Time series decomposition of groundwater level changes in wells due to the Chi-Chi earthquake in Taiwan: a possible hydrological precursor to earthquakes

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Abstract:

The largest and most disastrous earthquake in Taiwan (Mw: 7.3) in the 20th century, the Chi-Chi earthquake, hit central Taiwan at 01:47 local time on September 21, 1999. The groundwater level changes were rapid at that time. Studies have found that the rapid change in groundwater levels was a co-seismic phenomenon. This work analyzes the possibility that the abnormal change in groundwater levels may have occurred before the earthquake. Three well stations with a total of five wells are considered. They are all near the Che-Lung-Pu fault, which caused the Chi-Chi earthquake. The time series decomposition method was applied to decompose the seasonal groundwater level, the trend in groundwater levels, and the period of the change in the groundwater level. Residual groundwater levels were found by subtracting the determined seasonal, trend and period data from corresponding data for the original groundwater level. The computed residual water levels in July, August and September of 1999, were transformed into a frequency spectrum by a Fourier method. Additionally, the effects of barometric pressures on the groundwater level changes were also evaluated. Analytical results show that the spectral density functions of the irregular groundwater level in the confined aquifer at the Chu-Shan well in September behaved differently from those in July and August. We posit that a pre-seismic hydrogeological anomaly may have existed before the Chi-Chi earthquake, and can be considered in future studies of anomalies associated with earthquakes.

KEY WORDS seismic; ground water level; time series decomposition

INTRODUCTION

The largest and most disastrous earthquake of the 20th century in Taiwan (Mw: 7-3), the Chi-Chi earthquake, hit central Taiwan at 01:47 local time on September 21, 1999. The Chi-Chi earthquake sequence occurred beneath the fold-and-thrust belt along the western part of the Taiwan orogeny. That orogeny is being formed by an ongoing collision, which began 5 million years ago, between the Luzon volcanic arc along the western margin of the Philippine Sea plate and the passive continental margin of southeastern China (Kao and Chen, 2000). The epicenter of the earthquake was at 23.85°N, 120.82°E, at a depth of approximately 8.0 km (Shin, 1999). A widespread surface rupture, extending approximately 80 km in the north–south direction along the Che-Lung-Pu fault, accompanied violent ground shaking. Kao and Chen (2000) noted that the Che-Lung-Pu fault is the eastern boundary of the foreland basin of the Taiwan orogeny. The Che-Lung-Pu fault extends through the eastern part of the Cho-Shui River alluvial fan. It points from 20° to 30° to the east and is at a depth of 5 km.

The Cho-Shui River alluvial fan, in the western part of central Taiwan, is a major groundwater resource area. Seventy-seven hydrogeological investigations have been conducted and 188 groundwater-monitoring wells at 64 well stations in different aquifers were established from 1992 to 1998 to study comprehensively the hydrogeological characteristic of the Cho-Shui River alluvial fan. Each well station contains one to five wells, ranging in depth from 14 to 300 m (Water Conservancy Agency, 2000). The Chu-Shan, Hsin-Kun, Shang-Liao and Hsin-Min well stations are close to the Che-Lung-Pu fault (Figure 1). Since 1994, each observation well has installed automatic recorders to monitor the variation in the groundwater levels. They record water levels hourly. These automatic monitors thus completely recorded the changes in groundwater level during the Chi-Chi earthquake. The rapid change in water level was clearly measured; the groundwater level ranged from a rise of 8.3 m to a decline of 11.1 m from its original level (Water Conservancy Agency, 2000). Chia et al. (2001) considered data from 18:00 on September 20 to 18:00 on September 21, to analyze the variation in groundwater levels. He concluded that the rapid changes in water levels were co-seismic. The Water Conservancy Agency (2000) reached the same conclusion.
Predicting earthquakes is very important in the earth sciences because of the high cost in human lives and damage to property following an earthquake. Formation properties such as groundwater flow rate, electromagnetic fields, hydrogeochemical and tilt-strain components, and others, have been observed and considered as precursors to earthquakes (Tohjima et al., 1994; Depuev and Zelenova, 1996; Dal Moro et al., 2000; Tzanis et al., 2000; Kingsley et al., 2001; Fujinawa et al., 2002). Studies have demonstrated that the changes in water levels in the wells are closely related to pore-pressure changes and fault creep (Nason and Weertman, 1973; Johnson et al., 1973; Wesson, 1981; Chadha et al., 1997). Bredehoef (1967) showed that groundwater levels can respond to a small strain in the earth’s crust, implying that water levels in the wells could be observed to monitor stress changes along active fault zones, and may be a potential precursor of earthquakes (Kovach et al., 1975). Accordingly, researchers have examined water level data from nearby fault zones to determine possible changes before earthquakes (Kovach et al., 1975; Gavrilenko et al., 2000; King et al., 2000).

