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Mechanism of co-seismic water level change following four great earthquakes – insights from co-seismic responses throughout the Chinese mainland

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ABSTRACT

We analyze the co-seismic groundwater level responses to four great earthquakes recorded by China's network of groundwater monitoring wells. The large number of operational wells (164 wells for the 2007 Mw 8.5 Sumatra earthquake, 245 wells for the Mw 7.9 Wenchuan earthquake, 228 wells for the Mw 9.0 Tohoku earthquake and 223 wells for 2012 Mw 8.6 Sumatra earthquake) and co-seismic responses provide an opportunity to test hypotheses on mechanisms for co-seismic water level changes. Overall, the co-seismic water level responses are complex over large spatial scales, and there is great variability both in the sign and amplitude of water level responses in the data set. As shown in previous studies, permeability change, rather than static strain, is a more plausible mechanism to explain most of the co-seismic responses. However, we find through tidal analysis of water level responses to solid Earth tide that only one third of these wells that showed a sustained post-seismic response can be explained by earthquake-induced permeability change in aquifers, and these wells had sustained (>30 days) water level changes. Wells that did not show sustained changes are more likely affected by permeability changes only immediately adjacent to the wellbore.

1. Introduction

Hydrological responses caused by earthquakes have been reported for thousands of years (e.g., Institute of Geophysics – CAS, 1976). Instrument-measured responses, however, have become available only in the last few decades. These include changes in water level (Brodsky et al., 2003; Roeloffs et al., 2003), temperature (Mogi et al., 1989), chemical composition (Claesson et al., 2004; Skelton et al., 2014), stream flow (Manga et al., 2003; Montgomery and Manga, 2003; Muir-Wood and King, 1993; Rojstaczer et al., 1995), and properties of springs (Wang and Manga, 2015).

Among hydrological responses, water level changes are the most widely reported responses. Documented water level changes are typically analyzed in one of two ways: considering how one particular well responds to multiple earthquakes (Roeloffs, 1998; Weingarten and Ge, 2014; Zhang et al., 2015), or contrasting how a set of wells responds to a single earthquake (King et al., 1999; Roeloffs et al., 2003; Sil and Freymueller, 2006). Both approaches provide complementary insight into interactions between hydrogeological and tectonic processes (Manga and Wang, 2007). The first group of studies allows us to eliminate the various non-seismic effects on groundwater level and also the complications from different hydrogeological and geological settings, and thus to focus on the role of stress perturbations produced by the earthquakes. The second approach provides a spatial distribution of groundwater level responses and is useful to examine the relationship between strain and groundwater level changes.

Various mechanisms have been proposed to explain water level responses. These include: (1) poroelastic response to co-seismic static strain (Ge and Stover, 2000; Jónsson et al., 2003; Shi et al., 2013b); (2) undrained consolidation of sediments (Wang and Chia, 2008); (3) clogging or unclogging pore and fractures by oscillatory flows produced by passing seismic waves (Brodsky et al., 2003; Elkhoury et al., 2006; Lai et al., 2014; Shi et al., 2014); (4) co-seismic gas bubble nucleation and growth (Crews and Cooper, 2014; Linde et al., 1994); (5) shaking-induced

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compaction or dilatation (Bower and Heaton, 1978; Zhang et al., 2015).

There has been a large number of studies based on analyses of single well (Brodsky et al., 2003; Roeloffs, 1998; Shi and Wang, 2014; Weingarten and Ge, 2014; Xue et al., 2013), or the response of a small set of wells from a small region (King et al., 1999; Quilty and Roeloffs, 1997; Shi and Wang, 2015; Shi et al., 2014). There are fewer studies of large-scale responses with a dense network of wells. Some examples include responses over large alluvial fans following the 1999 M7.1 Chi-Chi earthquake in Taiwan where water level changes in over 180 wells were documented and analyzed (Wang et al., 2001; Wang and Chia, 2008), and the 2011 M7.1 Christchurch earthquake, New Zealand, where over 120 water level responses were analyzed (Cox et al., 2012). In both examples, responses were documented in unconsolidated aquifers, which may be significantly different from those in consolidated aquifers (Shi et al., 2014; Wang and Chia, 2008).

The present study aims to analyze the co-seismic response in consolidated rock over large spatial scales and to compare the responses to multiple earthquakes. We then use tidal analysis of the well response to test proposed mechanisms for the co-seismic responses.

2. Data and well network

Unlike the groundwater monitoring networks in Taiwan and New Zealand, which were installed on alluvial fans for monitoring and managing groundwater resources, the network in China was constructed in consolidated rock located along active faults or near points of special tectonic interest, as part of a program to monitor and predict earthquakes (Shi et al., 2013a). There are more than 400 wells specifically for groundwater-level monitoring. Among them, more than 200 wells were drilled for earthquake monitoring and the others are repurposed pre-existing wells (Shi et al., 2013a, 2015). The depth of wells varies from 31 m to as deep as 4000 m. The aquifers are mainly sandstone, limestone, and igneous rocks. Wells are maintained at different administrative levels: 1) basic wells and the regional wells are supported by the State Seismological Bureau, managed by the State Seismological Bureau and provincial seismological bureaus, respectively; 2) local wells are supported by local governments and managed by the local government seismological bureaus; 3) the enterprise wells (springs) are supported and managed by businesses such as petroleum companies. After digital upgrades that began in 2000, most of the basic and regional monitoring wells sample with periods of 1 h or 1 min. Water level sensors of type LN-3A were manufactured by the Institute of Earthquake Science, which belongs to the China Earthquake Administration (CEA). The digital piezometer readings are converted into groundwater level with a resolution of 1 mm over the range between 0 and 10 m; the absolute accuracy is 0.2% full scale. The data from the basic wells, regional wells and some local wells are digitally transmitted to the China Earthquake Network Center (CENC) each day for analysis (all of the data are raw records, without corrections for barometric pressure or tides). The rest are sent to the local earthquake administration or archived by the staff at the monitoring stations. The time recorded by the data logger is calibrated automatically through a link to a standard time (Beijing time) at the CENC each day. If the link between the data logger and the standard time system fails, staff at the monitoring stations calibrate the time-axis manually.

