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Groundwater–strain coupling before the 1999 M_w 7.6 Taiwan Chi-Chi earthquake

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SUMMARY

The coupling of pre-earthquake anomalous phenomena between long-term groundwater levels recorded at 42 monitoring stations and time-varying surface strain derived from 16 GPS stations was found in the Choshuichi Alluvial Fan before the 1999 M_w 7.6 Chi-Chi earthquake in Taiwan. The noise-free groundwater-level anomalies consistently comprised by a sequence of decrease, rise and flat phases, which agree very well with changes in strain rates computed from the GPS stations. These coupling agreements show that in addition to compression, tension can be generated before a thrust earthquake occurrence as well. This case demonstrates that short-term surface deformation as signals against noise and accuracy of pre-earthquake anomalous phenomena can be simultaneously examined by using multiple-parameter crosscheck for significantly reducing the uncertainty of earthquake precursory evaluation.

1. Introduction

Earthquakes are generally considered as a result of stress loading, which exceeds a threshold of the fault rupture in the crust. In past decades, groundwater levels were considered as a pressure transducer response to stress changes during earthquakes (Bredehoeft, 1967; Chia et al., 2001; Igarashi and Wakita, 1991, 1995; Kingsley et al., 2001; Quilty and Roeloffs, 1997; Roeloffs, 1988, 1998; Narasimhan et al., 1984; Van Der Kamp and Gale, 1983; Wang et al., 2001). Despite early optimism (Scholz et al., 1973), definitive and consistent evidence for hydrological precursors of earthquakes has remained elusive (Bakun et al., 2005). Difficulties include that anomalous changes in groundwater levels are recorded at some sites but not at other nearby sites (Biagi et al., 2001) and, most reported anomalous changes were not corrected for the fluctuations in barometric pressure, earth tides, and other environmental factors, so that some changes related to earthquakes are taken to be 'noise' (Hartmann and Levy, 2005). Notwithstanding these difficulties, the progress in the study of seismo-groundwater levels has been made in the past decade. Groundwater records are now routinely corrected by removing the noises unrelated to earthquake processes (Bredehoeft, 1967; Igarashi and Wakita, 1995; Kingsley et al., 2001; Narasimhan et al., 1984; Roeloffs, 1988; Van Der Kamp and Gale, 1983). Alternatively, those noises also can be effectively removed from groundwater data in the frequency domain through a band-pass filter via the Hilbert–Huang transform for adapting earthquake-related signals with non-linear and non-stationary nature (Chen et al., 2013a). Earthquake-related changes can be determined by

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using the cross comparison among entire well-network via enhanced amplitudes in the particular frequency band. Consistent enhancements of the amplitudes were repeatedly observed before three earthquakes ($M > 6$) within a 13-year period.

Global Positioning System (GPS) is widely used in determining accurate location and displacement of the Earth surface (e.g., Dow et al., 2009; Wdowinski et al., 1997). Crustal deformation resulted from earthquake-related stress can be repeatedly retrieved from GPS data after removing noises (Chen et al., 2011, 2013b, 2014). Those results suggested that signals of pre-earthquake crustal deformation are certainly contained within GPS time-series before earthquake occurrence. Because groundwater levels are sensitive to crustal pressure, simultaneous and comparable changes between groundwater and crustal deformation are expectable once earthquake-related stress accumulates in the same area. Chen et al. (2013a) found that uplift and depression of groundwater levels were closely related with changes in orientations of filtered surface displacements before the Chi-Chi earthquake. However, a debate regarding the aforementioned relationship still remains because the changes in the orientations do not agree with strain changes over a time interval on the basis of the physical meaning.

Here, groundwater level data recorded at 54 monitoring stations (Fig. 1 and Table 1 in Chen et al., 2013a), which are evenly distributed over the Choshuichi Alluvial Fan (in the footwall of the Chelungpu fault with an area of 1800 km^2), and data from 16 continuous GPS stations in Taiwan (Fig. 1) are utilized again to meet the argument that the groundwater level fluctuation is related with surface crustal deformation associated with the 20 September 1999 M_w 7.6 Chi-Chi earthquake in Taiwan. The relatively even distribution of the monitoring wells, their contiguity to the Chelungpu fault (less than 50 km in distance) and the relatively high sampling rate (one hour), makes this database unique and highly valuable. Meanwhile, those groundwater stations are well coved by the dense GPS stations that yields an excellent opportunity integrating two potential parameters (i.e. groundwater levels and surface deformation) to expose evolutions of physical factors during the Chi-Chi earthquake.