Many seasonal and periodic factors, including pumping, recharge (Gau and Liu, 2000), the earth’s tides (Bredehoef, 1967; Robinson and Bell, 1971), atmospheric loading (Roeloffs, 1988; Kawabe et al., 1988) and movement of the earth’s crust (Narasimhan et al., 1984; Gavrilenko et al., 2000), affect changes in groundwater level. If anomalous changes in groundwater level occur before an earthquake, both the period and the amplitude of changes vary from normal. Thus, some information may be missing if only the comparison of the amplitude changes in the groundwater levels is considered.

In this study, groundwater level data from well stations Chu-Shan, Hsin-Kun and Shang-Liao, were collected and the time series decomposition method was applied to separate the data into seasonal, trend and irregular components. The periods for which groundwater levels were irregular in the different months were compared to determine if the occurrence of abnormal behaviour of the levels was before the earthquake, and thus may be used as a precursor in predicting earthquakes.

MATERIALS AND METHODS

Observation wells

Changes in the levels of groundwater in wells around a fault zone may be a precursor of earthquakes, because the groundwater level can respond to small changes in strain in the earth’s crust. The changes in the groundwater levels in the wells near the Che-Lung-Pu fault, in the period before the Chi-Chi earthquake, were analyzed. Four well stations, Chu-Shan, Hsin-Kun, Shang-Liao, and Hsin-Min are near the Che-Lung-Pu fault. Moreover, the Hsin-Min well station is closed to the Cho-Shui River. The hydrograph of groundwater level in the four well stations were first compared with the hydrographs of river water level in order to ascertain whether the groundwater level was affected instantly by river water or not. The river water levels were collected from the Chang-Yun-Chiao flow monitoring station, which is not far away from the four well stations (Figure 1). The hydrograph of groundwater levels and river water levels are shown in Figure 2. However, it is difficult to differentiate between the hydrographs from Figure 2 because the changes of the water levels are not clearly exhibited. Therefore, the cross correlation between river water level and groundwater level were evaluated (Box et al., 1976). Cross correlation is a standard method of estimating the degree to which two series are correlated. Consider two series \(x(i)\) and \(y(i)\) where \(i = 0, 1, 2 \ldots n - 1\), then the cross correlation series can be calculated by the equation:

\[
r(d) = \frac{\sum_{i=1}^{n-1} (x(i) - m_x)(y(i) - m_y)}{\sqrt{\sum_{i=1}^{n-1} (x(i) - m_x)^2 \cdot \sum_{i=1}^{n-1} (y(i) - m_y)^2}}
\]

Where \(m_x\) and \(m_y\) are the means of the series \(x(i)\) and \(y(i)\), respectively; \(d\) is time lag between the two series; \(r\) is the cross correlation coefficient that is used to estimate the degree to which the two series are correlated. The cross correlation coefficients range between \(-1\) and 1. The bound indicates maximum correlation and 0 indicates no correlation. A high negative correlation indicates a high correlation but of the inverse of one of the series.

The cross correlation series between the river water level and groundwater level is shown in Figure 3. The result reveals the maximum correlation is achieved at a lag of 0 only at Hsin-Min station. That implies the variation of groundwater level at Hsin-Min station almost coincides with the river level. In addition, the dimensionless water levels, water levels divided by the maximum water level, were calculated and shown in Figure 4. The peaks of the dimensionless groundwater level curves and river water level curves coincide with each other and the shapes and trends of these curves behave similarly suggesting that the river water level changes directly influence the groundwater level changes in the Hsin-Min wells. Therefore, groundwater level data from the Hsin-Min wells were not included in this study.

