Apparent permeability variation of underground water aquifer induced by an earthquake: A case of the Zhouzhi well and the 2008 Wenchuan earthquake*

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Abstract Taking the M_2 wave as calibration signals, we extract the phase shifts of the water level relative to the Earth tide in the Zhouzhi well by utilizing the cross-correlation function. And we further obtain the apparent permeability variation in the aquifer of the Zhouzhi well in 2008. Comparison with the commonly used tidal analysis software Baytap-G shows that phase shifts obtained by cross-correlation function are more stable. The resulting apparent permeability of the Zhouzhi well aquifer fluctuates with time, indicating it is a dynamically controlled parameter. The 2008 Wenchuan earthquake caused the apparent permeability increasing drastically, which is interpreted as the combination effects of effective stress changes and the barriers removing in the flow channel due to seismic wave pressure pulse. After the Wenchuan earthquake, the effective stress began to recover and the impurities deposited gradually, causing the apparent permeability to decrease a month later and almost recover to the pre-earthquake level in six months.

Key words: apparent permeability; Zhouzhi well; underground water; Earth tide; 2008 Wenchuan earthquake

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1 Introduction

Fluids in pores and fractures of rock are the most sensitive to stresses in all underground media. The groundwater level, as an indicator of crustal stress and strain, is theoretically and practically important for the researches on earthquake prediction, crustal deformation, stress changes, underground runoff conditions and aquifer characteristics (Wang et al., 1988). Preseismic groundwater anomalies have been observed for many earthquakes; the groundwater level is considered to be one of the most promising indices to earthquake prediction. On the other hand, earthquakes can also cause various changes in groundwater, such as water level's

rise and fall, water level oscillation (Liu et al., 1989; Roeloffs, 1998; Huang, 2008), and stream discharge increase (Montgomery and Manga, 2003; Manga et al., 2003). According to characteristics of water level changes, the impact of earthquakes on groundwater can be divided into two types, one is poroelastic response to static seismic stress changes (Wakita, 1975; Roeloffs and Bredehoeft, 1985; Matsumoto and Roeloffs, 2003), the other is earthquake-induced permeability increase in well aquifers (Rojstaczer and Wolf, 1992; Kitagawa et al., 2002; Brodsky et al., 2003). The former mainly leads to coseismic water level fluctuation, which is directly related to transient stress changes induced by seismic wave propagation; the latter mainly causes different response rates of water level to stress changes. Therefore the study on aquifer permeability variation is significant for understanding the aquifer characteristics, the mechanism of coseismic groundwater level, the groundwater

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movement and the earthquake occurrence process.

Brodsky et al. (2003) studied the water level records in a well near Grant Pass, Oregon, and found that during a sudden coseismic step, the ratio of water level amplitude to seismic wave ground velocity increased 40 times. Based on this observation, they proposed a new model of coseismic pore pressure steps, in which the temporary barriers from the groundwater flow are removed by more rapid flow resulted from seismic waves. When the barrier is near to the fracture, the groundwater flow is so rapid that it no longer obeys the Darcy's law, so the obtained permeability is called apparent permeability. Shortly after that, this model was supported by the study of Wang et al. (2009). They studied the water level changes caused by the Wenchuan earthquake with 1 Hz sampled water level records from three boreholes in Taiwan of China. By comparing the water levels with broadband seismic records from a nearby station, they concluded that small oscillations of groundwater caused by S wave and Love wave may be sufficient to remove the barriers in sediment pores, and thus increased the aquifer permeability and accommodated for the subsequent major oscillations due to Rayleigh wave.

The apparent permeability can be estimated by the phase shift of water level relative to Earth tide at the frequency of M_2 wave (Hsieh et al., 1987; Elkhoury et al., 2006). Currently, Baytap-G (Bayesian tidal analysis Program—Grouping Model) is a commonly used tidal analysis software, by which the amplitude ratio and phase shift of a tidal wave can be obtained (see section 3.2 for details). However, because the sampling interval of input data such as water levels is one hour, the input data are required to be of high qualities. In contrast, it is a better choice to get the phase shift by the cross-correlation function method.

