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Implications of coseismic groundwater level changes observed at multiple-well monitoring stations

Yeeping Chia,[1] Jessie J. Chiu,[2] Yi-Hsuan Chiang,[1] Tsai-Ping Lee,[1] Yih-Min Wu[1] and Ming-Jame Horng[3]

[1]*Department of Geosciences, National Taiwan University, Taipei, Taiwan,* ROC 106. *E-mail: ypc@ntu.edu.tw*
[2]*Atomic Energy Council, Yonghe, Taipei County, Taiwan,* ROC 234
[3]*Water Resources Agency, Taipei, Taiwan,* ROC 106

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SUMMARY

Earthquake-related groundwater level changes have been recorded by a dense network of monitoring well stations in Taiwan. At most multiple-well stations, the direction and magnitude of coseismic water level changes vary in wells of different depths. Comprehensive water level data recorded in 209 wells in the vicinity of the seismogenic fault during the 1999 M_L7.3 earthquake demonstrate a preliminary 3-D distribution of coseismic changes. The largest coseismic rise at a station observed typically in a confined gravel aquifer indicates the association of the magnitude of coseismic change with characteristics, rather than depth, of the aquifer. The variation of coseismic changes in the vertical direction implies possible inconsistency between the observed water level changes and the volumetric strains calculated from simple dislocation models. At a given hypocentral distance, the coseismic change in the footwall of the ruptured segment of the fault was much greater than that of the unruptured segment. This phenomenon suggests that fault displacement plays an important role in the generation of coseismic changes. While hypocentral distance correlates well with coseismic rise or fall in the vicinity of the ruptured seismogenic fault, poor correlation is found for coseismic change further from the earthquake epicentre.

Key words: Hydrogeophysics; Hydrology; Seismic monitoring and test-ban treaty verification; Earthquake interaction, forecasting, and prediction; Dynamics and mechanics of faulting.

INTRODUCTION

Groundwater level can be changed abruptly during earthquakes, particularly in the seismically active area. As groundwater level in a confined aquifer may change in response to tidal strain, it has been considered as an indicator of crustal strain due to earthquake activities (Bredehoeft 1967). Moreover, change of groundwater level is thought to have the potential of searching signals of fault movement or crustal deformation before earthquakes (King *et al*. 2000).

Coseismic changes of groundwater level have been observed in many places in the world (Wakita 1975; Roeloffs 1988; Kissin & Grinevsky 1990; Rojstaczer & Wolf 1992; Ohno *et al.* 1997; Leonardi *et al.* 1997; Grecksch *et al.* 1999; King *et al.* 1999; Chia *et al.* 2001). Various mechanisms have been proposed to explain changes of water level in wells during earthquakes, such as static strain of aquifers, seismic shaking of deposits, fracturing of bedrock and permeability change at the site (Montgomery & Manga 2003). Of those, redistribution of static stress or strain field induced by fault displacement, which is believed to be associated with the generation of persistent coseismic changes in the near field of the epicentre, received more attention from earthquake hydrologists (Roeloffs 1996). The distribution of coseismic static strains can be estimated based on simple dislocation models (Okada 1992; Ge & Stover 2000), the magnitude of observed coseismic groundwater level changes, nevertheless, was not consistent with that of volumetric strains calculated from theoretical models in many cases (Quilty & Roeloffs 1997; Grecksch *et al.* 1999; Matstumoto *et al.* 2003). Obviously, more studies on observed earthquake-related groundwater level changes in the vicinity of seismogenic faults are needed for a better understanding of the distribution and the underlying mechanisms of coseismic changes.

Recently developed high-frequency automated recording of well water level has significantly improved techniques for monitoring earthquake activities. Observations of the distribution and process of earthquake-related groundwater level changes, however, are often impeded by sparsely distributed monitoring wells. In the study areas where groundwater levels have been intensively monitored, such as Tokai area of Japan, Parkfield in California and Koyna-Warna region in India, large earthquakes seldom occur (King *et al*. 2000; Chadha *et al*. 2003).

A new-generation dense network of multiple-well monitoring stations has been established in Taiwan. As large earthquakes with magnitude greater than 6.0 frequently occur around the island, numerous earthquake-related groundwater level changes have been recorded.

Here we use monitoring records of more than 200 multiple-well stations to investigate the distribution of coseismic changes during various earthquakes, and to discuss its implications in the underlying mechanism of coseismic responses.

NETWORK OF MONITORING WELL STATIONS

Taiwan is an island located at the convergent boundary of two tectonic plates. In the southeastern Taiwan, the Philippine Sea plate moves northwestward and overrides the Eurasian plate. In the northeastern Taiwan, however, the Philippine Sea plate subducts northward beneath the Eurasian plate (Lee *et al.* 1998). Being a part of the Circum-Pacific seismic belt, Taiwan is one of the most seismically active regions in the world. From 1998 to 2006, an average of approximately 4.4 earthquakes of magnitude 6.0 or larger on the Richter scale occur around the area every year. It is anticipated that well water level in Taiwan changes frequently in response to earthquakes.

In the coastal plain of Taiwan, the first generation network of monitoring wells was established during the 1950s and 1960s. The placement of the second generation network of monitoring stations began in 1992. As of 2005, 610 wells had been installed at 253 monitoring stations (Fig. 1). Each station consists of 1–5 wells with 6 inches casing screened at different permeable intervals. These wells were placed to monitor the water level of aquifers at different depths for the management of groundwater resources and land subsidence (Water Resources Agency 2002). Water level in the well is recorded by the digital data logger at 1-hr intervals. Some wells equipped with the analogue data logger also provide continuous records.