3. Co-seismic groundwater response caused by the earthquakes

In this study, we compiled groundwater response data from the CENC and focus on four large Asian earthquakes between 2007 and 2012 (Fig. 1), that caused widespread co-seismic groundwater responses across China: the 2007 Mw 8.5 Sumatra earthquake, the 2008 Mw 7.9 Wenchuan earthquake, the 2011 Mw 9.0 Tohoku, and the 2012 Mw 8.6 Sumatra earthquake. Among the four events, the Wenchuan and the Tohoku earthquakes caused the most widespread and largest responses (Shi et al., 2015; Yan et al., 2014).

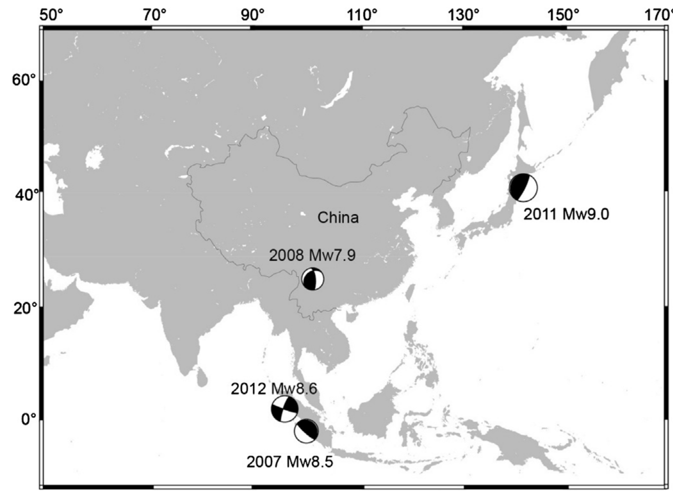

Fig. 1. Locations of four great earthquakes used in this study. Beach balls show the lower hemisphere projection of the earthquake focal mechanism, and their relative sizes reflect the earthquake magnitudes.

3.1. Types of co-seismic response

Several types of co-seismic water level responses have been recognized in previous studies: (1) abrupt (step-like) changes (Shi et al., 2013b; Weingarten and Ge, 2014); (2) gradual changes (Brodsky et al., 2003; Roeloffs et al., 2003); and (3) oscillations (Liu et al., 1989). With the development of high frequency digital instruments, new types of co-seismic response have also been observed: oscillation-abrupt changes (Weingarten and Ge, 2014), and oscillation-gradual changes (Wang et al., 2009), that is, oscillations accompanied by other responses (Fig. 2).

The three largest of these earthquakes (the Mw 8.5 Sumatra earthquake, the Mw 9.0 Tohoku earthquake, and the Mw 8.6 Sumatra earthquake), occurred far from the groundwater monitoring network in China, with epicenter distances beyond the near-field, i.e., greater than one rupture length. The Mw 7.9 Wenchuan earthquake occurred at epicenter distances from one to several fault rupture lengths to these wells. In order to be consistent in comparing the water level response following different earthquakes and to avoid the complexity introduced by details of the fault rupture, we exclude water level responses that occurred in the near-field of the Wenchuan earthquake in this study. Thus, all of the water level responses we consider occurred beyond the near-field, i.e., at epicentral distances greater than one rupture fault length.

As a consequence of logistical and technical issues with the monitoring network, we have different numbers of observations for each earthquake: 164 wells for the 2007 Sumatra earthquake, 245 wells for the 2008 Wenchuan earthquake, 228 wells for the 2011 Tohoku earthquake and 223 wells for the 2012 Sumatra earthquake. The details of co-seismic responses following each earthquake are listed in Table 1.

From Table 1, we observe that water level oscillations are the most common responses (nearly 41%, 41% and 40% of wells, respectively) for those earthquakes that occurred far from the Chinese mainland, while abrupt changes are the most common changes following the Wenchuan earthquake (39% of wells).

