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Anomalous frequency characteristics of groundwater levels before major earthquakes in Taiwan

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Abstract

Unusual decreases in water levels were consistently observed in 78 % (=42/54) of the wells in the Choshuichi Alluvial Fan of central Taiwan roughly 150 days before the Chi-Chi earthquake ($M = 7.6$ on 20 September 1999) when the influences of barometric pressure, earth tides, precipitation and artificial pumping were removed. Variations in groundwater levels measured in the anomalous wells between 1 August 1997 and 19 September 1999, the time period covering the unusual decreases, were transferred into the frequency domain to examine anomalous frequency bands associated with the Chi-Chi earthquake. Analytical results show that amplitudes at the frequency band between 0.02 day^{-1} and 0.04 day^{-1} were generally maintained at the low stage and were enhanced in the few weeks before the Chi-Chi earthquake. Variations in amplitude within this particular frequency band were further examined in association with earthquakes ($M > 6$) between 1 August 1997 and 31 December 2009. Enhanced amplitude phenomena are consistently observed prior to the other two earthquakes (the Rei-Li and Ming-Jian earthquakes) during the 12.5 yr, which sheds a promising light on research into precursors of strong earthquakes when combined with other geophysical observations such as geomagnetic anomalies and crustal displacements.

1 Introduction

Taiwan is an island located along the western margin of the Pacific Ocean and is approximately 400 km in length and 150 km in width. The convergent plate interaction between the Philippine Sea plate and the Eurasian plate has been uplifting Taiwan for the past 6 million years, forming the central mountain range of the island, which has an altitude of 3952 m (Ho, 1988). Annual precipitation in Taiwan is approximately 2500 mm on average (WRA, Water Resources Agency, 2010), but rainfall is mainly concentrated during the wet season (May to October, approximately 78 %) due to large contributions from the Meiyu and typhoons. Rainfall retention for effective water resource use is very important in Taiwan because the uneven distribution of precipitation is highly prominent both in temporal and spatial modes. When water consumption rapidly increased due to population growth and economic development after 1980, a great quantity of groundwater was used to make up for the insufficiency of surface water. During the past decades land subsidence has followed the depletion of groundwater resources in the western and southwestern regions of Taiwan due to excessive extraction and slow recharge (Liu and Huang, 2002; WRA, 2001; Wang, 2007).

The most notorious land subsidence is at the Choshuichi Alluvial Fan of central Taiwan (Fig. 1), with an active subsiding area of over 600 km^2 and a maximum subsiding rate of up to 10 $cm\,yr^{-1}$ (Chen et al., 2010a). To effectively utilize groundwater resources and control (or mitigate) subsidence along coastal areas, where pumping is intensive and recharge is very slow (Liu and Huang, 2002; WRA, 2001), 54 evenly distributed hydrologic stations (Table 1; a complete list can be found in WRB, Water Resource Bureau, 1999) were installed at depths ranging from 24 m to 306 m in the Choshuichi Alluvial Fan (Fig. 1; Hsu, 1998) during 1992–1997. The Choshuichi Alluvial Fan can be divided into three aquifers with depths of 250 m, according to subsurface hydrogeological surveys (Chen and Yuan, 1999; WRB, 1999). Each station has one to five screens situated in different wells to fully observe groundwater level changes from shallow to deep aquifers.

The convergent plate interaction also causes many earthquakes (Fig. 1). From 1 August 1997 to 31 December 2009, four earthquakes ($M > 6$) (Table 2) occurred near the Choshuichi Alluvial Fan. The most severe event was the Chi-Chi earthquake ($M = 7.6$) of 20 September 1999, which was the most destructive earthquake in Taiwan in the 20th century. This event destroyed more than one hundred thousand buildings and caused roughly 2500 casualties (Yen et al., 2004). The groundwater levels in monitoring wells distributed in the Choshuichi Alluvial Fan recorded intense co-seismic changes caused by the Chi-Chi earthquake, which have been widely reported (Wang et al., 2001, 2005). These co-seismic changes in groundwater levels took approximately 250 days to return to normal (also see Fig. 2). Because groundwater levels change

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when pressure in the crust near wells is modified by earthquakes, they could be considered a pressure indicator that responds to stress changes. Thus, groundwater level changes are not limited to co-seismic events; pre-earthquake signals are invaluable in earthquake hazard prevention. In reality, variations in groundwater levels are affected by barometric pressure, the Earth's tides, and other factors (Bredehoeft, 1976; Chen et al., 2010b; 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). Anomalous variations in groundwater level responses to earthquakes are generally considered meaningful, and these effects can be neatly removed (Brodsky et al., 2003; Igarashi and Wakita, 1991).

