 3-component acceleration recorders by the CWB (cf. Liu et al. 1999), recorded ground shaking in the vicinity of the HLC-05 and HLC-03 wells, respectively. Figure 7 shows, from top to bottom, the plots of peak water level fluctuation (PWL) versus peak ground acceleration (PGA), PWL versus peak ground velocity (PGV), and PWL versus peak ground displacement (PGD). The plots on the left side in Fig. 7 show the data for the HLC-05 well, and the plots on the right side show the data for the HLC-03 well. From Fig. 7, we can see that: (1) the relations between PWL and PGA values do not show any clear trends; (2) PWL values are positively proportional to either PGV or PGD values.

We have used a simple log-log equation to fit the data set by a least-squares method. The results are as follows.

For the HLC-05 well:

$$\ln(\mathrm{PWL}) = 0.83 \times \ln(\mathrm{PGV_H}) - 3.22,\ \rho = 0.96 \tag{4}$$

$$\ln(\mathrm{PWL}) = 0.97 \times \ln(\mathrm{PGV_V}) - 2.27,\ \rho = 0.92 \tag{5}$$

$$\ln(\mathrm{PWL}) = 0.80 \times \ln(\mathrm{PGD_H}) - 1.70,\ \rho = 0.91 \tag{6}$$

$$\ln(\mathrm{PWL}) = 0.91 \times \ln(\mathrm{PGD_V}) - 0.83,\ \rho = 0.84 \tag{7}$$

For the HLC-03 well:

$$\ln(\mathrm{PWL}) = 0.73 \times \ln(\mathrm{PGV_H}) - 3.29,\ \rho = 0.79 \tag{8}$$

$$\ln(\mathrm{PWL}) = 0.73 \times \ln(\mathrm{PGV_V}) - 2.65,\ \rho = 0.74 \tag{9}$$

$$\ln(\mathrm{PWL}) = 0.53 \times \ln(\mathrm{PGD_H}) - 2.44,\ \rho = 0.56 \tag{10}$$

$$\ln(\mathrm{PWL}) = 0.57 \times \ln(\mathrm{PGD_V}) - 1.93,\ \rho = 0.61 \tag{11}$$

