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Studies of mechanism for water level changes induced by teleseismic waves

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Abstract:	The 8.0 Wenchuan earthquake of May 12, 2008 induces large-amplitude water level changes at intermediate and far fields (epicentral distance >1.5 fault rupture length) in Chinese mainland. Although many hydrologic changes induced by teleseismic waves have been reported, the mechanisms responsible for the changes still remain unclear. We invoke Skempton's coefficient B in this paper to explain those co-seismic water level changes documented in the intermediate and far fields. Most of the abrupt co-seismic water level increases are found to favor the consolidation caused by the redistribution of particles in apertures induced by the shaking of teleseismic waves. While a little part of the increases, especially those more gradual co-seismic increases can be explained with the enhanced permeability caused by fracture clearing or overcoming the capillary entrapment in porous channels of the aquifer induced by the shaking of teleseismic waves. The dilatation caused by the earthquake shaking can not account for some of the co-seismic water level decreases, which, however, may be explained by the earthquake-enhanced fracture and permeability.
Author Comments:	1)Although coseismic water level changes induced by teleseismic waves have been widely studied, the mechanisms responsible for the changes are usually obscure. We invoke the Skempton's coefficient B in this paper to explore those mechanisms. 2)It is a brand new way to invoke the Skempton's coeffici-ent B in this paper to explore the mechanisms of those coseismic water level changes, and it is a complement of the laboratory experiments analysis of Liu and Manga [2009] (published in GRL) 3)Since both the laboratory study [Liu and Manga, 2009] Huang (2008),and our field analysis come to the similar conclusion, we argue our mechanism analysis are reasonable, and can be helpful to clarify the mechanisms of water level changes induced by teleseismic waves.
Suggested Reviewers:	Chi-yuen Wang chiyuen@berkeley.edu He is an expert in the region we studied in this paper, and several of his papers have been the references of this manuscript.
	Samik Sil samik_sil@yahoo.com He is an expert in the region we studied in this paper
Opposed Reviewers:	Yaowei Liu he has a conflict with one of these authors
	Yongtai Che

	he has a conflict with one of these authors

Ref.: Ms. No. BSSA-D-12-00070
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Dear Yan Zhang,

Your paper has been reviewed for publication in the Bulletin. I enclose two reviews by anonymous referees. I also enclose comments by the associate editor. There is a consensus that your paper has significant technical problems. The editorial board has evaluated the reviews and decided that the current version of the paper must be rejected for publication. We have removed it from the review process.

We are willing to consider a revised version in which you have addressed the issues raised by the referees and the associate editor. Any revision will be considered as a new submission but must be accompanied by a letter detailing the changes made in response to these reviews. The reason for taking this approach, rather than requesting revisions, is that we believe the required changes will result in essentially a new work and that the conclusions may change significantly.

Thank you for your interest in the Bulletin.

Sincerely

Diane I. Doser, PhD
Editor-in-Chief

Reviewers' and Editorial comments:

AE's comments: This manuscript attempts to explain the changes of water-well levels during the 2008 Wenchuan earthquake. Unfortunately, both reviewers found that the conclusions were not supported by current analysis. In addition, the manuscript needs significant improvement in English writing. As pointed out by the firs reviewer, it is inappropriate to include another published paper as the supplement. Please cite the paper instead. Finally, Figures 1 and 3 are directly from other papers, so the authors could suggest the readers to read those papers instead, or if they will be used, make sure to obtain the copyright from the publisher. Figure 2 is too long so the authors need to come up with a good way (perhaps with more than two columns) to present it. Please include a map to show the Wenchuan epicenter and those stations analyzed in this study. Due to those difficulties, we would recommend a rejection-resubmit. If the authors decide to resubmit, please make sure to come up with a one-to-one response to all the comments raised.

Answer:

1）I have deleted the supplement, and just cite that paper instead. All of those assumptions and calculations have been add into the part 2 “**An approach to Skempton’s coefficient B based on the poroelastic theory**” （highlighted in the yellow color）

2）Figure 1 and 3 have already been deleted and just suggest the readers to read those papers instead. Figure 2 has already been changed into 3 columns.

3）The map to show the Wenchuan epicenter and those stations analyzed in this study has been added in Figure 1.

4）Figure 3 and Figure 4-(a) are directly from other papers and books, and we have obtained the copyrights from the publishers, indicating that we just need to cite those published papers.

5）We have changed a lot in the paper, all those changes are highlighted in yellow color.

Reviewer #1: The authors seek a mechanical explanation for changes in water-well level coincident with the 2008 Wenchuan Earthquake. These changes occurred in the intermediate and far field, defined as > 1.5 fault rupture lengths from the epicenter. In addition to the changes in well level, changes are seen in the tidal sensitivity of the water level. Changes in level, tidal sensitivity, and phase lag due to the passage of seismic wave are extensively documented in the literature, and for the paper to constitute a novel contribution, some progress must be made in understanding the mechanism(s) by which such changes occur.

The approach taken is to examine the tidal sensitivity of the well water level, apparently considering only amplitude (and not phase) before and after the earthquake. Tidal sensitivity can be used to infer a value of Skempton's coefficient, which relates changes in pore pressure to changes in mean stress under undrained conditions, within the framework of linear poroelasticity. The value of Skempton's coefficient before and after the earthquake is calculated by assuming that the reservoir in each location is essentially undrained on tidal timescales and fitting a model of the tidally-induced volumetric strain to the well level time-series.

The apparent coseismic change in Skempton's coefficient is then argued to be attributable principally to changes in porosity. However, the authors do not attempt to make a quantitative link between the observed changes in B and the changes in porosity or other properties necessary to produce these changes. I think that this needs to be done in order for the key argument of the paper to be convincing. In addition, it must be shown that the necessary changes in porosity can be accommodated repeatedly over many earthquake cycles (i.e. that the porosity present at depth could persist despite being reduced repeatedly due to consolidation induced by the passage of seismic waves). Lastly, there is quite a bit of experimental work on changes in Skempton's coefficient due to changes in effective pressure, see for example Blocher et al. 2009 (Pure and Applied Geophysics) and references cited therein. I cannot find information in the paper about the screened depth of the wells used in the study so I cannot determine the magnitude of changes in effective pressure that accompany the passage of seismic waves.

Answer:

1) As suggested by the reviewer, it is really a good suggestion to read the paper Blocher et al. 2009 (Pure and Applied Geophysics) and references cited therein. From that we learn the change in Skempton's coefficient *B* is mainly due to the change of the effective pressure. We add the "4.2 Undrained Skempton's coefficient *B* as a function of effective pressure" in the paper, and detailedly discussed the relation between the Skempton's coefficient *B* and the effective pressure based on the research of Blocher et al. 2009.

2) We have added the depth of the wells used in the study in Table 1, from which we can determine the magnitude of changes in effective pressure that accompany the passage of seismic waves. Wang and Luo (2004) predicted the formation pore fluid pressure of wells in Ying-qiong basin (the main matrix rock is sandstone) based on the "equilibrium depth" method (Figure 3-(b)). The "pressure - depth" relationship of well YC21-1-1 is similar to other wells, so we assume those results could be applied to these wells we studied since there is a lack of the "pressure-depth" prediction of these wells. Based on the "pressure-depth" relationship of well YC21-1-1, we estimate the range of the effective pressure (effective pressure approximately equals to the lithostatic pressure minus the pore fluid pressure) of these wells (Table 1). See "4.2 Undrained Skempton's coefficient *B* as a function of effective pressure"

3) In the laboratory experiment, in order to reduce the irreversible deformation and to minimize the nonlinear effects, repeated pressure cycles are always applied on rock samples as preconditions (Hart and Wang, 1995; Blocher et al., 2009). The in-situ aquifer of those wells (well a～p) are under lithostatic pressures for a long time and affected by the transmission of seismic waves for countless times, the situation is much similar to those well bedrocks be applied on repeated pressure cycles, so the irreversible deformation and the nonlinear effects have been minimized. As described by Wang (1993), nonlinear compaction effects can be significant and they are not incorporated in the linear theory presented here. So changes in porosity can be accommodated repeatedly over many earthquake cycles may be possible. See "5. Discussion and Conclusion"

There are several scientific additional aspects of the paper that should be addressed:

1) The authors assume throughout the work that undrained conditions exist over the tidal time scale. This might be reasonable but should be justified rigorously given that all of the results hinge on this assumption.

Answer: The discussion of the undrained conditions exist over the tidal time scale has been add into the part 2 "**An approach to Skempton's coefficient B based on the poroelastic theory**"

2) It should be stated clearly in this paper how the tidal strains are calculated. What assumptions are made, what equations are solved, etc...

Answer: All of those assumptions and calculations have been added into the part 2 "**An approach to Skempton's coefficient B based on the poroelastic theory**" （highlighted in the yellow color）

3) Elkhoury et al. 2006 studied coseismic changes in the phase response in water wells. Was this effect seen in the wells studied? Why is phase not discussed in this paper?

Answer: Those phase lags have been added into **Table 1**, and this is really an important issue. We have added **"4.5 Wellbore storage effects"** into the paper, and discuss the phase lags, water level changes and *B* changes together to testify and analyze the mechanisms.

4) Are the changes in tidal sensitivity correlated with dissipated seismic energy or peak ground velocity?

Answer: No, the changes in tidal sensitivity are not correlated with the dissipated seismic energy or peak ground velocity, because the frequency of the M2 wave (we used to analyze the effect of the tidal strain to the water level) is much lower ($2.23636\times10^{-5}HZ$) than the seismic waves (about 1HZ--10 HZ), they have little interaction with each other.

5) Can wellbore storage effects (Roeloffs 1996) be ignored? This question is related to #3 regarding the phase of the tidal response.

Answer: We have added **"4.5 Wellbore storage effects"** into the paper. Please refer to question 3.

6) I think that the work of Beresnev 2011 (GRL) should be discussed in the section (second paragraph of page 2) about mechanisms.

Answer: This is a good suggestion and the work of Beresnev 2011 (GRL) has already been added into that section (highlighted in yellow color). We have also discussed and cited the mechanism of Beresnev 2011 (GRL) other where in the paper.

There are a few non-scientific issues that must be resolved before this paper can be suitable for publication.

1) The paper needs to be carefully edited for grammatical correctness.

Answer: We have corrected the paper carefully.

2) I feel that it is inappropriate and possibly a copyright violation to include an entire previously published paper as the supplement. It should be removed and simply cited as needed in the text, or the relevant methodology should be included in a clear and concise manner in a methods section.

Answer: I have deleted the supplement, and just cite that paper instead. All of those assumptions and calculations have been add into the part 2 "**An approach to Skempton's coefficient B based on the poroelastic theory**" （highlighted in the yellow color）

3) Figure 3a is copied directly, with no modification as far as I can tell from Liu and Manga 2009. Figure 3c is a minimally modified version of this figure. As this is not the authors' intellectual property, permission must be sought and granted for the re-use of the figure.

Answer: Figure 3 has already been discarded from the paper.

4) Equation 3 must be properly typeset.

Answer: Equation 3 has already been discarded from the paper.

5) Table 1 must be properly typeset so that no text is truncated.

Answer: Table 1 has already been modified and we have added some important information into it, such as: the well depths, the range of the effective pressures and the phase lags.

Reviewer #2: 1. The manuscript intends to explain the mechanism of co-seismic well water level changes in the intermediate and far field based on the change of Skempton's coefficient B before and after the Wenchuan earthquake. The authors adopted prevailing hypotheses of coseismic mechanism to explain the change of coefficient B and water level due to the earthquake. The interpretation, however, is oversimplified or inconsistent with the previous study results. The conclusions are not supported by the data presented in the manuscript.

Answer: We have changed a lot in the paper, see the content of those highlighted colors, it is true that we discussed the problem oversimplified in the first edition, and now according to the suggestions of the reviewers, we refer to several mportant papers and find the Skempton's coefficient *B* is the function of the effective pressure, and those changes just result in a new work and the conclusions also have changed. We think the mechanism analysis will be much more reasonable this time.