In this study, we first examine groundwater levels at the 54 monitoring wells in the temporal domain using corrected data before and after the Chi-Chi earthquake. To avoid co-seismic influences and the subsequent groundwater level recovery of the Chi-Chi earthquake, time-series water levels during the 2.5-yr before the Chi-Chi earthquake are utilized to study earthquake-related frequency bands using a Hilbert-Huang Transform (HHT) (Huang et al., 1998, 2003; Huang and Wu, 2008). After these frequency bands have been determined from records before the earthquake, variations in amplitude at the particular frequency bands, deduced from data recorded between 1 August 1997 and 31 December 2009 in Huhsi (HH), Huatang (HT) and Tungho (TH) are utilized to examine whether abnormal amplitude at determined frequency bands can be related to the other two major earthquakes (i.e., the Rei-Li and Ming-Jian earthquakes; details see Table 2) in Taiwan during the 12.5-yr period.

2 Hilbert-Huang Transform

In general, time-series data are transferred from the temporal domain into the frequency domain using either the Fourier transform (Bracewell, 2000) or wavelet transform (Daubechies, 1990), based on the assumption of signal linearity. When four earthquakes, which occurred near the Choshuichi Alluvial Fan between 1 August 1997 and

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31 December 2009, are taken into consideration, the intervals of these events are quite different. Three earthquakes (i.e., the Rei-Li (R), Chi-Chi (C) and Chia-Yi earthquakes) occurred before 2000, and the last (i.e., the Ming-Jian (M) earthquake) occurred at the end of 2009 (Table 2). The Hilbert-Huang transform (HHT), which adapts non-linear and non-stationary signals (Huang et al., 1998), is used to extract non-linear earthquake-related anomalies from groundwater levels.

HHT comprises the Empirical Mode Decomposition (EMD) and the Hilbert spectral analysis (Huang et al., 1998). In the temporal domain, the data are decomposed into a series of components, which are termed Intrinsic Mode Functions (IMFs), using the EMD Sifting process (details in Huang et al., 1998). In the Sifting process, the first step is to find the local maxima and minima of the analyzed data and connect them using the cubic spine method as the upper and lower envelops. The difference between the analyzed data and the average of the upper and lower envelops is computed and is repeatedly substituted for the analyzed data in the previous Sifting process. The Sifting process is temporally stopped when an average of the difference is less than 10^{-3} m. In this case, the difference is determined as IMF_1 and subtracted from the analyzed data accordingly.

The subtracted data replace the analyzed data to obtain the resulting IMF using the same Sifting process again. The Sifting process is consequently stopped when the upper and lower envelops cannot be constructed due to insufficient local maxima and minima. All of the derived IMFs are transferred into the frequency domain using the Hilbert transform. Thus, IMFs can be obtained from decomposed time-series data regarding groundwater levels at each hydrologic station. Moreover, the instantaneous frequency and amplitude in the frequency domain, as well as the quantity in the temporal domain at each measuring point of IMFs, can be obtained and employed in subsequent data analysis. Note that the marginal spectrum, which offers a measure of the total amplitude contributed by each frequency value and represents the accumulated amplitude over the entire data span, can be uniquely computed (see details in Huang et al., 1998).

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3 A case study: the Chi-Chi earthquake

The Chi-Chi earthquake ($M = 7.6$, occurred on 20 September 1999) was the biggest earthquake in Taiwan in the past century (Ma et al., 1999). To fully understand long-term trends and monitor any abnormal phenomena in groundwater level changes associated with this great earthquake, analytical data from 1 August 1997 (about two years prior to the earthquake) to the end of 31 December 2000 (about a year and a half after) are used. Variations in atmospheric pressure, the Earth's tides, precipitation and extraction of groundwater are major factors affecting water levels (Bredehoeft, 1967; Van der Kamp and Gale, 1983; Narasimhan et al., 1984; Roeloffs, 1988). The upper panel in Fig. 2 illustrates the variations in air pressure from 1 August 1997 to 31 December 2000 measured at the southern site (120.424° E, 23.498° N; the location can be viewed in Fig. 1) of the study area. Annual fluctuations dominated in the air pressure records. Low and high air pressures were regularly observed in the summer and winter seasons, respectively. Groundwater level responses to atmospheric pressure ranging between −0.2 m and 0.2 m were then utilized in the data correction (Rojstaczer, 1988; Inkenbrandt et al., 2005). Tide frequencies of 1 and 2 day^{-1} could be easily eliminated, while hourly data were down-sampled to a daily record. Corrected groundwater level data could then be obtained by removing responses to air pressure and the Earth's tides.