2. Groundwater measurements

Each groundwater stations distributed over the Choshuichi Alluvial Fan consisted of one to five wells ranging from 14 to 300 m in depth and equipped with a screen covering from 6 to 36 m in length (Chia et al., 2001). Each monitoring well only monitors one particular aquifer, which is primarily composed of gravel or sand. The gravel pack around well screen is overlain with 3- to 5-m thick bentonite to prevent groundwater from flowing between aquifers of different depths. Groundwater levels in these wells are recorded automatically by piezometric measurements with a sampling rate of one hour (Hsu, 1998; WRA, 2001). Drilling logs from the wells reveal unconfined and confined aquifers of Holocene to Pleistocene sands and gravels with the porosity of about 0.15–0.3, separated by impermeable clay and mud (Chen and Yuan, 1999; WCA, 1997; Tung, 2003; Wang et al., 2012, 2013). The shallowest aquifer is unconfined and the deeper aquifers are confined. The upper two aquifers are often affected by anthropogenic activities, while the third deep aquifer is not much affected and is considered to be the main reference in this study. The three aquifers are gradually pinched out at the western end of the alluvial fan and are integrated to a uniform thick impermeable aquitard off the western coast (WCA, 1997). Thus, the alluvial fan is isolated at the

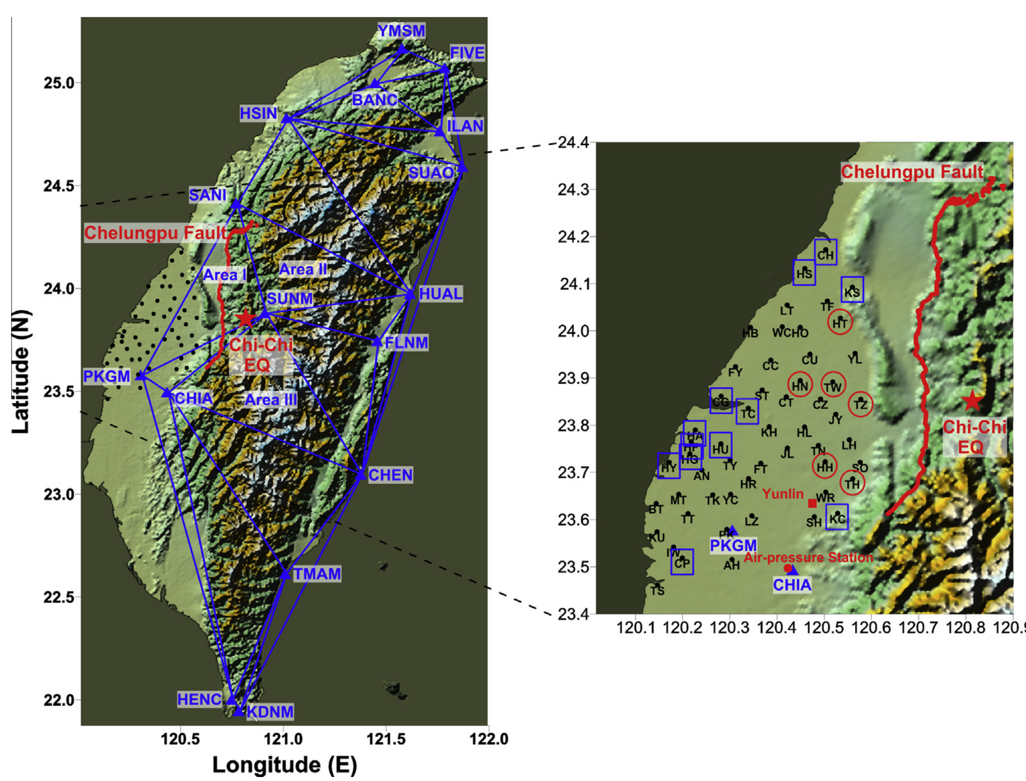

Fig. 1. Locations of groundwater, precipitation and air pressure stations in this work. The red star is the epicenter of the Chi-Chi earthquake and its exposed Chelungpu fault (~90 km in length) is represented by the red line. Solid black circles denote locations of groundwater stations discussed in the text with air-pressure and precipitation effects accounted. Blue triangles show locations of used GPS stations. Notably, Area I, Area II and Area III constructed by GPS stations cover the Chelungpu fault to evaluate strain changes before the Chi-Chi earthquake. Stations with (without) significant anomalies associated with the Chi-Chi earthquake are presented by red open circles (blue open rectangles). Precipitation and air-pressure stations are illustrated as blue solid triangle and dot, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

discharge ends and has no outlets for aquifers except through artificial drafting.