Figure 5 shows the geological profile of the three monitor wells. The Chu-Shan well is 210-m deep. The geological formation is divided into three layers: gravel, fine sand mixed clay and gravel. The upper layer is an unconfined aquifer that is 110-m thick. The lower layer is a confined aquifer, from 140 to 195 m deep below the surface of the ground. An impermeable aquitard lies between the two aquifers. Two independent monitoring wells, Chu-Shan(1) and Chu-Shan(2), at the well station are monitored and the depth of groundwater in these wells varied from 56 to 96 m and 156 to 192 m, respectively. Piezometers are installed 72 and 162 m below the surface of the ground, respectively, to monitor the changes in the levels of the groundwater at different aquifers. The Hsin-Kun well is 250 m deep. The geology of the Hsin-Kun
Figure 1. Observation wells in the Cho-Shui River alluvial fan

each well is similar to that of the Chu-Shan well and is divided into three different layers. Two independent monitoring wells, Hsin-Kun(1) and Hsin-Kun(2) measured the depth of groundwater between 78 and 120 m and 192 and 240 m, respectively. The piezometers in those wells were installed 84 and 216 m below the surface of the ground, respectively. The aquifer at the Shang-Liao well is only in the uppermost 15 m, and is comprises gravel, sand and silt.

The groundwater levels of the four wells were measured by piezometers to a precision of 0-1% with a scale in cm. The recording interval was 1 h. Historic precipitation was measured by automatic pluviometers that have been installed in the Cho-Shui River alluvial fan by the Water Resources Agency. Figure 6 plots the average rainfall of the east area of the Cho-Shui River alluvial fan and the changes in groundwater levels in the Chu-Shan, Hsin-Kun and Shang-Liao well stations from January 1, 1997 to September 21, 1999. The rapid changes in groundwater level caused by the Chi-Chi earthquake, except that in the Shang-Liao well where the piezometer malfunctioned because of the earthquake, were accurately measured (Figure 6). The distribution of precipitation over a 2-year period was highly non-uniform, and was concentrated between April and September. The groundwater levels in both Hsin-Kun(1) (in the unconfined aquifer) and Hsin-Kun(2) (in the confined aquifer) exhibited the same pattern: the change in groundwater levels followed but lagged the rainfall distribution. The time series of groundwater levels in Shang-Liao differs greatly from that in Hsin-Kun, but this difference was mainly the response to direct rainfall recharge as determined by correlating the difference with the data.

on groundwater level fluctuation. The groundwater level increased from 164.5 to 168 m on January 1998. The time series of the groundwater levels at Chu-Shan was similar to that at Hsin-Kun, but varied greatly in the confined aquifer (Chu-Shan(2)).

The groundwater levels can be decomposed into four components, trend, barometric response, tidal response and irregular components (Tamura et al., 1991). The barometric pressure and earth tide data were unavailable in the study area. Therefore, an abnormal change in groundwater levels before the earthquake could not be compared to the trend, barometric response, tidal response and irregular components. However, changes in groundwater levels, caused by rainfall, pumping, earth tides and barometric pressure, follow a time series function, with a trend, seasonality and periodicity. The groundwater levels are therefore decomposed into three components: the seasonal component, the trend-cycle component, and the irregular component. If groundwater level changed abnormally before the earthquake, then the abnormal signal would contribute to the irregular component. Accordingly, a comparison of irregular components in different periods should provide some information about abnormal changes. We therefore apply time series decomposition to decompose changes in groundwater levels into seasonal, trend-cycle and irregular components.

**Time series decomposition method**

The general mathematical representation of the time series decomposition method is,

\[ Y_t = f(S_t, T_t, E_t) \]  

where \( Y_t \) represents the time series (actual data); \( S_t \) is the seasonal component; \( T_t \) is the trend-cycle component,
Figure 4. Dimensionless river water level at Chang-Yun-Chiao station and dimensionless groundwater levels in (a) Hsin-Min wells (b) Chu-Shan wells (c) Hsin-Kun wells (d) Shang-Liao well from July, 1999 to September, 1999.

