Sensitivity of permeability changes to different earthquakes in a fault zone: Possible evidence of their dependence on the frequency of seismic waves

Xin Liao[1, 2, *], Yun Shi[1], Chun-Ping Liu[1], Guangcai Wang[2]

[1] Institute of Disaster Prevention, Beijing, China 101601

[2] China University of Geosciences, Beijing, China 100083

*** Corresponding author: Xin Liao (liaoxin19851224@126.com)**

Key Points:

- Permeability changes in fault zones are more sensitive to remote or regional earthquakes than near or local ones.
- The difference in sensitivity suggests that the permeability change is dependent on the frequency of the seismic waves.
- The frequency dependence of permeability change may be related to the length of the fracture in the fault zone.

Abstract

Changes in the permeability of a fault zone are dependent upon the frequency of seismic waves, and is an important phenomenon whose mechanisms have not be completely elucidated to date. In this study, the tidal response of water level in well Chuan06 was considered as an indicator of the permeability of the fault zone, and the sensitivity of permeability changes to earthquakes with different epicentral distances were investigated. The results suggested that the permeability change induced by seismic waves is frequency dependent. In addition, based on the mechanisms of permeability changes induced by the seismic waves, the difference in sensitivity may be attributed to the different sizes of the fractures in the fault zone. These findings are likely to contribute to an understanding of hydrogeological responses and seismic activity induced by the earthquakes.

Keywords: well water level; tidal response; seismic waves; permeability; frequency dependence

Plain Language Summary

Causative factors of changes in permeability are the key to understanding the mechanisms of the phenomenon induced by the seismic waves. To understand these mechanisms and causative factors, we study the tidal response of water level in well Chuan06 as an indicator of permeability; sensitivity of permeability change to different earthquakes was also analyzed. The results indicated that the permeability change induced by seismic waves is related to the frequency of the latter, which depended on fracture size of the fault zone. Our research is beneficial to understanding the mechanisms influencing permeability changes and hydrological responses triggered by earthquakes.

1 Introduction

Permeability is an important hydrogeological parameter largely governing the potential generation of high pore pressure and transport of fluids, solutes, and heat in fault zones. The permeability is altered by seismic waves (Lai et al., 2013; Yan et al., 2016; Shi et al., 2017; Shi et al., 2019); this significantly influences the pore pressure and fluid distribution, resulting in certain hydrological and geological phenomenon, such as changes in the well water levels, streams, spring discharge rates, and liquefaction (as summarized by Wang & Manga, 2010; Manga et al., 2012). Even the triggered earthquakes induced by a remote earthquake could be attributed to the permeability changes in the fault zone (van der Elst & Brodsky, 2010).

Several laboratory experiments (e.g., Elkhoury et al., 2011; Faoro et al., 2012; Liu & Manga, 2009) and field research (e.g., Elkhoury et al., 2006; Shi & Wang, 2017; Shi et al., 2019; Yan et al., 2016; Zhang et al., 2019) have shown that during earthquakes, seismic waves (dynamic stress) can alter the permeability. Based on these studies, models have been proposed to explain the mechanisms of permeability change induced by seismic waves (Candela et al., 2014; Elkhoury et al., 2006; 2011; Faoro et al., 2012; Wang et al., 2016); however, the proposed mechanisms have not been clearly confirmed. The frequency dependence of permeability changes is an important clue to understanding this process (Manga et al., 2012).

In this study, to explore the possible effect of frequency of seismic waves on the sensitivity of permeability changes, water levels observed in well Chuan06 in Southwest China were investigated as a case study. In addition, possible explanations for the frequency dependence of permeability changes were analyzed by comparing the observations recorded for different fields.

2 Observations

Well Chuan06 is located in Huili City, Sichuan Province, southwestern China (26.31° N, 102.06° E), and lies in the Ninghui fault (Figure 1a). The wellbore passes through a sequence of magmatic and metamorphic rocks, and then through a fault zone ~32 m in thickness, which is made up of fractured marble and is confined by dolerite and marble of ~251 m thick (refer to

Figure 1b for lithologic log data). Water level data collected from January 1991 to June 2007 were used to analyze the tidal responses (Figure 1c). Over approximately 16.5 years and documented at a relative precision of 1 mm. The measurement frequency is 1 sps. The recording of observations was terminated in 2007, because of the strong effect of adjacent groundwater pumping.