3. Methodology

The time-series of the groundwater level data spanned from 1 July 1997 to 31 December 2000, for sufficiently covering the Chi-Chi earthquake. Groundwater data were first down-sampled to 1 sample point using the data recorded at the time of 00:00 (local mid-night time) each day to mitigate visual cycles associated with the diurnal and semi-diurnal tides. The factors of the barometric pressure, earth tides and precipitation are examined and eliminated from all stations to determine potential seismo-groundwater anomalies using conventional methods (Inkenbrandt et al., 2005; Rojstaczer, 1988). Disturbance of groundwater extraction was suppressed by using data of the deep third aquifer due to its relatively limited extraction. Actual records in 1999 for each well were compared with the yearly variations of groundwater levels, which are mean values from the yearly noise-free data between 1998 and 2000, to roughly estimate effects of annul precipitations on groundwater levels. Once the fluctuations of pre-earthquake anomalous groundwater were observed, those anomalies were further compared with surface deformation to diagnose potential relationships.

Accurate time-series positioning analyses of the 16 GPS stations were computed by using Bernese 5.0 software (Dach et al., 2007). Shen et al. (1996) proposed that tension or compression stress loading in a particular region can be evaluated according to positive or negative changes in its region. Time-varying patterns in particular regions are computed from the positioning of adjacent 3 GPS stations (see blue triangles in Fig. 1). The value in the entire regions on 1 July 1998 was taken as a reference. Differences, which were estimated by subtracting the reference value for a time-various area, were divided by the reference value for normalizing surface strain. To better examine the relationship of the uplift/depression groundwater levels with negative/positive strain changes, we computed short-term strain (groundwater) rates by subtracting an average of surface stains (groundwater levels) within a 25-day window before the target day from it after the day. Short-term strain (groundwater) rates were further normalized to time (i.e. divided by 25 days) as the daily strain (groundwater) rates for fair comparison. In contrast, the long-term strain daily rate is calculated using the difference of surface strain via a 1-year window divided by 365 days for normalization. Furthermore, the strain rates derived from entire regions on the same day were integrated together to construct the strain rate maps to visualize situations of stress loading in the spatial domain in Taiwan.

4. Interpretation

Groundwater level changes in the third aquifer at the Tienchung (TZ), Huatang (HT), Tungho (TH), Huhsi (HH), Tienwei (TW) and Hohsin (HN) stations with corrections of the responses from atmospheric pressure using the standard methods (Inkenbrandt et al., 2005; Rojstaczer, 1988) and the Earth's tidal are shown in Fig. 2. Significant depression anomalies ranged between about −4 m at the HH station (Fig. 2f) and about −2 m at the HT station (Fig. 2d) can be consistently found from these six sample stations in the same period in 1999. Such big and large-scale anomalous depression in groundwater levels is very unusual in Taiwan. Note that those unusual anomalies somehow do overlap annual variations of groundwater levels in the time domain at the HH, TH