The middle and bottom plots in Fig. 2 present variations in the corrected groundwater data at the HH, HT, Honglung (HR) and Tienwei (TW) sites (see Fig. 1 for locations) and precipitation at the Yunlin station (120.476° E, 23.636° N) from 1 August 1997 to 31 December 2000. Unusual decreases of approximately 2–4 m in the corrected water levels can be clearly identified in these groundwater wells approximately 150 days before the Chi-Chi earthquake. We further examined all of the monitoring wells in the Choshuichi Alluvial Fan and found that similar patterns of unusual decreases are observed at 78 % (=42/54) of the wells, mostly distributed near the Chelungpu fault (see Fig. 1). Unusual decreases by artificial water pumping can be eliminated as the cause because the temporal duration of these anomalous decreases exceeded 200 days (from −250 to −50 day prior to the Chi-Chi earthquake) and the anomalous wells are widely distributed in most areas of the Choshuichi Alluvial fan. Drought can be excluded as well because the annual precipitation in 1999 was 80 % of Taiwan's annual average. The annual precipitation in 1999 (1980.5 mm) is higher than that in 2000 (1397.5 mm) and lower than in 1998 (2310.5 mm). If drought had played a major factor, the same pattern of low groundwater levels would have been repeated in 2000. Thus, the unusual decreases in groundwater levels in the Choshuichi Alluvial Fan were closely related to the Chi-Chi earthquake in both the temporal and spatial domains and are considered seismo-groundwater anomalies resulting from accumulated stress before the earthquake.

4 Interpretation

Groundwater levels at the HR site were further studied using the HHT technique for earthquake-related frequency bands with anomalous amplitudes. The analytical results are presented in Fig. 3. Figure 3a shows the time-series records of air pressure-free groundwater level variations at the HR station for approximately 800 days before the Chi-Chi earthquake. The annual changes in the time-series data at the HR station are very minor in this plot due to the location of HR, which is far from recharge areas (WRB, 1999). Unusual decreases appeared 250 days before the Chi-Chi earthquake but were absent from the record before the Rei-Li earthquake, which occurred 424 days before the Chi-Chi earthquake (Fig. 3a). When groundwater levels at HR from 1 August 1997 to 19 September 1999 were transferred into the frequency domain by HHT, the marginal spectrum revealed an obvious amplitude distribution at periods of 1 and 0.5 days (Fig. 3b) that is affected by the Earth's tides and is in agreement with previous studies (Quilty and Roeloffs, 1991). The time-frequency-amplitude distribution would be seriously damaged if co-seismic data with step changes resulted in an enhanced amplitude distribution at wide frequency bands. When the time-frequency-amplitude distribution of the HR site was examined in depth (Fig. 3c), the enhanced amplitude distribution at wide frequency bands essentially disappeared. This suggests that the effect of co-seismic changes caused by other earthquakes is either very small or can be mitigated by HHT. It is also of note that amplitude enhancements at the associated frequency band before the Rei-Li and Chi-Chi earthquakes are very apparent in Fig. 3c. Figure 3d demonstrates that the time-frequency-amplitude distribution ranged in frequency between 0.02 day^{-1} and 0.07 day^{-1} (i.e., with periods from 14 to 50 days) in the 800-day record before the Chi-Chi earthquake. It is of interest that amplitudes at the frequency band between 0.02 day^{-1} and 0.04 day^{-1} seem to be enhanced before the Rei-Li and Chi-Chi earthquakes. Thus, we further survey amplitude changes among entire frequency bands to find characteristics associated with earthquakes.

