WESTERN PACIFIC EARTH SCIENCES
Vol.2, No.3, P.261-272, 10 Figs., August, 2002

COSEISMIC CHANGES OF GROUNDWATER LEVEL IN RESPONSE TO THE 1999 CHI-CHI EARTHQUAKE

YEE-PING CHIA, YUAN-SHIAN WANG, CHIH-CHAO HUANG, JIA-SHING CHEN AND HSIUE-PIEN WU

Department of Geosciences, National Taiwan University, Taipei

ABSTRACT

Changes of groundwater level induced by the 1999 M_L 7.3 Chi-Chi earthquake were observed at 158 monitoring wells in the Choshui River alluvial fan. Examination of both analog and hourly digital records indicated that these abrupt changes of groundwater level occurred at the time of mainshock. These coseismic changes could be induced by stress redistribution due to fault movement or mechanical response to seismic shaking. Their magnitude, ranging from a rise of 7.42 m to a fall of 11.09 m on hourly records, varied with distance from the epicenter and depth of the monitoring well. The distribution of these changes suggests that tectonic extension prevailed in the area adjacent to the fault while tectonic compression predominated in the area further away. In the transition area, the direction of coseismic changes may vary with the depth.

Key words: Chi-Chi earthquake, coseismic changes, groundwater

INTRODUCTION

Groundwater level changes during the occurrence of earthquakes have often been reported (e.g. Wakita, 1975; Rieloffs and Quilty, 1997; Roeloffs, 1998; King *et al.*, 2000). Earthquake-induced changes of groundwater level are anticipated to be associated with crustal deformation, hydrogeologic characteristics, and possibly earthquake occurrence; but relevant groundwater information are rare in most cases.

An earthquake of M_L 7.3 occurred near the town of Chi-Chi in central Taiwan at 1:47 a. m. on September 21, 1999 local time. The epicenter is at 23.85°N, 120.82°E, and the hypocentral depth is about 8 km. Field investigations indicated that a widespread surface rupture, extending approximately 100 km in the north-south direction, was resulted from the thrust of the Chelungpu fault (Central Geological Survey, 1999). Abrupt changes of groundwater level in response to the Chi-Chi earthquake were recorded by 158 observation wells at 65 stations in the vicinity of that fault. The magnitude of observed groundwater level changes induced by the earthquake and the number of observation wells in the vicinity of the Chelungpu fault were unprecedented

(Chia *et al.*, 2001). This paper intends to evaluate the precise time, magnitude and direction of the earthquake-induced groundwater level changes on the analog and hourly digital records, and to discuss the mechanism and distribution of those changes in the Choshui River alluvial fan.

MONITORING WELLS

The Choshui River alluvial fan, lying in the coastal plain of central Taiwan, is located in the west vicinity of the southern segment of the Chelungpu fault. In order to acquire long-term data for groundwater resource management, 188 monitoring wells were installed at 73 stations in the alluvial fan from 1992 to 1997 (Water Conservancy Agency, 2000). These stations are located primarily in the footwall of the Chelungpu fault, approximately 12 to 78 km away from the epicenter and 1 to 50 km away from the fault. Each station consists of one to five wells, ranging in depth from 17 to 300 m. Nearly all of these wells were installed in the unconsolidated deposits. Each well was screened to monitor only one aquifer composed of either gravelly or sandy sediments.

All monitoring wells are instrumented with either a pressure transducer or a float-type sensor for measuring groundwater level. Either a digital data logger or a combination of strip-chart analog recorder and analog-to-digital recorder was used for data acquisition. Water levels have been recorded at one-hour intervals by the digital data logger for all wells and continuously recorded by the analog recorder at selected wells since 1994. The resolution of the digital and analog recorders is approximately 1 to 3 mm and 5 mm, respectively. The precision of hourly digital records is set to be 1 cm. The resolution of time on analog records is approximately 3 to 5 minutes.

TIME OF GROUNDWATER LEVEL CHANGES

Among the 188 observation wells examined, 158 observed abrupt groundwater level changes due to the Chi-Chi earthquake. Of those, the original hourly records at 59 wells showed abrupt groundwater level changes between 11 p.m. September 20 and 1 a.m. September 21, approximately one to two hours before 1:47 a.m. September 21 when the mainshock occurred. As the preseismic water level change would be a potential earthquake precursor, it is essential to examine and verify the exact time of groundwater level changes induced by the earthquake.

A rigorous evaluation of recording instruments in the field revealed that errors in the clock, ranging from a few minutes up to more than one hour, were identified at some wells. Comparison of groundwater tide with ocean tide was also conducted to validate the time of preseismic abrupt groundwater level changes. For example, original records at the DS3 well showed an abrupt rise between 0 a.m. and 1 a.m. September 21 as shown in Figure 1. Comparison of groundwater tide at DS3 with its nearby ocean tide indicated that, contrary to the natural process, the groundwater tide occurred 42 minutes earlier than the ocean tide and one hour earlier than groundwater tides at other coastal wells. The conflict situation was clarified by an inspection of information management process that specified an error of one-hour difference for the time of groundwater level records at many wells due to inadequate data handling. Accordingly, the entire groundwater level records had been adjusted. The verification process not only calibrated the time of groundwater level changes induced by the Chi-Chi earthquake, but also enhanced the long-term accuracy of groundwater monitoring records.