3 Tidal analysis

Tidal analysis was performed with BAYTAP-G (Tamura et al., 1991), calculating amplitude (*M*) and phase (μ) for different tidal constituents of well water level. The favored constituents and optimal parameters adopted in the tidal analysis were based on the discussion by Doan *et al*. (2006). The water level data were split over durations of 30 days. The tidal constituents of the water level were grouped into 12 classes: Q1, O1, M1, P1S1K1, J1, OO1, 2N2, N2, M2, L2, S2K2, and M3. Amongst these, S1 and S2 are solar tides affected by temperature and barometric tides; O1, Q1, M1, J1, OO1, 2N2, N2, L2, and M3 showed a very low signal-to-noise ratio compared to M2. Therefore, to avoid the effects of barometric tides and temperature as much as possible, the M2 tidal constituents were chosen for analysis in this study.

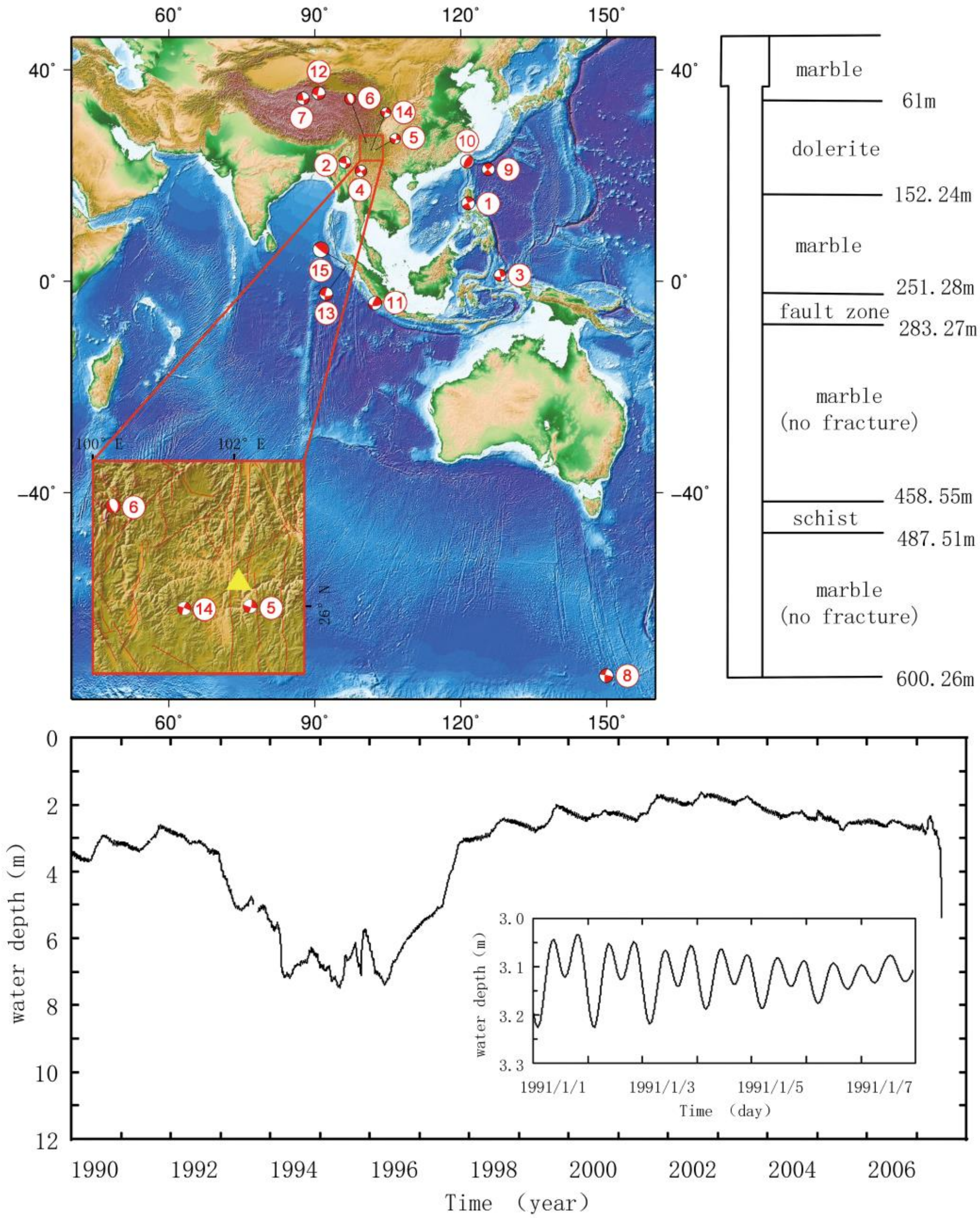

Figure 1. **a)** Location of well Chuan06 represented by a yellow triangle. The circled numbers denote earthquakes that have changed in the permeability (refer to Table S1 for detailed information). **b)** Log of well Chuan06; dashed lines indicate open section. **c)** Time series of water level changes in well Chuan06. **d)** Detrended water level time series showing the tidal response.