In order to monitor fault movement and earthquake activities, water level is also recorded every 2 min in 12 wells and every second in 6 of the 12 wells. High-frequency sampling of water level clearly has the advantage of observing the rapid process of earthquake-related changes. Although groundwater level can be influenced by pumping, rainfall, tide, barometric pressure, surface water and engineering practices, coseismic changes are usually recorded within a few minutes, and thus not required to remove effects of these factors.

The coastal plain is primarily composed of unconsolidated or semi-consolidated deposits. Hydrogeological investigations, including core logging, borehole logging, pumping test, dating and sediment analysis, have been conducted for each monitoring station (Central Geologic Survey of Taiwan 1999). Most wells are screened in highly permeable sand or gravel layers. Any changes of pore water pressure in the aquifer can be quickly reflected by changes of water level in the well.

COSEISMIC CHANGES

Two types of coseismic changes have been observed from monitoring well records: oscillatory changes and persistent changes. Oscillatory coseismic changes only appear on the high-frequency data. These changes are the response of water column in the well and pore-water pressure in the aquifer to passing earthquake waves, particularly Rayleigh waves (Liu *et al.* 1989; Ohno *et al.* 1997). Cooper *et al.* (1965) indicated that the magnitude of oscillatory water level change in the well reflects the amplification of pore pressure in the aquifer due to coseismic dilatational strain. The amplitude of oscillatory changes usually diminishes shortly after earthquake waves pass through, and the well water level recovers to its pre-earthquake level.

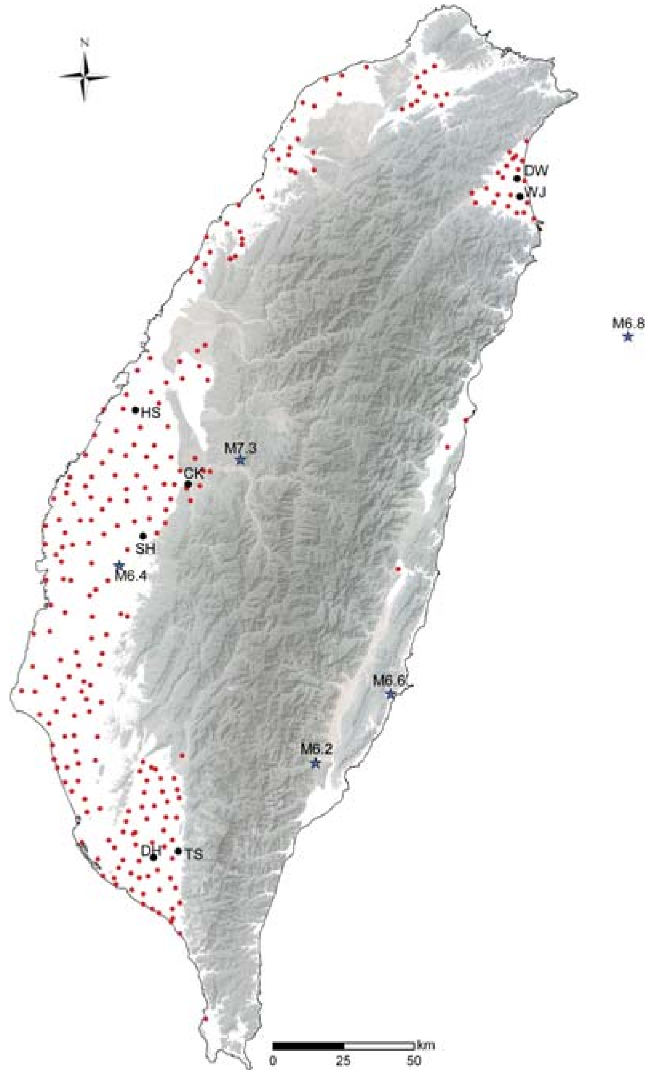

Figure 1. Map showing the distribution of monitoring well stations in Taiwan.

Persistent coseismic changes in the near field have been considered the response of pore pressure to the redistributed stress due to fault displacement (Muir-Wood & King 1993; Roeloffs 1996; Wang 1997). The concept is based on the poroelastic theory that couples crustal deformation and pore water flow (Biot 1941). Assuming the impact of shear stress is ignored, the equation for generating excess pore pressure in deformable porous media is given by Palciauskas & Domenico (1989):

$$\frac{\partial P}{\partial t} = \frac{K}{\rho_{\mathrm{w}} g(\beta_{\mathrm{p}} + n\beta_{\mathrm{w}})}\nabla^2 P + \frac{\beta_{\mathrm{p}}}{\beta_{\mathrm{p}} + n\beta_{\mathrm{w}}}\frac{\partial \sigma}{\partial t}, \tag{1}$$

where P is the pore water pressure, σ is the normal stress, K is the hydraulic conductivity, n is the porosity, β_{p} is the porous medium compressiblity, and β_{w} is the water compressibility. Here $\beta_{\mathrm{p}}/(\beta_{\mathrm{p}} + n\beta_{\mathrm{w}})$ is known as the Skempton coefficient B which is the ratio of the pore water pressure change to the stress change under undrained conditions. The parameter B approaches 1 for unconsolidated deposits, but becomes small for rigid rocks.

According to eq. (1), the earthquake-related change of groundwater level is associated with the groundwater flow and the stress change induced by fault displacement. As persistent coseismic change usually occurs within a short period of time, the groundwater flow is considerably small; therefore, the first term on the right-hand side of eq. (1) can be ignored. Consequently, the rise or fall of pore water pressure during the earthquake depends on whether the local stress change induced by fault displacement is a compression or extension. The magnitude of coseismic change is mainly controlled by the magnitude of stress change as well as the Skempton coefficient.

Montgomery & Manga (2003) indicated that persistent water level changes were also observed at certain wells in the far field. Brodsky *et al*. (2003) suggested the changes were possibly caused by the removal of a temporary barrier in a fracture due to the shaking of seismic waves. Such persistent changes have not been observed at monitoring well stations in Taiwan during the occurrence of strong distant earthquakes.