2. The authors used the increase of the Skempton's coefficient B as the criteria to conclude that consolidation of aquifers due to seismic shaking may account for most coseismic water level increases. As seismic shaking is a widespread phenomenon during the earthquake, it should be a more important mechanism for the coseismic increase in the near-field. Nevertheless, Zhang and Huang (2011) adopted poroelastic theory to

explain the near-field coseismic changes. In fact, the increase of the Skempton's coefficient B may result from either the static strain or the seismic shaking. Generally the increase of pore pressure due to seismic shaking is a rapid dynamic process often observed in the near-surface soil formation. The manuscript does not have any high-frequency data or direct evidence to show that consolidation due to seismic shaking is the dominant mechanism.

Answer:

1) Most of those water level increases in this area (>1.5 fault-rupture lengths, and most of the epicentral distances of those wells are even larger than 700 km), can not be induced by the change of the static strain, which are extremely tiny (Zhang and Huang, 2011).

2) This is a good suggestion, and question. We have added two examples to testify our mechanism analysis (Most of the abrupt co-seismic water level increases are found to favor the consolidation caused by the redistribution of particles in apertures induced by the shaking of teleseismic waves.) See "4.3.2 Examples support far field water level increases induced by consolidation"

Huang (2008) find that: the water level increase in Fuxin well (1409.98 km away from Wenchuan, the well depth is 60.74 m，stiff Granite with a little Whinstone is the bedrock and we assume the shear modulus = 60 Gpa) is induced by the increase of the volume strain (consolidation) (Figure 4-(a)). We also calculated the pre- and post-earthquake Skempton's coefficient B in FUXIN well. From the analysis we conclude: the water level increase induced by the consolidation incurred by transmission of teleseismic waves is reasonable, and a consolidation with large enough energy may also incur an enhanced permeability by fracture clearing or overcoming the capillary entrapment in porous channels. See "4.3.2 Examples support far field water level increases induced by consolidation"

3. The authors adopted the hypothesis of fracture clearing and increased permeability induced by shaking (Brodsky et al., 2003; Wang and Chia, 2008) to explain the coseismic increases accompanied with a decrease of B value. The hypothesis was originally proposed for interpreting coseismic water level changes only. Even the effect of seismic shaking is neglected, additional test results are needed to prove that the B value may reduce 25%~70% when pore pressure head increases 1 m.

Answer:

1) These water level changes studied in this paper are also co-seismic water level changes.

2) The coseismic increases accompanied with a decrease of *B* value only in well h-(HUANGHUA well) , we have calculated according to your suggestion, and it can fit for your estimation: The water level change in HUANGHUA well is 0.594 m, and the Skempton's coeffieient B reduces 25.303% according to our calculation, so we

can estimate when the pore pressure head increases 1 m, the B value may reduce 50%.

We not very understand what this suggestion indicates—"to prove that the B value may reduce 25%~70% when pore pressure head increases 1 m, in the well with coseismic increases accompanied with a decrease of B value".

4. There are 3 figures in the manuscript. Figs. 1 and 3 are unnecessary. The reader can refer to the figures in the original paper. The authors should at least provide a map to show the locations of the well stations in Fig. 2. Besides, Table 1 is not clear to readers.

Answer:

1) Figures. 1 and 3 have already been discarded from the paper.

2) We have added the map to show the locations of the well stations in Figure 1.

3) Table 1 has already been modified and we have added some important information into it, such as: the well depths, the range of the effective pressures and the phase lags.

5. The manuscript should provide the stratigraphic column and the type of the aquifer for the well stations. From the variation of water level in the well j, for instance, the aquifer is possibly semi-confined. Thus, the validity of the calculated B value at the well j before and after the earthquake becomes questionable

Answer:

This is a good question:

1) Most of those wells can record clear tidal strains and atmospheric pressure, and according to the <earthquake monitoring records of stations> they are well confined. There are not so much spaces for us to put all those stratigraphic columns of those wells in the paper, (and unfortunately we can not find the stratigraphic columns of well j in the <earthquake monitoring records of stations>), we have show the bedrocks of those wells in Table 1.

2) Phase lags of those wells have been calculated and added into Table 1, From Table 1 we can see the phase differences of the water level and the tidal strain of most wells are 0, which mean good correlations between the water level and the tidal strain, and those wells may be well confined. In several wells the phase lags are not 0 (well b, c, e, f, n and p), and most of them are small, except well b and well p, and the two wells may be semi-confined. Thus, the validity of the calculated *B* values in the two wells may be a little questionable. We just discussed this problem in "4.5 Wellbore storage effects".

Studies of mechanism for water level changes induced by teleseismic waves

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Abstract

The M_s 8.0 Wenchuan earthquake of May 12, 2008 induces large-amplitude water level changes at intermediate and far fields (epicentral distance >1.5 fault rupture length) in Chinese mainland. Although many hydrologic changes induced by teleseismic waves have been reported, the mechanisms responsible for the changes still remain unclear. We invoke Skempton's coefficient *B* in this paper to explain those co-seismic water level changes documented in the intermediate and far fields. Most of the abrupt co-seismic water level increases are found to favor the consolidation caused by the redistribution of particles in apertures induced by the shaking of teleseismic waves. While a little part of the increases, especially those more gradual co-seismic increases can be explained with the enhanced permeability caused by fracture clearing or overcoming the capillary entrapment in porous channels of the aquifer induced by the shaking of teleseismic waves. The dilatation caused by the earthquake shaking can not account for some of the co-seismic water level decreases,

which, however, may be explained by the earthquake-enhanced fracture and permeability.

1. Introduction

Various hydrologic responses to earthquakes have been documented, many occurred at great distances from the ruptured fault where static stress changes are extremely small (Liu and Manga, 2009; Wang and Manga, 2010). Hydrologic changes induced by teleseismic waves have been investigated in several studies of water wells (Roeloffs, 1998; Brodsky *et al*., 2003; Elkhoury *et al*., 2006; Geballe *et al*., 2011). These studies indicate that significant water level changes can be driven at great distances by moderate-amplitude dynamic (time-varying) stresses (Liu and Manga, 2009).

Several mechanisms have been proposed to explain these co-seismic changes in water level. Fracture clearing and increased permeability caused by the earthquake-induced dynamic stress have been widely used to explain most documented water level changes (Brodsky *et al*., 2003; Elkhoury *et al*., 2006; Wang and Chia, 2008; Wang and Manga, 2010). Overcoming the capillary entrapment in porous channels is hypothesized to be one of the principal pore-scale mechanisms by which natural permeability is enhanced by the passage of elastic waves (Beresnev, 2011). Other proposed, but also unverified mechanisms include pore pressure increases caused by a mechanism 'akin to liquefaction' (Roeloffs, 1998), shaking-induced dilatancy (Bower and Heaton, 1978), or increasing pore pressure through seismically induced growth of bubbles (Linde *et al*., 1994). In addition, Huang (2008) observed the co-seismic water level increase may be caused by the consolidation induced by the transmission of teleseismic waves. Experimental measurements of Liu and Manga (2009) indicate that permeability changes (either increases or decreases) owing to dynamic stresses are a reasonable explanation. In general, they find permeability decrease after shaking.

In the present study, we use the Skempton's coefficient *B* both pre and after earthquake to explain the co-seismic water level changes in the intermediate and far fields based on datasets from the Wenchuan earthquake in the Chinese mainland. Using a poroelastic relation between water level and solid tide (Zhang *et al*., 2009), we calculate the in-situ Skempton's coefficient *B* both pre and after earthquake. From the research we find: Most of the abrupt co-seismic water level increases can be explained with the consolidation caused by the redistribution of particles in apertures, which is induced by the shaking of teleseismic waves. Some of the co-seismic water level increases, especially those increases with gradual manner can be explained with the enhanced permeability caused by overcoming the capillary entrapment in porous channels induced by the shaking of teleseismic waves. While, some of the co-seismic water level decreases can not be attributed to the shaking-induced dilatation, however, may be explained with the increased permeability caused by teleseismic waves, which in turn lead to the redistribution of pore pressure.

2. An approach to Skempton's coefficient *B* based on the poroelastic theory

Skempton's coefficient *B* is a significant pore-fluid parameter in poroelastic theory. A poroelastic material consists of an elastic matrix containing interconnected fluid saturated pores. Fluid saturated crust behaves as a poroelastic material to a good degree of approximation.

Rice and Cleary (1976) summarized the following equations for a linearly elastic isotropic porous medium (they are the building blocks of the poroelastic theory):

$$2G\varepsilon_{ij} = \sigma_{ij} - \frac{\nu}{1+\nu}\sigma_{kk}\delta_{ij} + \frac{3(\nu_u - \nu)}{B(1+\nu)(1+\nu_u)} p\delta_{ij}, \quad (1)$$

$$m - m_0 = \frac{3\rho(\nu_u - \nu)(\sigma_{kk} + 3p/B)}{2GB(1+\nu)(1+\nu_u)}. \quad (2)$$

Here $m - m_0$ is the change of the fluid mass, ε_{ij} is the strain tensor, σ_{ij} is the stress tensor, δ_{ij} is the Kronecker delta function, G is the shear modulus, ρ is the density of the fluid, B is the Skempton's coefficient, p is the pore pressure, ν is the Poisson's ratio, and ν_u is the "undrained" Poisson's ratio. Rice and Cleary (1976) describe equation (1) as a stress balance equation and equation (2) as a mass balance equation.

For the undrained condition, the poroelastic effect on the crust can be obtained by putting $m - m_0 = 0$ in equation (2) to obtain

$$P = -B\sigma_{kk}/3 \text{ or } \Delta p = -B\Delta\sigma_{kk}/3. \quad (3)$$

Equation (3) indicates that, in the undrained condition, the change in fluid pressure (Δp) is proportional to the change in mean stress ($\Delta\sigma_{kk}/3$). This is the mechanism of water level changes for poroelastic material. ($p = \rho gh$, where h is the water column height, g is the acceleration due to gravity and ρ is the density of water).

According to equation (3), Skempton's coefficient B can be qualitatively defined: In the undrained condition, B is the ratio of the induced pore pressure divided by the change in mean stress (Wang, 2000). B governs the magnitude of water-level changes due to an applied stress because pore pressure is directly proportional to water level. The value of B is always between 0 and 1. When B is 1, the applied stress is completely transferred into changing pore pressure. When B equals 0, there is no change in pore pressure after applying the stress. Thus a low value of *B* indicates the stiff rock matrix that supports the load with low coupling to the fluid (Nur and Byerlee, 1971). Laboratory studies indicate the value of *B* depends upon the fluid-saturated pore volume of the sample (Wang, 2000).

Equation (3) can be expressed in terms of tidal strain as well (Roeloffs, 1996):

$$\Delta h = -\frac{2GB(1+\nu_u)}{3\rho g(1-2\nu_u)}\Delta\varepsilon_t \,. \qquad (4)$$

Equation (4) shows that water level changes proportionally in a poroelastic material under the influence of tidal strain (ε_t). Here, Δh is the change in height of water level, and $\Delta\varepsilon_t$ is the corresponding tidal strain change (Sil, 2006).

From equation (4) we obtain:

$$B = -\frac{3\rho g(1-2\nu_u)}{2G(1+\nu_u)}\frac{\Delta h}{\Delta\varepsilon_t} \,. \qquad (5)$$

With equation (5), we obtain the value of *B* with water level and tidal strain. However, the calculation must be on the strict premise of the undrained condition (the good correlation between the water level and the tidal strain) and should not be influenced by the other factors.

For the effect of the solid tide on the crust, when the wavelength of the tidal strain is much larger than the size of the aquifer, we can suppose the aquifer system is undrained (Huang, 2008). The wavelength of the M_2 wave is about 2,406,329 km ($\lambda = \omega r T$, where $\omega = 1.4\times10^{-4}/s$ is the angular frequency of M_2 wave, r=384,400 km is the distance from the Earth to the Moon, T=745.236 min is the period of the M_2 wave); this wavelength is much larger than the size of the radius of the Earth and is definitely much larger than the thickness of the aquifer systems of those wells. Thus, the effect of the M_2 wave in the crust can meet the undrained condition (Zhang *et al*., 2009). In addition, those wells can record clear tidal strains and thus, because we calculate the phase lags between the water levels and the tidal strains are small, the wells can readily meet the undrained condition. In the M_2 wave frequency domain, the water level and the tidal strain show a good correlation; Furthermore, the M_2 wave is hardly influenced by atmospheric pressure. We therefore distill the frequency domain of the M_2 wave from the water level and the tidal strain by using band-pass filter (the frequency of the M_2 wave is $2.23636\times10^{-5} HZ$) to calculate the Skempton's coefficient *B* (Figure 2). By converting the frequency domain of the M_2 waves (obtained from the water level and the tidal strain) by inverse fast Fourier transform and adjusting their phases (using the least-square fit and putting the results into equation (5)), we can finally derive *B*. (More details of the method are explained in Zhang *et al*., 2009). All the Water-level observations come from the sensor of water level, while tidal strain data are calculated via Mapseis software (see Data and Resources section).