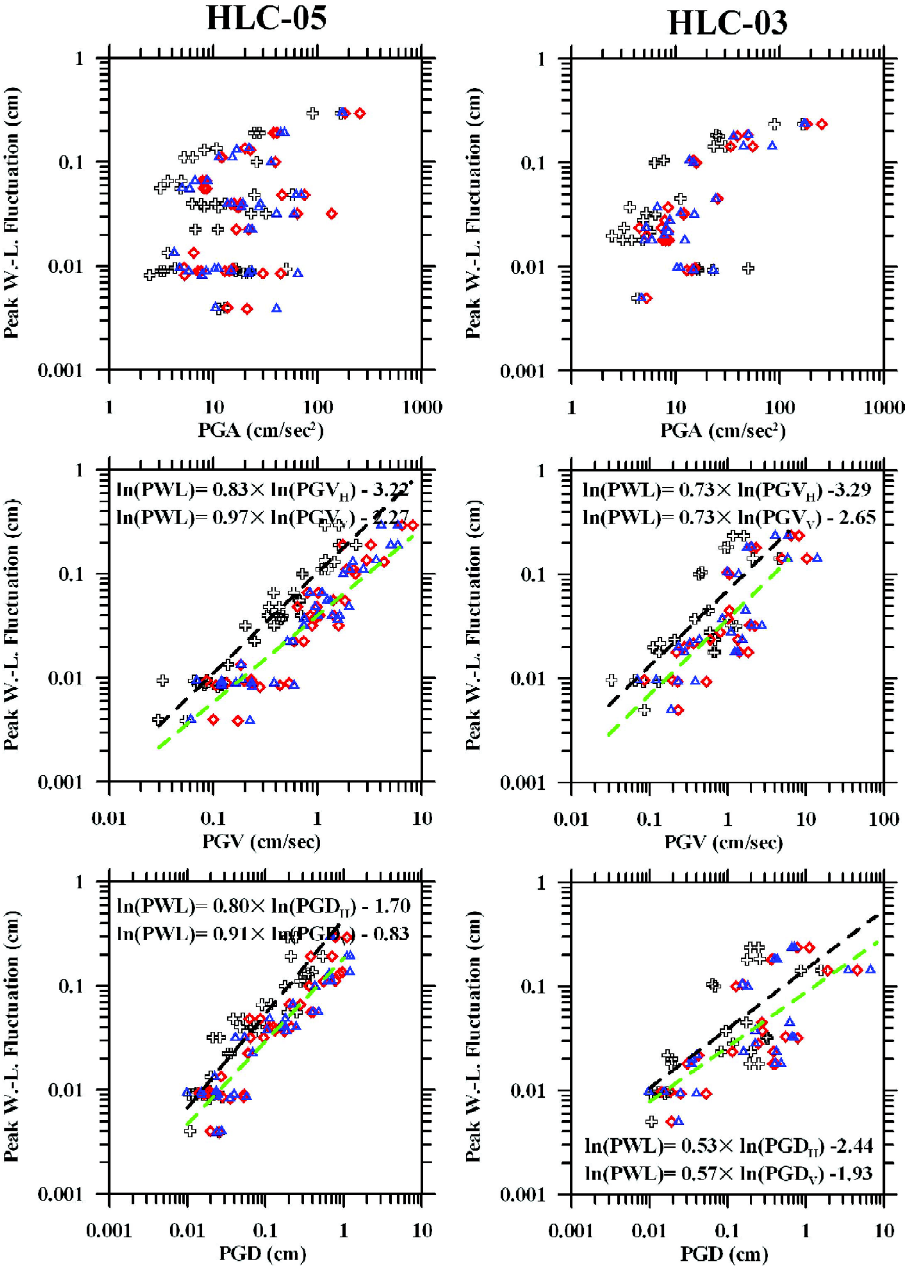


Fig. 7. Comparison between peak water level fluctuation (PWL) and peak ground acceleration (PGA) (Top), peak ground velocity (PGV) (Middle), and peak ground displacement (PGD) (Bottom), for the HLC-05 (Left) and HLC-03 (Right) wells.

where ρ is the correlation coefficient. The subscripts H and V denote the horizontal and vertical components, respectively.

B. Teleseismic Earthquakes

As mentioned above, the 26 December 2004 Sumatra, Indonesia, earthquake with magnitude 9.3 (about 3600 km away from the HLC-05 well) generated large amplitude of shear and surface waves. The passage of seismic waves has induced large water level fluctuations in the HLC-05 well that were digitally recorded for about 40 minutes. The NACB station in the Broadband Array in Taiwan for Seismology (BATS), deployed by the Institute of Earth Sciences, Academia Sinica, is equipped with three-component velocity sensors to record ground motions. The NACB station is about 15 km north of the HLC-05 well.

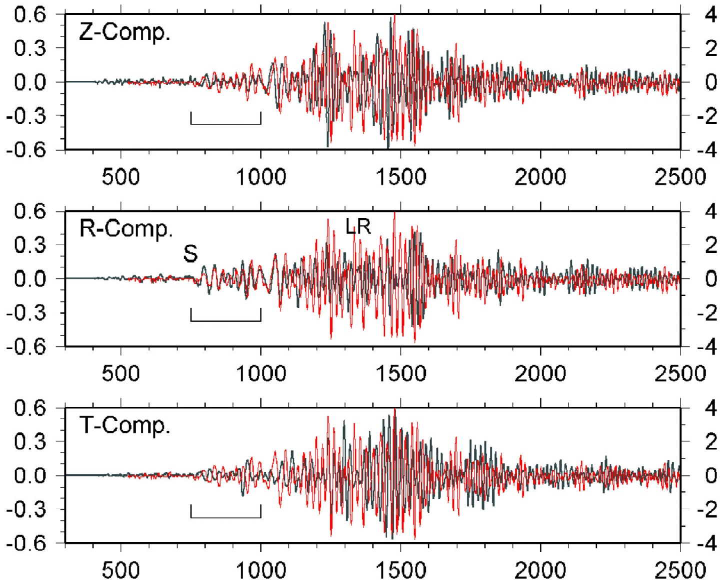
As shown in Fig. 8, the horizontal components of seismograms have been rotated from the original NS and EW directions to the radial (R) and transverse (T) ones. The arrivals of shear waves (*S*) and Rayleigh waves (*LR*) are marked on the traces. Three diagrams from top to bottom in Fig. 8a show the Z, R, and T-components (in black lines), respectively, of ground motion, together with the water level fluctuations (in red lines). It is remarkable that the water level fluctuations and the R-component velocity seismograms match each other almost perfectly in phase over the time range from 500 to 1500 sec, while the other two components (Z and T) of ground motion are out of phase with the water level fluctuations.