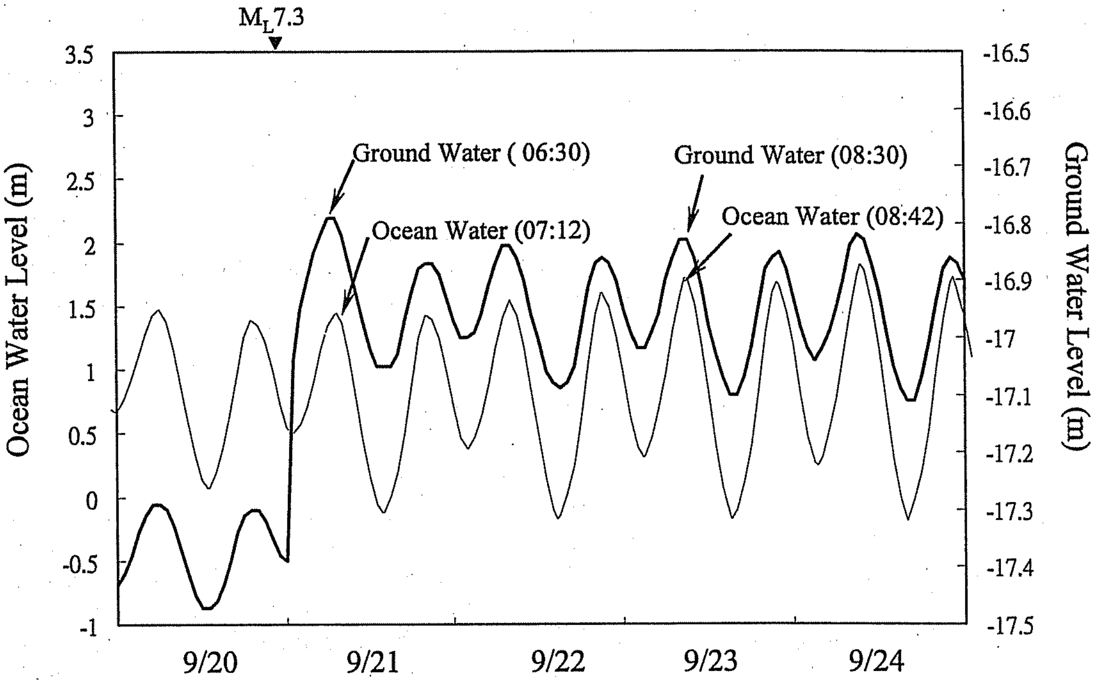


Figure 1. Comparison between ocean and groundwater tides at the DS3 well for calibrating the time of coseismic groundwater level change on hourly records.

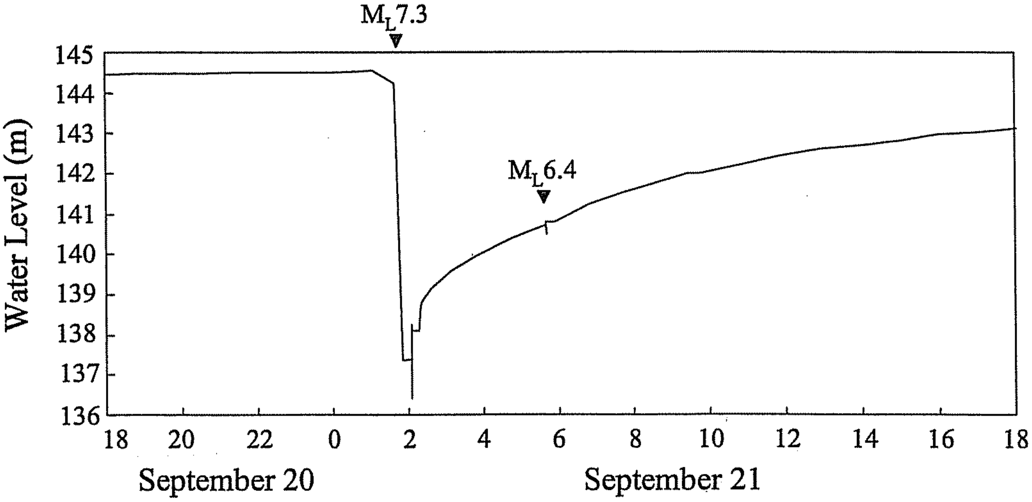


Figure 2. Analog records at the JS1 well showing a groundwater level fall of 6.9 m at approximately 1:50 a. m. A groundwater level fall of 0.2 m, observed approximately 15 minutes immediately before earthquake, was resulted from local pumping.

The calibrated hourly records indicated that abrupt groundwater level changes occurred between 1 a.m. and 2 a.m. September 21. At the JS1 well, for example, hourly records observed a groundwater level fall of 7.12 m between 1 a.m. and 2 a.m., but it was difficult to pinpoint the precise time of abrupt change. However, the strip-chart analog instrument at some wells, which is capable of recording continuous variation of water level, can be used to clarify this issue. Figure 2 shows that the water level declined 6.9 m at JS1 at approximately 1:50 a.m. In fact, after the correction of errors in the clock of recorders, abrupt groundwater level changes accompanied with oscillatory phenomena were observed approximately between 1:45 and 1:50 a.m. on all analog records. Because the oscillatory changes were related to the seismic waves of the Chi-Chi earthquake, it is believed that the correct time for all abrupt groundwater level changes should be 1:47 a.m. September 21 when the Chi-Chi earthquake occurred.