3. Assumptions of shear modulus and Poisson's ratio

Calculations are performed using $\rho = 1000 kg/m^3$, $g = 9.8 m/s^2$, and $\nu_u = 0.29$ according to equation (2). We suppose the undrained Poisson's ratio $\nu_u = 0.29$ both pre and after earthquake, and this kind of assumption is always used to simplify calculation issues of rocks near the crust (Zeng, 1984).

Gassmann (1951) predicted that the effective shear modulus would be independent of the saturating fluid properties (the shear modulus is a constant) in the undrained isotropic poroelastic media. As studied by Berryman (1999) and Berryman and Wang (2001), the theory applies at very low frequencies. At high enough frequencies (especially in the ultrasonic frequencies), as the numerical simulation of Berryman and Wang (2001) shows (based on the effective medium theory, and use a complete set of poroelastic constants for drained Trafalgar shale), with the increase of Skempton's coefficient *B*, the bulk modulus changes by as much as 100% in this example, whereas the shear modulus changes by less than 10%, and other rock examples also show similar results (Berryman and Wang, 2001).

As discussed above, we can know: It is obvious that the change of shear modulus G is extremely tiny, and even can be neglected (both in the drained or undrained cases) as compared with the change of Skempton's coefficient *B*. In this paper we suppose, shear modulus of well aquifer systems will not change after affected by the seismic waves (the frequencies of seismic waves are much lower than the ultrasonic frequencies, so the change of the shear modulus will just be neglectable compared to the change in *B* value).

4. Intermediate and Far Field Analysis

4.1 Calculation

Large numbers of stations with co-seismic water level changes induced by M_s 8.0 Wenchuan earthquake have been collected in the intermediate and far fields (>1.5 fault-rupture lengths). Most of those water level changes in this area can not be induced by the change of the static strains, which are extremely tiny (Zhang and Huang, 2011). We selected those co-seismic water level changes with distinct amplitude (tiny or obscured co-seismic water level changes have been excluded). In order to calculate the pre- and post- earthquake *B* values, water level data in stations should not be long-time missing or be influenced by other factors, such as pumping or other disturbances, and the data should be long enough (at least with a 10-day continuous data before and after the earthquake respectively), so that we can use the least-square fit to calculate *B*. Baring those rules in mind, we find 17 stations can be chosen during the Wenchuan earthquake (Table 1).

We apply the above method to those well-picked stations. The pre-and post-earthquake *B* values are respectively obtained from May 1, 2008 to May 11, 2008, and from May 13, 2008 to May 24, 2008 (Figure 2).

4.2 Undrained Skempton's coefficient *B* as a function of effective pressure

Pore pressure response to gravitational loading is similar to tectonic loading and can also be treated as a poroelastic problem (Green and Wang, 1986). Depth of those wells are show in Table 1, all of which are less than 2.6 km and most of those depths are even less than 1 km. Wang and Luo (2004) predicted the formation pore fluid pressure of wells in Ying-qiong basin (the main bedrock is sandstone) based on the "equilibrium depth" method. The "pressure - depth" relation of well YC21-1-1 (Figure 3-(b)) is similar to other wells of Ying-qiong basin, and the result is in accordance with the formation pore fluid pressure predicted with drilling (not show in the figure). The depth of the extra high pressure is usually larger than 3000 m, the pressure will be normal when the depth is less than 3000 m, so we assume those results could be applied to these wells we studied (well a ~ p) since we lack the "pressure-depth" predictions of these wells. Based on the "pressure-depth" relation of well YC21-1-1, we estimate the range of the effective pressure (effective pressure approximately equals to the lithostatic pressure minus the pore fluid pressure) of these wells (Table 1).

The undrained modulus *B* is considered as a function of effective pressure $p_c - p_f$ (Green and Wang, 1986; Blocher *et al.*, 2009). When the aquifr be consolidated the effective pressure will increase, while a dilation is in accordance to the decrease of the effective pressure. Blocher *et al.* (2009) measured the relationship between Skempton's coefficient *B* and effective pressure based on the laboratory experiment, at the beginning of the first pressure cycle, the isotropic Skempton's coefficient increased with increasing effective pressure to 20 MPa. This could be due to a possible dissolution of gas in the fluid of an incompletely saturated sample, and an additional saturation of the sample was performed Figure 3-(a). The in-situ aquifer of those wells (well a～p) are under lithostatic pressures for a long time and also be affected by the transmission of seismic waves for countless times, the situation is much similar to those well bedrocks be applied on repeated pressure cycles, so the situation will be much similar to the last several ramps rather than the first ramp (pressure cycle) in Figure 3-(a), and the isotropic Skempton's coefficient *B* will increase/decrease with the increase/decrease of effective pressure (when the effective pressure is less than ～4 Mpa), while *B* will decrease with the increase of effective pressure (when the effective pressure is larger than ～4 Mpa) (Figure 3-(a)). Although these results obtained from sandstone, because of the lack of the laboratory experiment study of those specific rocks, we assume the results can be applied to the bedrock of all those wells studied in this paper.

4.3 Mechanism of water level increase

4.3.1 Mechanism of water level increase in wells a~i

Most of those water level increases (water level increase in wells a ~ i (Figure 2)) accompanied with the increase of Skempton's coefficient *B*, which indicating shaking induced by the transmission of teleseismic waves may cause consolidation of the aquifer, and lead to the increase of the effective pressure. The ranges of the effective pressure of wells a ~ i are approximately between 0～3 MPa (except well g) (Table 1). The study of Blocher *et al.* (2009) indicates: when the effective pressure is less than ～4 Mpa, Skempton's coefficient *B* will increase with the increase of effective pressure (Figure 3-(a)). As explained by Blocher *et al.* (2009) this could be due to a possible dissolution of gas in the fluid of an incompletely saturated sample. To our understanding, when the aquifer be consolidated and the pressure not exceed a limitation (the fissures not be closed), the mean fracture width (the porosity and permeability) may decrease with the increase of the effective pressure, then the stiff rock matrix that supports the load could with a higher coupling to the fluid (Nur and Byerlee, 1971), and the value of *B* increase.

The depth of well g is 889 m, and the effective pressure range is 8~10 MPa (Table 1), according to the last several ramps of Figure 3-(a), with the increase of the effective pressure (consolidation), Skempton's coefficient *B* will decrease (because of the close of the fractures, the stiff rock matrix that supports the load could with a lower coupling to the fluid), however, as show in Figure 2, *B* turns to increase, this conflict may be described with the mechanism of an earthquake-enhanced permeability (porosity). Fracture clearing (such as overcoming the capillary entrapment in porous channels) and increased permeability induced by shaking may cause the pore-pressure to spread from nearby sources to sediment sites, and induce the increase of water level. The effective pressure will decrease accompanied with the increase of pore-pressure and the Skempton's coefficient *B* will increase according to Figure 3-(a). This is mainly because of the new microcracks and the broadened porosity, which will cause a better connectedness between the pore fluid and then the stiff rock matrix may supports the load with higher coupling to the fluid, so the Skempton's coefficient *B* increases.

Whereas, water level increase in two wells (well h and e, the effective pressure range is 0～3 MPa) do not accompanied with the increase of *B* values. As discussed by Wang and Chia (2008), an earthquake-enhanced permeability may be responsible for the more gradual water level changes in the intermediate field (such as well h) (Figure 2). Fracture clearing and increased permeability induced by shaking may cause the pore-pressure to spread from nearby sources to sediment sites, which can induce the increase of water level (Wang and Manga, 2010). Because the increased pore-pressure may hold the porosity even larger, Skempton's coefficient *B* will decrease accompanied with the decrease of the effective pressure in the effective pressure range 0～3 MPa. Then, the velocity of the water level increase will descend, and present a gradual ascending manner. The disagreement between the change of water level and *B* in well e (Qixian well), may be induced by the quick recovery of the water level after the co-seismic increase.

4.3.2 Examples support far field water level increases induced by consolidation

Permeability will increase/decrease, which is mostly related to the increase/decrease of porosity (Xue, 1986). As explained by rock mechanics the same porosity always corresponding to the same effective pressure (Terzaghi, 1925; Magara, 1978). From that we can know porosity and permeability are all directly connected with effective pressure, and they will decrease with the increase of the effective pressure (Blocher *et al.*, 2009).

From the laboratory experiment, Liu and Manga (2009) find that: in general, permeability decreases after shaking. They measured the evolution of permeability in fractured sandstone in response to repeated shaking under undrained conditions, and set the frequency and amplitude of the imposed shaking to be representative of those that cause distant hydrological responses. As they explained: Dynamic strains cause time varying fluid flow that can redistribute particles within fractures or porespaces, and can allow particles to move away from regions where they hold pore spaces open, and are expected to accumulate and get trapped at the narrowest constrictions along flow paths, and hence allow a consolidation (contraction) of the sample. Their result just supports our mechanism analysis. It implies that teleseismic waves can cause a consolidation of well aquifer and cause the increase of effective pressure (decrease of the porosity and permeability), which is in accordance with the increase of co-seismic water level changes accompanied with the increase of Skempton's coefficient *B* in wells: a, b, c, d, f, i (effective pressure range 0～3 MPa).

In addition, Huang (2008) find that: the water level increase in Fuxin well (1409.98 km away from Wenchuan, the well depth is 60.74 m，stiff Granite with a little Whinstone is the bedrock and we assume the shear modulus = 60 Gpa) is induced by the increase of volume strain (consolidation) (Figure 4-(a)). In the Chinese mainland, Fuxin is the only well in which there are observations of volume strain and water level in a specific aquifer medium, and both of them have obvious co-seismic responses to Wenchuan earthquake. There are clear and obvious effects of tidal strain and atmospheric pressure in the water level and volume strain, which indicates Fuxin is a terrific artesian well. This well has not be chosen in the above analysis because there is an abrupt large-amplitude increase in the water level, which starts from 11 p.m. May 22, 2008 (we can not find any interference of this abrupt increase according to the daily records of Fuxin station), and we can just use a shorter time period to calculate the post-earthquake *B* value, which may cause a little impact on the precise of *B*. The calculation is performed based on the M_2 wave distilled from the water level and the tidal strain (pre-earthquake: from May 1, 2008 to May 11, 2008, post-earthquake: from May 13, 2008 to May 22, 2008 (Figure 4-(b))). (The large-step abrupt water level increase starts from 09 p.m. May 22, 2008, which may cause large impact on the detrend process and influence the calculation result, so we just discard these data). From Figure 4-(a), we can see the co-seismic water level increase is induced by the change of the volume strain, which indicates the well aquifer has been consolidated. The depth of Fuxin well is 60.74 m, and we can assume the range of the effective pressure is 0～3Mpa (Figure 3-(b)), from the change of the pre- and post-earthquake *B* (Figure 4-(b)), we may infer the consolidation may be very extreme, accompanied with the coseismic water level increase it could cause an extra pressure, which just overcomes the capillary entrapment in porous channels of the aquifer or incures a fracture clearing and bring in the increase of the permeability, then water flow in from other places with a higher pressure, which lead to the decrease of the Skempton’s coefficient *B* with the decrease of the effective pressure (increase of the pore-pressure and porosity), and the water level increases more gradually. Finally with the further enhancement of the permeability (increase of the porosity), a permanent deformation could be induced, so there is an abrupt increase in the water level in 22 May, and remain in a relatively high level for several months(Figure 4-(c)). From the picture we can see it may be in a drained condition after the abrupt water level increase, because the water level fluctuates irregularly.