Persistent coseismic rises or falls usually last for a period of time after earthquakes. They appear to be abrupt or step-like changes on long-term records or hourly records. Based on 1-s data during the 2006 April 1 M_L 6.2 earthquake, however, the persistent change in the Drun-Wei No. 3 (DW3) well appeared to be accompanied by oscillatory changes at the beginning, and occurred gradually over an approximately 4-min period after seismic waves passed through (Fig. 2a). In some wells, the process of coseismic change is slow regardless of the focal mechanism or location of the earthquake. In the Tse-Shan No. 3 (TS3) well, for instance, the process of water level fall lasted for more than 1 hr after the earthquake (Fig. 2b). This phenomenon may reflect the impact of local geological or hydrologic conditions on the process of coseismic changes.

Persistent coseismic changes are difficult to identify during small earthquakes. As shown in Fig. 3, a 1-cm water level rise was recorded shortly after 11:30, while a 1-cm fall observed shortly after 14:46 on 2004 April 11 in the DW3 well. The climate data at the station did not show any rainfall or significant change of atmospheric pressure that day. The seismic data, however, indicate the occurrence of an M_L 1.93 earthquake located 38 km from DW3 at 11:30 and an M_L 1.71 earthquake located 286 km from DW3 at 14:46. Since the two changes were of similar magnitude and recorded within less than 4 hr, they were probably associated with a local compression and a subsequent relaxation induced by fault movement. Whether the coupled changes were related to the small earthquakes remain to be further investigated.

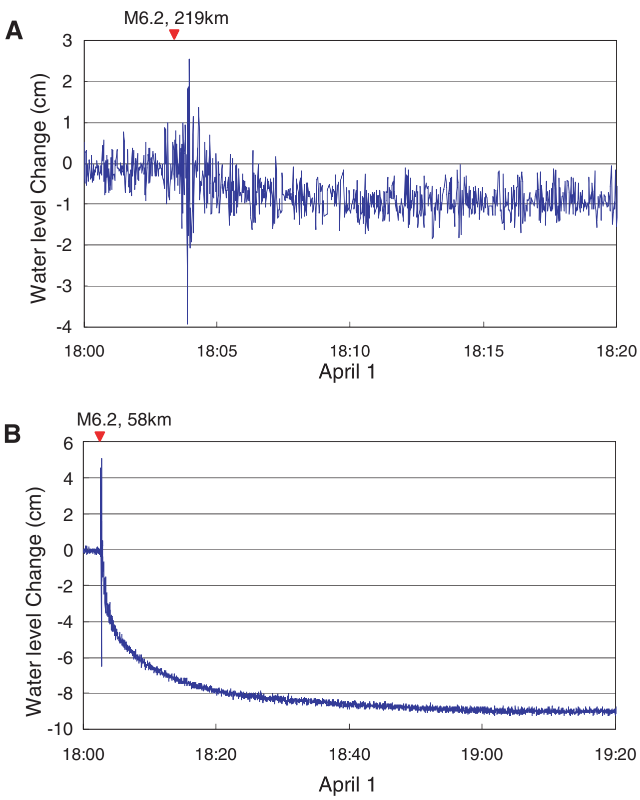

Figure 2. Oscillatory and persistent coseismic changes of groundwater level in the DW3 well (a) and the TS well during the 2006 April 1 M_L 6.2 earthquake (b). The distance above the inverted triangle denotes the epicentral distance of the well.

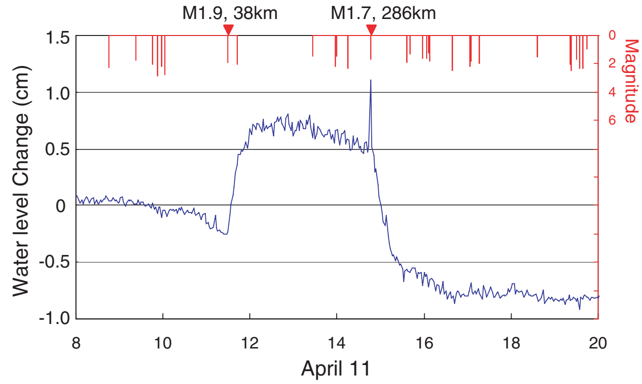

Figure 3. A 1-cm coseismic rise and a 1-cm coseismic fall recorded during two small earthquakes.

OBSERVATIONS AT MULTIPLE-WELL STATIONS

Observations at multiple-well monitoring stations revealed the variation of groundwater level change in the vertical direction during earthquakes. Fig. 4(a) shows water level changes in four wells at the How-Show (HS) station during the 1999 September 21 M_L 7.3 earthquake. The coseismic rises were 3.51, 3.72 and 3.24 m in HS1, HS3 and HS4, respectively, while a higher rise, 5.28 m, was observed in HS2. At the Wu-Jay (WJ) station during the 2002 March 31 M_L 6.8 earthquake, as shown in Fig. 4(b), the 0.16-m rise observed in the WJ4 well is much smaller than the rises, ranging from 0.42 to 0.69 m, in other wells. The water levels in WJ2 and WJ3 were close before and after the earthquake, indicating a hydraulic connection between two permeable layers. The coseismic rise in WJ2 is also close to that in WJ3, implying that they are of similar pore compressibilities.

Fig. 5 shows coseismic falls in two wells at the Chu-Ko (CK) station. The change of well water levels is influenced primarily by the fluctuation of discharge in the nearby river. Normally the water level change in CK2 is approximately 1.8 times of that in CK1 in response to the variation of vertical load due to the fluctuation of water level in the river. During the 1999 September 21 M_L 7.3 earthquake, coseismic changes were 4.05 and 2.74 m in CK1 and CK2, respectively (Fig. 5a). The greater change in CK1 implies that the stress change induced by fault displacement was mainly in the lateral direction, rather than in the vertical direction. During the 1999 October 22 M_L 6.4 earthquake, the coseismic fall in CK2 was four times of that in CK1 (Fig. 5b). Obviously, the ratio of stress change in CK1 to that in CK2 varies during different earthquakes.