MECHANISMS OF COSEISMIC CHANGES

Two types of earthquake-induced groundwater level changes can be identified on analog records: dynamic change and static change. The dynamic change is the response of groundwater water column in the well to seismic shaking during earthquakes. Seismic shaking often results in oscillatory changes of groundwater level. But mechanical response of sediments to seismic shaking was also proposed to explain the sustained groundwater level changes (Roeloffs, 1998; Wang *et al.*, 2001). The dynamic change in the unconsolidated sand or silt formation at shallow depths during earthquakes may cause soil liquefaction. As shown in Figure 3, the TC well monitored the water level of an unconfined aquifer. Oscillatory water level changes, up to 6 m approximately, were observed at the time of Chi-Chi earthquake. Although the dynamic change of groundwater level quickly recovered after earthquake, it did cause widespread soil liquefaction hazard in the vicinity of the TC well.

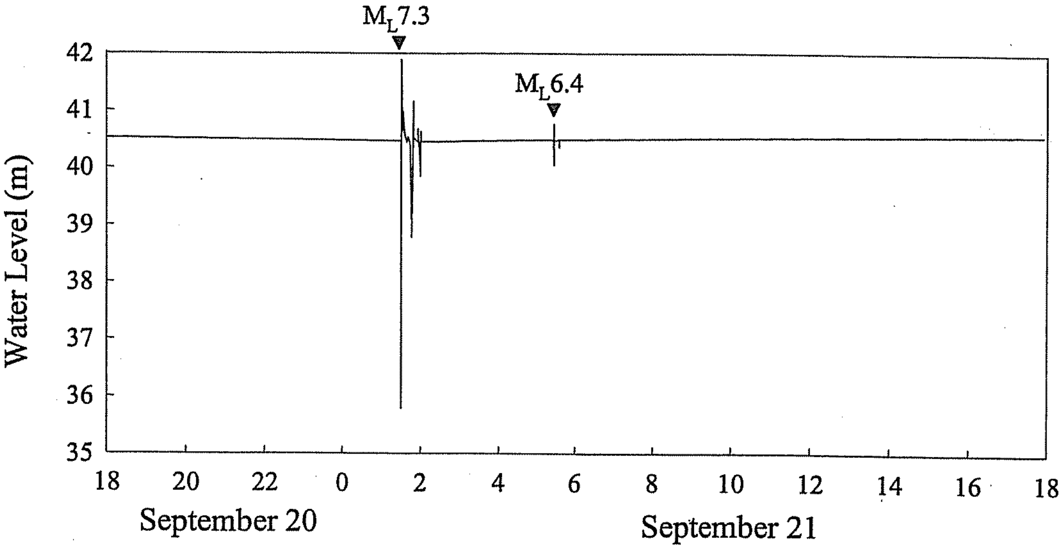


Figure 3. Analog records at the TC well showing oscillatory groundwater level changes at the mainshock and a few aftershocks in an unconfined aquifer.

Because of insufficient time resolution on analog records, it was hard to see the detailed oscillatory water level changes. Recently a pressure transducer was installed at a monitoring well on campus of the National Taiwan University to record groundwater level data every 3 seconds. Figure 4 shows the detailed oscillatory process of dynamic response to the M_L 6.2 earthquake occurred on May 29, 2002. The epicenter is located offshore east coast, approximately 59 km east of Hualian city and 200 km away from the monitoring well. The largest amplitude was about 7 cm and the oscillation lasted only for 1 minute.

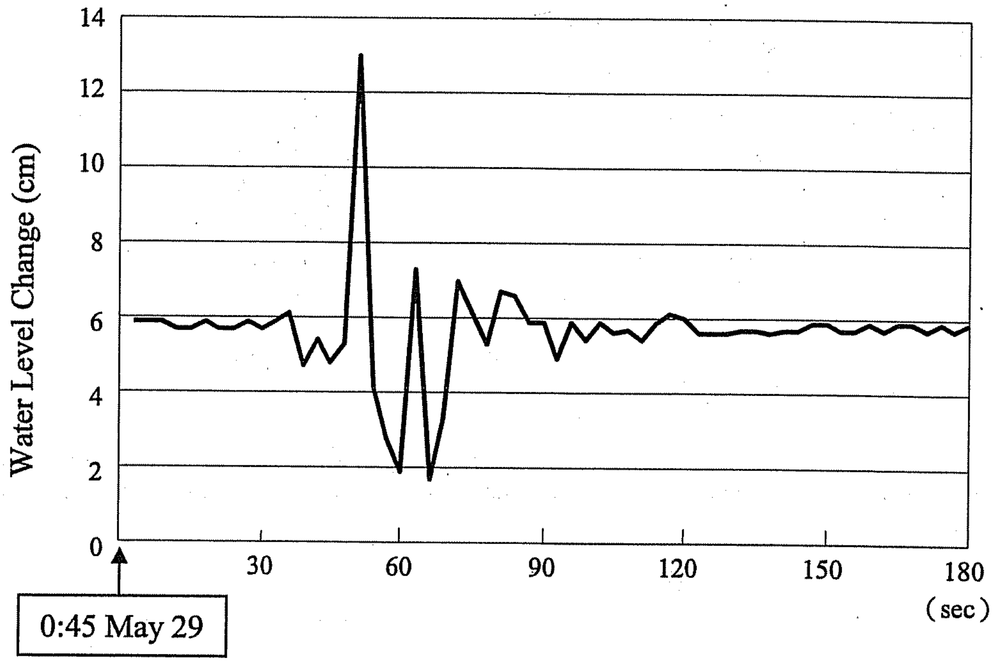


Figure 4. Digital records showing the detailed process of oscillatory groundwater level change in response to the ML 6.2 earthquake at 0:45 a.m. on May 29, 2002. A pressure transducer, recorded groundwater level every 3 second, was installed at a monitoring on campus of the National Taiwan University.