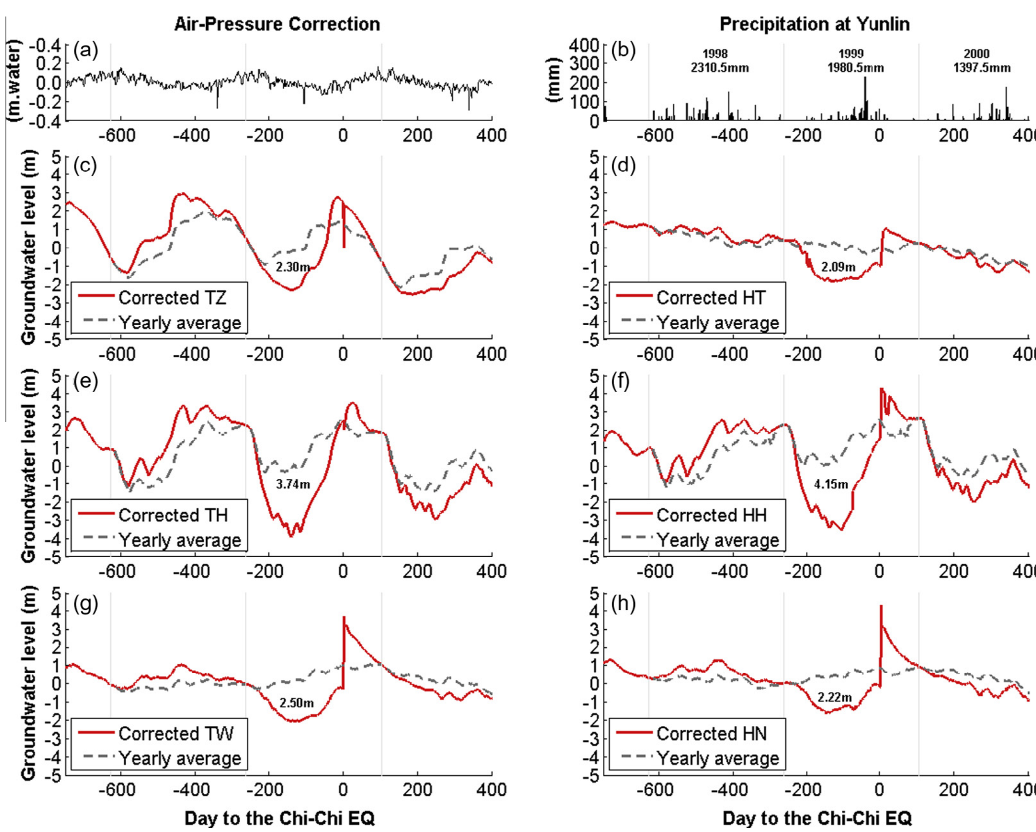

Fig. 2. Long-term variations of atmospheric pressure, precipitation and groundwater level for the six selected stations. (a) Responses of the atmospheric pressure on groundwater level; (b) precipitation and (c)–(h) the groundwater level changes of selected stations. Red and dash lines are the corrected groundwater level and estimated yearly variations, respectively. The maximum negative deviations (in meters) between the groundwater level and estimated yearly variations are revealed in (c)–(h). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and TZ stations. However, the anomalies with unique frequency characteristics can be well determined and/or distinguished in the frequency domain (Chen et al., 2013a). Fig. 2a shows responses of the barometric noise on groundwater levels in the study period. In particular, the responses are very small (in centimeters) as compared with the anomalous depression before the Chi-Chi earthquake (in meters, see Fig. 2a and c–h). Fig. 2b presents yearly precipitation from 1998 to 2000. Since the annual precipitation (1980.5 mm) in 1999 is right in the middle of those in 1998 (2310.5 mm) and in 2000 (1937.5 mm), there was no major drought or flood during the period. The groundwater levels, which are significantly below the estimated yearly variations in 1999, show consistent unusual depression prior to the Chi-Chi earthquake (i.e. the day of 0) against the effects of the annual precipitation. Through an investigation of entire area, the common characteristic of those depression anomalies can be consistently observed in 78% (=42/54) of stations in the Choshuichi Alluvial Fan in central western Taiwan about 250 days before the mainshock by removing influences of localized descending of groundwater level around the wells.

Groundwater levels recorded in the third aquifer at the HT station are taken as an example to illustrate the development of the unusual depression within relatively short durations before the Chi-Chi earthquake. Variations of the unusual depression anomalies can be separated into three phases (Fig. 3). In Phase 1, groundwater levels started decreasing sharply and significantly about the 220 days before the earthquake. In Phase 2, groundwater stayed in a low level at around the −130 day and then increased to a local maximum on the 13th day prior to the mainshock. We determined the minimum (Pmin) and the maximum (Pmax) from the uplift patterns in Phase 2 for all stations in this study (Fig. 3). The ΔGW (=Pmax–Pmin, in meters) and ΔD (in days) were computed by using differences and durations in groundwater levels between Pmin and Pmax, respectively, to construct spatial maps of the