At some stations, both coseismic rises and falls were observed in wells of different depths during an earthquake. The coseismic

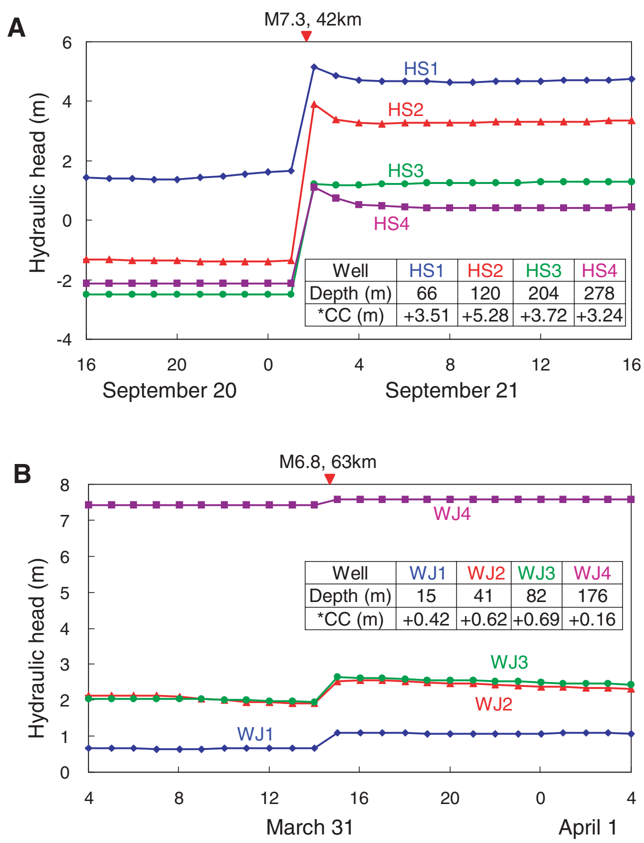

Figure 4. Records of groundwater level showing the variation of coseismic rises in wells of different depths at the HS station during the 1999 September 21 M_L 7.3 earthquake (a) and the WJ station during the 2002 March 31 M_L 6.8 earthquake (b).

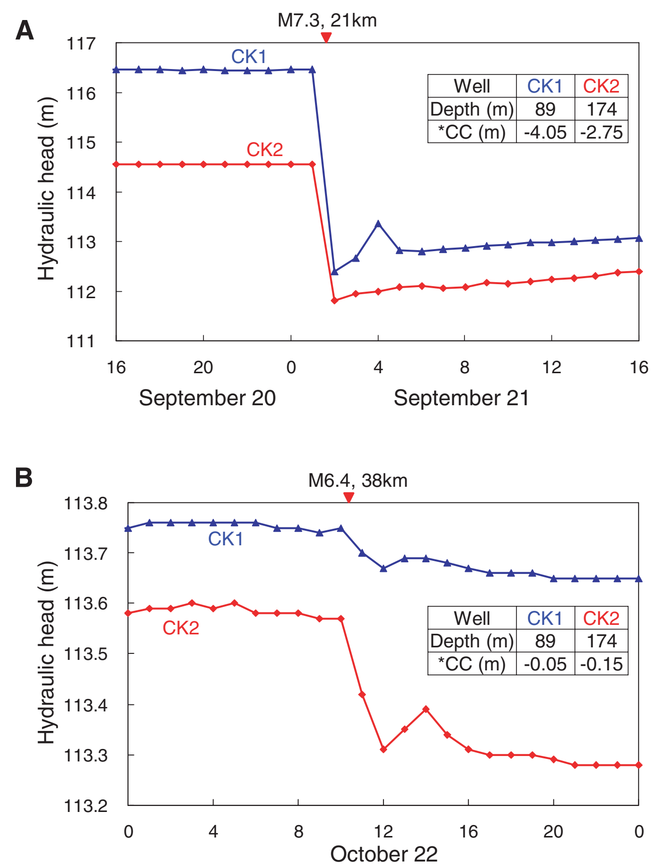

Figure 5. 24-hr records of groundwater level showing coseismic falls in two wells of different depths at the CK station during the 1999 September 21 M_L 7.3 earthquake (a) and the 1999 October 22 M_L 6.4 earthquake (b).

rise was observed either in a shallower well or in a deeper well. For instance, as shown in Fig. 6(a), we observed a coseismic rise in DH2, but a coseismic fall in DH3 at the Da-Hu (DH) station during the 2003 December 10 M_L 6.6 earthquake. However, at the San-Ho (SH) station, a coseismic fall was recorded in SH1, but a rise was recorded in SH2 during the 1999 September 21 M_L 7.3 earthquake (Fig. 6b). Most of these stations are located in the area between stations where only coseismic rises are observed and those where only coseismic falls are observed. In other words, the direction of coseismic change could be reversed over a short distance in the vertical direction in the transition between the compression zone and the extension zone.

Evidently field observations indicate that the direction and magnitude of coseismic changes may vary in wells of different depths at a station. Based on eq. (1), such a variation may be caused by the difference in aquifer properties or stress change. Ge and Stover (2000) indicated that, in addition to fault displacement, stress change can be influenced by boundary conditions at the land surface. The variation of coseismic changes at a multiple-well station inevitably causes inconsistency between the observed water level changes and the calculated volumetric strains from simple dislocation models.