We separated groundwater levels at the HR site between 400 and 1 days prior to the Chi-Chi earthquake into 8 phases (i.e., I to VIII in Fig. 4a) using a sliding window of 50 days. We computed marginal spectrums within each phase using derived amplitudes via HHT to examine earthquake-related frequency bands (Fig. 4b). In general, the amplitudes of the marginal spectrums are inversely proportional to frequency, except for (VII), for unknown reasons. Regarding the unusual groundwater level decrease in the temporal domain from (III) to (V), an enhanced amplitude at the frequency between 0.02 day^{-1} and 0.04 day^{-1} is observed, especially in phase (III). To examine whether the enhanced amplitude at a certain frequency band (i.e., between 0.02 day^{-1} and 0.04 day^{-1}) can be employed as a common index associated with earthquakes, long-term groundwater data from 1 August 1997 to 31 December 2009 at the HH, HT and TH sites were all transferred into the frequency domain using HHT. Note that the data from the HR station were eliminated from the analysis due to gaps in the record.

To avoid disturbances from intense co-seismic signals and the subsequent groundwater recovery after the Chi-Chi earthquake, data from 1 August 1997 to 31 December 2009 were separated into two time-series slots: 1 August 1997–19 September 1999 and 1 January 2000–31 December 2009 (Fig. 5a). These two records were transferred into the frequency domain using HHT. Amplitude ratios were computed using

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the integrated amplitude at the frequency band between 0.02 day^{-1} and 0.04 day^{-1} relative to the total amplitude (of the entire frequency band) within a 50-day moving window. The analytical process of amplitude ratios was thus normalized to mitigate the effects of unknown changes in total energy. Figure 5b shows variations in the amplitude ratios over time. During the study period (1 August 1997–31 December 2009), three significantly enhanced peaks can be found in these 12.5-yr data before the occurrence of three major earthquakes (the R, C and M earthquakes; see details in Table 2) at three sites, even though these sites are widely distributed across the Choshuichi Alluvial Fan. The results clearly suggest that the enhanced amplitudes at the frequency between 0.02 day^{-1} and 0.04 day^{-1} derived from corrected groundwater level variations are a very promising signal of immense accumulating strain during the earthquake incubation period because these peaks all appear right before the major earthquakes (magnitudes larger than 6). Note that a step change in the groundwater level at the HT site occurred a few months before the Ming-Jian earthquake (label M in Fig. 5a). The enhanced amplitude at the HT site before the Ming-Jian earthquake could be caused by both the step change and earthquake-related variations.

5 Discussion and conclusions

Long-term groundwater levels in Fig. 5a can be viewed as two distinct types. The first type reflects apparent annual cycles that dominate groundwater levels, particularly at the HH and TH sites. The second type is a decreasing trend in the first half of the study period (before 2004) and then a rising tendency in the latter half. The second feature is an accurate reflection of regional climatic and hydrological variations over the last decade in Taiwan (Huang, 2011; WRA, 2010). Regarding the unusual drop in groundwater levels prior to the Chi-Chi earthquake in 1999, the feature is very distinct in the temporal domain of the 2-yr records for all three sites (Fig. 2). However, if the record extends to 12.5 yr, as shown in Fig. 5a, only the HT site had this abnormal drop; for the HH and TH sites, larger annual variations in groundwater levels easily

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obscured the important pre-earthquake signal in the time-series record due to a similar fluctuation and in-phase variation. Moreover, for the other two major earthquakes (i.e., the R and M earthquakes), none of the three sites show any pre-earthquake signals in their corrected records. This observation vividly illustrates the inherent weakness of groundwater level records in the temporal domain, especially for those with large annual fluctuations.

Figure 5b demonstrates the advantage of transformation from the temporal domain to the frequency domain. It is apparent that the amplitude ratios were significantly enhanced before the Chi-Chi earthquake and other major earthquakes (the R and M earthquakes). A comparison between Fig. 5a and b suggests that earthquake-related anomalies in groundwater levels are often difficult to distinguish from long-term records in the temporal domain but can be identified using the transferred time-frequency-amplitude distribution and/or marginal spectrums in the frequency domain.

Because strong earthquakes occur as a result of large-scale stress accumulation and plate movements, significant surface and subsurface displacements are expected. Subsurface groundwater level variation is a promising candidate because it is very sensitive to pressure changes from stress accumulation at favorable sites. The debate regarding pre-earthquake groundwater anomalies in previous studies is primarily due to the limited number of observation wells over a wide area (Biagi et al., 2001) and the anomalous patterns for different strong earthquakes, which are often very hard to repeat and define. In this study, we have shown that an anomalous decrease in groundwater levels was observed in corrected records at 78 % (=42/54) of the wells widely distributed across the Choshuichi Alluvial near the Chelungpu fault during the months before the Chi-Chi earthquake. It is suggested that groundwater levels can faithfully reflect tectonic stress accumulation prior to the occurrence of strong earthquakes if the monitoring wells are densely distributed and close to the epicenter. Note that there are some relatively-small events of enhanced amplitude ratios can be observed at HT and/or TH in Fig. 5b but cannot be simultaneously observed at the other two stations.