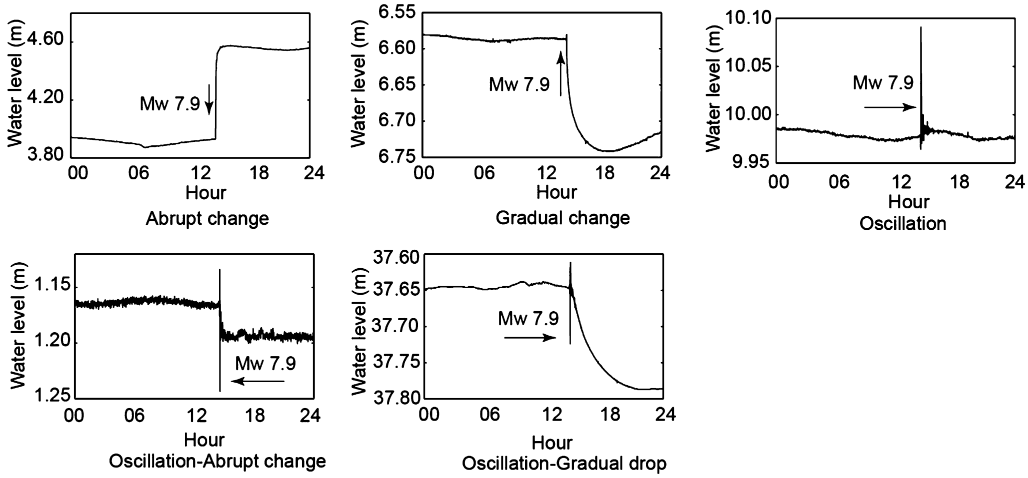

Fig. 2. Patterns of typical water level changes. Vertical axis is groundwater level; horizontal axis shows time over a 1-day interval.

Table 1
Summary of co-seismic responses following four earthquakes.

Events	No response	Oscillation	Abrupt	Gradual	Oscillation-abrupt	Oscillation-gradual	Total number
Mw 8.5	69	68	22	4	0	1	164
Mw 7.9	63	42	96	22	20	2	245
Mw 9.0	50	94	35	21	23	5	228
Mw 8.6	97	89	16	9	8	4	223
Total number	279	293	169	56	51	12	

Table 2
Summary of wells with sustained changes.

Events	Number of wells with responses[a]	Number with sustained changes	Percentage (%)
Mw 8.5	27	6	22.2
Mw 7.9	140	41	29.3
Mw 9.0	84	35	41.7
Mw 8.6	37	13	35.1
Total number	288	95	33

[a] Wells which show only oscillations are not counted.

The percentage of no-response wells is similar for the Mw 7.9 Wenchuan and Mw 9.0 Tohoku earthquake (25.7% and 22%), and also similar for the 2007 and 2012 Sumatra earthquakes (42% and 43%). The most common type of the co-seismic response is water level oscillations, followed by no response, and the least frequently observed response is an oscillation-gradual change.

Two categories of post-seismic groundwater level changes maybe distinguished: sustained changes (co-seismic changes lasting from several weeks to several months) and transient changes (co-seismic changes lasting less than one week). Sustained changes occurred in 6 wells following 2007 Mw 8.5 Sumatra earthquake, 41 wells following 2008 Wenchuan earthquake, 35 wells following 2011 Tohoku earthquake and 13 wells following 2012 Sumatra earthquake (Table 2). While the 2008 Wenchuan earthquake caused the largest number of sustained changes, the 2011 Tohoku earthquake caused the greatest fraction of sustained changes.

3.2. The sensitivity of groundwater level response to seismic strain

Several studies have reported a threshold for co-seismic water level response based on earthquake magnitude and epicenter distance (King et al., 1999; Montgomery and Manga, 2003; Roeloffs, 1998). It is not unexpected that a threshold exists because the earthquake magnitude (M) and epicenter distance (r) are the two most important parameters controlling the magnitude of stress at a specific location (Shi and Wang, 2014; Weingarten and Ge, 2014). Wang (2007) derived an empirical scaling relation to combine the parameters of M and r into a single quantity, the seismic energy density (e J/m^3):

$$\log r = 0.48\mathrm{M} - 0.33 \log e - 1.4 \tag{1}$$

where r is in km. This parameter is approximately proportional to the square of the peak ground velocity (Wang et al., 2006), which in turn is proportional to the dynamic strain (Brodsky et al., 2003). This relationship was used to interpret a global data set of different types of hydrological response in order to identify the different thresholds for the various hydrological responses (Wang and Manga, 2010).

Using this general equation for seismic energy density, we recompiled the co-seismic response plot (Fig. 3). Data come from several sources: (1) groundwater level response to four large earthquakes (2007 Sumatra Mw 8.5, 2008 Wenchuan Mw 7.9, 2011 Tohoku Mw 9.0 and 2012 Sumatra Mw 8.6) recorded in China; (2) groundwater wells in Taiwan responding to the 1999 Chi-Chi Mw 7.3 earthquake and 2006 Hengchun Mw 7.0 earthquake (Chia et al., 2008); (3): data from New Zealand, responses to the 2010 Mw 7.1 Darfield (Canterbury) earthquake (Cox et al., 2012); (4) data from an earlier global catalog of well responses (Wang and Manga, 2010) and responses recorded in Devils Hole, Nevada (Weingarten and Ge, 2014).