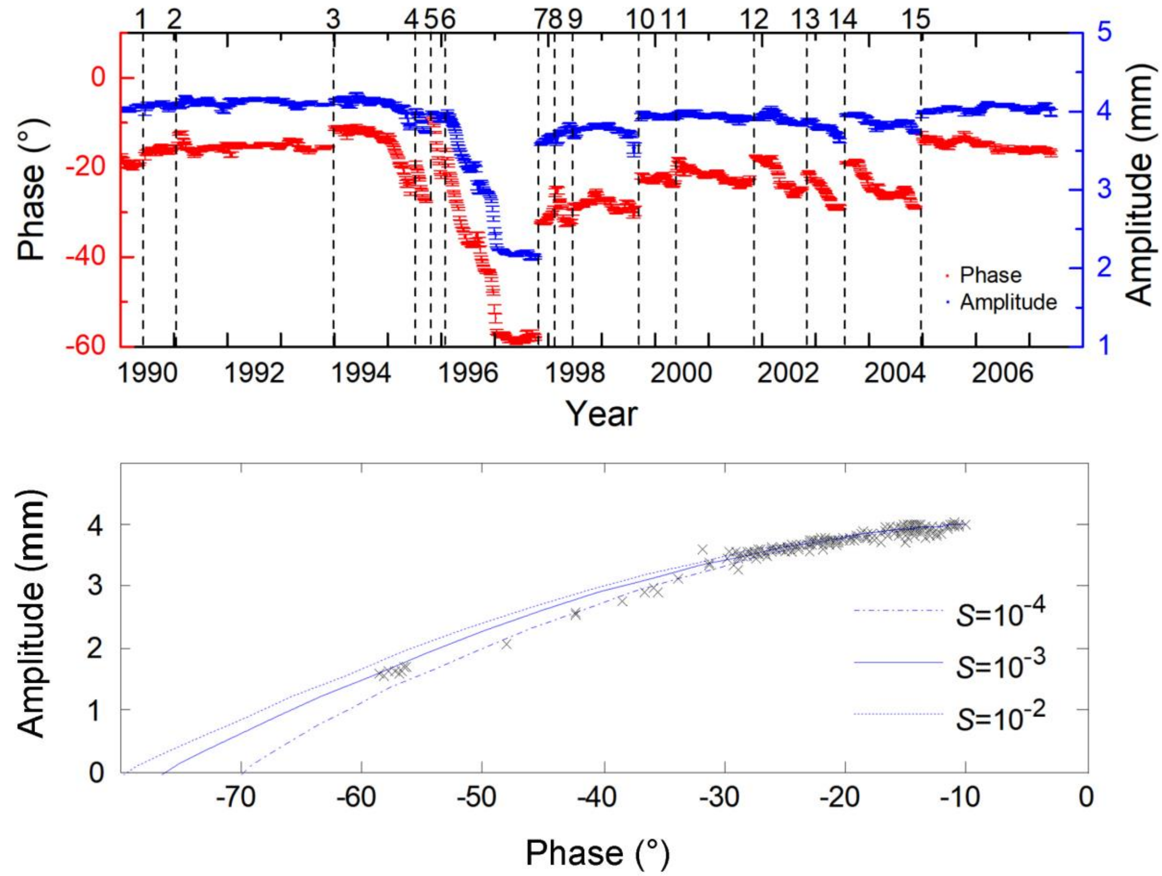

Figure 2. Tidal analysis result of water level monitored in well Chuan06. **a)** The amplitude and phase shift for the M2 tide with respect to time. Vertical dashed lines represent the earthquakes that changed the tidal response (detailed information shown in Table S1) and were selected from the USGS earthquake catalog (https://earthquake.usgs.gov/earthquakes/search/). The error bars indicate the root-mean-square error (RMSE) of the tidal analysis. To explore all earthquakes that may have affected the tidal response of the water level, earthquakes that caused a seismic energy density larger than 10^{-6} J/m^3 were chosen from the USGS catalog; this value is the possible threshold value for most wells as per global observations (Zhang et al., 2019). **b)** Practical and theory relation between the amplitude and phase for the M2 tide of the water level. The scatter

plot was obtained using field data for the well water level, and the theoretical curves under different conditions of storativity were obtained from Hsieh et al. (1987).