So we argue that the water level increase induced by the consolidation incurred by transmission of teleseismic waves is reasonable, and a consolidation with large enough energy may also lead to an enhanced permeability by overcoming the capillary entrapment in porous channels.

4.4 Mechanism of water level decrease

Water levels decrease with the decrease of Skempton's coefficient *B* in wells j, m and o. The spreading of shear waves may cause dilation of the aquifer medium, which can broaden the porosities and give birth to new fractures, and the effective pressure will reduce leading to the decrease of Skempton's coefficient *B* (Figure 3-(a)) (in wells: j, m and o, the effective pressure range is 0～3 MPa). This explanation is similar to the mechanism of shaking-induced dilatancy (Bower and Heaton, 1978).

However, several of those water level decreases accompanied with the increase of the Skempton's coefficient *B* (well: k, l, n, p). For wells k, l and p, the the range of the effective pressures are approximately less than 4 MPa (Table 1). According to the last several ramps of Figure 3-(a), with the decrease of the effective pressure (dilation) Skempton's coefficient *B* should decrease. Fracture clearing (unclogging) and increased permeability may be used to explain those contradictories in wells k, l and p. Since pore-pressure heterogeneity may be the norm in the field, an enhancement of permeability among sites of different pore pressure may cause pore pressure to spread (Roeloffs, 1998; Brodsky *et al.*, 2003; Wang, 2007; Wang and Manga, 2010). Pore-pressure of those wells may be higher than other places before the earthquake, an enhancement of permeability incured by overcoming the capillary entrapment in porous channels induced by the passage of elastic waves will decrease the pore-pressure in those wells (the pore-pressure will shift to other places), and water level will decrease. Then the effective pressure will increase accompanied with the decrease of pore-pressure, so the Skempton's coefficient *B* increase in wells k, l and p (Figure 3-(a)).

The depth of well n (2600 m) is much larger than other wells, and the effective pressure range of this depth is 20～25 MPa (Table 1). According to the last several ramps of Figure 3-(a), with the decrease of the effective pressure (dilation) Skempton's coefficient *B* will increase during this range of effective pressure. So our result of well n is in accordance with the laboratory experiment of Blocher *et al.* (2009), which indicates that as the effective pressure decrease (dilation caused by shear waves), the porosity may increase and new microcracks may be incurred, then the connectedness between the fluid will be better and the stiff rock matrix may supports the load with higher coupling to the fluid, so the Skempton's coefficient *B* will increase in this effective pressure range.

4.5 Wellbore storage effects

Tidal phase lags are caused by wellbore storage. "Wellbore storage" is the term used to describe a lag of piezometer water level behind aquifer pressure resulting from the need for water to flow into the borehole in order to equilibrate water level with aquifer pressure. Wellbore storage effects increase (phase lags increase) as the transmissivity (and permeability) of the formation decreases (Roeloffs, 1996; Doan *et al.*, 2006).

Most of those wells can record clear tidal strains and atmospheric pressure, and according to the <earthquake monitoring records of stations> they are well confined. From Table 1 we can see the phase differences of the water level and the tidal strain of most wells are 0, which mean good correlations between the water level and the tidal strain, and those wells are well confined and under the undrained condition. Because we use the hourly data, we can not identify the phase difference when it is less than 1 hour, and we just neglected the wellbore storage effects in those wells. Before and after the earthquake, if phase lags remain the same, it indicates the permeability of the well aquifer keeps the same or just changes a little (the phase difference may be lees than 1 hour). There are phase lags ≧ 1 hour in well: b, c, e, f, n and p, and most of them are small, except well b and well p, and the two wells may be semi-confined. Thus, the validity of the calculated *B* values in well b and well p may be a little questionable. In well: e, f and n the phase lags (the lag of piezometer water level behind the aquifer pressure induced by the tidal strains) are different before and after the earthquake. Those phase lags just come up to our expectations. In wells e and f the coseismic water levels increase with the increase of the effective pressures, and the porosities just decrease leading to the decrease of the permeabilities, so the phase differences will increase. In well n the coseismic water level decrease with the decrease of the effective pressure (dilation caused by shear waves), and the porosity may increase leading to the increase of the permeability, so the phase lag will decrease. The phase lag of Fuxin well decreases after the earthquake (L1=2 hours, l2=1 hour), which indicates the permeability increases after the shakig of the earthquake, this is also in accordance with the mechanism analysis of the co-seismic water level increase in Fuxin well.

5. Discussion and conclusion

Our analysis is not conflict with any of those existing theories. Although those water level changes happened in the intermediate and far fields, most of those water levels present abrupt and obvious co-seismic changes owing to the huge energy of M_s 8.0 Wenchuan earthquake. From the study we can conclude: consolidation (decrease of porosity and permeability) attribute to the redistribution of particles in apertures induced by shaking of teleseismic waves, may account for much of the mechanism of those abrupt coseismic water level increases. While, fracture clearing and increased permeability may be used to explain part of those coseismic water level decreases and a little part of the coseismic water level increases, especially the more gradual water level increases in this area. Other water level decreases may be attributed to the dilatation caused by the transmission of shear waves.

From the analysis of Fuxin well, we can see a consolidation with large enough energy may also incur an enhanced permeability by overcoming the capillary entrapment in porous channels or by fracture clearing. So as discussed by Liu and Manga (2009), permeability changes (either increases or decreases) owing to dynamic stresses are a reasonable explanation for earthquake-induced hydrologic responses to earthquakes. The mechanisms analyzed in this paper are similar to the experiment results of Liu and Manga (2009), and our in-situ analysis may complement the limitation of the initial condition of their laboratory experiments. However, both of our results seem different from the results of Elkhoury *et al.* (2006), since we and Liu and Manga (2009) all use the undrained condition, while work of Elkhoury *et al.* (2006) are under drained condition (Owing to the long-wavelength of seismic waves, natural geological materials experience time varying stress under undrained conditions (Liu and Manga, 2009)) .

In reality, the shear modulus G and the undrained Poisson's ratio ν_u would change slightly after the shaking of seismic waves, and the discussed "undrained" condition can hardly last for a long time, as long as the fluid flow exists, the undrained condition will disrupt and be replaced by the drained condition soon. We assume the results get from sandstone can be applied to all those bedrocks in those wells (Figure 3), however this is not very precise. As described by Wang (1993) nonlinear compaction effects can be significant and they are not incorporated in the linear theory presented here, because the well aquifers are under lithostatic pressures for a long time and withstand large numbers of seismic shaking, the irreversible deformations and the nonlinear effects have been minimized (In the laboratory experiment, in order to reduce the irreversible deformation and to minimize the nonlinear effects, repeated pressure cycles are always applied on rock samples as preconditions (Hart and Wang, 1995; Blocher *et al.*, 2009)). Discard all those ideal assumptions, things may be different. Further studies need to be carried out, so as to clarify those mechanisms more precisely.

6. Data and Resources

Data used in this paper were collected using a classified network (Groundwater Monitoring Network, GMN) of the China Earthquake Networks Center and cannot be released to the public. We use the Mapseis software (Lu *et al.*, 2002) to calculate the tidal strain data.

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Table 1. Water Level Changes, Pre- and Post- Earthquake *B* Values, Shear Modulus, phase lags, well depths and effective pressures of the bedrocks of those well Picked Stations. L1 and L2 represent the pre- and post- earthquake phase lags (the lag of piezometer water level behind the tidal strain induced aquifer pressure) separately .

Station	Epicentral Distance /km	Pre-Earthquake B	Post-Earthquake B	Water Level Change/m	Lithology	Shear Modulus G*/Gpa	Phase lag/hour	Well Depth/m	Range of Effective Pressure/MPa
(a) Xiaxian	465.9465	0.0123	0.0149	0.106	Gneiss	40	L1=L2=0	168	0～3
(b) Mile	726.4589	0.0872	0.1103	0.579	Limestone	20	L1=L2=-6	614	3～5
(c) Qinxianmanshui	983.8517	0.0557	0.0653	0.172	Sandstone	8	L1=L2=-2	240.05	0～3
(d) Xiaoyi	1062.0768	0.1493	0.186	0.398	Sandstone	8	L1=L2=0	502.47	0～3
(e) Qixian	1152.6034	0.0906	0.0153	0.831	Limestone	20	L1=0 L2=-3	410	0～3
(f) Hejiazhuang	1582.0754	0.0678	0.0851	0.063	Granite	28	L1=-1 L2=-2	301.04	0～3
(g) Jurong	1750.2357	0.124	0.1282	0.263	Sandstone	8	L1=L2=0	889.18	8～10
(h) Huanghua	1786.978	0.1897	0.1417	0.594	Sandstone	8	L1=L2=0	250.59	0～3
(i) Wafangdianloufang	1801.5625	0.1252	0.1677	0.478	Granite	28	L1=L2=0	224.5	0～3
(j) Haiyuanganyanchi	606.402	0.0407	0.0395	-0.036	Sandstone	8	L1=L2=0	306.73	0～3
(k) Guyuanzhenqi	638.7904	0.0026	0.0047	-0.026	Sandstone	8	L1=L2=0	618.39	3～5
(l) Kaiyuan	805.4263	0.0724	0.077	-0.155	Limestone	20	L1=L2=0	224	0～3
(m) Meizhou	1345.951	0.0873	0.0823	-0.075	Quartzite	20	L1=L2=0	338.86	0～3
(n) Zuojiazhuang	1354.8715	0.2137	0.3461	-1.917	Limestone	20	L1=-2 L2=0	2600	20～25
(o) Chaohu	1587.6013	0.091	0.0798	-0.455	Limestone	20	L1=L2=0	331	0～3
(p) Yongchun	1745.9768	0.6855	0.8854	-1.64	Granite	28	L1=L2=-5	5	0～3

G* see Yan Zhang and Fuqiong Huang (2011).

Figure 1. The well selected 17 stations with distinct amplitude co-seismic water level changes during the Wenchuan earthquake in mainland China. The well numbers are in accordance with the numbers listed in Table 1.

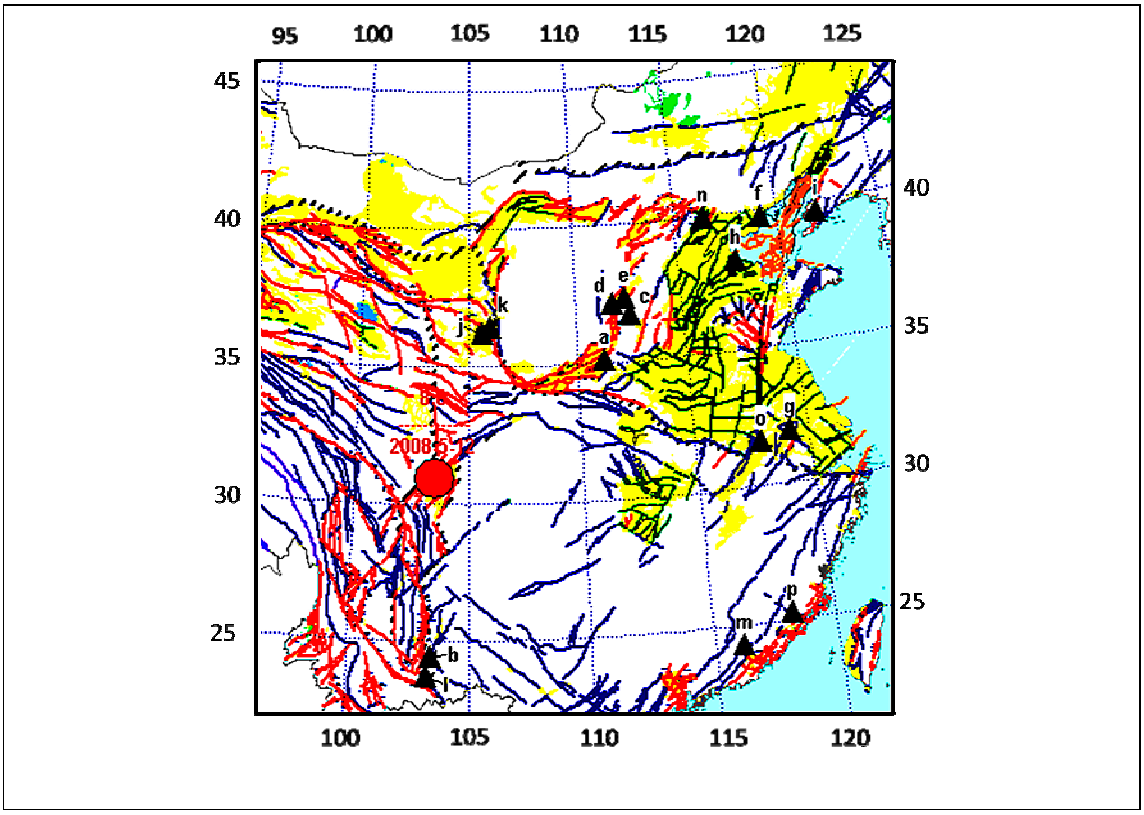


Figure 2. (A) Left y-coordinate: original water levels, the sequential number of y-coordinate depends on the type of the well, "sequential number increase from low to high" indicates an artesian well, the coordinate value means the height from the free water surface to the artesian discharge point or to the ground. "Sequential number decrease from low to high" indicates a non-artesian well, and the coordinate value means the depth from the free water surface to the ground. All the ascendant/ descendent patterns in the picture indicate water level ascending/ descending. (B) Right y-coordinate: the calculated Skempton's coefficient *B*. Red curves indicate the continuous *B* values both pre- and post- earthquake. The dashed lines indicate the mean *B* values, which are clearly shown in numbers.