A large aftershock of the Sumatra earthquake occurred on 28 March 2005 with magnitude 8.7 also radiated large seismic wave energy, and was recorded at both the HLC-05 well and the NACB station. In Fig. 8b, the black and red lines show ground motions at the NACB station and water level fluctuations in the HLC-05 well, respectively. The *S* and surface wave trains are also marked on the traces. A similar in-phase relationship is observed between the water level fluctuations and the R-component ground motions during the time period from 1000 to 1500 sec.

Figure 9 shows the spectral amplitude of the velocity seismograms (on the left-hand side scale) and of water level fluctuations (on the right-handed side scale) at each plot for the two teleseismic earthquakes. The three plots at the left are for the main shock of the Sumatran earthquake while the aftershock is at the right. In this case, the spectral amplitudes distribute in the same frequency range of 0.01 - 0.1 Hz for both the seismograms and the records of water level fluctuations. The ratio of spectral amplitudes between water level fluctuations and seismograms are about 800 for the main shock and 667 for the aftershock over the frequency range of 0.01 - 0.1 Hz.

As mentioned above, clear surface wave trains follow the clear *S*-wave ones. We pick the peak values of both the *S*-waves and surface waves to compare with the peak water level fluctuations of the corresponding time periods. As shown in Fig. 10, the triangles and diamonds are for the peak values of the two horizontal components and the crosses for the vertical ones. The open and solid symbols represent the *S* and surface waves, respectively, in Fig. 10. The upper diagram shows the relation between PWL and PGV by the red line, along with the black and green dashed lines from the results for local events (Fig. 7). Meanwhile, the bottom diagram represents the relation of PWL and PGD, together with the results of local events. The

(a) 2004/12/26 M_w9.0



(b) 2005/3/28 M_w8.7

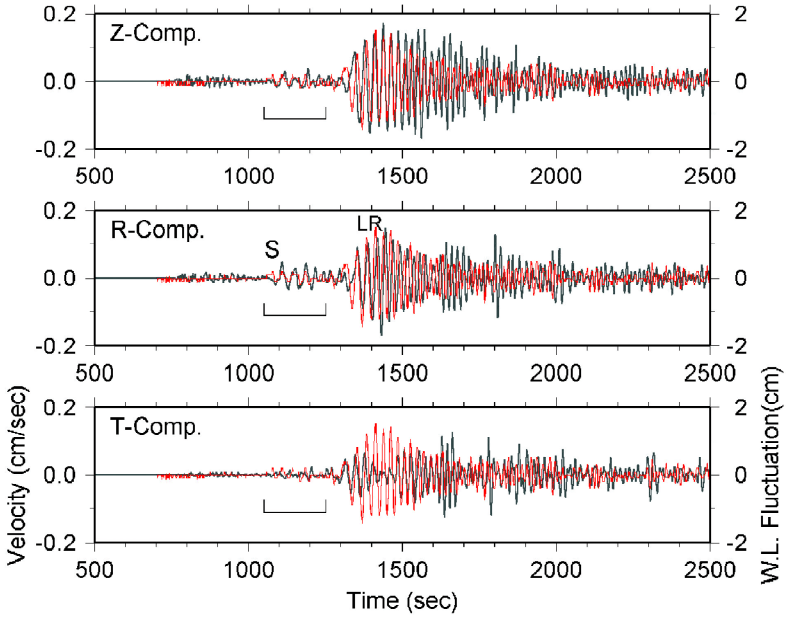


Fig. 8. Comparison of the records of water level fluctuations at the HLC-05 well with seismograms from the NACB broadband seismic station for: (a) the 12/26/2004 M9.3 Sumatra earthquake; (b) the 3/28/2005 M8.7 aftershock.