As shown in Figure 2, there are transient increases in both the amplitude (M) and phase (μ) of M2 tidal waves during the earthquakes. After these earthquakes, the amplitude and phase decreased gradually. In addition, there is a step-like decrease followed by a gradual decrease in the amplitude and phase in 1996; the cause of these trends has not been determined. While what could be certain is that no earthquakes were responsible for the large decreases in both amplitude and phase.

4 Interpretation

In well Chuan06, the phase of the tidal response to the M2 tide is negative and is positively correlated with the amplitude (Figure 2); this is similar to the expected behavior of confined aquifers described by Hsieh et al. (1987). Following Hsieh's model (Hsieh *et al.*, 1987), the response of the water level in a confined well to the far field pressure head disturbance in a homogenenuous and isotropic aquifer can be expressed as follows (Xue et al., 2016):

$$A = \left|\frac{x_0}{\varepsilon_0}\right| = \frac{1}{S_s}(E^2 + F^2)^{-0.5} \text{ and} \quad (1)$$

$$\eta = \arg\left(\frac{x_0}{\varepsilon_0}\right) = -\tan^{-1}(F/E), \quad (2)$$

where $E \approx 1 - \omega r_c^2 \mathrm{Kei}(\alpha)/2T$, $F \approx \omega r_c^2 \mathrm{Ker}(\alpha)/2T$, $\alpha = r_w(\omega S/T)^{0.5}$, $S = S_s b$, A is the amplitude response, η is phase shift in the water level relative to the pressure head in the far-field aquifer, r_w is the radius of the well where the water flows in and out the well, r_c is radius of the casing in which the water level rises and falls, S is storativity, S_s is undrained specific storage, b

is the thickness of the open interval of the well, T is transmissivity, ω is frequency, and Ker and Kei are Kelvin functions of order zero.

According to Hsieh's model, the permeability can be inferred from the measured phase and amplitude for the M2 wave. As shown in Figure 3, there are step-like increases in permeability coincident with remote and more proximal earthquakes (Table S1 of the USGS earthquake catalog).