The researches on coseismic groundwater changes due to the 2008 Wenchuan earthquake have made some progress. Huang (2008) studied the coseismic water level steps of observation wells in Chinese mainland in response to the 2008 Wenchuan earthquake, and proposed that in confined and consolidated aquifers, water level changes reflect the change in the in-situ borehole strain. Zhang (2010) studied the Skempton's coefficient B of a number of wells and found that B changed slightly after the 2008 Wenchuan earthquake. In addition, the B val-

ue before the earthquake is related to the amplitude of coseismic water level steps. In this paper, we collected the underground water level records and Earth tides of the Zhouzhi well, calculated the phase shifts at the frequency of M_2 wave from the cross-correlation function, obtained the apparent permeability of the Zhouzhi well aquifer from January 1 to October 26 in 2008, and then analyzed the response process of apparent permeability to the 2008 Wenchuan earthquake.

2 Observation instruments and data

The Zhouzhi well is located in Xiguan seismic station in the Zhouzhi county, Shaanxi province. It is in the west of Xi'an-Zhouzhi depression in Fenwei rift basin, the junction of the northern edge of Qinling fault and Qishan-Mazhao fault (see Figure 1). Its drilling depth is 3 201.5 m, while the casing is down to 2 778.3 m deep and the well screen is below that. The observed aquifer is at the depth range of 2 341–2 658 m and the aquifer lithology is mainly Paleogene Oligocene sandstone. The inner diameter of casing and the open-hole are both 90 mm. The well is cemented and the capping pressure is 200 kPa with the wellhead temperature about 27 °C. It is confined and artesian. The water column height is observed. The well is far away from the recharge source, and the water level records are less affected by ambient water sources. There is an obvious tidal and barometric effect on the water level, and one can also see some responses of water level to some earthquakes. Generally speaking, this kind of well is quite appropriate for carrying out seismic observation of underground fluids (Zhang et al., 2006). In 2001, the Seismological Administration of Shaanxi Province made a comprehensive digital upgrade to the Zhouzhi well, leading to high-quality continuous digital records of water level, water radon, geothermal, discharge, atmospheric temperature, barometric pressure and rainfall. And the sampling rate of the digital record is once per minute. The Zhouzhi well is about 570 km away from the Wenchuan epicenter and it had continuous water level records in 2008. The coseismic groundwater level step due to the Wenchuan earthquake in this well is up to 64.4 cm, as shown in Figure 2.

Figure 1 The epicenter (star) and the ruptured area (quadrangle) for the Wenchuan $M_S8.0$ earthquake. F_1 . The northern edge of Qinling fault; F_2 . Qishan-Mazhao fault.

Figure 2 Groundwater level records of the Zhouzhi well in May of 2008. The coseismic water level step due to the 2008 Wenchuan earthquake is marked by an arrow.

3 Analysis method

3.1 Basic principle for calculating permeability

The fact that permeability controls fluid flow is evidenced from the response rate of the groundwater level to dynamic input signals. In addition to the random disturbances such as rainfall and earthquakes, periodic variations of the well water level are mainly affected by Earth tide and barometric pressure. Barometric pres-

sure signals are relatively random and complex, while Earth tide signals are more regular and stable. Figure 3 shows the amplitude spectra of theoretical Earth tide, groundwater level and barometric pressure records of the Zhouzhi well from January 1 to May 11 in 2008 (one day prior to the Wenchuan earthquake). From Figure 3, we can see that multiple waves such as S_2 and K_1 exist

Figure 3 The amplitude spectra of theoretical Earth tide, groundwater level and barometric pressure records of the Zhouzhi well from January 1 to May 11 in 2008. The M_2 wave has the largest amplitude and is not contaminated by barometric pressure.

both in Earth tide and barometric pressure. If we use these constituents to analyze the response of water level to Earth tide, it could be strongly contaminated by barometric pressure. Waves of O_1 , M_2 and N_2 are the diurnal, semi-diurnal and large elliptical waves due to the moon, which are not affected by barometric pressure. However, the amplitude of N_2 is small and the phase shift from O_1 is unstable. Fortunately, M_2 wave has large amplitude and the resulting phase shift from M_2 wave is quite stable, so it is the best signal source for tidal analysis (Hsieh et al., 1987; Doan and Brodsky, 2006). In this paper, M_2 wave is taken as a standard calibration signal and used for determining the permeability of well aquifer.