For the global data set, the minimum seismic energy density required to trigger sustained groundwater level responses is

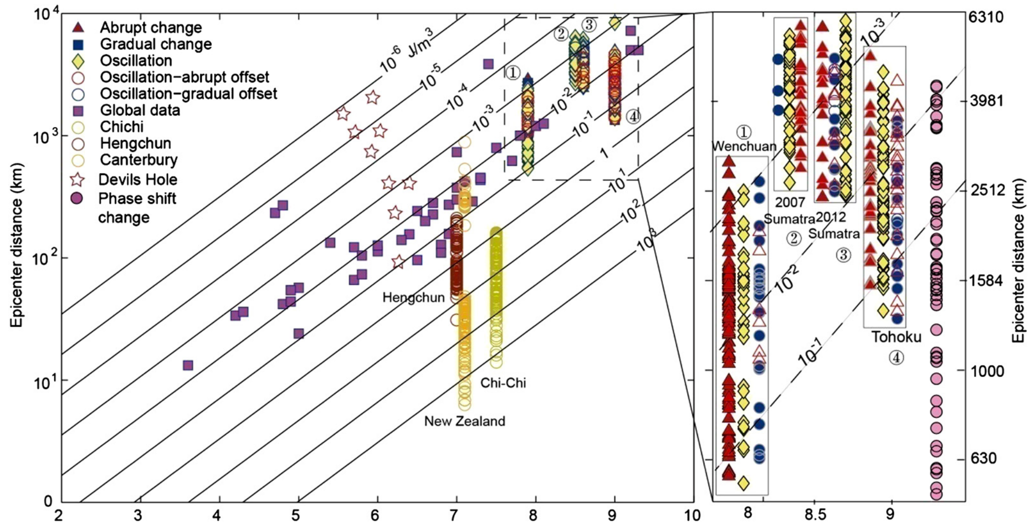

Fig. 3. Groundwater level response to four great earthquakes (①. 2008 Wenchuan Mw 7.9, ②. 2007 Sumatra Mw 8.5, ③.2012 Sumatra Mw 8.6, and ④. 2011 Tohoku Mw 9.0) and to the 1999 Chi-Chi Mw 7.3 earthquake, the 2006 Hengchun Mw 7.0 earthquake (Wang and Chia, 2008), and the 2010 Canterbury Mw 7.1 earthquake in New Zealand (Cox et al., 2012). Purple squares show data from a global catalog of well responses (Wang and Manga, 2010). Stars show selected co-seismic data recorded in Devils hole (Weingarten and Ge, 2014), and purple circles show co-seismic M_2 earth tide phase shift changes in different wells. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

bounded by $e \sim 10^{-3}$ J/m^3 although seismic energy density as small as $\sim 10^{-6}$ J/m^3 can trigger co-seismic oscillation or water level changes in Devils Hole, Nevada (Fig. 3; Weingarten and Ge, 2014).

Our new data show that the sustained changes (Fig. 3) are bounded by seismic energy density of 10^{-3} J/m^3, consistent with that for the global data set. In addition, the data show that the abrupt changes occur thousands of kilometers from the epicenter, well beyond the near-field and at seismic energy density far smaller than 0.1–10 J/m^3. The difference between our observations and those in Taiwan and New Zealand may have two origins: (1) most of the responding wells to the Chi-Chi earthquake in Taiwan and Darfield earthquake of New Zealand were located in near field and intermediate field for Hengchun earthquake while the distribution of groundwater wells in China ranges from near to far field; (2) most wells in Taiwan and New Zealand were installed in unconsolidated aquifers while the wells in China mainland are installed in consolidated aquifers. Wang et al. (2001) invoked the mechanism of undrained consolidation or dilation to explain the abrupt changes of groundwater level in Taiwan. The wells in this study were installed in consolidated rock and would require a different mechanism for water level change.

4. Mechanism

As summarized in the introduction, many mechanisms have been proposed to explain the various water level changes. The records of co-seismic groundwater level changes following four great earthquakes across China provide an opportunity to assess proposed mechanisms.

4.1. Unlikely mechanisms

Although all proposed mechanisms can operate under the right conditions and circumstances, some of them should not apply to our data. (1) Undrained consolidation: this mechanism leads to step-like changes of water level after ground shaking causes sediments around wells to consolidate (Wang and Chia, 2008). However, our groundwater monitoring wells are installed in consolidated aquifers. (2) Co-seismic bubble growth: passing seismic waves may nucleate gas bubbles or cause pre-existing bubbles to grow, increasing pore pressure because of volume expansion (Crews and Cooper, 2014; Linde et al., 1994; Matsumoto and Roeloffs, 2003). This mechanism requires that the groundwater contains or can nucleate gas bubbles such as CO_2 and also predicts that water levels should always rise. Thus, the mechanism fails to explain the wide variety of responses observed across our large-scale dataset. (3) Co-seismic discharge changes: earthquakes increase discharge from the aquifers to the surface leading to water level changes in wells (Roeloffs, 1998). However, the screened intervals in the wells of this study are mostly too deep to discharge groundwater to surface. (4) Diffusion of a localized co-seismic pressure change: earthquakes cause a localized change of fluid pressure and lead to the changes of water level in the wells owing to pore pressure diffusion. To induce pressure changes by seismic waves require a physical mechanism such as earthquake-induced liquefaction or removal of gas from the pore space (Matsumoto and Roeloffs, 2003; Roeloffs, 1998). As pointed out by Roeloffs (1998), the liquefaction-type mechanism cannot explain co-seismic water level changes in consolidated rock. Also, the gas mechanism only applies to groundwater systems rich in gas.