Figure 5. Geological profiles of well stations at Chu-Shan, Hsin-Kun and Shang-Liao (Enlarging in the horizontal direction)
and \( E_t \) is the irregular component. The exact functional form of Equation (2) depends on the method of decomposition applied. A common approach assumes Equation (2) of the additive form,

\[
Y_t = S_t + T_t + E_t
\]

The alternative multiplicative decomposition has the form

\[
Y_t = S_t \times T_t \times E_t
\]

An additive model is appropriate if the magnitude of the seasonal fluctuation does not vary with the level of the time series. However, if the seasonal fluctuation is proportional to the level of the series, then a multiplicative model is preferred. The seasonal trend-cycle components in both models are straightforwardly estimated by time series decomposition (Makridakis et al., 1998). Then, the irregular component can be determined by simply subtracting the estimated seasonality, trend and cycle components from the original data series. Makridakis et al. (1998) explained in detail approaches to estimating seasonality, and trend and cycle components. The abnormal change in groundwater levels before earthquakes can be analysed by comparing with irregular components in other months.

The groundwater levels from January 1, 1997 to September 21, 1999 were decomposed into three components by time series decomposition. The additive model was adopted here because the amplitude of the fluctuation in the groundwater levels (Figure 6) did not clearly vary with the level of the series. The decomposition for the additive model is performed by the software STATISTICA (Statsoft Inc., 2003) that include the following steps.

1. Determine the duration of one season. One season was 12 months in this study.

2. Compute the centered moving average of the series, with a moving average window width of one season. All seasonal variability is eliminated from the moving average series; therefore, subtracting the moving average from the observed series isolates the seasonal component plus irregular component.

3. Assume the seasonal component is constant from season to season. The seasonal component is then computed from the isolated series as the average of each point in one season. The resulting values represent the average seasonal component of the series.

4. The original series is modified by subtracting the seasonal component. The resulting series is the seasonally adjusted series (i.e., the one from which the seasonal component has been removed).

5. The cyclical component differs from the seasonal component in that it is usually longer than one season, and different cycles can be of different lengths. Consequently, the combined trend and cyclical component is approximated by applying to the seasonally adjusted series. The weights of the moving average curve are calculated by Bartlett window method (Statsoft Inc., 2003). Figure 7 shows the average moving curves based on three different weighting numbers, five-point, eleven-point and twenty-one–point. These curves behave similarly. Thus, a five-point centered, weighted moving average, smoothed by a transformation with weights 1, 2, 3, 2, 1 is adopted in the study.

6. Finally, the irregular component is determined by subtracting the trend-cycle component from the seasonally adjusted series.

RESULTS AND DISCUSSION

Time series decomposition

Figure 8 shows the result of seasonal decomposition of groundwater levels in Chu-Shan(2) well as an example.
The irregular components obtained by seasonal decomposition of the groundwater time series of five wells are summarized in Figure 9. The variations in the irregular components at the Chu-Shan(1) and Hsin-Kun(1) are more evident than in the other wells, implying that groundwater in the unconfined aquifer is easily perturbed by a change in environmental conditions, including air pressure, pumping and recharge. Although the irregular component in the confined aquifer (see the irregular component in Chu-Shan(2) and Hsin-Kun(2)) varies less, this component still changes rapidly. The cause of the rapid changes is unknown, but a similar frequency can be found by comparing with the irregular component. The description of the abnormal changes before the earthquake by qualitative analysis in the time domain is difficult; hence, the irregular components were transformed from the time domain into the frequency domain using the Fourier method. The transformation can clearly explain the strength of the effects of the irregular component on the groundwater table at different frequencies.