According to the confined well aquifer model, the aquifer is assumed to be isolated, homogeneous, isotropic, and horizontally extended (Cooper et al., 1965). Periodical changes in Earth tide cause well aquifer to expand or compact, resulting in fluctuation of pore fluid pressure, further leading to the corresponding fluctuation of water level in the well bore that is connected with the confined aquifer (Hsieh et al., 1987). The relationship between pore fluid pressure fluctuation h and the corresponding water level response x can be described by

$$h = h_0 e^{i\omega t} \quad (1)$$

and

$$x = x_0 e^{i\omega t}, \quad (2)$$

where h_0 and x_0 are the complex amplitudes and ω is the angular frequency of the fluctuation. Because of the flow resistance, there is a phase shift η when water level responds to Earth tide.

$$\eta = \arg \frac{x_0}{h_0} \quad (3)$$

After a series of derivations, Hsieh et al. (1987) expressed the phase shift η as a function of the aquifer transmissivity T , storage coefficient S , well radius r_w , well casing radius r_c and the angular frequency of the harmonic disturbance ω as following:

$$\eta = -\arctan(F/E), \quad (4)$$

$$E \approx 1 - \frac{\omega r_c^2}{2T} \text{Kei}(\alpha_w), \quad (5)$$

$$F \approx \frac{\omega r_c^2}{2T} \text{Ker}(\alpha_w), \quad (6)$$

$$\alpha_w = \sqrt{\frac{\omega S}{T}} r_w, \quad (7)$$

where $\text{Ker}(\alpha_w)$ and $\text{Kei}(\alpha_w)$ are the real and imaginary part of zero-order Kelvin function. Because the solution is insensitive to the dimensionless storage coefficient S ,

when the phase shift of water level relative to Earth tide at the frequency of M_2 wave is known, one can get the corresponding transmissivity T from equation (4) to (7), and further obtain the permeability k by

$$k = \frac{\mu}{\rho g d} T, \quad (8)$$

where μ is the dynamic viscosity, ρ the density, g the gravitational acceleration, and d is the aquifer thickness (Elkhoury et al., 2006).

3.2 Extraction of the phase shift at the frequency of M_2 wave

It is an important step to extract reliable phase shift at the frequency of M_2 wave so as to get the aquifer permeability. Permeability reflects the response pace of water level to input signals, namely, the phase shift changes between water level and input signals. In order to reduce the influence from data steps and obtain the true phase changes, we preprocessed the data by gaps interpolation and step correction. The main frequency components of groundwater level are diurnal and semi-diurnal waves, so when the missing data length is less than one hour, the gaps are filled by linear interpolation from adjacent good records; when more than one hour, the gaps are interpolated by tidal signals from data before and after the day, which can basically eliminate the discontinuity of signals. Due to instrument's zero-drift or earthquakes, data steps exist in some periods. In order to remove the effects from steps, we subtract the step value from the post-step data.

