Proc. IAHS, 372, 101–104, 2015
proc-iahs.net/372/101/2015/
doi:10.5194/piahs-372-101-2015

Frequency anomaly of groundwater level before major earthquakes in Taiwan

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Published: 12 November 2015

Abstract. Anomalous decreases on water levels were observed in 78 % of wells in central Taiwan about 250 days before the Chi-Chi earthquake whose magnitude is 7.6 on 20 September 1999. Variations in groundwater levels measured on anomalous wells from 1 August 1997 to 19 September 1999, were transferred into the frequency domain to unveil frequency characteristics. Analytical results show that amplitudes at the frequency band between 0.02 and 0.04 day^{-1} generally maintained at low stage and were apparently enhanced a few weeks before the Chi-Chi earthquake. Variations of amplitude at this particular frequency band were further examined along with other Taiwan earthquakes whose magnitude is larger than 6 from 1 August 1997 to 31 December 2009. Features of the enhanced amplitudes at the frequency band are consistently observed prior to the other two earthquakes during the 12.5-year study period. Result confirms that abnormal rise and fall changes in groundwater level yield an agreement with forward and backward surface displacements around epicenter prior to the Chi-Chi earthquake.

1 Introduction

Taiwan is an island located at the western margin of the Pacific Ocean with about 400 km in length and 150 km in width (Fig. 1). The convergent plate interaction between the Philippine Sea plate and the Eurasia plate has raised Taiwan and formed the central mountain with an altitude up to about 3952 m since around 6 million years ago. Annual precipitation in Taiwan is about 2500 mm on average based on the long-term records of Water Resources Agency, but rainfall is mainly concentrated in the wet season (May–October, about 78 % of the annual total; also see Fig. 2) due to high contributions from Meiyu and typhoons. Rainfall retention for effective water resource management is very important in Taiwan because uneven distribution of precipitation is very prominent both in temporal and spatial modes. When water consumption has rapidly increased by population growth and economic development after 1980, a great quantity of groundwater has been used to make up the insufficiency of surface water. Consequently, land subsidence happens following rapid depletion of groundwater resources in the western and southwestern regions of Taiwan from the past decades, due to excessive extraction and slow recharge (Liu et al., 2004).

The most notorious land subsidence region with an active subsiding area of over 600 km^2 and a maximum subsiding rate up to 10 cm yr^{-1} is located at the Choshuichi Alluvial Fan of central Taiwan (Chen et al., 2010). To effectively utilize groundwater resource and control land subsidence along coastal areas, where pumping is intensive and recharge is very slow, 54 evenly distributed hydrologic stations that record hourly changes in water levels using piezometers were installed at depths ranged from 24 to 306 m in the Choshuichi Alluvial Fan during 1992–1997 (Fig. 1). The Choshuichi Alluvial Fan, with an area of about 1800 km^2, can be divided into three aquifers for a depth of 250 m according to hydrogeological surveys in subsurface (Chen and Yuan, 1999). Each station may have one to five screens situated in different wells for fully observing groundwater level changes from shallow to deep aquifers.