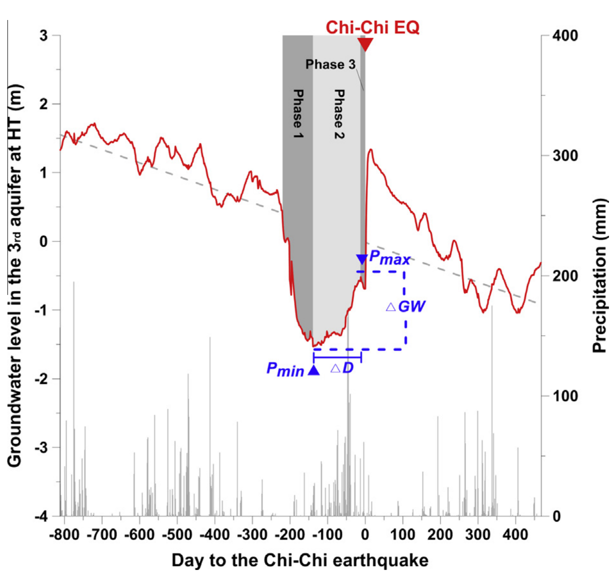

Fig. 3. Variations of groundwater level and precipitation during 1997.7.1–2000.12.31 at the HT station. The red line denotes air-pressure corrected data of groundwater level in the third aquifer at the HT station. The gray dash line suggests that a decrease tendency of about −0.7 m/yr in the groundwater level. Grey bars show precipitations at the Yunlin station. Shadow areas present unusual decrease (Phase 1), rise (Phase 2) and flat (Phase 3) modes in the groundwater level prior to the Chi-Chi earthquake. Blue dash lines indicate that beginning (Pmin) and ending (Pmax) times of groundwater level rise (Phase 2) following an unusual decrease (Phase 1). The ΔGW and ΔD are defined in the text. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Choshuichi Alluvial Fan (Fig. 4). The maximum uplift of ΔGW is about 7 m and observed at stations nearby the Chelungpu Fault and the mainshock epicenter (Fig. 4a). The ΔGW is inversely proportional with the distance of stations to the fault and epicenter. On the other hand, ΔD roughly ranged between the −130 and −13 days, implying that the anomalous uplift of groundwater levels could last about 110 days (Fig. 4b). In Phase 3, its duration (~13 days) is much shorter than the previous two phases. Uplift of groundwater levels was stopped at wells near the fault that was earlier than those located away from. This suggests that accumulating stress seemed to approach a critical threshold, in which strata is maximum clamped. Groundwater flowed to the surrounding areas along the pressure gradient a few days before the mainshock occurred. The Chi-Chi earthquake was a thrust event mainly dominated by the compressive stress. Uplift and smooth changes of groundwater levels in Phase 2 and Phase 3 can be considered of the compressive strain loading in the crust. However, groundwater depression in Phase 1, which would be resulted from tension stress loading, was very unusual and raised a question against the compressive strain loading of thrust earthquake.

To expose potential relationship between the groundwater level and strain accumulation, the surface strains in three chosen

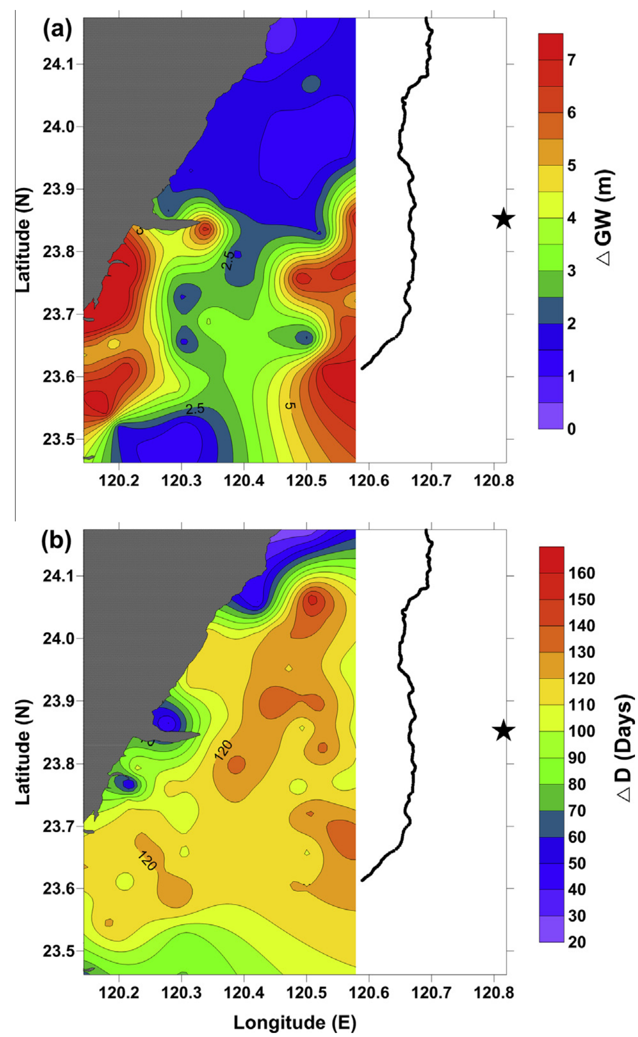

Fig. 4. The spatial distributions of ΔGW and ΔD. The spatial distributions of ΔGW (meter) and ΔD (day) prior to the Chi-Chi earthquake in the third aquifer of Choshuichi Alluvial Fan are shown in (a) and (b), respectively. The grey area denotes the ocean.