4.2. Possible mechanisms

4.2.1. Mechanism of co-seismic static strain

Many studies have suggested that co-seismic water level changes are due to the co-seismic volumetric strain caused by the slip on the ruptured fault (Jónsson et al., 2003, Ge and Stover, 2000), though for wells installed in unconsolidated sedimentary aquifers, the changes in water-level have sometimes show the opposite sign to those predicted by the co-seismic static strain change (Koizumi et al., 2004; Wang et al., 2001). Here we reevaluate this mechanism by assessing the relationship between static volumetric strain and co-seismic water level response. The static volumetric strain was inferred from a fault dislocation model in a uniform half space with the analytical expression of Okada (Okada, 1992) and implemented in the software Coulomb 3.3 (Lin and Stein, 2004; Toda et al., 2005) so that we can use a finite fault model. Because both Sumatra earthquakes are far from the China mainland, their impact on static strain is much smaller than that of the Wenchuan and Tohoku earthquakes. We thus only use data from the Wenchuan and Tohoku earthquakes.

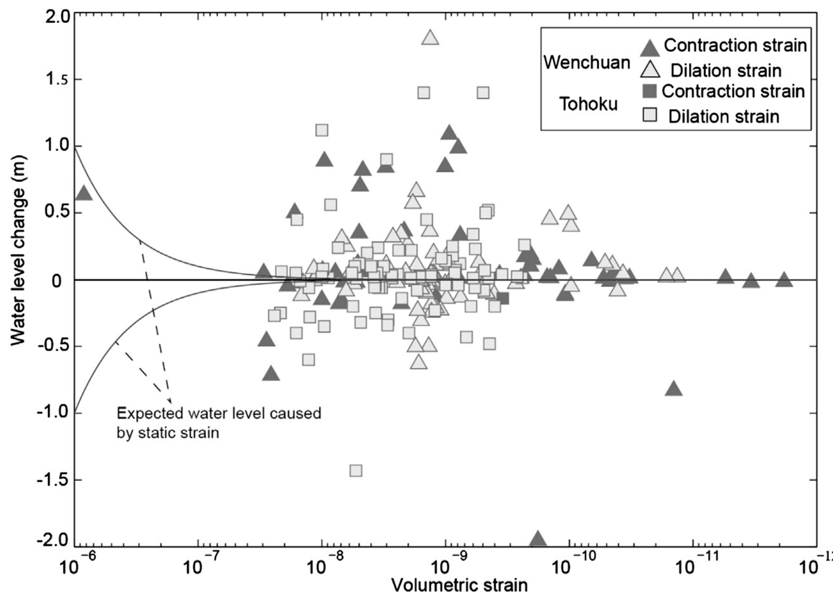

Fig. 4. Relationship between water-level response and the absolute value of the calculated volumetric strain (the volumetric strains are calculated from the Okada fault dislocation model and a finite fault solution for displacement on the fault). Dark colors indicate contraction strain and light colors indicate dilation strain, the two curves indicate the expected water level caused by static strain under the assumption of a typical aquifer. The volumetric strain ε_{kk} can be related to pore-pressure change p in a well by $p = (2GB/3)[(1+\nu_u)/(1-2\nu_u)]\varepsilon_{kk}$, where G is the shear modulus of the material, B is Skempton's coefficient, and ν_u is the 'undrained' Poisson ratio. Typical values of the coefficient $((2GB/3)[(1+\nu_u)/(1-2\nu_u)])$ on the right side are 5 to 50 GPa (assuming G ranging from 5 GPa to 30 GPa, B from 0.5 to 0.8, $\nu_u = 0.3$; Detournay and Cheng, 1993). If the coefficient equals 10 GPa, volumetric strain of 10^{-6} can produce a water-level change of 1 m, whereas a strain of 10^{-8} would produce a 1 cm change (Montgomery and Manga, 2003; Roeloffs, 1996).

The finite fault model used in the calculation is from Chen Ji (http://earthquake.usgs.gov/earthquakes/eqinthenews/). The relationship between static strain and water level response is shown in Fig. 4. Many co-seismic water level responses show the opposite sign to that predicted by the co-seismic static strain change: groundwater level can decline for contraction static strain but rise for dilation strain. Moreover, the predicted groundwater level response for strains $<10^{-8}$ should not produce changes larger than 1 cm (Montgomery and Manga, 2003). We observe much larger water level changes than this estimate in our dataset. Thus, the co-seismic static strain may not explain most of the co-seismic water level changes beyond the near-field. This result is consistent with recent studies of the groundwater response to the Wenchuan and Tohoku earthquakes (Shi et al., 2013b, 2015; Yan et al., 2014).

4.2.2. Mechanism of dynamic strain induced permeability changes

Several studies proposed that dynamic strains may enhance permeability through the interactions between seismic waves and aquifers (e.g., Brodsky et al., 2003; Elkhoury et al., 2006; Rojstaczer et al., 1995), which can lead to either positive or negative changes in the water level because enhanced permeability can occur either up-gradient or down-gradient of the well. If the enhanced permeability is located up-gradient of the well, then the water level in the well will exhibit a co-seismic rise. If the enhanced permeability occurs down-gradient of the well, then a co-seismic fall in water level would be expected (Shi et al., 2015). If many observations are available, the model of enhanced permeability would predict a statistically random occurrence in the sign of the water level change as a function of distance from the epicenter (Wang and Chia, 2008). This is the case for the four great earthquakes considered here (Fig. 4).