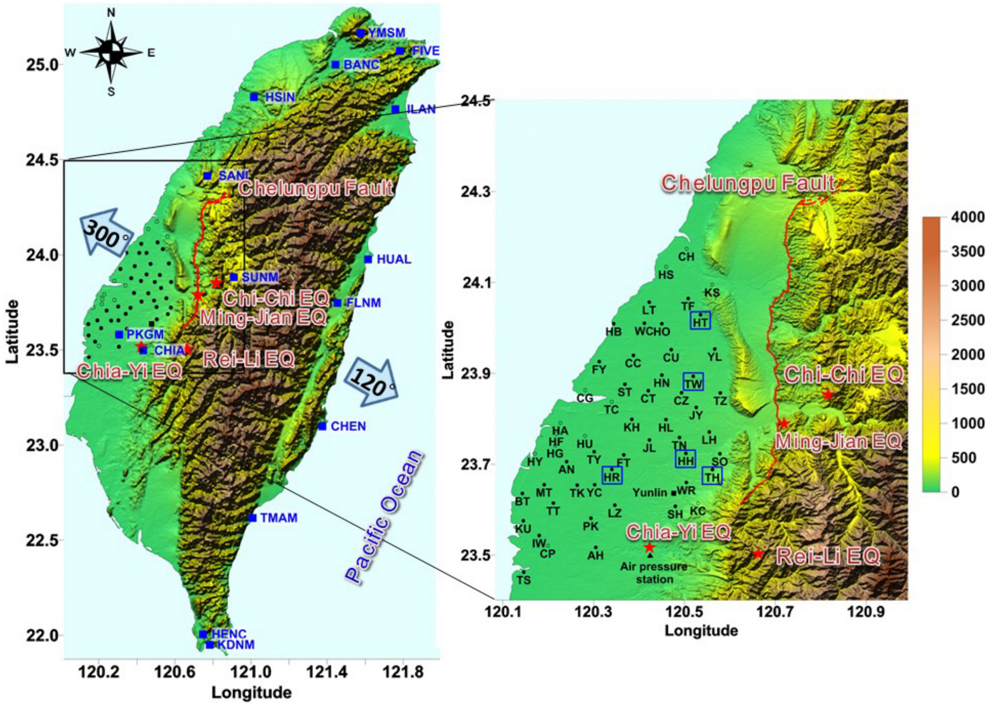

Figure 1. Locations of 4 earthquakes, 54 groundwater wells and 15 GPS stations in Taiwan.

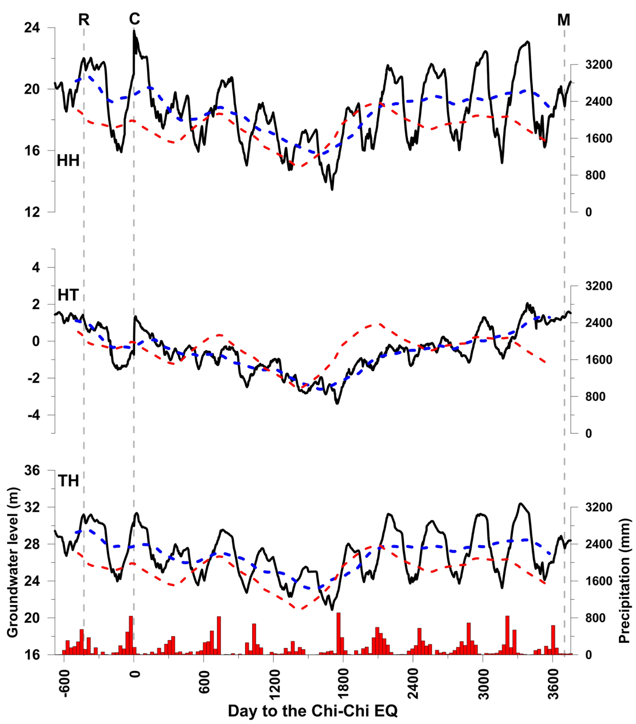

Figure 2. Variations in groundwater levels at HH, HT and TH stations from 1 August 1997 to 31 December 2009. The red line shows the average annual precipitation and the blue line displays the groundwater levels.

In this study, effects of the barometric pressure and Earth's tide on groundwater levels at 54 monitoring wells in the Choshuichi Alluvial Fan are mitigated first to examine any unusual variation associated with the Chi-Chi earthquake in the normally temporal domain. Notably, time-series water levels in the period of 2.5-year right before the Chi-Chi earthquake are utilized to reveal frequency characteristics associated with the Chi-Chi earthquake via the Hilbert–Huang Transform (HHT) and retrieve suspect signals buried in the temporal domain (Huang et al., 1998; Huang and Wu, 2008). After the earthquake-related frequency band have been determined from records before the Chi-Chi earthquake, amplitude at the particular frequency bands, which has deduced from 12.5-year data from 1 August 1997 to 31 December 2009 in groundwater stations of Huhsi (HH), Huatang (HT) and Tungho (TH), are further examined to check whether the identified anomalous amplitude can be repeatedly observed for other two major earthquakes. In addition, stress variations deduced by the surface displacements from the GPS data are compared with abnormal changes in groundwater level during the Chi-Chi earthquake to examine possible physical mechanisms.

2 Long-term variations of groundwater level in central Taiwan

It is well known that precipitation is highly related to climatic changes and is the major factor dominating the variations of groundwater levels. Before retrieving earthquake-related signals from groundwater levels, long-term changes (3–5 years) were considered first. Figure 2 shows variations in groundwater level at the HH, HT and TH stations and records in precipitation at the Yunlin station (120.476° E, 23.636° N) between 1 August 1997 and 31 December 2009. Precipitation effects on groundwater level can be viewed as two distinct features during this 12.5-year period. The first feature, which comprises many short (3–5 years) cycles lying on the generally decreasing trend in the first half and then a rising tendency in the latter half, yields an agreement between 1-year running average in annual precipitation (red line) and groundwater levels (blue line) at the HH, HT and TH sites.