SPATIAL DISTRIBUTION OF COSEISMIC CHANGES

Field observations indicate that the distribution pattern of coseismic changes during large earthquakes is more complicated than the quadrantal distribution pattern expected from the theoretical model of fault dislocation. For instance, Fig. 7 shows the distribution of observed coseismic rises and falls due to the 2003 December 10 M_L 6.6 earthquake. Coseismic rises (blue triangles) were observed in 65 wells; most are located in the area near the shoreline in central and southern coastal plains. Coseismic falls (red inverted triangles) were observed in 53 wells. They are located primarily in southwestern coastal plain and the area near the mountains in central and southern coastal plains. Such a distribution reflects the complexity of stress redistribution in the coastal plain across the mountains from the earthquake epicentre in southeastern Taiwan.

The most comprehensive earthquake-related well water level data were recorded during the M_L 7.3 Chi-Chi earthquake occurred in central Taiwan at 1:47 a.m. on 1999 September 21 local time (17:47 GMT on September 20). The depth of hypocentre is about 10 km. Surface rupture resulted from thrusting along the scarp of the Chelungpu fault extended approximately 100 km in the north–south direction (Angelier *et al*. 2003). The net slip ranges from less than 1 to 12 m in the hanging wall of the thrust fault (Lee *et al*. 2003). Coseismic water level changes were observed in 209 out of 240 monitoring wells in southwestern Taiwan during the earthquake. Of those, 84 recorded a change greater than 1 m. The largest rise, +7.42 m, was observed in the HW2 well located 27 km from the fault, while the largest fall, −11.09 m, was recorded in the JS2 well located 2 km from the fault. Both changes are the largest ever documented.

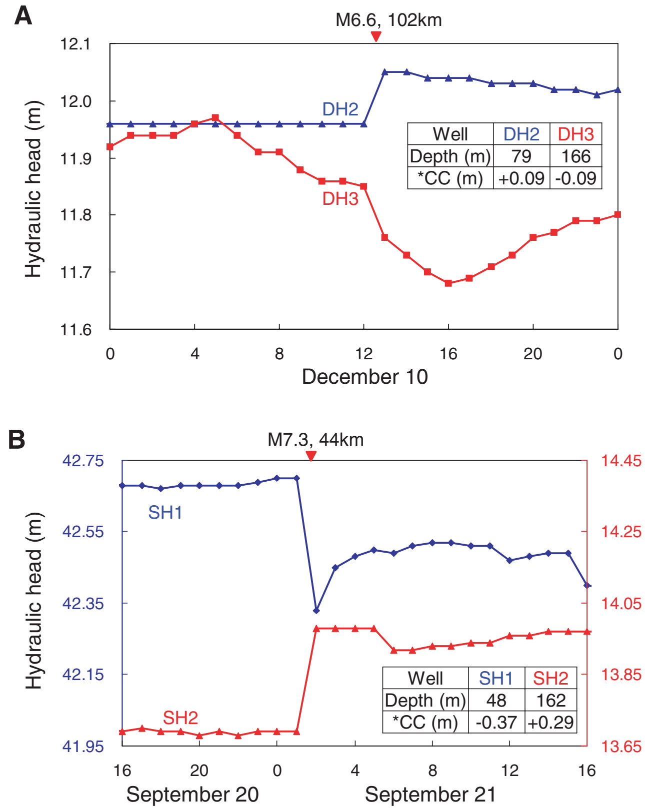

Figure 6. 24-hr records of groundwater level showing both coseismic rise and coseismic fall in wells of different depths at the DH station during the 2003 December 10 M_L 6.6 earthquake (a), and the SH station during the 1999 September 21 M_L 7.3 earthquake (b).

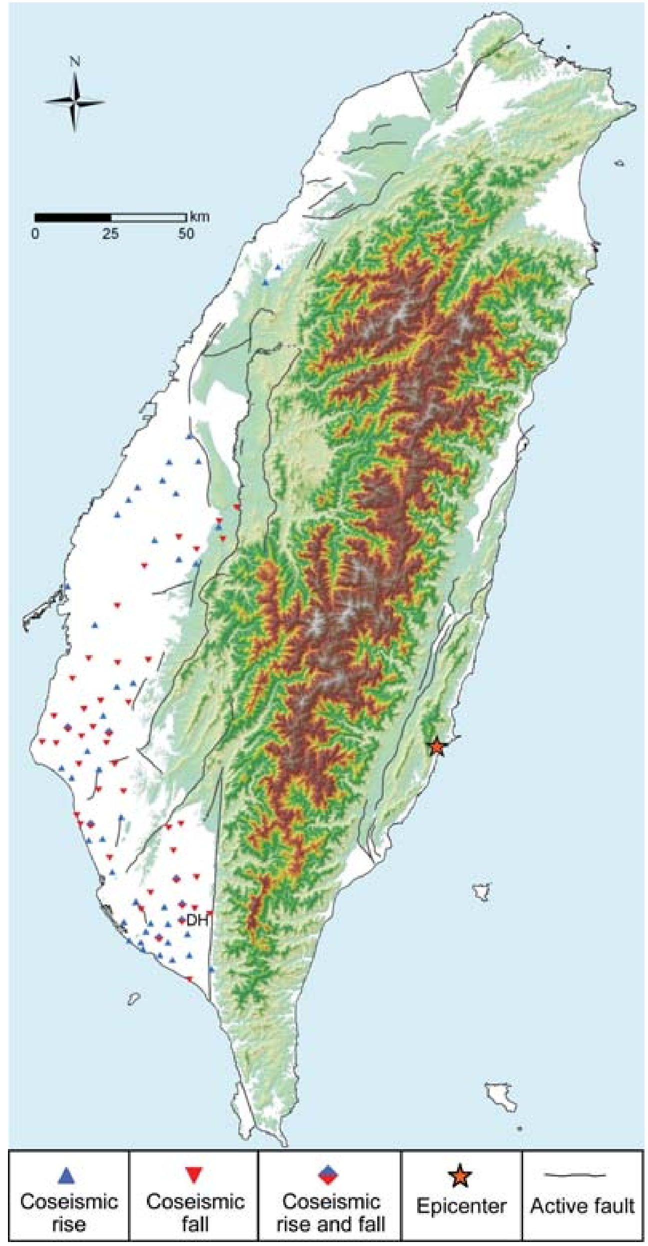

Figure 7. Spatial distribution of coseismic rises and coseismic falls of groundwater level in Taiwan during the 2003 December 10 M_L 6.6 earthquake.