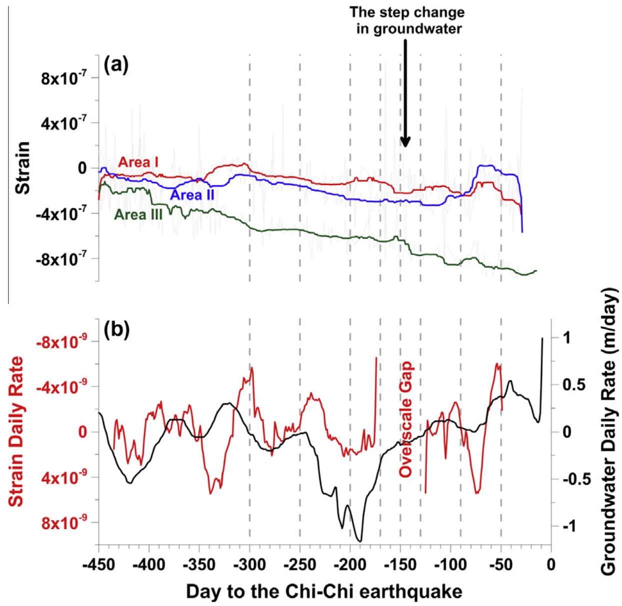

Fig. 5. The surface strain, strain daily rate and groundwater daily rate before the Chi-Chi earthquake. The surface strains in Area I, Area II and Area III are shown in (a). The strain daily rate of Area I (red line) and the groundwater rate (black line) are shown in (b). The vertical dash lines denote the target days of −300, −250, −200, −170, −150, −130, −90 and −50 days to the Chi-Chi earthquake for further examination in the spatial domain in figure 6. Note that the vertical axis in (b) is an inverse axis to yield a proportional relationship between daily rates of strain and groundwater. The over-scale gap is resulted from a step change in surface displacement on −150 and −130 days to the Chi-Chi earthquake that also can be found in groundwater level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

regions surrounding the epicenter (i.e. Areas I–III show in Fig. 1) were examined and shown in Fig. 5. The surface strain of Area III exhibits a significant decreasing trend from the −450 day to the datum time (i.e., 0 day) of the Chi-Chi earthquake (Fig. 5a). In contrast, the surface strain of Area I and Area II shows various fluctuations along with relatively-smooth decreasing trends. It is worth mentioning that significant decrease of the surface strain in Area I, where covering most groundwater stations in this study, can be clearly found on spots about 325, 175, 120 and 75 days before the Chi-Chi earthquake. Those decreasing spots roughly agree with the uplift of the groundwater levels (also see in Fig. 3). The troughs of Area I in the strain daily rate appeared about 420, 340, 270, 200 and 70 days before the Chi-Chi earthquake (Fig. 5b). Notably, overscale changes can be found around 150 days before the mainshock and agrees well with the significant step changes in both GPS and groundwater data. In contrast, low stages of groundwater daily rates can be found on 420, 360, 270, 200, 70 days before the mainshock (Fig. 5b). Thus, in-phase changes starting from 300 days prior to the earthquake between the inverse of strain rates and groundwater rates suggest that development of the unusual depression of groundwater levels are highly related to the crustal deformation during the seismogenic period of the Chi-Chi earthquake. The descending of the groundwater levels (i.e. about 300 days before the Chi-Chi earthquake) and the increasing surface strain suggest that tension stress loading in the alluvial fan was very plausible before the compress-dominating thrust earthquake.

The long-term strain rate map of Fig. 6 shows that the negative values mainly distribute in central region of Taiwan except for the northeastern and southwestern regions due to the back-arc extension of the Okinawa Trough and Southern Longitudinal Trough, respectively (Hsu et al., 1996). The distribution of the long-term rate is also consistent with annual strain changes obtained in recent studies (Loevenbruck et al., 2001; Lin et al., 2010). We further computed the rates of short-term daily strains on 8 aforementioned target days (i.e. 300, 250, 200, 170, 150, 130, 90 and 50 days before the Chi-Chi earthquake) to compare with the anomalous variation of groundwater level. While the groundwater level increased about 300 days before the earthquake, the negative short-term strain rates can be observed in our study area accordingly. Short-term strain rates varied from negative to positive values between 300 and 200 days before the mainshock while the relatively high groundwater level rapidly descended. Negative short-term strain rates gradually moved toward positive values around 170 days when groundwater level was mitigated and maintained at a low stage. It is clear that the significant step changes in groundwater level happened around 150 and 130 days before the mainshock and the short-term strain rates also yielded an inversely relationship. After that period, groundwater level gradually ascended and reached to a high level until the earthquake occurrence. The strain rates remained negative between 90 and 50 days before the mainshock.