As a commonly used software for analyzing the response of groundwater level to Earth tide, Baytap-G, (Ishiguro et al., 1984; Ishiguro and Tamura, 1985; Tamura, 1987; Tamura et al., 1991) describes the observed groundwater level y_i approximately as

$$y_i = \sum_{g \in \text{groups}} H_g \sum_{m \in \text{waves } g} [A_m \cos(\omega_m t + \phi_g) + B_m \sin(\omega_m t + \phi_g)] + \sum_{k=0}^K b_k x_{i-k} + di + \varepsilon. \quad (9)$$

The first item on the right side of equation (9) shows the tidal response. The double sum reflects the grouping: tidal components with close frequency will be assigned to one group, and each group are expressed as a sum of cosines and sines. Tidal coefficient of H_g , A_m and B_m , and the phase ϕ_g will be determined through tidal analysis. The second item represents barometric response considering the lag effect, the third long-term trend, and the fourth means some noise. To assess the quality of the fit, the matching between the data and the model should satisfy

$$\text{criterion} = \sum_{i=1}^n \left\| y_i - \sum_{g \in \text{groups}} H_g \sum_{m \in \text{waves}}^M (A_m C_{m_i} + B_m S_{m_i}) - \sum_{k=0}^K b_k x_{i-k} - d_i \right\|^2. \quad (10)$$

Two constrains need to be added. One is the smoothness of the trend:

$$D^2 \sum_{i=1}^n \|d_i - 2d_{i-1} + d_{i-2}\|^2, \quad (11)$$

the other is the smoothness of the response to the Earth

tides:

$$W^2 \sum_{m=2}^M \left\| (A_m - A_{m-1})^2 + (B_m - B_{m-1})^2 \right\|. \quad (12)$$

Then the ABIC (Akaike's Bayesian Information Criterion) is

$$\begin{aligned} \text{ABIC} = & \sum_{i=1}^n \left\| y_i - \sum_{g \in \text{groups}} H_g \sum_{m \in \text{waves } g}^M (A_m C_{m_i} + B_m S_{m_i}) - \sum_{k=0}^K b_k x_{i-k} - d_i \right\|^2 + \\ & D^2 \sum_{i=1}^n \|d_i - 2d_{i-1} + d_{i-2}\|^2 + W^2 \sum_{m=2}^M \left\| (A_m - A_{m-1})^2 + (B_m - B_{m-1})^2 \right\|. \end{aligned} \quad (13)$$

By given the superparameter D and W , Baytap-G will determine several parameters including the phase, which will minimize ABIC.

The M_2 wave response of water level to Earth tide can be deemed as a response to a single signal, for there is no or very little interference from barometric pressure. Using the cross-correlation function, one can calculate the advanced or lagged phase shift of one signal relative to the other. In this paper, we use both Baytap-G and cross-correlation function methods to calculate the phase shift at the frequency of M_2 wave. The specific steps are as following:

1) Baytap-G method. Firstly filter the preprocessed water level data and theoretical Earth tides from 2 h to 30 h by a second-order Butterworth band-pass filter. Then resample the filtered data to hourly spaced series, which is the standard interval for tidal analysis. With a moving time window of 30 days and a running step of 5 days, the phase shifts of groundwater level relative to Earth tide at the frequency of M_2 wave are obtained by Baytap-G program.

2) Cross-correlation method. The filtered frequency range is 735–755 min, as the period of M_2 wave is 745.2 min and there is no other tidal constituent within this range. With the same moving time window and running step, we calculate the cross correlation between water levels and Earth tides. The time shift t is obtained when the maximum cross correlation is reached, and the corresponding phase shift is calculated by $\eta = 360t/745.2$

in degree. When the phase shift is negative, it means water level signals lag behind the Earth tides.

4 Result analysis

4.1 Phase shifts of the water level relative to theoretical Earth tide at the frequency of M_2 wave

The preprocessed groundwater levels, Earth tides and phase shifts of groundwater level relative to Earth tide at the frequency of M_2 wave are shown in Figure 4. We can see that the resulting phase shifts from the two methods are close to each other within the time windows away from the Wenchuan earthquake. However, when the time window include the Wenchuan earthquake, the phase shifts from Baytap-G program change greatly, and the average error is up to 3.8° with the background error about 0.5° ; while the phase shifts from the cross-correlation function are more stable. That may be resulted from different filter bandwidth. A narrow band filter is used in cross-correlation method, which greatly excludes other tidal constituent. But for the Baytap-G method, there may be the influences from barometric pressure. Especially when an earthquake occurs, the weight of Earth tide's effect on water level could be reduced. Moreover, the shift value has a decaying tendency after the Wenchuan earthquake, which is not considered in equation (9). So during this period, the Baytap-G model is no longer applicable for calculating the phase shift.