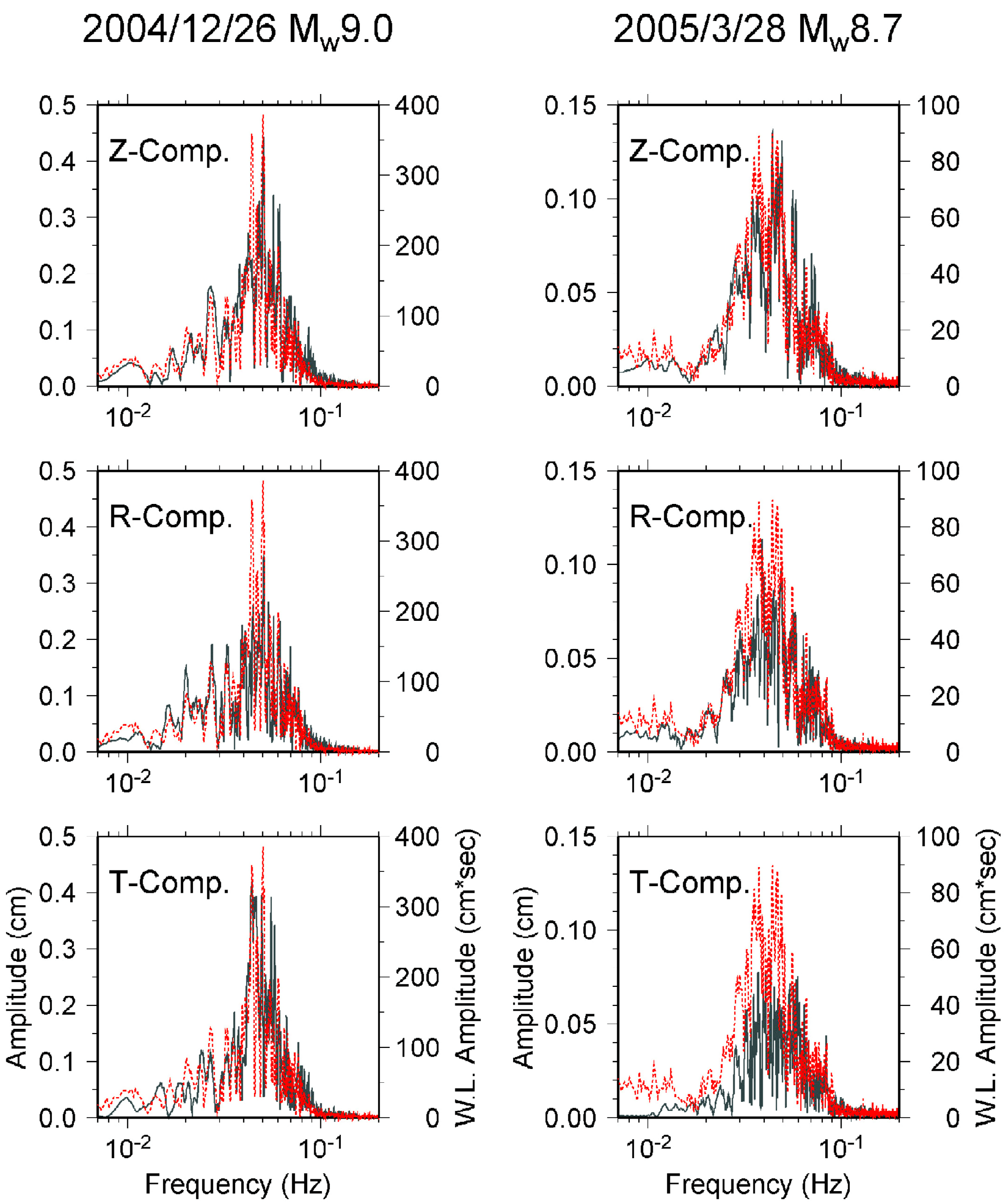


Fig. 9. Comparison of spectral amplitudes of the records of water level fluctuations at the HLC-05 well (red curves) with that of the seismograms from NACB station (black curves) for: Left side: the 12/26/2004 M9.3 Sumatra earthquake; Right side: the 3/28/2005 M8.7 aftershock.