In order to establish a direct and more quantitative connection between earthquake response and permeability changes, we use changes in the tidal response of the wells as a proxy for the permeability evolution after earthquakes. The phase shift between Earth tides and the water level response can be used to estimate the transmissivity of the local aquifer (Hsieh et al., 1987) and several studies have used this approach to document permeability changes caused by earthquakes (Elkhoury et al., 2006; Lai et al., 2014; Shi and Wang, 2014, 2015; Shi et al., 2013c; Xue et al., 2013). For the wells that show co-seismic oscillation responses, the commonly accepted mechanism is resonant coupling of flow between the well and the aquifer caused by seismic waves (Kano and Yanagidani, 2006; Liu et al., 1989). Thus, here we only focus on those wells that can record clear tidal signals and show co-seismic step-like or gradual changes following the Wenchuan and Tohoku earthquakes (a clear tidal signal is identified as one for which both the M_2 phase shift and tidal amplitude are at least two times larger than their RMSE). In total, 93 and 75 wells are chosen for analysis for the Wenchuan and Tohoku earthquakes (Fig. 5). We obtained water level data for six months before and after those two earthquakes for each of these wells. The phase shifts between water level changes and the M_2 Earth tide were calculated using the program Baytap-G, that incorporates a Bayesian inversion process (Burbey and Zhang, 2010; Tamura et al., 1991). During the analysis, theoretical tidal strains are used as the reference because strain measurements at the wells are not available. We performed tidal analysis using a 10 day periods with a sliding window of 5 days to extract the phase shifts in each well (Fig. 6 shows, as an example, the temporal evolution of water level changes and tidal response in the LF well). We use the difference between the average phase shift one month before and after each earthquake as being representative of the changes. Also, tidal amplitude changes can be obtained in this way. Tables S1 and S2 summarize results.

Fig. 7 shows the relationship between co-seismic water level changes and the phase shift changes. There is no strong relationship between co-seismic water level changes and phase shift changes. The depth of the wells also has no obvious effect on the magnitudes of these responses and their relationship. We also plot in Fig. 8 the length of screened section versus the phase shift change. The available data (Liao et al., 2011; Lai et al., 2014; Gong, 2009; Tang et al., 2013) show no relationship between the phase shift change and the length of the screened section.

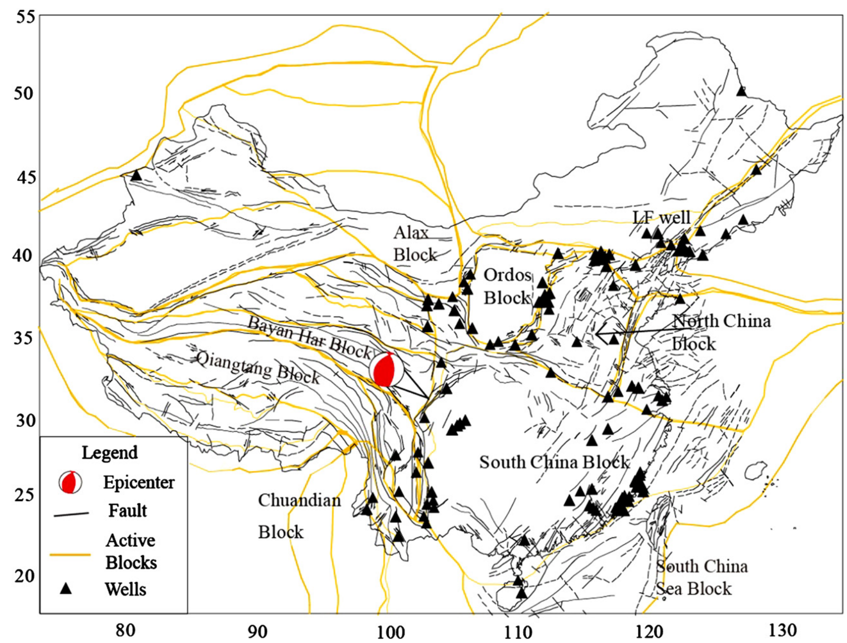

Fig. 5. Distribution of the groundwater monitoring wells that used for tidal analysis in this study.