Coseismic groundwater level changes due to the Chi-Chi earthquake have been reported by Chia *et al*. (2001), Wang *et al*. (2001) and Lee *et al*. (2002). Changes in groundwater level following the earthquake have been studied by Wang *et al*. (2004). The comprehensive groundwater level data recorded during the earthquake revealed a preliminary 3-D framework of spatial distribution of coseismic changes in the vicinity of the seismogenic fault, as illustrated in Fig. 8(a). In the footwall, coseismic rises prevailed at stations away from the ruptured segment of the thrust fault while coseismic falls were mainly observed in the area near the ruptured segment. At some stations in the transition area, both rises and falls were observed in wells of different depths. A similar but less distinct distribution pattern of coseismic rises and falls was observed in the footwall of the unruptured segment of the fault. In the vicinity of the seismogenic fault, coseismic changes are expected to reflect static strains arising from aquifer compression or dilation (Montgomery & Manga 2003). However, the observed coseismic rises and falls are not consistent with polarities of volumetric strains calculated from a simple dislocation model of the Chelungpu fault (Lee *et al.* 2002).

Fig. 8(b) illustrates the distribution of the direction and magnitude of coseismic changes in monitoring wells along six cross-sections shown in Fig. 8(a). The magnitude of coseismic rises and falls at stations in the footwall of the ruptured segment of the fault, as shown along cross-sections AA', BB', CC' and DD', tend to decrease with increasing distance from the fault. A similar distribution pattern of coseismic changes was observed in the footwall of the unruptured segment, as shown along cross-sections EE' and FF', but the magnitude of changes is much smaller.

In the vertical direction, the magnitude of coseismic changes does not show any trend of increase or decrease with well depth. Instead, it varies in wells of different depths. An investigation was conducted for coseismic rises in wells at 9 multiple-well stations, including four stations along cross-section AA', in the Area A as marked in Fig. 8(a). The data of well screen depth, coseismic change, aquifer lithology and confining condition for the 9 stations are summarized in Table 1. We found the largest rise typically observed in the well screened at the depth between 100 and 130 m. Based on hydrogeological investigations by the Central Geological Survey (1999), these screened permeable layers correlate well with a local confined gravel aquifer. The coseismic change in a gravel layer is generally