The second one is apparent annual cycles that dominate in groundwater levels, particularly for those of the HH and TH sites. Annual cycles of the groundwater levels in Taiwan are caused by the apparent shift between wet and dry seasons in one year. For stations that are located relatively far away from recharge areas, their annual changes in the time-series data are comparatively weak (such as the HT shown in Fig. 2). It is worth mentioning that an unusual drop can be clearly identified from records at 78 % (= 42/54) stations (including HT, HH and TH) about 250 days prior to the Chi-Chi earthquake. The HT site had this obviously unusual drop standing out in the temporal domain due to weak annual changes. By contrast, for sites of HH and TH, the abnormal drops would be masked by in-phase annual variations in groundwater levels in the time-series record. This feature vividly illustrates the primary drawbacks in retrieving the abnormal drops of groundwater levels via the temporal records.

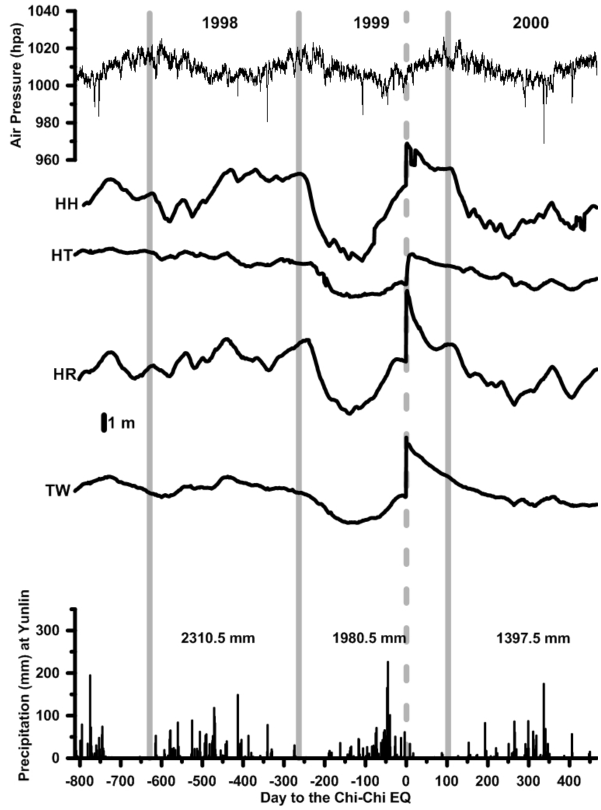

Figure 3. Variations of air pressure, groundwater level at HH, HT, HR and TW sites as well as annual precipitations about 800 days before and 450 days after the Chi-Chi earthquake.

3 Removal of short-term effects on groundwater level

Since the unusual drop with duration of ∼ 250 days should not relate with long-term climatic changes, variations of atmospheric pressure, Earth's tides, precipitation and human extraction, which are considered to be the major factors affecting groundwater levels, are further taken into account. We examine these short-term effects (i.e. atmospheric pressure, Earth's tides, precipitation and human extraction) using groundwater data with a time span between 1 August 1997 and 31 December 2009 to adequately cover the unusual drop. The upper panel in Fig. 3 illustrates the variations of air pressure measured at the southern site of the study area. It is clear that annual fluctuations are dominated in the air pressure records. Low and high air pressures were regularly observed in summer and winter seasons, respectively. Effects of the atmospheric pressure on the groundwater level ranged between −0.2 and 0.2 m were then utilized in data correction. The Earth's tides with the frequencies of 1 and 2 day^{-1} could be easily eliminated while hourly data were down-sampled as a daily record. Corrected groundwater level data could thus be obtained while responses of air pressure and the Earth's tide were removed.