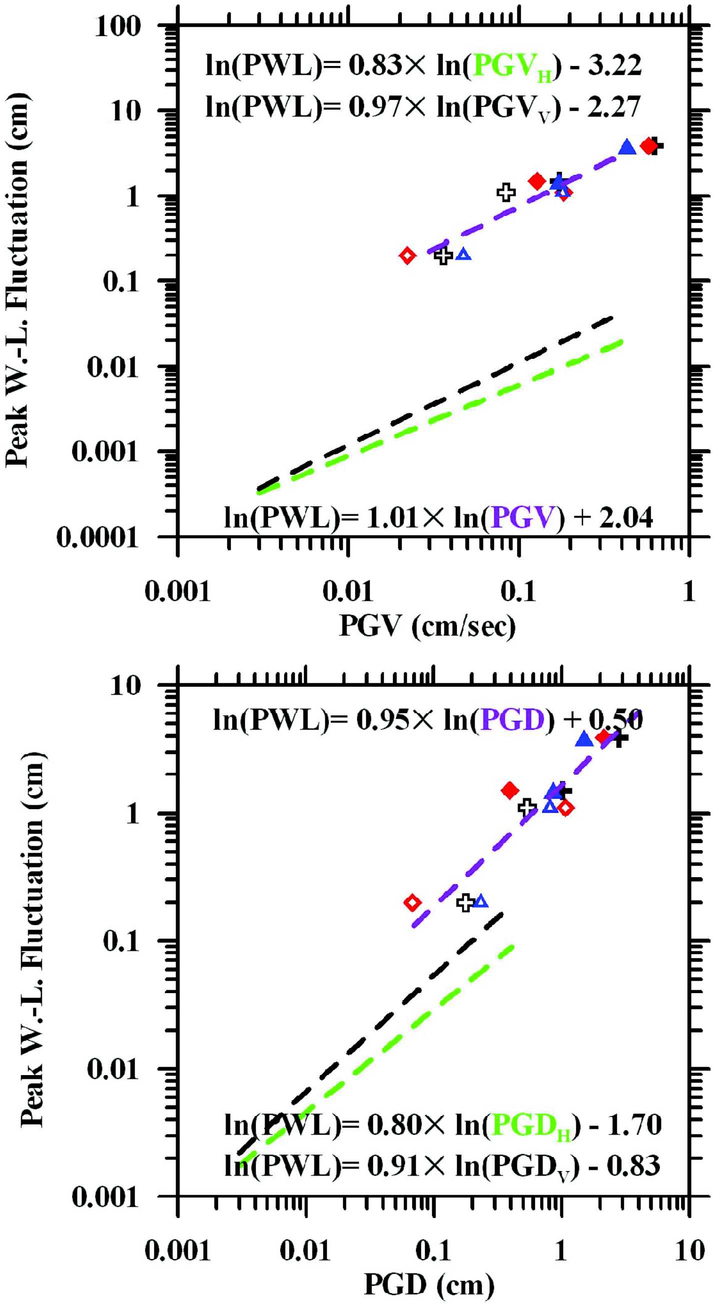


Fig. 10. Comparison of the relations of peak water level fluctuations with peak ground velocity (top) and with peak ground displacement (bottom) between local and teleseismic earthquakes.

difference between the two horizontal and vertical components is not so significant for the teleseismic earthquakes. Evidently, for a given value of either PGV or PGD, teleseismic events can induce much larger PWL values than local earthquakes, because of frequency overlapping in the signals of teleseismic events.

5. CONCLUSIONS AND DISCUSSION

In this study, we have observed that the earthquake-induced water level fluctuations in wells can occur only when the earthquakes are above certain magnitude thresholds. The two wells in the Hualien area, observed in this study, are more susceptible than other wells observed by Matsumoto and Takahashi (1994) or Mogi et al. (1989). A revised formula for the magnitude threshold has been determined in Eq. 3 to fit our data from both the HLC-05 and HLC-03 wells over the monitoring period. The dependence on M and D is aquifer-specific and the difference of susceptibility between the two wells is small. Approximately 90% of earthquakes above Eq. 3, did not induce water level changes in the wells because the ground motion was not strong enough. The focal mechanisms of the 10% of earthquakes, which had induced water level changes, include reverse and strike slip faults, and the focal depths are in the range of 8 - 92 km. It seems that the water level changes do not depend on focal mechanism or focal depth.

No clear correlation between PWL and PGA is found. On the contrary, clear linear relations on a logarithmic scale between PWL and PGV or PGD are found. The correlation coefficient of PWL and PGV is higher than that of PWL and PGD. It is suggested that the changes of strain underneath a specified area, which strongly correlated with the ground velocity, can be proportional to water level changes due to volumetric changes of the aquifer. Larger ground motions, including PGV and PGD, can induce larger water level fluctuations. It seems that the horizontal PGV is the most robust ground motion parameter to correlate with peak water level fluctuation.