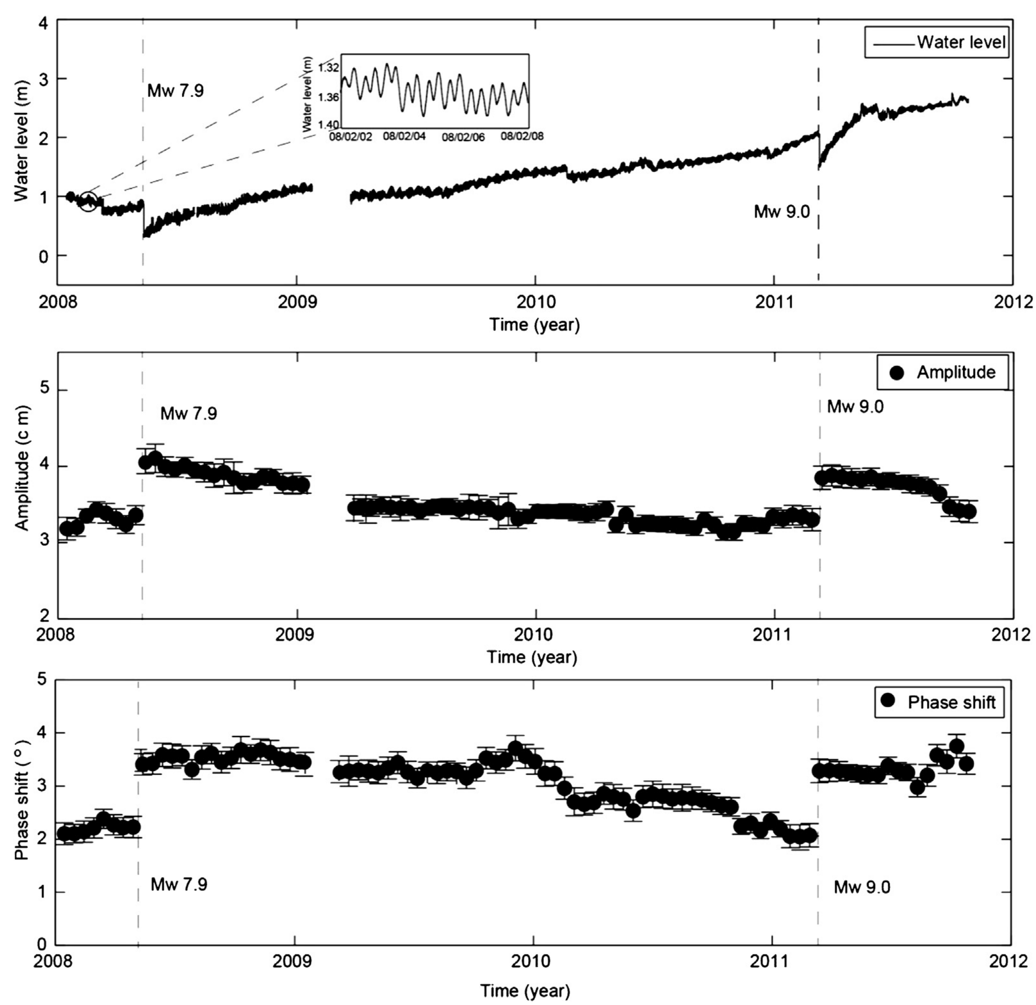

Fig. 6. Temporal evolution of water level and tidal response in the LF well.

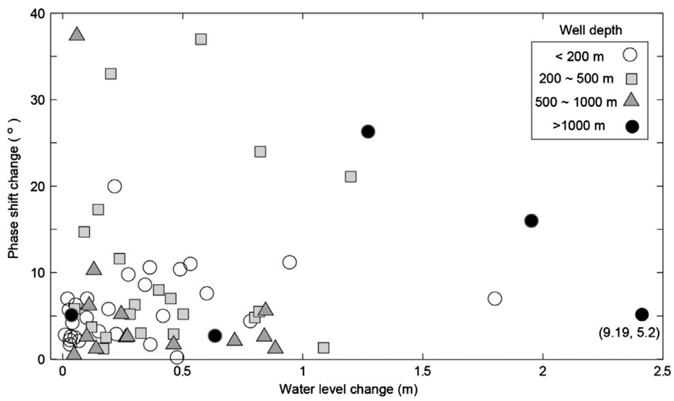

Fig. 7. Plot of the co-seismic water level change versus the phase shift change.

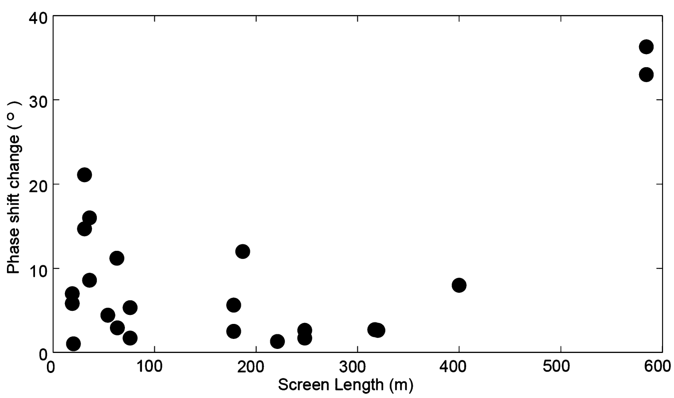

Fig. 8. Plot of the phase shift changes versus the screen length.