Figure 4 Preprocessed groundwater level (a), theoretical Earth tide (b) and the phase shifts of water level relative to Earth tide (c) at the frequency of M_2 wave in the Zhouzhi well. The red and blue dotted lines correspond to the phase shifts from Baytap-G program and cross-correlation function, and the black vertical lines mark the corresponding errors.

After the Wenchuan earthquake, major phase shifts from the two methods are positive, which means that water level signal is ahead of Earth tide. One possible reason for it is that we used the theoretical values of Earth tide, rather than the actually observed values. The theoretical Earth tides are calculated from simplified Earth model without elliptical correction and rotation effects, and just according to the positions of moon and sun. Moreover, the actual Earth tides also have something to do with the in-situ geological and topographic conditions.

4.2 Phase shifts of the observed water level relative to bulk strain at the frequency of M_2 wave

The bulk strain is observed by a gauge installed downhole in intact rock. In addition to earthquakes and some other factors, its records indicate good tidal signals. Unlike the water level signal, no fluid-induced lag for bulk strain response to Earth tide, and the phase shift of bulk strain relative to Earth tide should be much

smaller than that of water level does, so observed bulk strains can be used for tidal analysis instead of Earth tides. Since there is no bulk strain gauge in the Zhouzhi well, we selected the bulk strain data from Xi'an station about 55 km away, and calculated the phase shifts of water level relative to bulk strain at the frequency of M_2 wave, as shown in Figure 5. As the Zhouzhi well is located to the east of Xi'an station, the longitudinal difference between the two sites is 0.7° , therefore we added a phase shift of -1.3527° (2.8 min delay) for longitudinal correction according to the calculation principle of theoretical Earth tide.

Figure 5 shows that the variation trends of the phase shifts at the frequency of M_2 wave are very similar, suggesting that the variation of the phase shifts is causal; compared with the theoretical Earth tide, the resulting phase shifts of water level relative to bulk strain fluctuate more obviously. That is because the observed bulk strain is affected not only by Earth tide, but also by earthquakes and other factors; all the phase shifts

Figure 5 Preprocessed groundwater level in the Zhouzhi well (a), bulk strain in Xi'an well (b), and the phase shifts of water level relative to Earth tide (the asterisk line) and to bulk strain (the circle line) at the frequency of M_2 wave from cross-correlation function (c).

of water level relative to bulk strain are negative, implying that the water level ahead of the Earth tide is quite probably due to the phase deviation between the theoretical Earth tides and the actual tidal signals.

4.3 Apparent permeability based on observed water level and corrected Earth tide

As some interfering signals are introduced by using Earth tides, we calculate the phase shifts of Earth tide relative to bulk strain at the frequency of M_2 wave, and find that from some periods of high quality data, the Earth tide lags behind the bulk strain for 10 minutes, and the corresponding phase shift at the frequency of M_2 wave is 4.8309° . Based on the assumption that bulk strain response to Earth tide is almost simultaneous, we can move the earth tide signals ahead of 4.8309° , as well as the longitudinal correction of 1.3527° , so as to get the corrected phase shifts of water level relative to Earth tide. According to the relationship between permeability and phase shift, taking $r_c=r_w=0.045$ m, $d=317$ m, $S=10^{-4}$ and 10^{-6} (the upper and lower limits of typical value of storage coefficient S), we obtain the temporal apparent permeability of the Zhouzhi well aquifer from the corrected phase shifts at the frequency of M_2 wave by using cross-correlation function (see Figure 6).