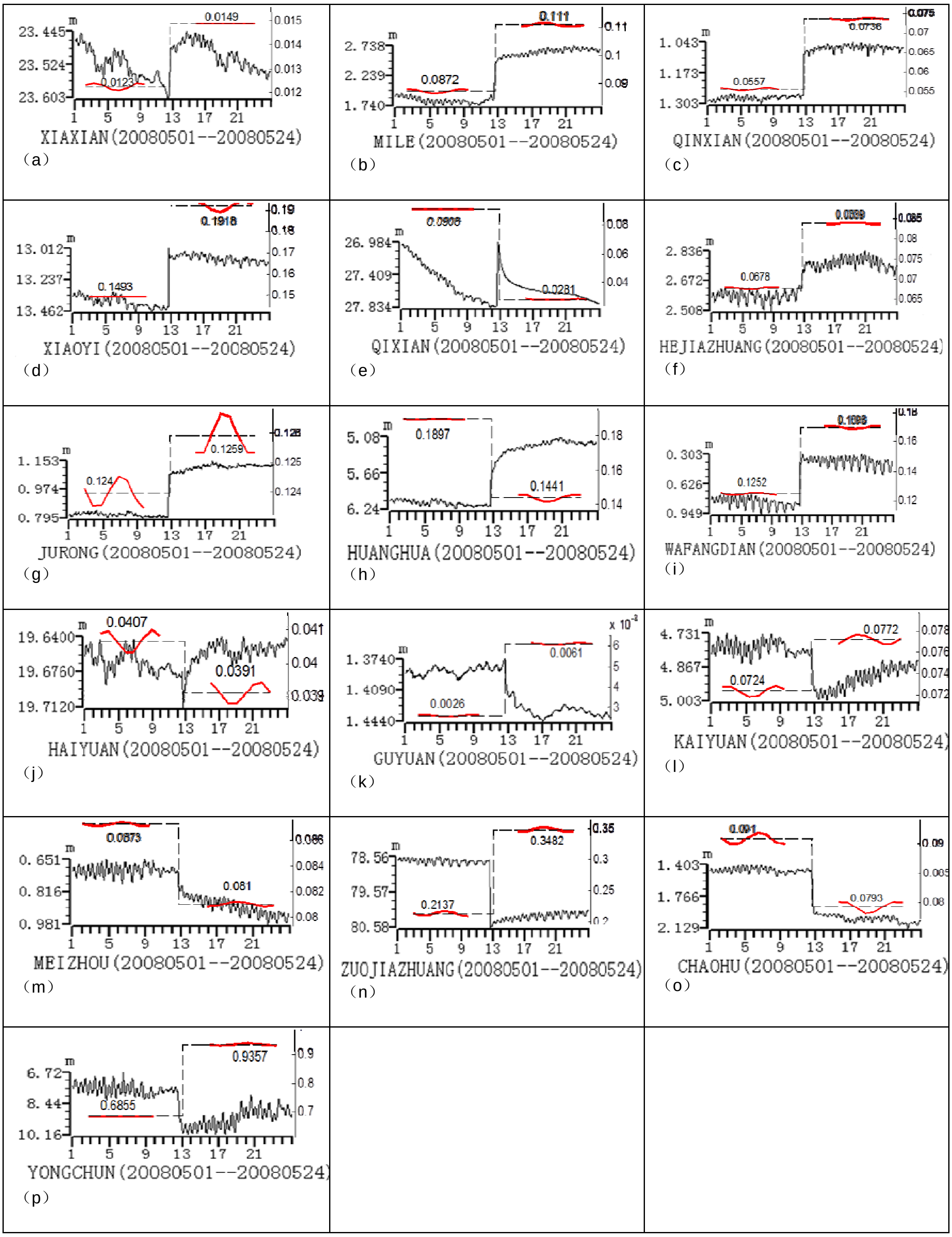

XIAXIAN(20080501--20080524)
(a)
MILE(20080501--20080524)
(b)
QINXIAN(20080501--20080524)
(c)
XIAOYI(20080501--20080524)
(d)
QIXIAN(20080501--20080524)
(e)
HEJIAZHUANG(20080501--20080524)
(f)
JURONG(20080501--20080524)
(g)
HUANGHUA(20080501--20080524)
(h)
WAFANGDIAN(20080501--20080524)
(i)
HAIYUAN(20080501--20080524)
(j)
GUYUAN(20080501--20080524)
(k)
KAIYUAN(20080501--20080524)
(l)
MEIZHOU(20080501--20080524)
(m)
ZUOJIAZHUANG(20080501--20080524)
(n)
CHAOHU(20080501--20080524)
(o)
YONGCHUN(20080501--20080524)
(p)

Figure 3. (a) Skempton's coefficient *B* measured for Flechtinger sandstone as a function of effective pressure. The color from black to light grey indicates the chronological sequence of the experiment. The vertical branches of the curves are due to a saturation deficit. The dots indicate the Skempton's coefficient change over an effective pressure interval of 1 MPa (Blocher *et al.*, 2009). (b) Pressure section of well YC21-1-1 in Ying-qiong basin get from the "equilibrium depth" method, the main bedrock of Ying-qiong basin is sandstone (Wang and Luo, 2004).

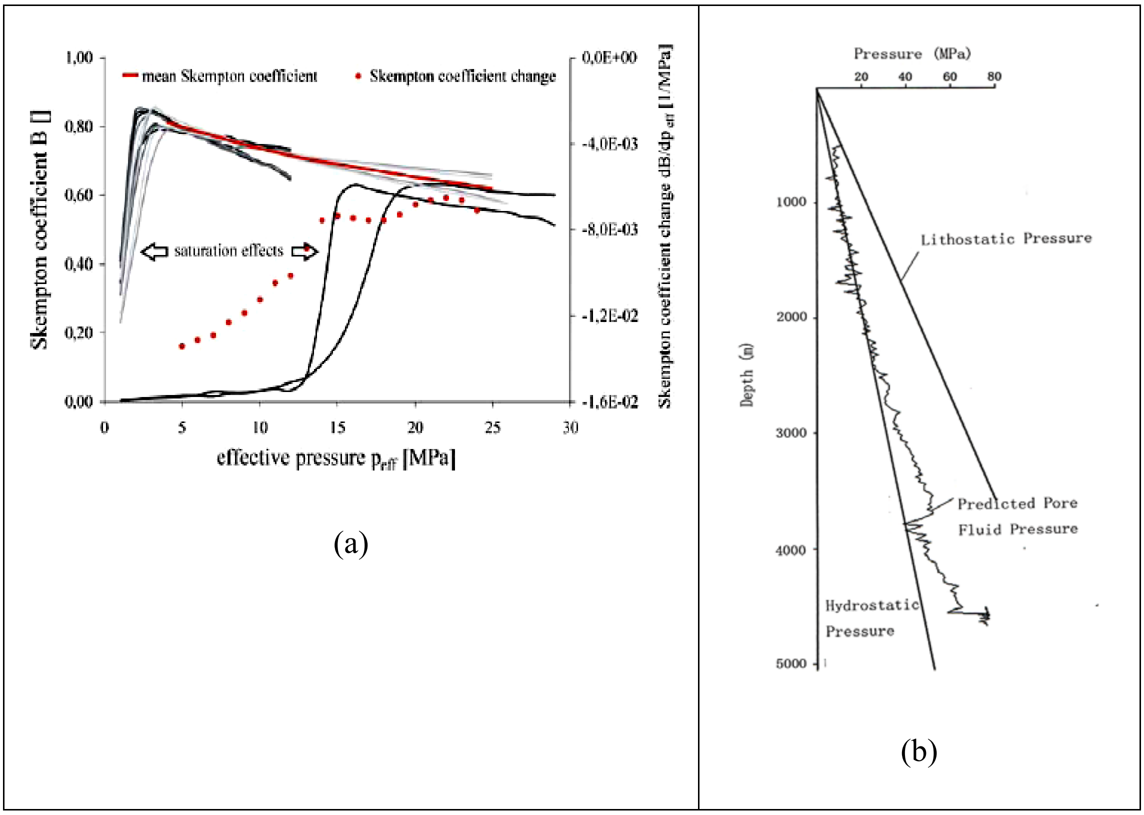
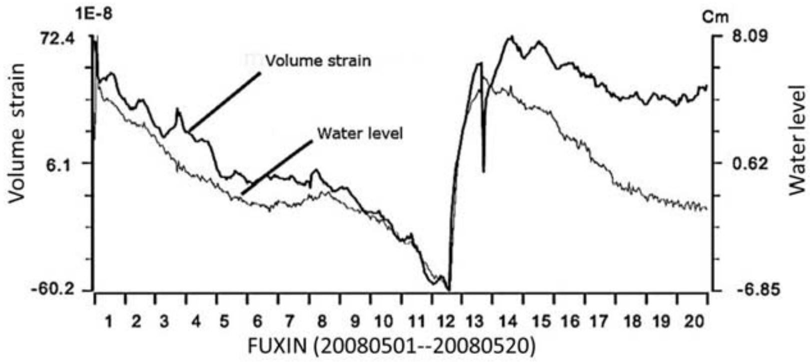
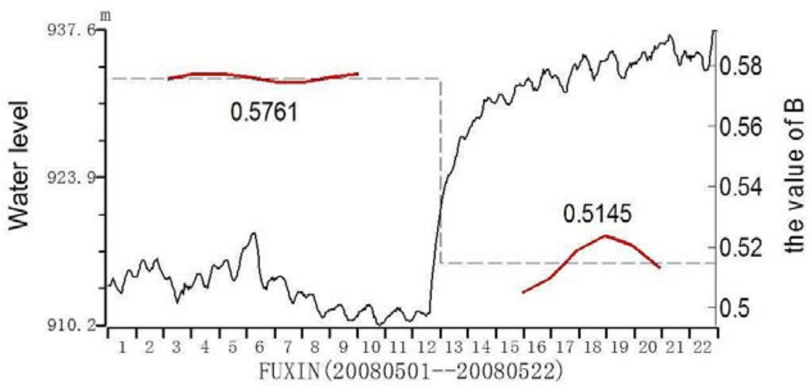


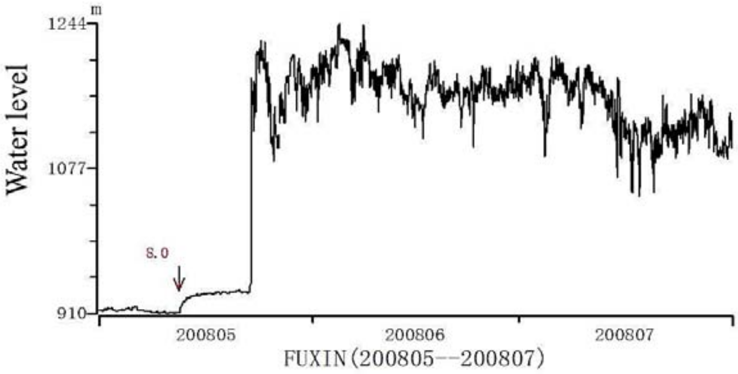
Figure 4. Fuxing well (a) Corrected water level and volume strain after removing the influence of atmospheric pressure and tidal srain (based on the harmonic analysis method). In order to avoid the interfere of thunder, there is a power cut protection on 13 May, which is in accordance with the break point of the volume strain in the figure (Huang, 2008). (b) Original water level and the pre- and post- earthquak Skempton's coefficient *B*. (c) Original water level of Fuxin well form May, 2008 to July 2008.