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This suggests that seismo-groundwater anomalies do be apparent at most stations, so it is risky to assess pre-earthquake anomalous phenomena using one isolated station.

Our study shows that it is difficult to obtain the features observed for the Chi-Chi earthquake ($M > 7$) for other strong earthquakes ($M < 7$) in Taiwan using temporal domain data series due to significant disturbances from annual variations. However, in the frequency domain, the seismo-groundwater anomalies could be clearly identified for all three strong earthquakes ($M > 6$) because amplitudes at the frequency band between 0.02 day^{-1} and 0.04 day^{-1} were consistently enhanced in the groundwater level records of monitoring wells. In short, this new method sheds light for research on the precursors strong earthquakes; however, further work is needed to refine the technique and test its applicability to forthcoming strong earthquakes. If this method is combined with other geophysical observations such as geomagnetic anomalies (Chen et al., 2010c) and crustal displacements (Chen et al., 2011), it will be possible to build a strong earthquake forecast system in the future.

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Table 1a. Locations and observation aquifers of the Choshuichi alluvial fan used in this study.

Station	code	Long.	Lat.	Aquifer 1	Aquifer 2	Aquifer 3	Screen depth(m)
Anho	AH	120.3045	23.5166	O	O	O	260–278
Annan	AN	120.2407	23.7058		O	O	159–195
Chaochia	CC	120.3872	23.9393		O	O	180–198
Chiulung	JL	120.4229	23.7529	O	O	O	179–191
Chiungpu	CP	120.1992	23.5202		O		
Chuanhsin	CH	120.5043	24.1738	O	O	O	183–192
Chutang	CT	120.4202	23.8617	O	O		
Fangtsao	FT	120.3659	23.7202	O	O		
Fangyuan	FY	120.3123	23.9256		O	O	187–205
Haifeng	HF	120.2178	23.7667		O	O	166–178
Haiyuan	HY	120.1709	23.7226	O	O	O	160–196
Hanbao	HB	120.3442	24.0088		O	O	173–197
Haoshiu	HO	120.4501	24.0087		O	O	174–204
Hofeng	HG	120.2153	23.7409		O	O	202–220
Hohsin	HN	120.4500	23.8959	O		O	197–227
Honglung	HR	120.3399	23.6884	O		O	209–212
Hou-An	HA	120.2267	23.7910		O		
Hsiantien	ST	120.3689	23.8757	O		O	194–218
Hsichou	CZ	120.4931	23.8569	O	O		
Hsienhsi	HS	120.4595	24.1340	O	O	O	158–194
Hsihu	CU	120.4708	23.9517		O	O	176–200
Hsikang	CG	120.2813	23.8625	O	O	O	263–275
Hsilo	HL	120.4592	23.7977	O	O		
Hsinhua	HU	120.2808	23.7620		O	O	185–197
Huatang	HT	120.5352	24.0285	O	O	O	264–294
Huhsi	HH	120.5030	23.7240	O	O	O	282–294
I-wu	IW	120.1802	23.5431	O	O	O	200–215

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Table 1b. Continued.

Station	code	Long.	Lat.	Aquifer 1	Aquifer 2	Aquifer 3	Screen depth(m)
Kanchiao	KC	120.5298	23.6142	O	O		
Kanghou	KU	120.3839	23.7983		O	O	195–210
Kanyuan	JY	120.5255	23.8248	O	O		
Kinghu	KU	120.1452	23.5751	O	O		
Kuoshen	KS	120.5610	24.0945	O	O	O	197–227
Liuho	LH	120.5544	23.7708	O	O		
Lochin	LT	120.4220	24.0562	O	O	O	180–198
Lungtze	LZ	120.3467	23.6095		O		
Minte	MT	120.1911	23.6547	O	O	O	198–216
Paotze	BT	120.1434	23.6353	O	O	O	176–206
Peikang	PK	120.2938	23.5807		O	O	162–180
Sanho	SH	120.4798	23.6070	O	O		
Shiliu	SO	120.5777	23.7225	O	O		
Tanchien	TC	120.3394	23.8374	O	O		
Tienchung	TZ	120.5787	23.8564	O	O		
Tienwei	TW	120.5192	23.8932	O		O	210–240
Tienyang	TY	120.3009	23.7272	O	O	O	262–274
Tsaitso	TT	120.2111	23.6141	O	O		
Tungfang	TF	120.5078	24.0646		O	O	162–174
Tungho	TH	120.5612	23.6877	O	O	O	222–252
Tungkuang	TK	120.2639	23.6537	O	O	O	166–175
Tungshi	TS	120.1464	23.4622		O	O	228–237
Tzetung	TN	120.4887	23.7586	O	O		
Wenchang	WC	120.4114	24.0100	O	O	O	186–204
Wentso	WR	120.5040	23.6596	O	O		
Yuanchang	YC	120.3019	23.6547		O		
Yuanlin	YL	120.5666	23.9534	O	O	O	134–140