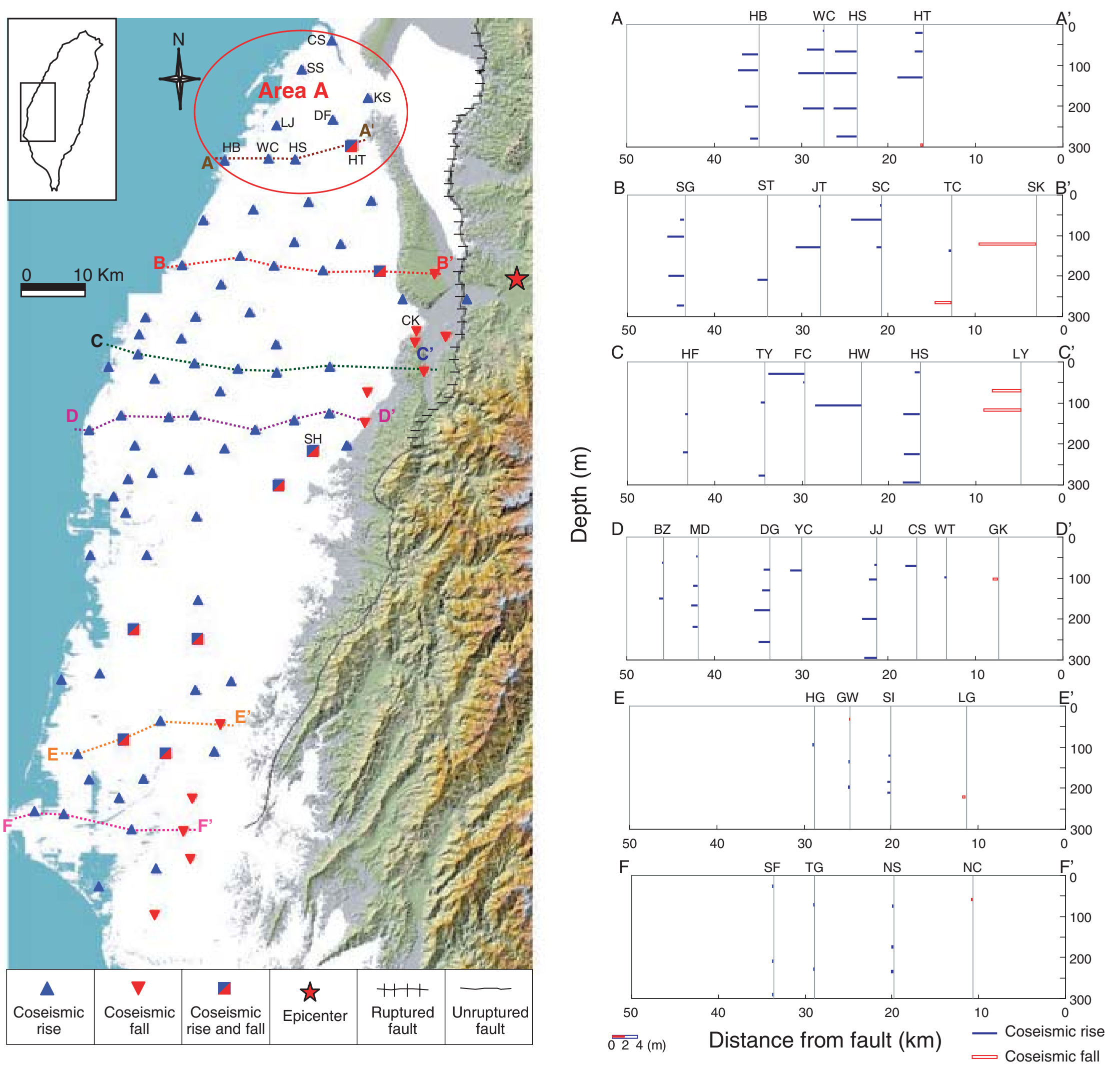

Figure 8. (a) Spatial distribution of coseismic rises and coseismic falls of groundwater level in the southwestern coastal plain of Taiwan during the 1999 September 21 M_L 7.3 earthquake. (b) Vertical distribution of the magnitude and direction of coseismic changes in wells of different depths along six cross-sections shown in (a).

greater than that in a sand layer, suggesting that the magnitude of coseismic changes is associated with characteristics, rather than depth, of the aquifer.

As gravel is generally less compressible than sand, the Skempton coefficient B for gravel is expected to be smaller than that for sand. According to eq. (1), the magnitude of coseismic change can be influenced by the Skempton coefficient and the stress change of the aquifer. The field observations, as shown in Table 1, reveal a larger coseismic water level change in the gravel layer than in the sand layer, indicating a higher pore pressure change in the gravel aquifer. Consequently, the stress change in the gravel layer has to be greater than that in the sand layer during the earthquake. The stress redistribution induced by fault displacement could be complicated. If local compression is in the vertical direction, the stress change should be similar for all horizontal layers at a station. However, if local compression is in the lateral direction, the less compressible layer (such as gravel) is expected to have a greater stress change than the more compressible layer (such as sand). In the Area A, the greater stress change in the less compressible gravel layer implies that local compression is primarily in the lateral direction.

VARIATION OF COSEISMIC CHANGES WITH HYPOCENTRAL DISTANCE

During the 1999 September 21 M_L 7.3 earthquake, the magnitude of coseismic falls in the footwall of the fault decreased rapidly with increasing hypocentral distance, as shown in Fig. 9. Here coseismic changes in unconfined aquifers are excluded because they fail to represent the magnitude of actual coseismic changes. The equation of the best-fitting regression curve for the scatter plot of coseismic fall versus hypocentral distance is $\log h_f = 3.67 - 2.43 \log d$, where h_f is the magnitude of the coseismic change in metres and d is the hypocentral distance in kilometres. The squared correlation coefficient (R^2) of 0.80 indicates a good correlation between coseismic fall and distance from the hypocentre in the vicinity of the ruptured segment. The magnitude of coseismic rises in the footwall of the fault tends to decrease gradually with increasing hypocentral distance. The equation of the best-fitting regression curve for the plot of coseismic rise (h_r) against hypocentral distance is $\log h_r = 2.75 - 0.05 \log d$. The squared correlation coefficient of 0.52 suggests a moderate correlation between coseismic rise and hypocentral distance.

Table 1. Coseismic changes, well screen depths and aquifer characteristics at 9 multiple-well stations in the study area A.

Well name	Screen depth (m)	Coseismic change (m)	Aquifer lithology	Confining condition
KS1	8–14, 24–30	0.38[a]	Sandy gravel	Partially confined
KS2	120–126	5.21	Sand	Confined
KS3	185–197	1.05	Sand	Confined
DF1	101–125	3.38	Gravel	Confined
DF2	162–174	3.73	Gravelly sand	Confined
LJ1	25–34	0.62	Sand	Confined
LJ2	108–120	5.22	Gravelly sand	Confined
LJ3	180–198	3.47	Gravelly sand	Confined
SS1	10–16, 22–28	0.23	Sand	Confined
SS2	105–117	4.20	Gravelly sand	Confined
SS3	55–71	4.28	Sand	Confined
SS4	158–170, 182–194	2.75	Sand	Confined
CS1	8–17	0.19[a]	Sand	Partially confined
CS2	102–120	4.66	Gravel	Confined
CS3	183–192	3.86	Gravel	Confined
CS4	240–252	2.70	Gravelly sand	Confined
WC1	5–17	0.13[a]	Sand	Unconfined
WC2	18–60	2.76	Sand	Confined
WC3	108–120	4.09	Gravelly sand	Confined
WC4	186–204	3.38	Sandy gravel	Confined
HT1	8–20	1.25[a]	Sand	Partially confined
HT2	44–56, 59–65	1.31	Gravelly sand	Confined
HT3	112–130	3.98	Gravel	Confined
HT4	264–276, 288–294	−0.26	Sand	Confined
HS1	48–54, 60–66	3.51	Gravelly sand	Confined
HS2	102–108, 114–120	5.28	Sand gravel	Confined
HS3	174–186, 192–204	3.72	Gravelly sand	Confined
HS4	254–278	3.24	Gravelly sand	Confined
HB1	59–71	2.56	Sand	Confined
HB2	103–115	3.23	Gravelly sand	Confined
HB3	173–197	2.12	Sand	Confined
HB4	266–284	1.25	Gravelly sand	Confined

[a]The coseismic change in an unconfined or a partially confined aquifer on hourly records only reflects a fraction of the actual coseismic change.