(a)



(b)


m
1244
1077
910
Water level
8.0
200805
200806
200807
FUXIN(200805--200807)

(c)

Studies of mechanism for water level changes induced by teleseismic waves

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Abstract

The M_s 8.0 Wenchuan earthquake of May 12, 2008 induces large-amplitude water level changes at intermediate and far fields (epicentral distance >1.5 fault rupture length) in Chinese mainland. Although many hydrologic changes induced by teleseismic waves have been reported, the mechanisms responsible for the changes still remain unclear. We invoke Skempton's coefficient *B* in this paper to explain those co-seismic water level changes documented in the intermediate and far fields. Most of the abrupt co-seismic water level increases are found to favor the consolidation caused by the redistribution of particles in apertures induced by the shaking of teleseismic waves. While a little part of the increases, especially those more gradual co-seismic increases can be explained with the enhanced permeability caused by fracture clearing or overcoming the capillary entrapment in porous channels of the aquifer induced by the shaking of teleseismic waves. The dilatation caused by the earthquake shaking can not account for some of the co-seismic water level decreases,

which, however, may be explained by the earthquake-enhanced fracture and permeability.

1. Introduction

Various hydrologic responses to earthquakes have been documented, many occurred at great distances from the ruptured fault where static stress changes are extremely small (Liu and Manga, 2009; Wang and Manga, 2010). Hydrologic changes induced by teleseismic waves have been investigated in several studies of water wells (Roeloffs, 1998; Brodsky *et al*., 2003; Elkhoury *et al*., 2006; Geballe *et al*., 2011). These studies indicate that significant water level changes can be driven at great distances by moderate-amplitude dynamic (time-varying) stresses (Liu and Manga, 2009).

Several mechanisms have been proposed to explain these co-seismic changes in water level. Fracture clearing and increased permeability caused by the earthquake-induced dynamic stress have been widely used to explain most documented water level changes (Brodsky *et al*., 2003; Elkhoury *et al*., 2006; Wang and Chia, 2008; Wang and Manga, 2010). Overcoming the capillary entrapment in porous channels is hypothesized to be one of the principal pore-scale mechanisms by which natural permeability is enhanced by the passage of elastic waves (Beresnev, 2011). Other proposed, but also unverified mechanisms include pore pressure increases caused by a mechanism 'akin to liquefaction' (Roeloffs, 1998), shaking-induced dilatancy (Bower and Heaton, 1978), or increasing pore pressure through seismically induced growth of bubbles (Linde *et al*., 1994). In addition, Huang (2008) observed the co-seismic water level increase may be caused by the consolidation induced by the transmission of teleseismic waves. Experimental measurements of Liu and Manga (2009) indicate that permeability changes (either increases or decreases) owing to dynamic stresses are a reasonable explanation. In general, they find permeability decrease after shaking.

In the present study, we use the Skempton's coefficient B both pre and after earthquake to explain the co-seismic water level changes in the intermediate and far fields based on datasets from the Wenchuan earthquake in the Chinese mainland. Using a poroelastic relation between water level and solid tide (Zhang *et al.*, 2009), we calculate the in-situ Skempton's coefficient B both pre and after earthquake. From the research we find: Most of the abrupt co-seismic water level increases can be explained with the consolidation caused by the redistribution of particles in apertures, which is induced by the shaking of teleseismic waves. Some of the co-seismic water level increases, especially those increases with gradual manner can be explained with the enhanced permeability caused by overcoming the capillary entrapment in porous channels induced by the shaking of teleseismic waves. While, some of the co-seismic water level decreases can not be attributed to the shaking-induced dilatation, however, may be explained with the increased permeability caused by teleseismic waves, which in turn lead to the redistribution of pore pressure.

2. An approach to Skempton's coefficient *B* based on the poroelastic theory

Skempton's coefficient B is a significant pore-fluid parameter in poroelastic theory. A poroelastic material consists of an elastic matrix containing interconnected fluid saturated pores. Fluid saturated crust behaves as a poroelastic material to a good degree of approximation.

Rice and Cleary (1976) summarized the following equations for a linearly elastic isotropic porous medium (they are the building blocks of the poroelastic theory):

$$2G\varepsilon_{ij} = \sigma_{ij} - \frac{\nu}{1+\nu}\sigma_{kk}\delta_{ij} + \frac{3(\nu_u - \nu)}{B(1+\nu)(1+\nu_u)} p\delta_{ij}\,, \quad (1)$$

$$m - m_0 = \frac{3\rho(\nu_u - \nu)(\sigma_{kk} + 3p/B)}{2GB(1+\nu)(1+\nu_u)}\,. \quad (2)$$

Here $m - m_0$ is the change of the fluid mass, ε_{ij} is the strain tensor, σ_{ij} is the stress tensor, δ_{ij} is the Kronecker delta function, G is the shear modulus, ρ is the density of the fluid, B is the Skempton's coefficient, p is the pore pressure, ν is the Poisson's ratio, and ν_u is the "undrained" Poisson's ratio. Rice and Cleary (1976) describe equation (1) as a stress balance equation and equation (2) as a mass balance equation.

For the undrained condition, the poroelastic effect on the crust can be obtained by putting $m - m_0 = 0$ in equation (2) to obtain

$$P = -B\sigma_{kk}/3 \text{ or } \Delta p = -B\Delta\sigma_{kk}/3\,. \quad (3)$$

Equation (3) indicates that, in the undrained condition, the change in fluid pressure (Δp) is proportional to the change in mean stress ($\Delta\sigma_{kk}/3$). This is the mechanism of water level changes for poroelastic material. ($p = \rho g h$, where h is the water column height, g is the acceleration due to gravity and ρ is the density of water).

According to equation (3), Skempton's coefficient B can be qualitatively defined: In the undrained condition, B is the ratio of the induced pore pressure divided by the change in mean stress (Wang, 2000). B governs the magnitude of water-level changes due to an applied stress because pore pressure is directly proportional to water level. The value of B is always between 0 and 1. When B is 1, the applied stress is completely transferred into changing pore pressure. When B equals 0, there is no change in pore pressure after applying the stress. Thus a low value of B indicates the stiff rock matrix that supports the load with low coupling to the fluid (Nur and Byerlee, 1971). Laboratory studies indicate the value of B depends upon the fluid-saturated pore volume of the sample (Wang, 2000).

Equation (3) can be expressed in terms of tidal strain as well (Roeloffs, 1996):

$$\Delta h = -\frac{2GB(1+\nu_u)}{3\rho g(1-2\nu_u)}\Delta\varepsilon_t \cdot \qquad (4)$$

Equation (4) shows that water level changes proportionally in a poroelastic material under the influence of tidal strain (ε_t). Here, Δh is the change in height of water level, and $\Delta\varepsilon_t$ is the corresponding tidal strain change (Sil, 2006).

From equation (4) we obtain:

$$B = -\frac{3\rho g(1-2\nu_u)}{2G(1+\nu_u)}\frac{\Delta h}{\Delta\varepsilon_t}. \qquad (5)$$

With equation (5), we obtain the value of B with water level and tidal strain. However, the calculation must be on the strict premise of the undrained condition (the good correlation between the water level and the tidal strain) and should not be influenced by the other factors.

For the effect of the solid tide on the crust, when the wavelength of the tidal strain is much larger than the size of the aquifer, we can suppose the aquifer system is undrained (Huang, 2008). The wavelength of the M_2 wave is about 2,406,329 km ($\lambda = \omega r T$, where $\omega = 1.4\times10^{-4}/\mathrm{s}$ is the angular frequency of M_2 wave, r=384,400 km is the distance from the Earth to the Moon, T=745.236 min is the period of the M_2 wave); this wavelength is much larger than the size of the radius of the Earth and is definitely much larger than the thickness of the aquifer systems of those wells. Thus, the effect of the M_2 wave in the crust can meet the undrained condition (Zhang *et al.*, 2009). In addition, those wells can record clear tidal strains and thus, because we calculate the phase lags between the water levels and the tidal strains are small, the wells can readily meet the undrained condition. In the M_2 □ wave frequency domain, the water level and the tidal strain show a good correlation; Furthermore, the M_2 wave is hardly influenced by atmospheric pressure. We therefore distill the frequency domain of the M_2 wave from the water level and the tidal strain by using band-pass filter (the frequency of the M_2 wave is $2.23636\times10^{-5}HZ$) to calculate the Skempton's coefficient *B* (Figure 2). By converting the frequency domain of the M_2 waves (obtained from the water level and the tidal strain) by inverse fast Fourier transform and adjusting their phases (using the least-square fit and putting the results into equation (5)), we can finally derive *B*. (More details of the method are explained in Zhang *et al.*, 2009). All the Water-level observations come from the sensor of water level, while tidal strain data are calculated via Mapseis software (see Data and Resources section).

3. Assumptions of shear modulus and Poisson's ratio

Calculations are performed using $\rho = 1000kg/m^3$, $g = 9.8m/s^2$, and $\nu_u = 0.29$ according to equation (2). We suppose the undrained Poisson's ratio $\nu_u = 0.29$ both pre and after earthquake, and this kind of assumption is always used to simplify calculation issues of rocks near the crust (Zeng, 1984).

Gassmann (1951) predicted that the effective shear modulus would be independent of the saturating fluid properties (the shear modulus is a constant) in the undrained isotropic poroelastic media. As studied by Berryman (1999) and Berryman and Wang (2001), the theory applies at very low frequencies. At high enough frequencies (especially in the ultrasonic frequencies), as the numerical simulation of Berryman and Wang (2001) shows (based on the effective medium theory, and use a complete set of poroelastic constants for drained Trafalgar shale), with the increase of Skempton's coefficient *B*, the bulk modulus changes by as much as 100% in this example, whereas the shear modulus changes by less than 10%, and other rock examples also show similar results (Berryman and Wang, 2001).

As discussed above, we can know: It is obvious that the change of shear modulus G is extremely tiny, and even can be neglected (both in the drained or undrained cases) as compared with the change of Skempton's coefficient *B*. In this paper we suppose, shear modulus of well aquifer systems will not change after affected by the seismic waves (the frequencies of seismic waves are much lower than the ultrasonic frequencies, so the change of the shear modulus will just be neglectable compared to the change in *B* value).

4. Intermediate and Far Field Analysis

4.1 Calculation

Large numbers of stations with co-seismic water level changes induced by M_s 8.0 Wenchuan earthquake have been collected in the intermediate and far fields (>1.5 fault-rupture lengths). Most of those water level changes in this area can not be induced by the change of the static strains, which are extremely tiny (Zhang and Huang, 2011). We selected those co-seismic water level changes with distinct amplitude (tiny or obscured co-seismic water level changes have been excluded). In order to calculate the pre- and post- earthquake *B* values, water level data in stations should not be long-time missing or be influenced by other factors, such as pumping or other disturbances, and the data should be long enough (at least with a 10-day continuous data before and after the earthquake respectively), so that we can use the least-square fit to calculate *B*. Baring those rules in mind, we find 17 stations can be chosen during the Wenchuan earthquake (Table 1).

We apply the above method to those well-picked stations. The pre-and post-earthquake *B* values are respectively obtained from May 1, 2008 to May 11, 2008, and from May 13, 2008 to May 24, 2008 (Figure 2).