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Table 2. Basic information for the major earthquakes ($M > 6$) during the entire study period from (1 August 1997 to 31 December 2009).

Parameters/ Earthquake	Time	Longitude (° E)	Latitude (° N)	Depth (km)	Magnitude (M)
Rei-Li (R)	1998/07/17 04:51:14.96	120.663°	23.503°	3	6.2
Chi-Chi (C)	1999/09/20 17:47:15.85	120.816°	23.853°	8	7.6
Chia-Yi	1999/10/22 02:18:56.90	120.423°	23.517°	17	6.4
Ming-Jian (M)	2009/11/05 09:32:57.66	120.719°	23.789°	24	6.2

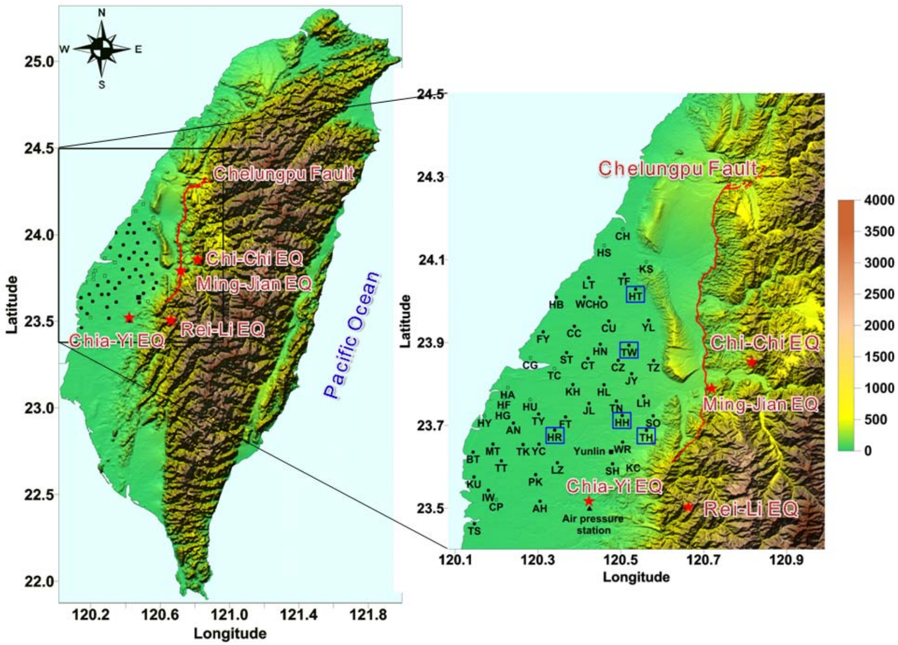

Fig. 1. Locations of 4 earthquakes and 54 groundwater wells in Taiwan. Earthquakes and wells lies on topography of Taiwan. The red lines and stars denote the Chelungpu fault of the Chi-Chi earthquake and distinct epicenters, respectively. The solid and open circles present groundwater levels with and without anomalous level changes before the Chi-Chi earthquake, respectively. Air pressure (triangle) and precipitation (rectangle) are measured at stations located in the southern part of the study area. Note that the blue rectangles denote the stations in which the data shown in this study.