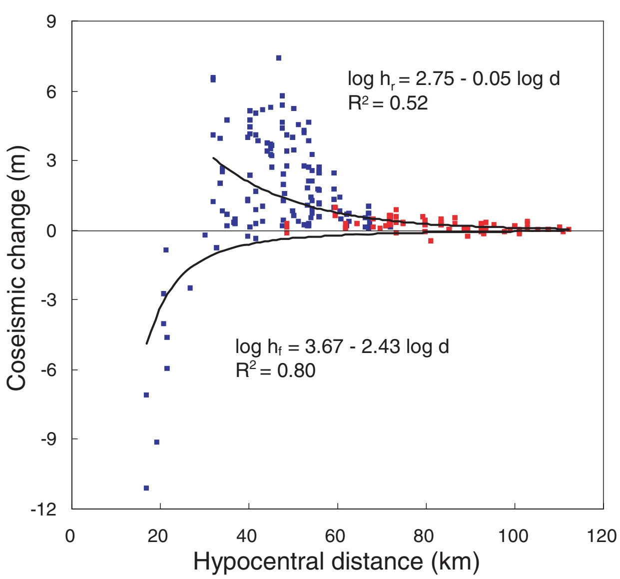

Figure 9. Magnitude of coseismic rises and falls versus hypocentral distance of monitoring well stations in southwestern Taiwan during the 1999 September 21 M_L 7.3 earthquake. Blue squares are coseismic changes in the footwall of the ruptured segment and red squares are coseismic changes in the footwall of the unruptured segment.

Between 50 and 70 km from the hypocentre, coseismic changes were observed in the footwall of both the unruptured segment and the ruptured segment of the thrust fault. It is noticed that, at a given hypocentral distance, the magnitude of coseismic rises in the footwall of the unruptured segment is much smaller than that of the ruptured segment (Fig. 9). The strong contrast between coseismic changes in the footwall of the ruptured segment and those of the unruptured suggests that fault displacement plays an important role in the generation of coseismic groundwater level changes.

Fig. 10 is a scatter plot of coseismic changes for the wells in the footwall of the unruptured segment of the fault during the 1999 September 21 M_L 7.3 earthquake. We found that neither coseismic rise nor coseismic fall correlates well with hypocentral distance (Fig. 10). Apparently the redistributed stress pattern in the footwall of the unruptured segment is different from that of the ruptured segment. A similar scatter plot was established for the 2003 December 10 M_L 6.6 earthquake (Fig. 11). All of coseismic changes were observed in the coastal plain across the mountains from the earthquake epicentre. A poor correlation was also found between coseismic changes and hypocentral distance. This phenomenon further suggests that the redistributed stress beyond the vicinity of the ruptured fault could be complicated by factors other than displacement, such as local geological conditions.

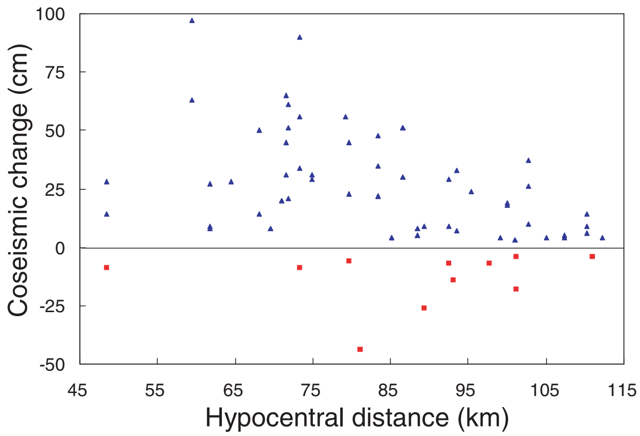

Figure 10. Magnitude of coseismic rises and falls in the footwall of the unruptured segment versus hypocentral distance of monitoring well stations in southwestern Taiwan during the 1999 September 21 M_L 7.3 earthquake.

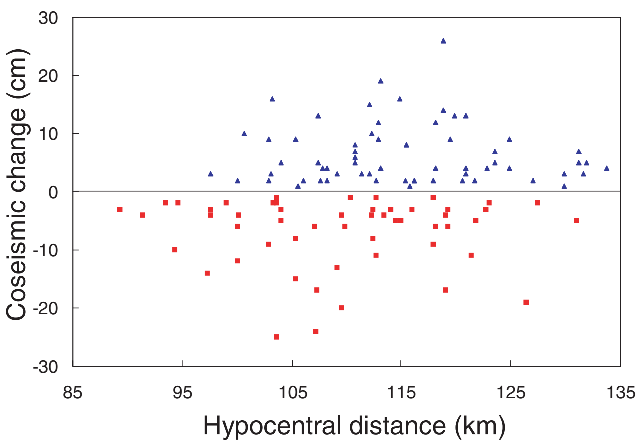

Figure 11. Magnitude of coseismic rises and falls versus hypocentral distance of monitoring well stations during the 2003 December 10 M_L 6.6 earthquake.

CONCLUSIONS

Field observations reveal that fault displacement has a strong impact on the occurrence of coseismic groundwater level change. The phenomenon is consistent with the concept of poroelastic theory which couples stress, displacement and pore pressure in porous media. Thus, the spatial distribution of coseismic groundwater level changes may reflect the redistributed stress field in the shallow subsurface due to fault displacement during earthquakes.

The inconsistency between observed coseismic groundwater level changes and calculated volumetric strains from simple dislocation models could be caused by different physical properties of aquifers and complicated stress redistribution due to local geological conditions. Obviously, a simple dislocation model may provide a conceptual understanding in the distribution of coseismic compression and dilatation zones, but not suitable for predicting the magnitude or direction of pore pressure change at a specific site.

While a well tapping the deep confined aquifer is commonly considered for monitoring fault movement and earthquake activities, results of our analysis do not show significant advantage of a deep well. Instead, the characteristics of an aquifer, including the elastic and hydrologic properties, are keys to obtaining a quick and large response to earthquake activities.

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