The static change is the response of groundwater to the redistributed stress field caused by fault movement. During the occurrence of the Chi-Chi earthquake, the stress field in Taiwan and its adjacent area must have undergone a rapid adjustment in response to the thrust of the Chelungpu fault. The redistributed tectonic stress could result in a sudden change of pore water pressure and effective stress in the formation. Because the compressibility of pore water is considerably smaller than that of porous medium skeleton in the unconsolidated deposits, most of the tectonic stress change was responded by an abrupt change of pore water pressure at the time of earthquake (Figure 5). During the recovery of pore water pressure after an earthquake, effective stress would change gradually and result in a volumetric strain in the formation.

Before the coseismic groundwater level change in an aquifer could be detected at its monitoring well, a period of time would be elapsed to allow groundwater to flow between the well and its connected aquifer. For a well connected to a less permeable aquifer or covered with clogged screen, such as the YL4 well (Figure 6), it might take a few days to observe a full-scale coseismic groundwater level change. As aquifers in the Choshui River alluvial fan are generally highly permeable, most monitoring wells observed a full scale coseismic groundwater level change in the connected aquifer immediately after the earthquake.

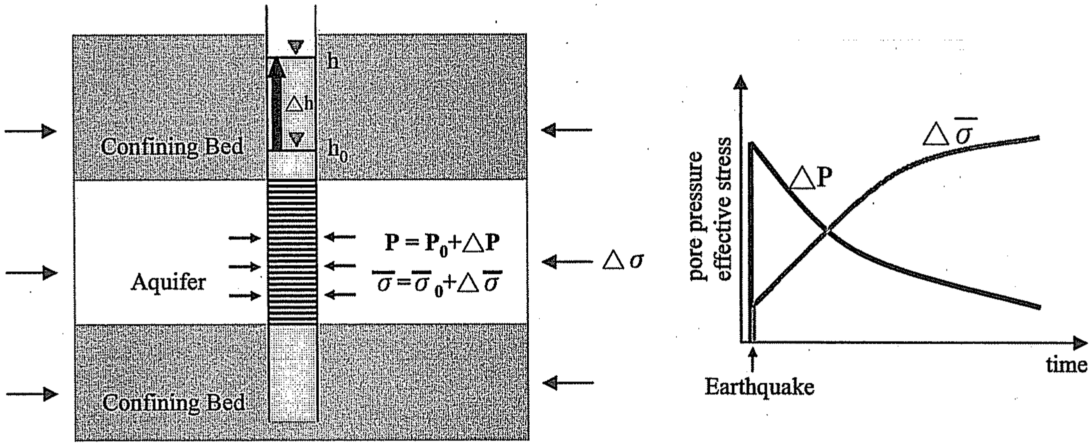


Figure 5. Schematic diagram showing the static response of groundwater level change to tectonic stress adjustment ($\Delta\sigma$). In the diagram, **h** is hydraulic head, **P** is pore water pressure, and $\bar{\sigma}$ is effective stress.

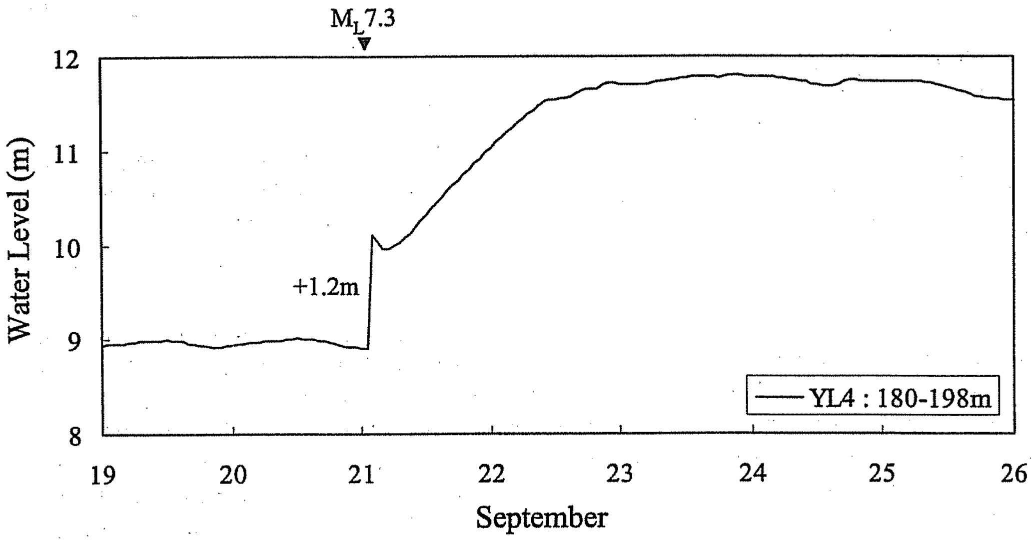


Figure 6. Groundwater level records at the YL4 well showing a post-seismic rise, up to approximately 2.1 m, after the initial coseismic rise of 1.20 m.