The second (from top) and bottom plots in Fig. 3 present variations in corrected groundwater data at the HH, HT, Honglung (HR) and Tienwei (TW) sites and precipitation at the Yunlin station (120.476° E, 23.636° N) from 1 August 1997 to 31 December 2000, respectively. Unusual decreases of approximately 2–4 m in corrected water levels can be clearly identified in these groundwater wells about 150 days before the Chi-Chi earthquake. We further examined records of 54 monitoring wells in the Choshuichi Alluvial Fan and found that similar patterns of unusual decrease are observed at 78 % wells, primarily distributed near the Chelungpu fault. Unusual decreases by artificial water pumping can be eliminated as the cause because temporal duration of these anomalous decreases exceeded 200 days 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 accounted to 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 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, possibility of the unusual drops in the Choshuichi Alluvial Fan can be ascribed to the Chi-Chi earthquake in both temporal and spatial domains, after factors from the long-term and short-term effects have been removed. We further survey the 12.5-year time-series data; however, no similar drop-like variations can be repeatedly observed for other two major earthquakes in the temporal domain.

4 Discussion and conclusions

The debate regarding pre-earthquake groundwater anomalies is primarily due to the limited number of observation wells over a wide area 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 effect-corrected records at the 78 % (= 42/54) of the wells widely distributed across the Choshuichi Alluvial Fan nearby the Chelungpu fault a few months before the Chi-Chi earthquake. Thus, groundwater level has the potential to reflect the tectonic stress accumulation prior to the occurrence of the Chi-Chi earthquakes if the monitoring wells are densely distributed and close to the epicenter, as demonstrated in Fig. 4. Apart from the large signals, some relatively-small peaks of enhanced amplitude ratios can be observed at HT and/or TH in Fig. 4, but cannot be simultaneously observed at the other two stations, implying that they are local and small-magnitude events resulting limited peaks.

Critical earthquake-related signals are often hidden behind substantial and common effects with various frequencies. For the stand-out of anomalous patterns, our study shows that it is difficult to retrieve and/or understand these vital earthquake-related signals without removing these common effects via an adequate filter. The seismo-groundwater anomalies in the Choshuichi Alluvial Fan in Taiwan could be clearly identified for all three strong earthquakes ($M > 6$) because amplitudes at the frequency band between 0.02 and 0.04 day^{-1} were consistently enhanced in groundwater level records of many monitoring wells in the frequency domain. In short, this new method sheds the light for the precursory-seeking research of strong earthquakes, but needs further work to refine the technique and test its applicability for the forthcoming strong earthquakes. Naturally, the method presented in this work has also limitation and prerequisite. For example, an adequately dense monitoring network has to be established first. Another one is that it cannot apply to the earthquake right after a strong one, such in the case of Chia-Yi earthquake discussed in this study. Nonetheless, if this method is well integrated with other geophysical observations, such as geomagnetic anomalies and crustal displacements, variation in groundwater levels and electromagnetic anomalies could be quantified and/or estimated by using volume changes via possibly physical mechanisms. These integrated results will be highly promising to understand underlying mechanisms of major earthquakes and to build a strong earthquake forecast system in the future.

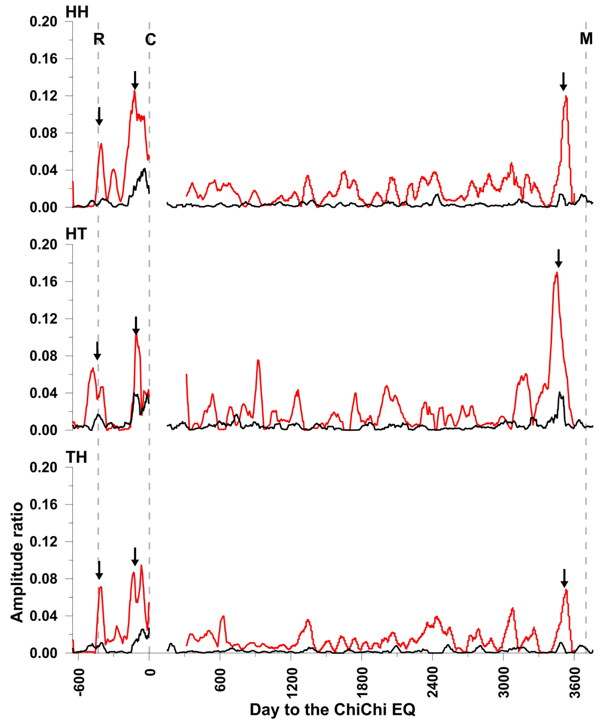

Figure 4. The amplitude ratios of groundwater levels at HH, HT and TH stations from 1 August 1997 to 31 Dececember 2009.

Acknowledgements. The authors would like to thank the Ministry of Science and Technology of the Republic of China, Taiwan, for financially supporting this research under Contract No. MOST 103-2119-M-305-001.

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