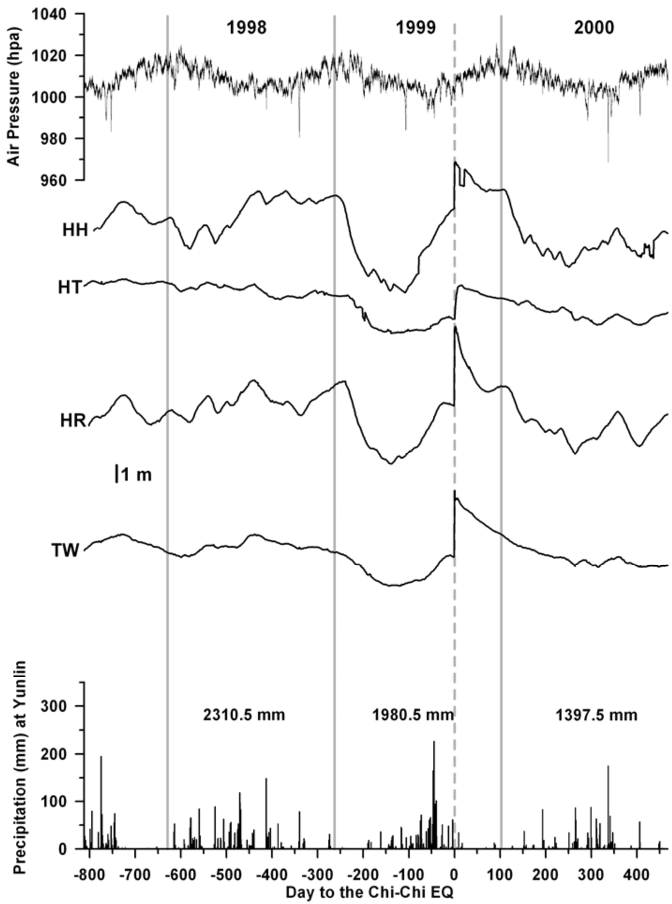

Fig. 2. Variations of air pressure, groundwater level at HH, HT, HR and TW as well as annual precipitations about 800 days before and 450 days after the Chi-Chi earthquake.

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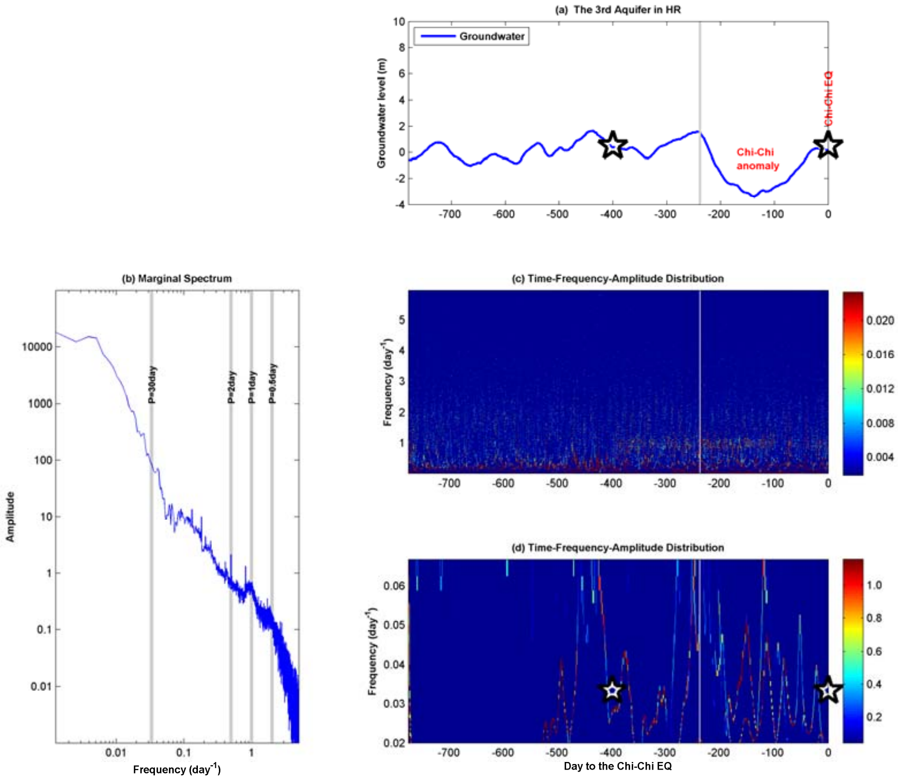

Fig. 3. (a) Temporal variations, **(b)** the marginal spectrum of the groundwater levels, **(c)** the time-frequency-amplitude distribution and **(d)** the partial amplification of the time-frequency-amplitude distribution before the Chi-Chi earthquake at the HR station. Vertical grey lines in **(a)**, **(c)** and **(d)** reveal a beginning of unusual decrease anomalies associated with the Chi-Chi earthquake. The black stars at about −424 and 0 day to the Chi-Chi earthquake denote the Rei-Li and Chi-Chi events, respectively.