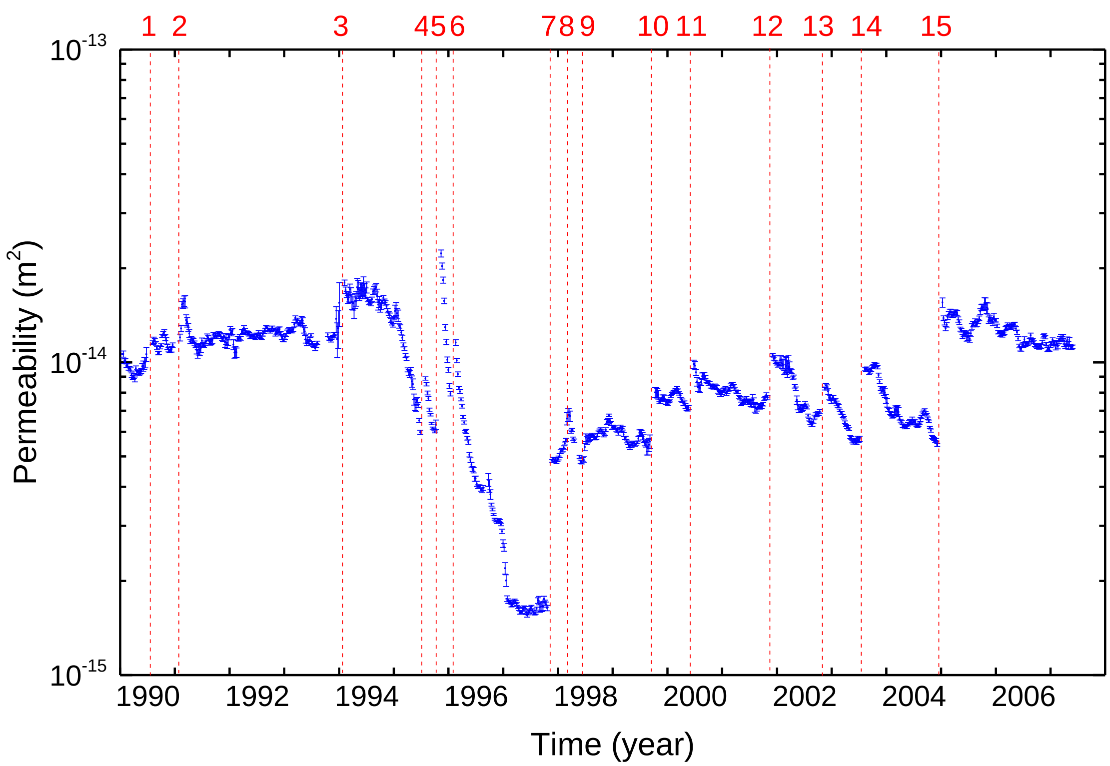

Figure 3. Changes in permeability according to the tidal responses of the water level in well Chuan06. The errors in the permeability (black error bars) were estimated by propagating the range of the phase and amplitude errors. Vertical dashed lines and the dotted line show the earthquakes (Table S1) selected from the USGS earthquake catalogue. The permeability, k, is

related to transmissivity, T, as: $\boldsymbol{k = T\mu/\rho g b}$, where μ (= 10^{-3} Pa·s at 20 °C) is the fluid dynamic viscosity, ρ (= 10^3 kg/m^3) is the density of the fluid, g (= 9.8 m/s^2) is the acceleration due to gravity, and b (= 32m) is the thickness of the open interval of the well.

It's common knowledge that earthquakes produce seismic waves (transient strain) and change the regional tectonic stress (static strain). Several laboratory experiments and field research have shown that both transient strain and fluid pressure oscillation (e.g., Shmonov et al., 1999; Liu and Manga, 2009; Elkhoury et al., 2006, 2011; Faoro et al., 2012; Lai et al., 2014; Yan et al., 2016; Zhang et al., 2019; Shi et al., 2019) and the static strain (e.g., Ngwenya et al., 2003; Faoro et al., 2009) can change the permeability. For well Chuan06, changes in the static or permanent strain are reflected in co-seismic changes in the well water level (see Table S1) and are too small to affect the permeability; therefore, the changes in permeability should be attributed to the seismic waves.

The mechanism of permeability change induced by seismic waves (dynamic waves) has been explored by many scholars through simulated experiments and field research (reviewed by Manga et al., 2012). There are several models to explain the permeability changes induced by seismic waves: fracture unclogging (Elkhoury et al., 2006; 2011; Candela et al., 2014), fluid pressure induced changes in fracture aperture (Faoro et al., 2012), and new fractures creation (Wang et al., 2016). In fact, no large permanent strain induced by these earthquakes is indicated by the well water level (recalling that $\boldsymbol{\varepsilon = \rho g h / B K_u}$, $\boldsymbol{K_u}$ is equal to 4–40 GPa (Wang, 2000), and supposing Skempton's Coefficient, B, to be equal to 0.5, the largest sustained change ($\boldsymbol{h}$) in the well water level is < 0.3 m (see Table S1), which suggests that the static strain, $\boldsymbol{\varepsilon}$, is < 10^{-6}), such as would be required by the fracture aperture changes or creation of new fractures during and after the earthquake. In addition, the energy density of the seismic waves is too small to create fractures or change fracture apertures at well Chuan06. Therefore, the changes in the permeability here should be attributed to the unclogging of fractures.

5 Discussion

The clear response of the water level to the earth tide suggests that there were no bubbles in the fault zone (Manga et al., 2012). In addition, a pumping test showed no gas or oil in the fault zone. Therefore, the change in permeability induced by the seismic waves can best be attributed to colloid migration. We infer that some fractures are usually blocked by colloids before earthquakes. If there is sufficient seismic energy for groundwater flow to unclog the blocked fracture, by driving colloids away from the narrow part of the fracture, permeability will increase immediately as the seismic waves pass.