Spectral analysis

The spectral density function of a time series is given as follows (Fuller, 1976):

\[
E(f) = \frac{1}{2T} \int_{-T}^{T} E_t(t)e^{-i2\pi f t} \, dt
\]

where \(E(f)\) is the spectral density function; \(E_t(t)\) is random process; \(f\) represents the frequency, \(T = k/2f\) and \(k = 0, \pm 1, \pm 2, \ldots\). As the precursor of earthquake has an 88% probability of occurrence in the time interval 7–97 days before the earthquake takes place (Kingsley et al., 2001) and to avoid the rapid changes affect the pattern of the spectral density function, only irregular components in the period from July 1 to September 21, 1999 were transformed into the frequency domain. Kingsley et al. (2001) an estimated the probability that earthquake takes place in the time interval of 7–20 days, 20–58 days and 58–97 days after the precursor onset is 25, 25, and 38%, respectively. According to their analysis, a 25% of precursor would have taken place in the period from September 1 to September 21, 1999, a 25% of precursor would have taken place in the period from July 25 to September 1, 1999 and a 38% of precursor would have taken place in the period from June 16 to July 25. Obviously, the probability in the third period is higher than that in other periods. If the third period is reset from June 30 to July 25, the probability of precursor can be adjusted to 25%. However, period resetting complicates the process of data transformation. Therefore, the irregular components in the entire months of July, August and September were adopted for the transformation. The transformed results of each well for July, August and September are shown in Figures 10 to 14. Figure 10 plots the transformed results of the irregular components of the groundwater level profiles in July, August and September, respectively, at Chu-Shan(1). The ordinate represents spectral density in dimensionless units. The abscissa represents frequency in units of cycles per unit hour (cph). Comparing the distribution of spectral density of the 3 months reveals that the peaks of spectral density occur at the same frequency as the frequency below 0.21 cph. However, as the frequency exceeds 0.21 cph, the peaks of spectral density in the distribution of the frequency in September clearly behave differently compared to the same in July and August. Therefore, it is inferred that groundwater levels in September might have behaved abnormally.

Figure 11 plots the transformed irregular components of the groundwater level at Chu-Shan(2). The peaks of spectral density curves in July and August look similar over the entire range. However, the peaks of the spectral density curve in September also differ from those in July and August. The extreme values of density curves occur at the frequency 0.17 and 0.21 cph in September and occur at the frequency 0.08 cph in July and August. Therefore, the groundwater levels in September are again inferred to have been an abnormal change before the earthquake.

Figure 12 shows the transformed irregular component of the groundwater level at Hsin-Kun(1). The appearances of the spectral density in the 3 months are similar, but the peak values are all different in the 3 months. Generally, the peak values in September are always larger than that in August and July. The peak values in July are smaller than other months. Though the distribution curves of the spectrum are similar in appearance, the peak values are different among the 3 months. Therefore, data available are insufficient to assess the anomalous changes in the groundwater level before the Chi-Chi earthquake.

Figure 13 shows the transformation of the irregular component of the water level in Hsin-Kun(2). The spectral density curve in July is obviously different from that.

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in August and September due to the multiple peaks occurring in July. However, a similarity exists between spectral density curves in the 3 months because the frequencies that correspond to the higher peaks in July have smaller peaks occurring in August and September. Therefore, it is not possible to use the groundwater level in assessing the anomalous changed before the Chi-Chi earthquake.

Figure 14 presents the transformation of the irregular component of the water level at Shang-Liao. The spectral density curves in the 3 months are highly disturbed. It is difficult to compare the differences between the observed spectral densities. Therefore, we could not assess anomalous change of groundwater level before the Chi-Chi earthquake.

Table I shows the correlation matrix of spectral density. The correlation coefficient in the matrix is a measure of the relationship between the spectral density in July, August and September. The correlation coefficients can range from −1.00 to +1.00. The value of −1.00 represents a perfect negative correlation while a value of +1.00 represents a perfect positive correlation. A value of 0.00 represents a lack of correlation. The correlation coefficient of the spectral density at Chu-Shan(1) and Chu-Shan(2) has a higher degree of correlation between
July and August than the correlations between September and other months. According to the result, we infer again that an abnormal change of groundwater level occurred in September significantly and caused the distribution of spectral density in September to be obviously different from that in other months. At other wells, the correlation coefficient is not high enough to infer an abnormal change in groundwater level. Though the correlation of spectral density between September and other months at Hsin-Kun(2) are high, it is difficult to infer in which month the abnormal change occurred.