5. Discussion

The variations of the substantial dropping were clearly observed in groundwater levels for most monitoring wells in Phase 1 prior to the occurrence of strong Chi-Chi thrust earthquake (Fig. 3). The positive strain rates derived from GPS data of the same period suggest that tension stress was dominated in a wide area covering the Choshuichi Alluvial Fan (Fig. 6). Many studies observed that numerous cracks would be generated before earthquake occurrence (Booth et al., 1990; Crampin, 1994; Crampin et al., 1999; Winterstein and Meadows, 1991). Alternatively, the tension stress loading may increase the porosity of affected strata. These features would lead the fluid in the aquifer filled into cracks and resulted in the significant decrease of groundwater levels in Phase 1. However, this observation that the tension stress was loading in the strata before the Chi-Chi earthquake is against the common knowledge of thrust fault development. To illustrate the existence of the tension stress loading, variations of surface strains in Areas II and III, were compared with those in Area I (see Figs. 1 and 5). It is clear that the surface strain shows a generally decreasing trend in all three regions (i.e. Areas I, II and III) where were dominated by the thrust Chi-Chi earthquake. When quantity of changes in the surface strain is taken into consideration for comparison, slopes of the surface strains of Areas II and III were significantly higher than that of Area I in Phase 1 (Fig. 5a; days of −220 to −130). Relatively-large compressive stress in Areas II and III would baffle at Area I to result in temporary tension stress loading in the crust and thus decreasing groundwater level. This suggests that the strain changes were not uniform within a wide area during the earthquake preparation period but very complex due to the inhomogeneous structure underground. In Phase 2 (days of −130 to −13), negative strain rates suggest that compressive stress had replaced tension stress loading in the crust. The compressive stress would decrease of the porosity and prompt groundwater level rising even though little or no rainfall was recharged to the aquifer. The analytical results show an anticorrelation between groundwater level and strain rates (Fig. 5b). This is agreement with the hypothesis in Chen et al. (2013a) that the tension and compressive stress would dominate the down and up of groundwater levels before the Chi-Chi earthquake from the filtered surface deformation. However, it is very difficult to estimate groundwater level fluctuations by using the volume strain because the vertical effect of the