As shown in Fig. 10, the same values of either PGV or PGD of the teleseismic earthquakes can induce much larger PWL values than that of local events. Brodsky et al. (2003) showed that the amplification factor $\chi(f)$, as the ratio between water level fluctuation and ground velocity, is a function of frequency that can be represented by:

$$\chi(f) = A\Gamma\left|1 - \frac{4\pi^2 H f^2}{g} + \frac{\pi}{2}\left(\frac{r}{l}\right)^2 \sqrt{\frac{\pi f}{K S_s}}(1+i)\right|^{-1} , \qquad (12)$$

where A is the ratio of the dilatational strain to the vertical ground velocity, Γ is tidal response (Rojstaczer and Agnew 1989), f is frequency, H is the water level height, r is the well bore radius, l is the fracture length, K is hydraulic conductivity, and S_s is specific storage. For the case of NVIP-3 well in America (Brodsky et al. 2003), the $\chi(f)$ reaches a value of about 240 at frequency less than 0.1 Hz and gradually decays to about 40 at frequency greater than

0.1 Hz. Most parameters in Eq. 12 can be obtained from pumping tests. Unfortunately, detailed information is not available for the HLC-05 well, because the original purpose of the well was not for monitoring water level fluctuations. For the HLC-05 well the only two known parameters are the H and r values. Nevertheless, the remaining unknown parameters can be considered constant for a given well during a specified time. Thus the $\chi(f)$ curves will resemble the computation of Brodsky et al. (2003), for which the seismic waves with high frequency contents will result in smaller $\chi(f)$ values than those with low frequency contents. In general, ground motions of teleseismic earthquakes contain greater long-period seismic waves than local ones because of attenuation along the path (Figs. 6 and 9). Hence, greater PWL values can be induced by teleseismic earthquakes than by the local ones.

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REFERENCES

Brodsky, E. E., E. Roeloffs, D. Woodcock, I. Gall, and M. Manga, 2003: A mechanism for sustained groundwater pressure changes induced by distant earthquakes. *J. Geophys. Res.*, **108**, 2390.

Grecksch, G., F. Roth, and H. J. Kmpel, 1999: Coseismic well-level changes due to the 1992 Roermond earthquake compared to static deformation of half-space solutions. *Geophys. J. Int.*, **138**, 470-478.

Lee, M., T. K. Liu, K. F. Ma, and Y. M. Chang, 2002: Coseismic hydrological changes associated with dislocation of September 21, 1999 Chichi earthquake, Taiwan. *Geophys. Res. Lett.*, **29**, 1824.

Liu, K. S., T. C. Shin, and Y. B. Tsai, 1999: A free-field strong motion network in Taiwan: TSMIP. *Terr. Atmos. Ocean. Sci.*, **10**, 337-396.

Liu, L. B., E. Roeloffs, and X. Y. Zheng, 1989: Seismically induced water level fluctuations in the Wali well, Beijing, China. *J. Geophys. Res.*, **94**, 9453-9462.

Matsumoto, N., and M. Takahashi, 1994: State space modeling to detect changes of ground water level associated with earthquakes, paper presented at IUGG XXI General Assembly, Int. Union of Geod. And Geophys., Boulder, Colo..

Mogi, K., H. Mochizuki, and Y. Kurokawa, 1989: Temperature changes in an artesian spring at Usami in the Izu Peninsula (Japan) and their relation to earthquakes. *Tectonophysics*, **159**, 95-108.

Montgomery, D. R., and M. Manga, 2003: Streamflow and water well response to earthquakes. *Science*, **300**, 2047-2049.

Roeloffs, E., 1998: Persistent water level changes in a well near Parkfield, California, due to local and distance earthquakes. *J. Geophys. Res.*, **103**, 869-889.

Rojstaczer, S., and D. Agnew, 1989: The influence of formation material properties on the response of water levels in wells to earth tides and atmospheric loading. *J. Geophys. Res.*, **94**, 12403-12411.

Yu, G. K., and B. J. Mitchell, 1988: A study of the nontectonic influences on groundwater level fluctuations. *Proc. Geol. Soc. China*, **31**, 111-124.

Liu, C., Huang, M. W., and Tsai, Y. B., 2006: Water level fluctuations induced by ground motions of local and teleseismic earthquakes at two wells in Hualien, eastern Taiwan. Terr. Atmos. Ocean. Sci., ***17****, 371-389.*