**Analysis of barometric pressure effect**

From the results of spectral analysis, the groundwater levels in Chu-Shan(1) and Chu-Shan(2) are inferred to have had anomalous changes before the earthquake. The abnormal change in groundwater levels could not solely ascribe to the earthquake, because it may also have been caused by other factors such as the change of barometric pressure. Therefore, the effects of groundwater level changes by the barometric pressure are evaluated herein. The records of barometric pressure near the well stations are not available, therefore the barometric pressure...
Figure 10. Spectral density of the irregular component of the water level in the Chu-Shan(1) well

Figure 11. Spectral density of the irregular component of the water level in the Chu-Shan(2) well
Figure 12. Spectral density of irregular component of the water level in the Hsin-Kun(1) well

Figure 13. Spectral density of irregular component of the water level in the Hsin-Kun(2) well
Figure 14. Spectral density of irregular component of the water level in the Shang-Liao well

Figure 15. History of barometric pressure distribution at Sun-Moon-Lake station and the position of Sun-Moon-Lake station relative to the well stations
Figure 16. Scatter plot of the spectral density of the irregular groundwater level versus the barometric pressure and the linear regression curves (solid line) in the July, August and September at Chu-Shan(1) well station.

The relative position between the Sun-Moon-Lake station and Chu-Shan station, and the hydrograph of the barometric pressure from July to September, 1999 are shown in the Figure 15. Because the Sun-Moon-Lake station is a distance away from the Chu-Shan station, the results of the correlation analysis may not describe the exact relationship between the barometric pressure and groundwater level change. However, the results could provide the information of whether the barometric pressure effects on groundwater levels in July, August and September have a similar strength. The groundwater table in an open well may instantly be affected by a barometric pressure change (Rasmussen and Crawford, 1997). In the study, the groundwater level is measured from the observation well which contacts the atmosphere; hence, the assumption that the barometric pressure instantly affects groundwater level variation is adopted. If the barometric pressure
effects on the groundwater levels have a similar strength, the groundwater level changes caused by the varied barometric pressure could be subtracted proportionally in July, August and September and this would hold the abnormality conclusion drawn in the previous section. Figure 16 is the scatter plot of irregular groundwater level spectral density versus the irregular barometric pressure in the July, August and September at Chu-Shan(1) well station. The slopes of the linear regression curves in July, August and September are 0.00039, 0.0038 and 0.0179, respectively, indicating the regression slopes in July and August are similar and are quite different from that in September. It means that the effect of the barometric pressure on the groundwater level change in September were different from July and August. Therefore, we could not infer that the anomalous changes at Chu-Shan(1) well station was a precursor of an earthquake because the anomalous changes may also have been caused by the varied barometric pressure.
Figure 17 shows the scatter plot of irregular groundwater level spectral density versus the irregular barometric pressure in July, August and September 1999 at Chu-Shan(2) well station. The slopes of the linear regression curves in July, August and September are 0-00063, 0-00053 and 0-00088, respectively, which are all in the same range. It means that the effects of the barometric pressure on the groundwater level changes are all in a similar pattern among the 3 months. Therefore, the anomalous changes at Chu-Shan(2) well station is attributed to the Chi-Chi earthquake and may be inferred to be a precursor of earthquake.

CONCLUSION

The Chi-Chi earthquake was the largest and most disastrous earthquake of the 20th century in Taiwan (Mw: 7.3). The changes in the groundwater level were rapid at that time. The rapid change of the groundwater level caused by the Chi-Chi earthquake was found to be a co-seismic phenomenon. This study investigates the probability that an abnormal change in groundwater level may occur before the earthquake. Groundwater levels were decomposed into three components—seasonal, trend-cycle and irregular—by time series decomposition method. If abnormal changes in the groundwater level occurred before the earthquake, they would be reflected in the irregular components. The irregular components were transformed from the time domain to the frequency domain, using the Fourier method. Comparing the results of the distribution of the spectral density functions and the correlogram of the barometric pressure versus groundwater level change revealed that an abnormal change in the groundwater level may occur in the confined aquifer at Chu-Shan before the Chi-Chi earthquake. We suggest that a pre-seismic hydrogeological abnormality could be considered in future studies of anomalies associated with earthquakes.

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REFERENCES