The results show that the permeability values with $S=10^6$ and $S=10^4$ are in the same order and those two

Figure 6 Temporal variations of apparent permeability of the Zhouzhi well aquifer from the corrected phase shifts of water level relative to Earth tide at the frequency of M_2 wave by cross-correlation function. During the Wenchuan earthquake, the permeability increases drastically.

curves have the similar tendency. According to a pumping test in the Zhouzhi well, the obtained hydraulic conductivity is 0.069 m/d, and the corresponding permeability is estimated to be $8.15 \times 10^{-14} \text{ m}^2$, while our re-

sulting apparent permeability is $2 \times 10^{-15} - 6 \times 10^{-15} \text{ m}^2$. As the permeability from a pumping test is obtained on a quasistatic condition, the apparent permeability in this paper is affected by some dynamic factors. Besides, the hydraulic parameters of the well aquifer could vary with time due to the change in the amount of impurities in the pore of the rock, so the difference is acceptable.

The aquifer apparent permeability fluctuates with time, indicating it is not a static parameter but an ever-evolving, dynamically controlled parameter (Elkhoury et al., 2006). The apparent permeability values within the ellipse are calculated from data covering the Wenchuan earthquake. Although step correction is carried out, there might be a little interference inevitably. Comparing the two apparent permeability values before and after the Wenchuan earthquake, we can find that the coseismic apparent permeability increases drastically. According to the model of Rice (1992), permeability k is a strongly decreasing function in relation to effective normal stress $\bar{\sigma}_n$:

$$k = k_0 \exp(-\bar{\sigma}_n/\sigma^*), \quad (14)$$

where k_0 is the permeability when the effective normal stress is equal to zero; σ^* is a constant, and lower values of σ^* corresponds to highly cracked rocks.

The effective stress is equal to the confined stress minus the pore pressure. Obviously the passing seismic waves affect the confined stress; from the very beginning we mentioned that there is a coseismic rise in groundwater level, implying the pore fluid pressure increases during the earthquake. So the effective stress will be changed consequently. According to the crack model of Wang et al. (2008), the raise of the pore fluid pressure seems to be dominant and increases the average crack density, which opens more space to the fluids and increases the aquifer permeability. Besides, the removing of barriers in the flow channel due to seismic waves is also known to increase the apparent permeability (Brodsky et al., 2003). When the seismic waves arrive, it causes rapid fluid flow in the fracture, which removes barriers deposited in the channel, and leads to the apparent permeability increasing.

About a month later, the apparent permeability begins to decrease. During the periods from July 19 to September 6, it dropped quickly and then rose. However, we do not find any obvious anomaly from the water level, which needs to be further analyzed. About six months after the earthquake, the apparent permeability almost recovered to the pre-quake level. We attribute this change to the effective stress recovery and

the groundwater impurities gradual depositing.

5 Conclusions

In this study, we analyzed the observed underground water level records of the Zhouzhi well. Taking the M_2 wave as a standard calibration signal, we extracted the phase shifts of water level relative to Earth tide at the frequency of M_2 wave by the cross-correlation function, and further obtained the apparent permeability of the Zhouzhi well aquifer from January 1 to October 26, 2008. Some conclusions are drawn.

We used the cross-correlation function to calculate the phase shift of water level relative to Earth tide. Compared with the conventional analysis method of Baytap-G program, cross-correlation function can well extract the phase shift at the frequency of M_2 wave, which has been used to obtain the apparent permeability of the Zhouzhi well aquifer successfully.

The apparent permeability of the Zhouzhi well aquifer fluctuates over time rather than a fixed value, indicating it is a dynamically controlled parameter. Due to the Wenchuan earthquake, the coseismic apparent permeability increases drastically. We interpret this increase as the combination effect of changes in effective stress and the removing of the barriers in the flow channel by rapid flow due to seismic wave pressure pulse. After the earthquake, the effective stress recovered and the impurities deposited gradually, causing the apparent permeability to decrease about a month later and almost recovered to the previous level in six months, which is beneficial to understanding of the aquifer property and the earthquake process.

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