DIRECTION OF COSEISMIC CHANGES

Coseismic groundwater level changes were recorded by 158 wells clustered at 65 monitoring stations in the Choshui River alluvial fan. There are 54 well stations where coseismic groundwater level rises were observed and 8 well stations where coseismic groundwater level falls were observed at different depths. Figure 7 shows the distribution of well stations where coseismic water level changes were observed.

Bredehoeft (1967) indicated that the water level in an artesian well is as sensitive to strains of the crust as the strain seismometer; and thus, the potential for monitoring small strains exists in the artesian well. Based on the quadrantal pattern of rising and falling groundwater level following the 1974 Izu-Hanto-Oki earthquake, Wakita (1975) suggested that water level of wells can be used to monitor changes of tectonic strain. A network of observation wells has been established in the Parkfield earthquake prediction experiment to monitor crustal deformation and fault creep since 1985 (Roeloffs *et al.*, 1989). The distribution of groundwater level changes was generally consistent with the sign of calculated strain (Quilty and Roeloffs, 1997).

Generally, coseismic groundwater level changes should be in the directions expected for responses to the redistribution of tectonic stress due to the thrust of the Chelungpu fault. Groundwater level rose at stations subjected to compressive stress state and fell at stations subjected to tensile stress state. As shown in Figure 7, coseismic groundwater level rises were observed in most of the fan. In other words, tectonic compression predominated in the footwall of the Chelungpu fault as a result of thrusting. Coseismic groundwater level falls were observed only in the western vicinity of the Chelungpu fault. This phenomenon suggests that tectonic expansion existed in the footwall, but only in a narrow, belted area adjacent to the fault.

Besides, the TC, DZ and SH well stations are located in the transition between the extension and the compression zone. At these multiple-well stations, both coseismic rise and fall were observed at different depth. For example, the SH station consists of two monitoring wells tapping two confined aquifers at different depths. As depicted in Figure 8, groundwater level fell 37 cm at SH1, but rose 29 cm at SH2 at the time of earthquake.

The direction of coseismic groundwater level changes recorded at monitoring wells may provide subsurface information for evaluating the distribution of volumetric strain in unconsolidated deposits to the depth of 200 to 300 m as a result of the thrust of the Chelungpu fault. It is anticipated that the area of tectonic expansion might extend northward along the west vicinity of the Chelungpu fault, and possibly extend southward along the western vicinity of the Chuko fault. However, further study is needed to better understand the relationship among volumetric strain, coseismic groundwater level change and fault movement.

MAGNITUDE OF COSEISMIC CHANGES

At the time of the Chi-Chi earthquake, the largest coseismic groundwater level rise, 7.42 m, was observed on hourly records at HW2 (Figure 9a). The HW2 well, located approximately 10 km west of the Chelungpu fault and 43 km west of the epicenter, is screened at the depth between 72 m and 102 m in a confined gravel aquifer. The largest coseismic groundwater level fall, 11.09 m, was observed at JS2 (Figure 9b). The JS2 well, located approximately 1 km west of the fault and 14 km west of the epicenter, is screened at the depth between 156 m and 186 m in a confined gravel aquifer.