4.2 Undrained Skempton's coefficient *B* as a function of effective pressure

Pore pressure response to gravitational loading is similar to tectonic loading and can also be treated as a poroelastic problem (Green and Wang, 1986). Depth of those wells are show in Table 1, all of which are less than 2.6 km and most of those depths are even less than 1 km. Wang and Luo (2004) predicted the formation pore fluid pressure of wells in Ying-qiong basin (the main bedrock is sandstone) based on the "equilibrium depth" method. The "pressure - depth" relation of well YC21-1-1 (Figure 3-(b)) is similar to other wells of Ying-qiong basin, and the result is in accordance with the formation pore fluid pressure predicted with drilling (not show in the figure). The depth of the extra high pressure is usually larger than 3000 m, the pressure will be normal when the depth is less than 3000 m, so we assume those results could be applied to these wells we studied (well a ~ p) since we lack the "pressure-depth" predictions of these wells. Based on the "pressure-depth" relation of well YC21-1-1, we estimate the range of the effective pressure (effective pressure approximately equals to the lithostatic pressure minus the pore fluid pressure) of these wells (Table 1).

The undrained modulus *B* is considered as a function of effective pressure $p_c - p_f$ (Green and Wang, 1986; Blocher *et al.*, 2009). When the aquifr be consolidated the effective pressure will increase, while a dilation is in accordance to the decrease of the effective pressure. Blocher *et al.* (2009) measured the relationship between Skempton's coefficient *B* and effective pressure based on the laboratory experiment, at the beginning of the first pressure cycle, the isotropic Skempton's coefficient increased with increasing effective pressure to 20 MPa. This could be due to a possible dissolution of gas in the fluid of an incompletely saturated sample, and an additional saturation of the sample was performed Figure 3-(a). The in-situ aquifer of those wells (well a～p) are under lithostatic pressures for a long time and also be affected by the transmission of seismic waves for countless times, the situation is much similar to those well bedrocks be applied on repeated pressure cycles, so the situation will be much similar to the last several ramps rather than the first ramp (pressure cycle) in Figure 3-(a), and the isotropic Skempton's coefficient *B* will increase/decrease with the increase/decrease of effective pressure (when the effective pressure is less than ～4 Mpa), while *B* will decrease with the increase of effective pressure (when the effective pressure is larger than ～4 Mpa) (Figure 3-(a)). Although these results obtained from sandstone, because of the lack of the laboratory experiment study of those specific rocks, we assume the results can be applied to the bedrock of all those wells studied in this paper.

4.3 Mechanism of water level increase

4.3.1 Mechanism of water level increase in wells a~i

Most of those water level increases (water level increase in wells a ~ i (Figure 2)) accompanied with the increase of Skempton's coefficient *B*, which indicating shaking induced by the transmission of teleseismic waves may cause consolidation of the aquifer, and lead to the increase of the effective pressure. The ranges of the effective pressure of wells a ~ i are approximately between 0～3 MPa (except well g) (Table 1). The study of Blocher *et al.* (2009) indicates: when the effective pressure is less than ～4 Mpa, Skempton's coefficient *B* will increase with the increase of effective pressure (Figure 3-(a)). As explained by Blocher *et al.* (2009) this could be due to a possible dissolution of gas in the fluid of an incompletely saturated sample. To our understanding, when the aquifer be consolidated and the pressure not exceed a limitation (the fissures not be closed), the mean fracture width (the porosity and permeability) may decrease with the increase of the effective pressure, then the stiff rock matrix that supports the load could with a higher coupling to the fluid (Nur and Byerlee, 1971), and the value of *B* increase.

The depth of well g is 889 m, and the effective pressure range is 8~10 MPa (Table 1), according to the last several ramps of Figure 3-(a), with the increase of the effective pressure (consolidation), Skempton's coefficient *B* will decrease (because of the close of the fractures, the stiff rock matrix that supports the load could with a lower coupling to the fluid), however, as show in Figure 2, *B* turns to increase, this conflict may be described with the mechanism of an earthquake-enhanced permeability (porosity). Fracture clearing (such as overcoming the capillary entrapment in porous channels) and increased permeability induced by shaking may cause the pore-pressure to spread from nearby sources to sediment sites, and induce the increase of water level. The effective pressure will decrease accompanied with the increase of pore-pressure and the Skempton's coefficient *B* will increase according to Figure 3-(a). This is mainly because of the new microcracks and the broadened porosity, which will cause a better connectedness between the pore fluid and then the stiff rock matrix may supports the load with higher coupling to the fluid, so the Skempton's coefficient *B* increases.

Whereas, water level increase in two wells (well h and e, the effective pressure range is 0～3 MPa) do not accompanied with the increase of *B* values. As discussed by Wang and Chia (2008), an earthquake-enhanced permeability may be responsible for the more gradual water level changes in the intermediate field (such as well h) (Figure 2). Fracture clearing and increased permeability induced by shaking may cause the pore-pressure to spread from nearby sources to sediment sites, which can induce the increase of water level (Wang and Manga, 2010). Because the increased pore-pressure may hold the porosity even larger, Skempton's coefficient *B* will decrease accompanied with the decrease of the effective pressure in the effective pressure range 0～3 MPa. Then, the velocity of the water level increase will descend, and present a gradual ascending manner. The disagreement between the change of water level and *B* in well e (Qixian well), may be induced by the quick recovery of the water level after the co-seismic increase.

4.3.2 Examples support far field water level increases induced by consolidation

Permeability will increase/decrease, which is mostly related to the increase/decrease of porosity (Xue, 1986). As explained by rock mechanics the same porosity always corresponding to the same effective pressure (Terzaghi, 1925; Magara, 1978). From that we can know porosity and permeability are all directly connected with effective pressure, and they will decrease with the increase of the effective pressure (Blocher *et al*., 2009).

From the laboratory experiment, Liu and Manga (2009) find that: in general, permeability decreases after shaking. They measured the evolution of permeability in fractured sandstone in response to repeated shaking under undrained conditions, and set the frequency and amplitude of the imposed shaking to be representative of those that cause distant hydrological responses. As they explained: Dynamic strains cause time varying fluid flow that can redistribute particles within fractures or porespaces, and can allow particles to move away from regions where they hold pore spaces open, and are expected to accumulate and get trapped at the narrowest constrictions along flow paths, and hence allow a consolidation (contraction) of the sample. Their result just supports our mechanism analysis. It implies that teleseismic waves can cause a consolidation of well aquifer and cause the increase of effective pressure (decrease of the porosity and permeability), which is in accordance with the increase of co-seismic water level changes accompanied with the increase of Skempton's coefficient B in wells: a, b, c, d, f, i (effective pressure range 0～3 MPa).

In addition, Huang (2008) find that: the water level increase in Fuxin well (1409.98 km away from Wenchuan, the well depth is 60.74 m，stiff Granite with a little Whinstone is the bedrock and we assume the shear modulus = 60 Gpa) is induced by the increase of volume strain (consolidation) (Figure 4-(a)). In the Chinese mainland, Fuxin is the only well in which there are observations of volume strain and water level in a specific aquifer medium, and both of them have obvious co-seismic responses to Wenchuan earthquake. There are clear and obvious effects of tidal strain and atmospheric pressure in the water level and volume strain, which indicates Fuxin is a terrific artesian well. This well has not be chosen in the above analysis because there is an abrupt large-amplitude increase in the water level, which starts from 11 p.m. May 22, 2008 (we can not find any interference of this abrupt increase according to the daily records of Fuxin station), and we can just use a shorter time period to calculate the post-earthquake *B* value, which may cause a little impact on the precise of *B*. The calculation is performed based on the M_2 wave distilled from the water level and the tidal strain (pre-earthquake: from May 1, 2008 to May 11, 2008, post-earthquake: from May 13, 2008 to May 22, 2008 (Figure 4-(b))). (The large-step abrupt water level increase starts from 09 p.m. May 22, 2008, which may cause large impact on the detrend process and influence the calculation result, so we just discard these data). From Figure 4-(a), we can see the co-seismic water level increase is induced by the change of the volume strain, which indicates the well aquifer has been consolidated. The depth of Fuxin well is 60.74 m, and we can assume the range of the effective pressure is 0～3Mpa (Figure 3-(b)), from the change of the pre- and post-earthquake *B* (Figure 4-(b)), we may infer the consolidation may be very extreme, accompanied with the coseismic water level increase it could cause an extra pressure, which just overcomes the capillary entrapment in porous channels of the aquifer or incures a fracture clearing and bring in the increase of the permeability, then water flow in from other places with a higher pressure, which lead to the decrease of the Skempton's coefficient *B* with the decrease of the effective pressure (increase of the pore-pressure and porosity), and the water level increases more gradually. Finally with the further enhancement of the permeability (increase of the porosity), a permanent deformation could be induced, so there is an abrupt increase in the water level in 22 May, and remain in a relatively high level for several months(Figure 4-(c)). From the picture we can see it may be in a drained condition after the abrupt water level increase, because the water level fluctuates irregularly.

So we argue that the water level increase induced by the consolidation incurred by transmission of teleseismic waves is reasonable, and a consolidation with large enough energy may also lead to an enhanced permeability by overcoming the capillary entrapment in porous channels.

4.4 Mechanism of water level decrease

Water levels decrease with the decrease of Skempton's coefficient *B* in wells j, m and o. The spreading of shear waves may cause dilation of the aquifer medium, which can broaden the porosities and give birth to new fractures, and the effective pressure will reduce leading to the decrease of Skempton's coefficient *B* (Figure 3-(a)) (in wells: j, m and o, the effective pressure range is 0～3 MPa). This explanation is similar to the mechanism of shaking-induced dilatancy (Bower and Heaton, 1978).

However, several of those water level decreases accompanied with the increase of the Skempton's coefficient *B* (well: k, l, n, p). For wells k, l and p, the the range of the effective pressures are approximately less than 4 MPa (Table 1). According to the last several ramps of Figure 3-(a), with the decrease of the effective pressure (dilation) Skempton's coefficient *B* should decrease. Fracture clearing (unclogging) and increased permeability may be used to explain those contradictories in wells k, l and p. Since pore-pressure heterogeneity may be the norm in the field, an enhancement of permeability among sites of different pore pressure may cause pore pressure to spread (Roeloffs, 1998; Brodsky *et al.*, 2003; Wang, 2007; Wang and Manga, 2010). Pore-pressure of those wells may be higher than other places before the earthquake, an enhancement of permeability incured by overcoming the capillary entrapment in porous channels induced by the passage of elastic waves will decrease the pore-pressure in those wells (the pore-pressure will shift to other places), and water level will decrease. Then the effective pressure will increase accompanied with the decrease of pore-pressure, so the Skempton's coefficient *B* increase in wells k, l and p (Figure 3-(a)).

The depth of well n (2600 m) is much larger than other wells, and the effective pressure range of this depth is 20～25 MPa (Table 1). According to the last several ramps of Figure 3-(a), with the decrease of the effective pressure (dilation) Skempton's coefficient *B* will increase during this range of effective pressure. So our result of well n is in accordance with the laboratory experiment of Blocher *et al.* (2009), which indicates that as the effective pressure decrease (dilation caused by shear waves), the porosity may increase and new microcracks may be incurred, then the connectedness between the fluid will be better and the stiff rock matrix may supports the load with higher coupling to the fluid, so the Skempton's coefficient *B* will increase in this effective pressure range.

4.5 Wellbore storage effects

Tidal phase lags are caused by wellbore storage. "Wellbore storage" is the term used to describe a lag of piezometer water level behind aquifer pressure resulting from the need for water to flow into the borehole in order to equilibrate water level with aquifer pressure. Wellbore storage effects increase (phase lags increase) as the transmissivity (and permeability) of the formation decreases (Roeloffs, 1996; Doan *et al.*, 2006).