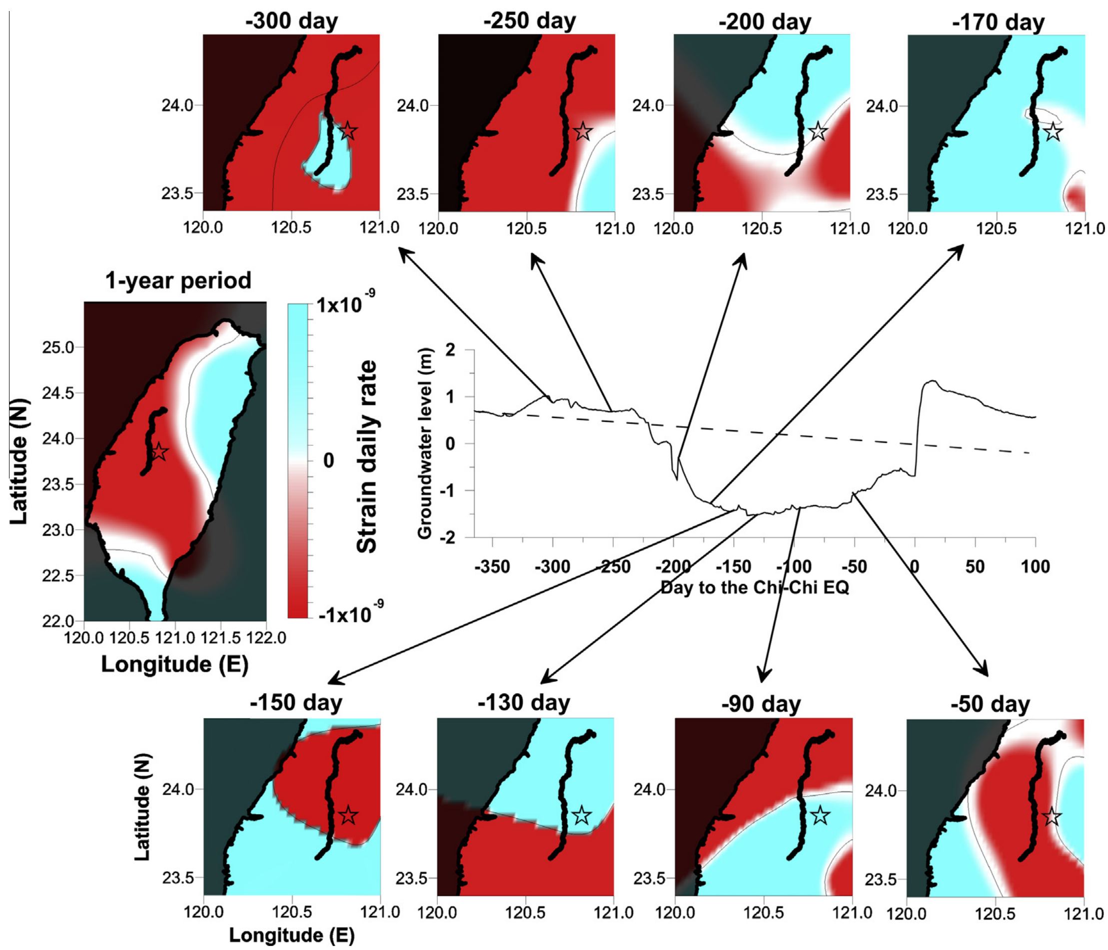

Fig. 6. The long-term (1-year) and short-term (25-days) strain daily rates on the particular days versus changes in groundwater levels of the third aquifer at the HT station. The central part shows changes in the groundwater levels. The dash line denotes the long-term decreasing trend. The red and blue color show the negative and positive strain rates that suggests compressive and tension stress loading in the crust, respectively. The open star indicates the mainshock epicenter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

earthquake-related stress loading cannot be evaluated without the measurement of strainmeter which was not available in 1999.

From Fig. 5a, it is obvious that short-term interferences, which laid on the generally decreasing long-term pattern, were highly related to the fluctuated anomalies of groundwater level before the occurrence of main thrust Chi-Chi earthquake (Fig. 5b). Although the development of short-term strain rate were sometimes against the common feature of the long-term stress accumulation, and these anomalous phenomena cannot reveal the entire mode of a strong earthquake preparation, the detectable short-term signals do provide important insights before a strong earthquake.

Daily solutions of accurate position recorded by the GPS stations are often used in studying the long-term changes within the plate movements. However, the short-term changes in daily solution of GPS time-series are generally ignored because of high noise. We also found that the variations of the GPS data possibly were very difficult to separate the noise neatly with components of known factors in data processing. In practice, it is highly risky to diagnose the pre-earthquake signals only by a single factor, such as groundwater level in this case. However, the agreement between the groundwater level and strain change in the temporal domain and the physical mechanism strongly implies that the determined short-term changes from the GPS data are actually very useful signals.

6. Conclusion

In this study, we examine the existence of possible precursory component during the preparation period of the Chi-Chi earthquake by comparing two different parameters with the same physical mechanism. Multiple-parameter crosscheck is a reliable and efficient way to avoid mistakes and achieve the real nature of the earth system sciences while exploring unknown factors. Significant anomalies before the Chi-Chi earthquake have been consistently observed at 78% (=42/54) groundwater level data of monitoring stations that surmounts the previous doubts in the Choshuichi Alluvial Fan, Taiwan. The analytical results show good agreements between up and down of groundwater levels with negative and positive strain rates derived from GPS data, respectively. This observation not only benefits the identification of pre-earthquake anomalous phenomena from multiple measurements, but also understands the potential usage of short-term changes in GPS time-series. The tension stress loads was yielded in a relatively-large compressive stress accumulating environment of the central Taiwan and resulted in exceptional groundwater depression. The existence of a tension stage breaks the preconceived assumption of the solely compressive stress in a dominating thrust earthquake. The short-term signals hidden in the intense displacements of long-term plate movements can be effectively retrieved once the multiple-parameter crosscheck is employed. In this regard, a comparison study integrating the groundwater level, GPS strain rates and other physical parameters should be pursued in other strong earthquakes of similar geological setting.

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