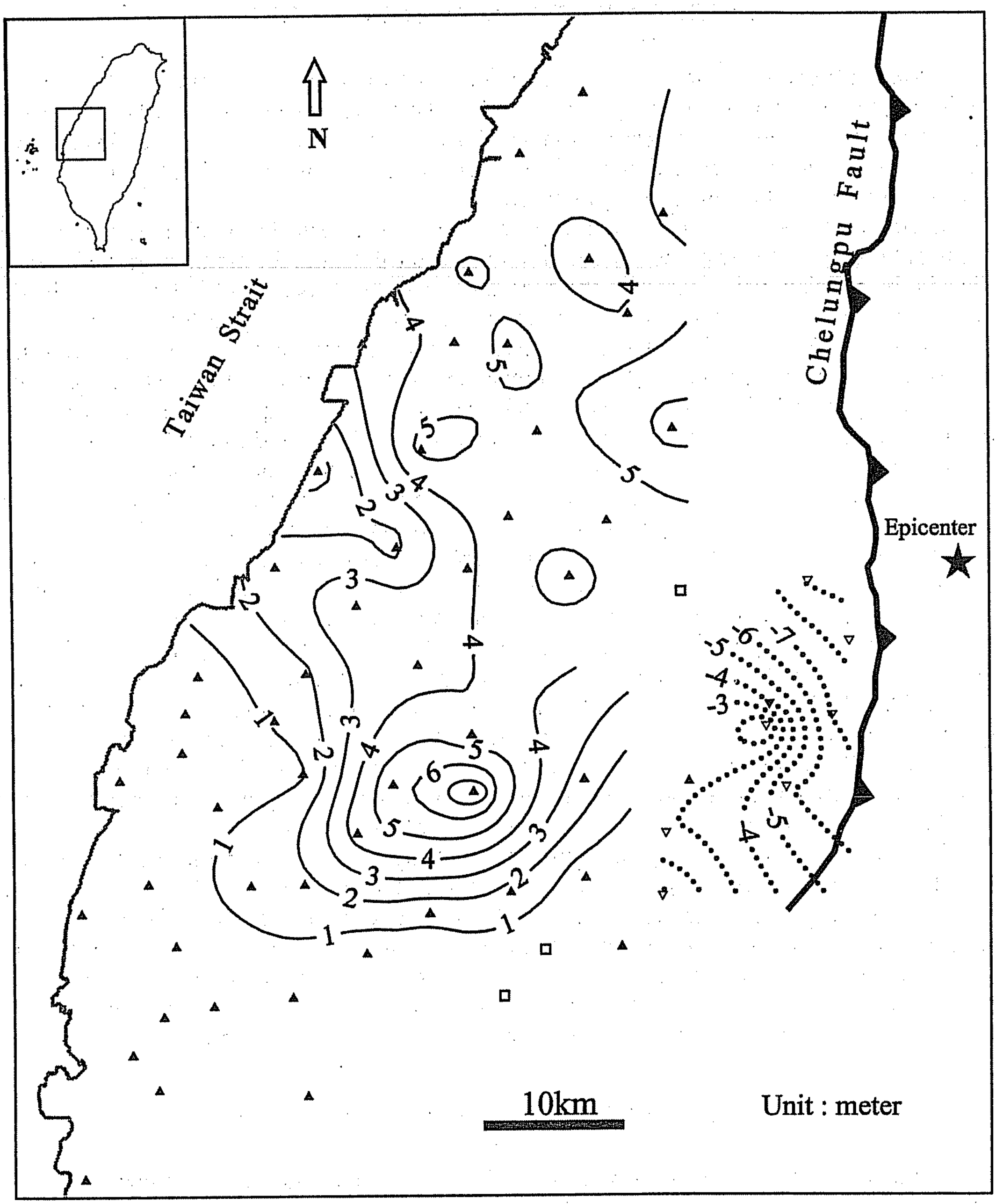


Figure 7. Distribution of the direction and magnitude of coseismic groundwater level changes at 65 monitoring stations in the Choshui River alluvial fan induced by the 1999 Chi-chi earthquake. Solid triangles indicate stations in which the water level fell, open inverted triangles indicate stations in which the water level rose, and open squares indicate stations where both the water level rise and fall were observed.

The contour map in Figure 7 illustrates the distribution of the largest magnitude of coseismic groundwater level changes recorded at monitoring stations in the fan. In the tectonic compression zone, locations of the large coseismic rises are spotted, but the magnitude of coseismic rise tends to increase toward the epicenter or the Chelungpu fault. Generally, coseismic groundwater level rise was greater than 3 m in most of the northern and eastern parts, but smaller than 1 m in the southwestern part. In the tectonic extension zone, the magnitude of coseismic fall of groundwater level also tends to increase toward the epicenter or the Chelungpu fault, from -0.74 m at the GK station to -11.09 m at the JS station.

Vertical variation of the magnitude of coseismic groundwater level changes was identified by the observation at multiple-well stations. At the DG station, as shown in Figure 10, four well records indicated that the changes fluctuated with well depth. Coseismic rises of water level at the DG2, DG3, DG4 and DG5 wells were 0.99, 1.34, 2.48, and 1.76 m, respectively. Therefore, the magnitude of coseismic groundwater level change not only varied with distance from the epicenter but depth of the monitoring well.