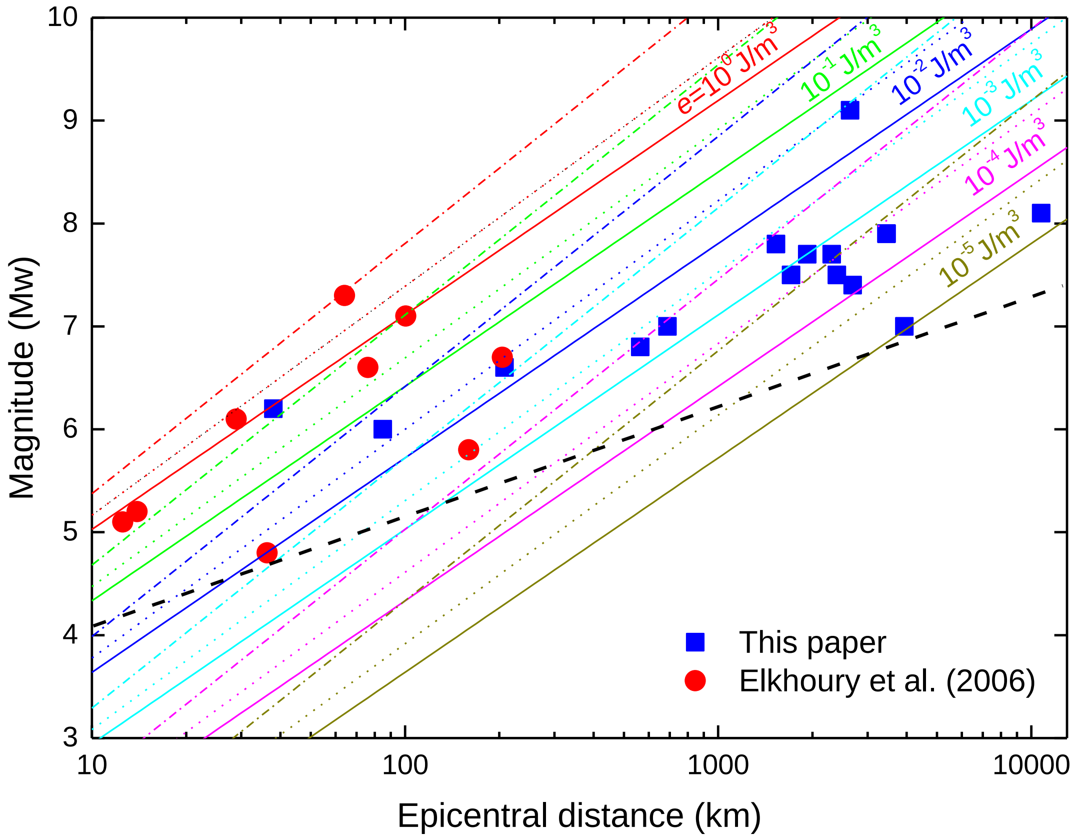

Figure 4. Threshold for changes in permeability in this study and Elkhoury et al. (2006) as a function of earthquake magnitude and epicentral distance. As there were no local data for reference, we used the theoretical seismic energy density ($\boldsymbol{e}$) calculated through the empirical relationship: $\mathbf{log}\,\boldsymbol{e} = \mathbf{1.45}\boldsymbol{M} - \mathbf{3}\,\mathbf{log}\,\boldsymbol{r} - \mathbf{4.24}$ (solid line) derived by Wang et al. (2006), Wang (2007), and Wang & Manga (2010) by using the empirical relationship for seismic wave energy density attenuates (e) with epicentral distance (r) for South California ($\boldsymbol{e}\sim\boldsymbol{r}^{-\mathbf{3}}$); $\mathbf{log}\,\boldsymbol{e} = \mathbf{1.45}\boldsymbol{M} - \mathbf{3.2}\,\mathbf{log}\,\boldsymbol{r} - \mathbf{4.24}$ (dotted line), and $\mathbf{log}\,\boldsymbol{e} = \mathbf{1.45}\boldsymbol{M} - \mathbf{3.5}\,\mathbf{log}\,\boldsymbol{r} - \mathbf{4.24}$ (dash-dotted line) derived by using the empirical relationship for Nevada ($\boldsymbol{e}\sim\boldsymbol{r}^{-\mathbf{3.2}}$) and central Asia ($\boldsymbol{e}\sim\boldsymbol{r}^{-\mathbf{3.5}}$), respectively (Wang et al., 2006); where M is the magnitude of earthquake.