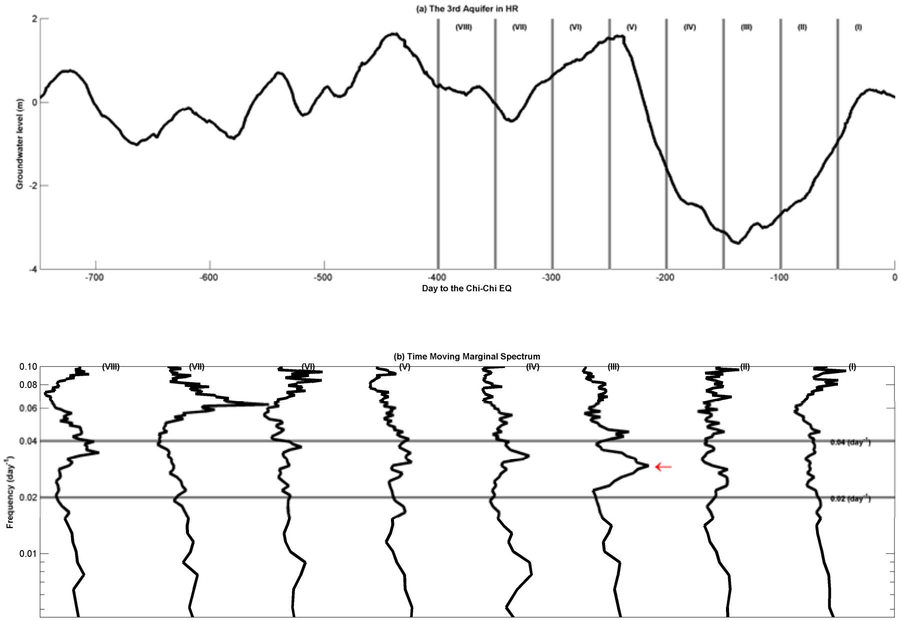

Fig. 4. Changes of the marginal spectrum derived from the 50-days temporal moving window the HR station. The red arrow denotes the significantly enhanced amplitude at the III phase.

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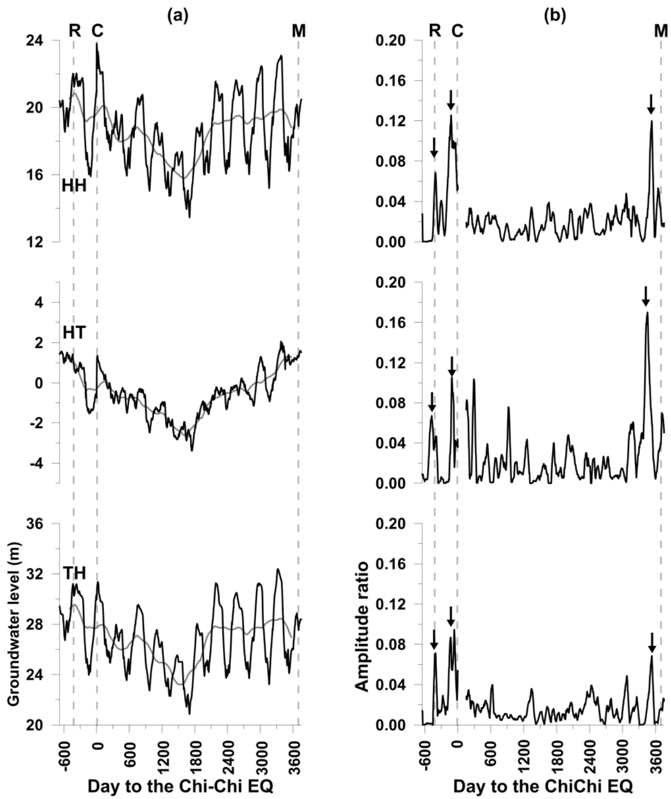

Fig. 5. Variations and the amplitude ratios of groundwater levels at the HH, HT and TH stations from 1 August 1997 to 31 December 2009. Panel **(a)** presents the temporal variations. The shadow lines show variations of the 1-yr running average. Panel **(b)** reveals the amplitude ratio. Vertical dash lines denote occurrence time of the Rei-Li (R), Chi-Chi (C), Ming-jian (M) earthquakes, respectively. Note that the arrows indicate the enhanced amplitude ratios associated with these three earthquakes.

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