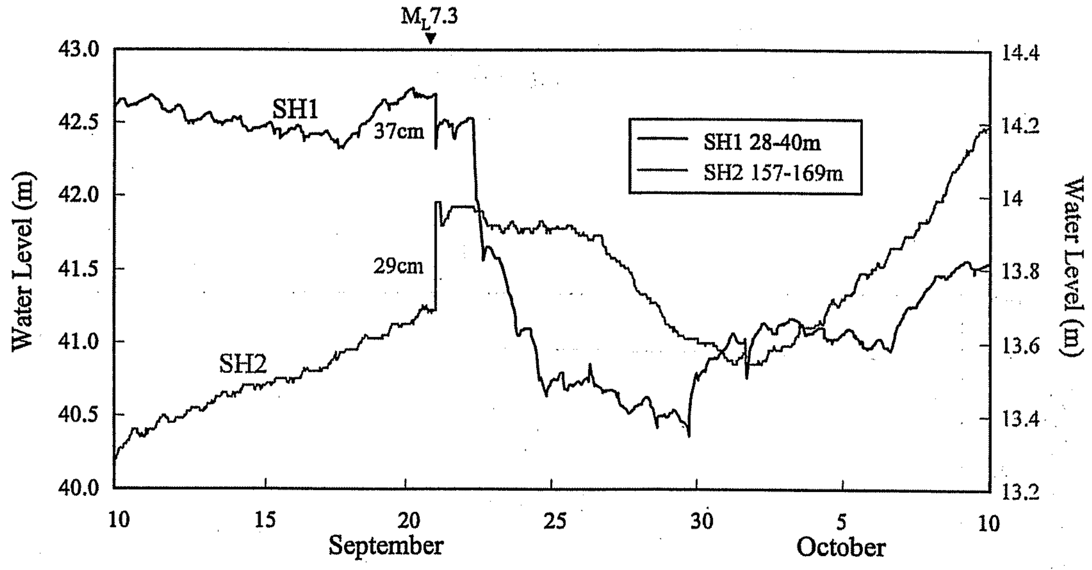
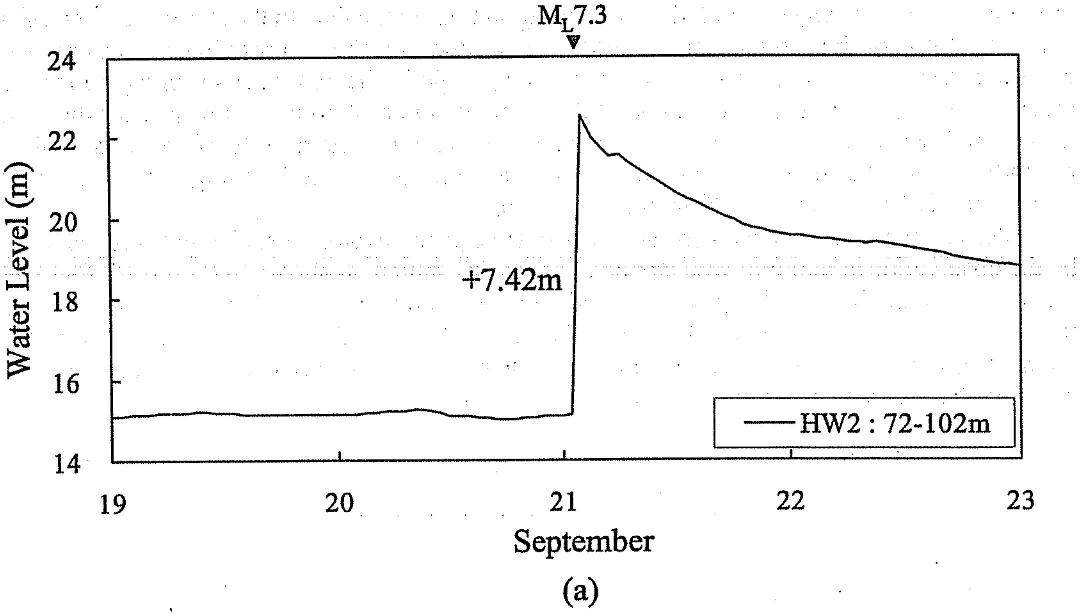


Figure 8. Variation of groundwater levels at the SH well station showing a coseismic fall of 37 cm at SH1 and a coseismic rise of 29 cm at SH2.

CONCLUSIONS

Examinations of the clock of recording instruments, time of groundwater tides, information management process and analog records indicate that abrupt groundwater level changes induced by the Chi-Chi earthquake are believed to be coseismic. To ensure the correct time of groundwater monitoring records in the future, it is essential to increase the sampling rate of groundwater level and to adopt real-time monitoring system.



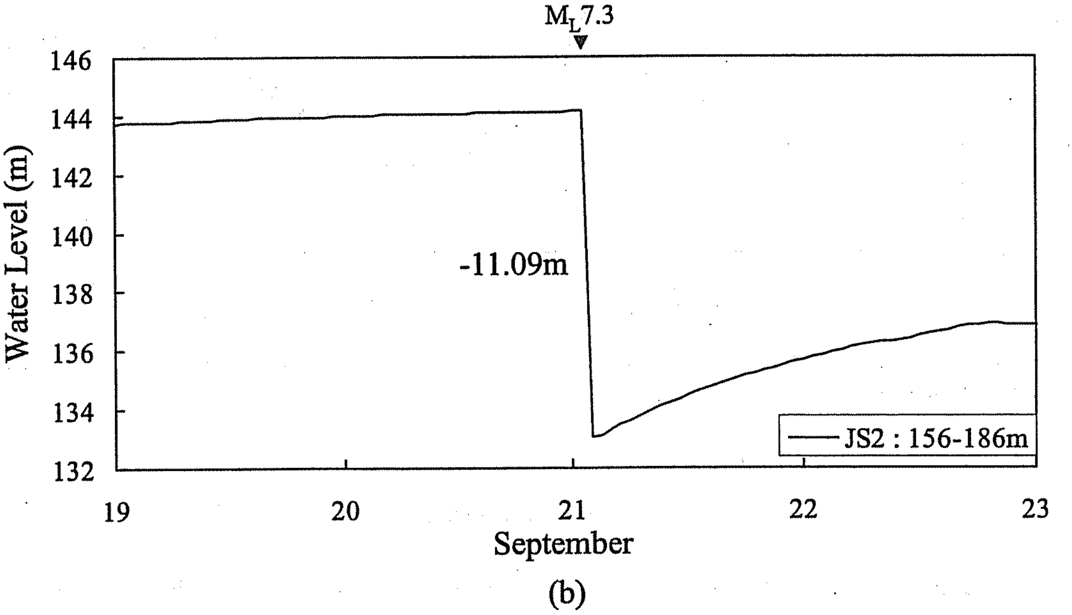


Figure 9. Hourly groundwater level records showing (a) the largest coseismic rise, 7.42 m, at the HW2 well and. (b) the largest coseismic fall, -11.09 m, at the JS2 well.