Figure 4 shows the threshold of the seismic energy density for permeability changes induced by earthquakes at different distances to the well. To eliminate the influence that the uncertainty of the empirical relationship of the seismic wave energy density has on this study to the greatest extent possible, we summarize the empirical relations from existing studies at different field sites (Wang et al., 2006). The difference between the threshold value (approximately four orders of magnitude) for earthquakes with different distances to the well is too large to be attributed to systemic error in the empirical relationship derived by Wang et al. (2006), Wang (2007), and Wang & Manga (2010). Therefore, there is a difference in the sensitivity of changes in the permeability induced by earthquakes at different distances to the well; for the fault zone in our study, the permeability is more sensitive to large remote earthquakes than to small adjacent earthquakes with the same seismic energy density.

Large regional earthquakes produce seismic waves with long periods and a long shaking duration, whereas small localized ones have short periods and a short duration. The duration of seismic waves has little impact on changes in the permeability; a few cycles of dynamic stimulation are sufficient to induce the observed changes (Manga et al., 2012). For instance, 80% of the increase in permeability may be reached during the first oscillation (Candela et al., 2015). Therefore, the difference in the sensitivity of this particular aquifer can be attributed mainly to frequency dependence.

To better understand the factors influencing the frequency dependence, we compare the results from this work with those from previous studies (Elkhoury *et al*., 2006; Xue et al., 2013). As shown in Figure 4, for the field areas in Elkhoury et al. (2006), the change in permeability was more sensitive to high-frequency seismic waves, suggesting that different fields may have a different "sensitive frequency". In addition, different fields can also display different sensitivities for changes in permeability induced by seismic waves of the same frequency (see Figure 4). Regional earthquakes were more likely to increase the permeability than local ones with the same seismic energy density. This indicates that for seismic waves with the same energy density, permeability is more sensitive to low frequencies than it is to high frequencies.

Theoretically, the shorter the period of seismic waves, the higher the velocity and viscous shearing of groundwater flow (Barbosa et al., 2019), such that the flow can more easily unclog a fracture. The apparent contradiction between the theoretical analysis and the field results suggests that the properties of a fault zone may play an important role in affecting the sensitivity towards the changes in permeability. It is well known that a fault zone can be treated as a fracture network in which large fractures usually act as conductors and dominate the level of permeability. Therefore, the sensitivity of a fault zone can also be controlled by the sensitivity of the long fractures therein. In addition, for a fracture network, the presence of longer fractures could increase the potential of fracture unclogging occurring at the same frequency, as suggested by Barbosa et al. (2019) based on a numerical simulation. Thus it could be inferred that the greater the number of long fractures there are in a fault zone, the more sensitive that the fault zone will be.

The fact that the frequency dependence of changes in permeability could be explained by the number of long fractures in a fault zone suggested that the length of a fracture could be a very important factor governing the sensitivity to seismic waves. Long factures are sensitive to low frequency seismic waves while short fractures are sensitive to high frequency seismic waves. Thus, changes in the permeability were found to be sensitive to low frequency seismic waves, which in turn can easily unclog the conductive fracture.

The difference in response to earthquakes between the well Chaun06 and the PF observatory well reflects the fact that the well Chaun06 did actually penetrated a well-defined fault zone, whereas the PF observatory well is located in fractured granodiorite between the San Andreas Fault (25 km distant) and the San Jacinto Fault (12 km distant), and does not penetrate a well-defined fault zone. The fault zone investigated in this study may have more long fractures than the formation studied by Elkhoury et al. (2006), or the longer fractures in the fault zone in this study may be associated with the fault itself. Because of the longer fractures in the fault zone, or the fault itself, the permeability changes in the fault zone are more sensitive to the long period seismic waves than to the short period ones.

6 Conclusions

In this study, the tidal response of the water level in well Chuan06 was considered as an indicator of the permeability of a fault zone, and the sensitivity of permeability changes to earthquakes with different epicentral distances was investigated. The results of the tidal analysis indicated that permeability changes in the fault zone are more sensitive to remote or regional earthquakes than adjacent or local earthquakes. The difference in sensitivity suggests that the permeability change induced by seismic waves is frequency dependent. However, the reason for this frequency dependence on permeability changes cannot be directly proven until practical observations can be obtained at the micro-scale.

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Data Availability Statement

Data may be downloaded through an application of China Earthquake Networks Center, National Earthquake Data Center (URL: http://data.earthquake.cn/gcywfl/index.html, there is no English translation available for the data).

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