Previous field studies show that the time required for permeability recovery observed in the field usually ranges from weeks to years (Davis et al., 2001; Kinoshita et al., 2015; Manga et al., 2012; Manga and Rowland, 2009; Shi et al., 2013c; Xue et al., 2013), but in some cases perhaps as short as minutes (Geballe et al., 2011). Laboratory experiments, in contrast, document that permeability recovery can finish in tens of minutes (Candela et al., 2014, 2015; Elkhoury et al., 2011) but with a sensitivity to flow rate (Candela et al., 2015). The faster recover in the lab may thus be a consequence of the faster flow rates in the lab. Hence, in our case, the tidal analysis period of 10 days with sliding window of 5 days should be able to capture most of the permeability changes that may occur during the earthquake. From Tables S1 and S2, we find that permeability changes inferred from the phase shift of M_2 earth tide (Elkhoury et al., 2006; Roeloffs et al., 2003; Xue et al., 2013) occurred only at 37 wells following the Wenchuan earthquake and 33 wells following the Tohoku earthquake. Among them, 8 wells in the Wenchuan earthquake and 9 wells in the Tohoku earthquake show a co-seismic phase decrease. In previous studies, post-earthquake increases of phase shift were the most commonly observed phenomena, which implies permeability enhancement after the earthquakes (Elkhoury et al., 2006; Lai et al., 2014; Shi and Wang, 2015; Shi et al., 2013c). However, it should be noted that the Hsieh et al. (1987) aquifer inversion model was developed for an isotropic, homogeneous aquifer and can only be applied for the case with a negative phase shift, i.e., the phase of the water level tide lags behind the tidal strains. In our dataset, 47% of the wells show positive phase shifts (Tables S1, S2). Positive phase shift may be caused by leakage to the water table (Roeloffs, 1996). In this model, a phase shift increase, such as from 5° to 10°, indicates an increase in the vertical hydraulic diffusivity of the aquifer, caused by an increase in the vertical permeability (Roeloffs, 1996; Rojstaczer and Riley, 1990). Taken together, we consider increase of the co-seismic phase shift (either positive or negative) as permeability enhancement and co-seismic phase shift (either positive or negative) decrease as evidence of permeability decrease (Yan et al., 2014). We found that phase changes occur not only in the near field but also in far field (Tables S1 and S2 in the supplementary material). The lower limit of seismic energy to initiate permeability change for our data is about 0.01 J/m^3 (Fig. 3), far above the threshold of permeability change inferred from an earlier analysis of global data (Wang and Manga, 2010). Presumably the tectonic setting and local geology near the well are also important factors for permeability change. Thus, some sensitive wells located in far field can still show permeability changes while some wells may be less sensitive even if they are closer to the epicenter. We also document changes in the amplitude of tidal responses for wells with a phase shift (Fig. 6), but changes are proportionally smaller (Tables S1, S2). Tidal amplitude depends on the mechanical properties of aquifer such as undrained compressibility, Poisson's ratio and fluid compressibility (Matsumoto and Roeloffs, 2003). It reflects the ability of well-aquifer system to respond to earth tides. Thus, the changes in tidal amplitude indicate that the aquifer properties may have changed, but proportionally less than the permeability changed.

Interestingly, 56 wells in the Wenchuan earthquake and 42 wells in the Tohoku earthquake that exhibit co-seismic water level responses did not show phase shifts or tidal amplitude changes during the earthquakes. Thus, the mechanism of permeability change cannot explain these co-seismic water level changes. A new mechanism is needed in order to explain these co-seismic responses.

One possible mechanism is that the permeability changed in the wellbore skin zone, which is a zone produced during well installation. Auger rotation and retrieval can smear silt- and clay-sized sediment on the borehole wall. The smearing produces a wellbore skin that has lower permeability than the undisturbed formation (Paul, 1987); on the other hand, extensive well development can remove fine silt and clay particles from the surrounding formation, and increase permeability in the wellbore skin. The former would slow water-level recovery in the well and the latter would accelerate water level recovery (Yang and Gates, 1997). Seismic waves can dislodge particles in the skin zone hence changing the local permeability leading to water level changes in the wellbore. After the water level changes (either a rise or drop), water level in the well will return to pre-seismic levels. This process is similar to a slug test, with a recovery time from hours to days. At early times, the groundwater flowing in (or out) the wellbore may be released from storage in the skin zone (Bouwer, 1989). The wellbore skin zone is small in spatial dimensions (usually less than 0.1 m) relative to the lateral extent of the water-level drawdown around the well under tidal loading (hundreds of meters; Elkhoury et al., 2006). Thus the changes in the wellbore skin zone will not have a significant effect on the tidal response of the aquifer as a whole. In our data, for all wells that recovered within several days, we do not see a phase change in the tidal response. For those wells that have longer water level recovery time (more than one month), tidal analysis results also show that their permeability in the aquifer changed, consistent with our model to explain transient and persistent water level changes. Moreover, if the co-seismic well water level changes are caused by the fluid pressure changes immediately adjacent to the wellbore (e.g., in the skin zone), the well level in the well and aquifer pressure will equilibrate at least as quickly as the step response to surface loading, and this response will be completed in about 37 h (using $T = 2.4 \times 10^{-5}$ m^2/s, $S = 5.0 \times 10^{-4}$, and a thickness of skin zone of 5 cm; Matsumoto and Roeloffs, 2003). This estimate is also consistent with our observation.

Thus, we propose that the water level responds to seismic waves through two mechanisms: (1) earthquake induced permeability changes in the local aquifer, as suggested before, and (2) earthquake induced permeability changes immediately adjacent to the wellbore. We also deduce that sustained post-seismic water level responses are most likely caused by permeability changes in the local aquifer, while those that only show transient co-seismic responses are caused by permeability changes near the wellbore. If correct, we estimate that about one third of the co-seismic responses (22.2% wells in 2007 Mw 8.5 earthquake, 29.3% wells in the 2008 Mw 7.9 earthquake, 41.7% wells in the 2011 Mw 9.0 earthquake, and 35.1% wells in the 2012 Mw 8.6) were caused by aquifer permeability changes, while the others may be caused by the permeability changes near the wellbore.

5. Conclusions

In this paper, we report the groundwater level changes induced by four great earthquakes and recorded by Chinese groundwater monitoring wells. The large number of wells and recorded responses allow us to identify five types of co-seismic groundwater level responses and two types of post-seismic responses. The co-seismic water level responses are complex, and there is great variability both in the sign and amplitude of water level responses. Permeability change is a viable mechanism to explain the various water level changes. However, only one third of the co-seismic responses to the four earthquakes can be explained by the changes of the aquifer permeability while the others may be caused by the permeability changes near the wellbore.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2015.08.012.

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