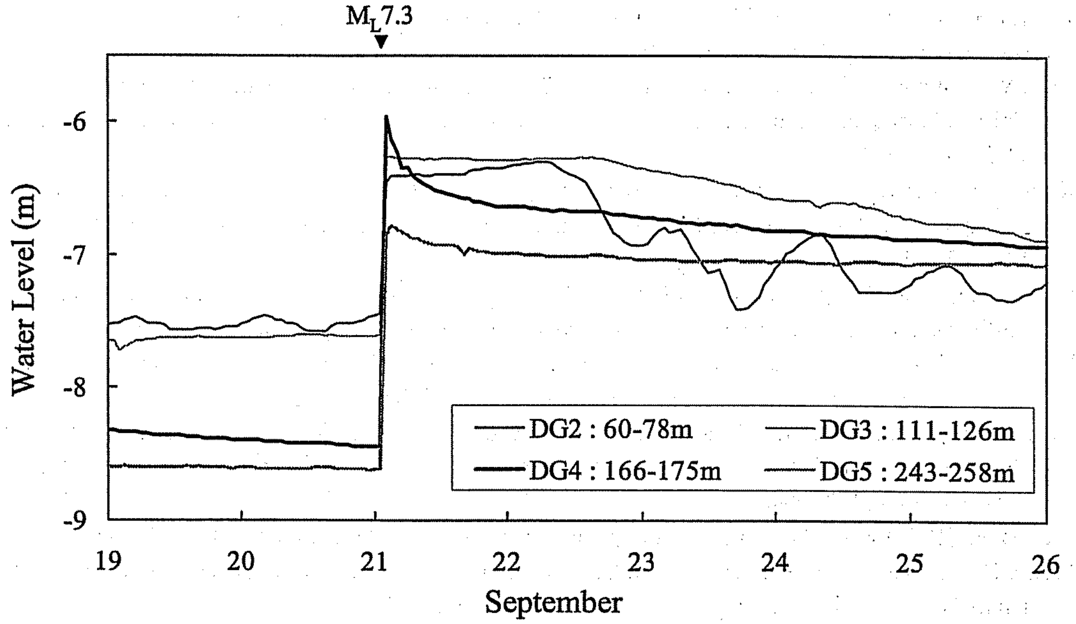


Figure 10. Groundwater level records of DG station showing variation of coseismic groundwater level changes with well depth. Coseismic rises of water level at the DG2, DG3, DG4 and DG5 wells were 0. 99, 1.34, 2.48, and 1.76 m, respectively.

The strain field inferred from the direction of the coseismic water level changes suggests that tectonic compression predominated in most of the Choshui River alluvial fan, while tectonic extension prevailed in a narrow, belted area adjacent to the fault within the depth of 300 m in the footwall of the Chelungpu fault. The magnitude of the coseismic water level changes tends to vary not only with distance from the epicenter or the fault but with well depth, implying that the impact of stress change by fault thrusting is three-dimensional. It is anticipated that these monitoring records may provide a rigorous basis for future studies on the relations of groundwater level changes to crustal deformation, hydrogeologic characteristics, and possibly earthquake occurrence.

ACKNOWLEDGMENTS

We gratefully acknowledge the support from the Water Conservancy Agency for providing groundwater level data, field information and other assistance. This study was financially supported by the National Science Council of R.O.C. under contract No. NSC-90-2116-M-002-027.

REFERENCES

Bredehoeft, J.D. (1967) Response of Well-Aquifer Systems to Earth Tides: *Journal of Geophysical Research*, **72**, 3075-3087.

Central Geological Survey (1999) Geological Investigation of the 921 Earthquake: *Report of the Central Geological Survey*, Taipei, Taiwan, ROC.

Chia, Y. P., Wang, Y. S., Chiu J. J., and Liu, C. W. (2001) Changes of Ground Water Level due to the 1999 Chi-Chi Earthquake in the Choshui River Alluvial Fan: *Bulletin of Seismological Society of America*, **91, 5**, 1062-1068.

King, C.-Y., S. Azuma, G. Igarashi, M. Ohno, H. Saito, and H. Wakita (1999) Earthquake related water-level changes at 16 closely clustered wells in Tono, Central Japan: *Journal of Geophysical Research*, **104**, 13073-13082.

Quality E.G. and E.A. Roeloffs (1997) Water-level Changes in Response to the 20 December 1994 Earthquake near Parkfield, California: *Bulletin of Seismology Society of America*, **87**, 310-317.

Roeloffs, E.A. (1998) Persistent water level changes in a well near Parkfield, California, due to local and distant earthquake: *Journal of Geophysical Research*, **103**, 869-889.

Roeloffs, E.A., S.S. Burford, F.S. Riley, and A.W. Records (1989) Hydrologic Effects on Water Level Changes Associated with Episodic Fault Creep Near Parkfield, California: *Journal of Geophysical Research*, **94**, 12387-12402.

Wakita, H. (1975) Water Wells as Possible Indicators of Tectonic Strain: *Science*, **189**, 553-555.

Wang, C. Y., Cheng, L. H., Chin, C. V., and Yu, S. B.(2001) Coseismic hydrologic response of an alluvial fan to the 1999 Chi-Chi earthquake: *Geology*, Taiwan, **29**, **9**, 831-834.

Water Conservancy Agency (2000) Analysis of the Changes of Surface Water Levels and Groundwater Levels Caused by the 21 September 1999 Chi-Chi Earthquake: *Report of the Water Conservancy Agency, Taichung*, Taiwan, ROC.