Most of those wells can record clear tidal strains and atmospheric pressure, and according to the <earthquake monitoring records of stations> they are well confined. From Table 1 we can see the phase differences of the water level and the tidal strain of most wells are 0, which mean good correlations between the water level and the tidal strain, and those wells are well confined and under the undrained condition. Because we use the hourly data, we can not identify the phase difference when it is less than 1 hour, and we just neglected the wellbore storage effects in those wells. Before and after the earthquake, if phase lags remain the same, it indicates the permeability of the well aquifer keeps the same or just changes a little (the phase difference may be lees than 1 hour). There are phase lags ≧ 1 hour in well: b, c, e, f, n and p, and most of them are small, except well b and well p, and the two wells may be semi-confined. Thus, the validity of the calculated *B* values in well b and well p may be a little questionable. In well: e, f and n the phase lags (the lag of piezometer water level behind the aquifer pressure induced by the tidal strains) are different before and after the earthquake. Those phase lags just come up to our expectations. In wells e and f the coseismic water levels increase with the increase of the effective pressures, and the porosities just decrease leading to the decrease of the permeabilities, so the phase differences will increase. In well n the coseismic water level decrease with the decrease of the effective pressure (dilation caused by shear waves), and the porosity may increase leading to the increase of the permeability, so the phase lag will decrease. The phase lag of Fuxin well decreases after the earthquake (L1=2 hours, l2=1 hour), which indicates the permeability increases after the shakig of the earthquake, this is also in accordance with the mechanism analysis of the co-seismic water level increase in Fuxin well.

5. Discussion and conclusion

Our analysis is not conflict with any of those existing theories. Although those water level changes happened in the intermediate and far fields, most of those water levels present abrupt and obvious co-seismic changes owing to the huge energy of M_s 8.0 Wenchuan earthquake. From the study we can conclude: consolidation (decrease of porosity and permeability) attribute to the redistribution of particles in apertures induced by shaking of teleseismic waves, may account for much of the mechanism of those abrupt coseismic water level increases. While, fracture clearing and increased permeability may be used to explain part of those coseismic water level decreases and a little part of the coseismic water level increases, especially the more gradual water level increases in this area. Other water level decreases may be attributed to the dilatation caused by the transmission of shear waves.

From the analysis of Fuxin well, we can see a consolidation with large enough energy may also incur an enhanced permeability by overcoming the capillary entrapment in porous channels or by fracture clearing. So as discussed by Liu and Manga (2009), permeability changes (either increases or decreases) owing to dynamic stresses are a reasonable explanation for earthquake-induced hydrologic responses to earthquakes. The mechanisms analyzed in this paper are similar to the experiment results of Liu and Manga (2009), and our in-situ analysis may complement the limitation of the initial condition of their laboratory experiments. However, both of our results seem different from the results of Elkhoury *et al.* (2006), since we and Liu and Manga (2009) all use the undrained condition, while work of Elkhoury *et al.* (2006) are under drained condition (Owing to the long-wavelength of seismic waves, natural geological materials experience time varying stress under undrained conditions (Liu and Manga, 2009)) .

In reality, the shear modulus G and the undrained Poisson's ratio ν_u would change slightly after the shaking of seismic waves, and the discussed "undrained" condition can hardly last for a long time, as long as the fluid flow exists, the undrained condition will disrupt and be replaced by the drained condition soon. We assume the results get from sandstone can be applied to all those bedrocks in those wells (Figure 3), however this is not very precise. As described by Wang (1993) nonlinear compaction effects can be significant and they are not incorporated in the linear theory presented here, because the well aquifers are under lithostatic pressures for a long time and withstand large numbers of seismic shaking, the irreversible deformations and the nonlinear effects have been minimized (In the laboratory experiment, in order to reduce the irreversible deformation and to minimize the nonlinear effects, repeated pressure cycles are always applied on rock samples as preconditions (Hart and Wang, 1995; Blocher *et al.*, 2009)). Discard all those ideal assumptions, things may be different. Further studies need to be carried out, so as to clarify those mechanisms more precisely.

6. Data and Resources

Data used in this paper were collected using a classified network (Groundwater Monitoring Network, GMN) of the China Earthquake Networks Center and cannot be released to the public. We use the Mapseis software (Lu *et al.*, 2002) to calculate the tidal strain data.

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Table 1. Water Level Changes, Pre- and Post- Earthquake *B* Values, Shear Modulus, phase lags, well depths and effective pressures of the bedrocks of those well Picked Stations. L1 and L2 represent the pre- and post- earthquake phase lags (the lag of piezometer water level behind the tidal strain induced aquifer pressure) separately .

Station	Epicentral Distance /km	Pre-Earthquake B	Post-Earthquake B	Water Level Change/m	Lithology	Shear Modulus G*/Gpa	Phase lag/hour	Well Depth/m	Range of Effective Pressure/MPa
(a) Xiaxian	465.9465	0.0123	0.0149	0.106	Gneiss	40	L1=L2=0	168	0～3
(b) Mile	726.4589	0.0872	0.1103	0.579	Limestone	20	L1=L2=-6	614	3～5
(c) Qinxianmanshui	983.8517	0.0557	0.0653	0.172	Sandstone	8	L1=L2=-2	240.05	0～3
(d) Xiaoyi	1062.0768	0.1493	0.186	0.398	Sandstone	8	L1=L2=0	502.47	0～3
(e) Qixian	1152.6034	0.0906	0.0153	0.831	Limestone	20	L1=0 L2=-3	410	0～3
(f) Hejiazhuang	1582.0754	0.0678	0.0851	0.063	Granite	28	L1=-1 L2=-2	301.04	0～3
(g) Jurong	1750.2357	0.124	0.1282	0.263	Sandstone	8	L1=L2=0	889.18	8～10
(h) Huanghua	1786.978	0.1897	0.1417	0.594	Sandstone	8	L1=L2=0	250.59	0～3
(i) Wafangdianloufang	1801.5625	0.1252	0.1677	0.478	Granite	28	L1=L2=0	224.5	0～3
(j) Haiyuanganyanchi	606.402	0.0407	0.0395	-0.036	Sandstone	8	L1=L2=0	306.73	0～3
(k) Guyuanzhenqi	638.7904	0.0026	0.0047	-0.026	Sandstone	8	L1=L2=0	618.39	3～5
(l) Kaiyuan	805.4263	0.0724	0.077	-0.155	Limestone	20	L1=L2=0	224	0～3
(m) Meizhou	1345.951	0.0873	0.0823	-0.075	Quartzite	20	L1=L2=0	338.86	0～3
(n) Zuojiazhuang	1354.8715	0.2137	0.3461	-1.917	Limestone	20	L1=-2 L2=0	2600	20～25
(o) Chaohu	1587.6013	0.091	0.0798	-0.455	Limestone	20	L1=L2=0	331	0～3
(p) Yongchun	1745.9768	0.6855	0.8854	-1.64	Granite	28	L1=L2=-5	5	0～3

G* see Yan Zhang and Fuqiong Huang (2011).

Figure 1. The well selected 17 stations with distinct amplitude co-seismic water level

changes during the Wenchuan earthquake in mainland China. The well numbers are in accordance with the numbers listed in Table 1.

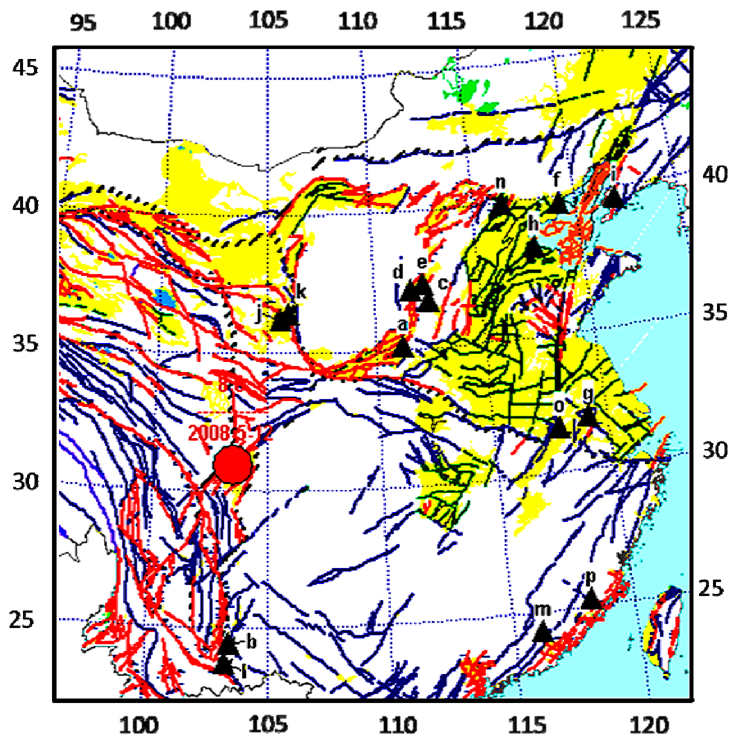
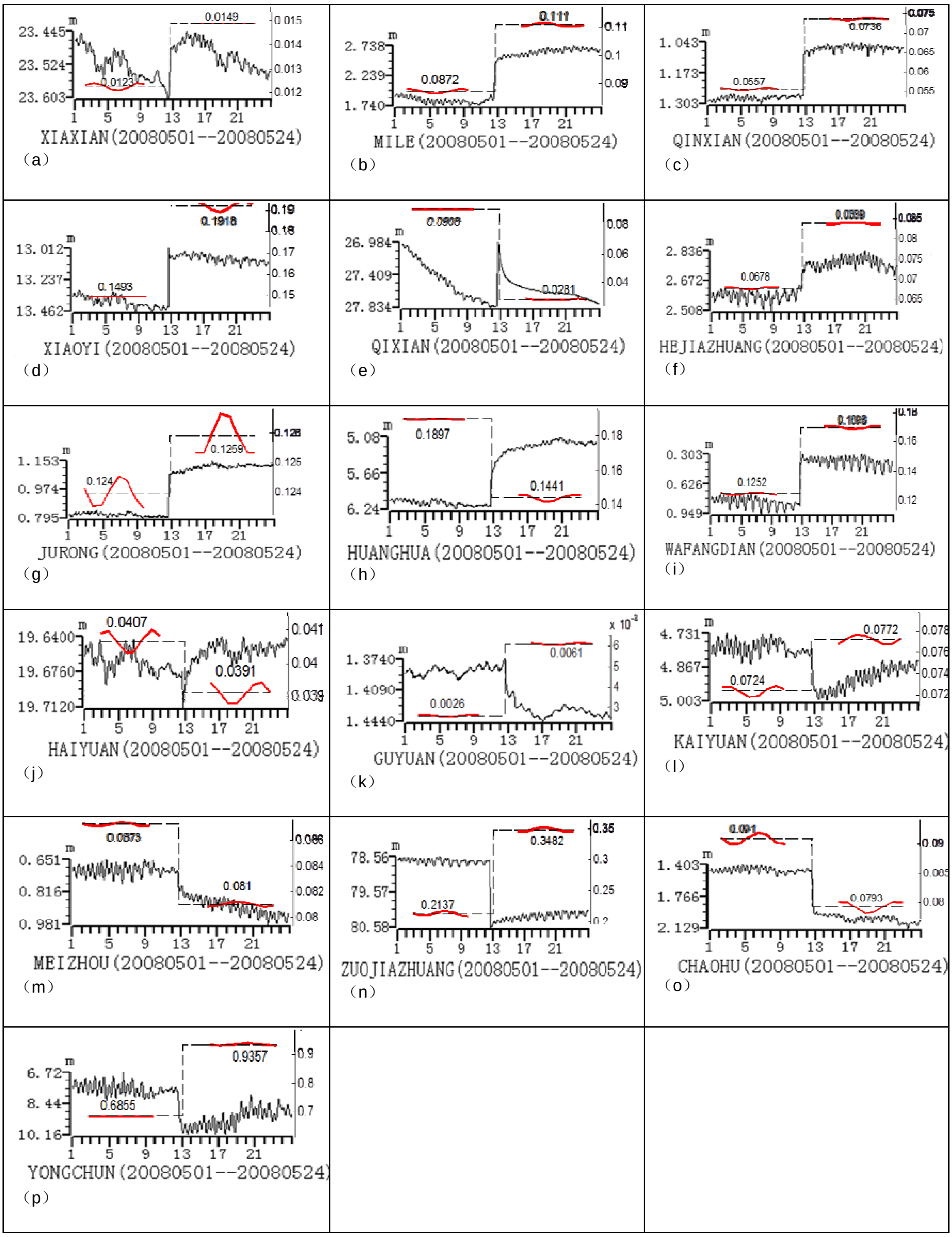
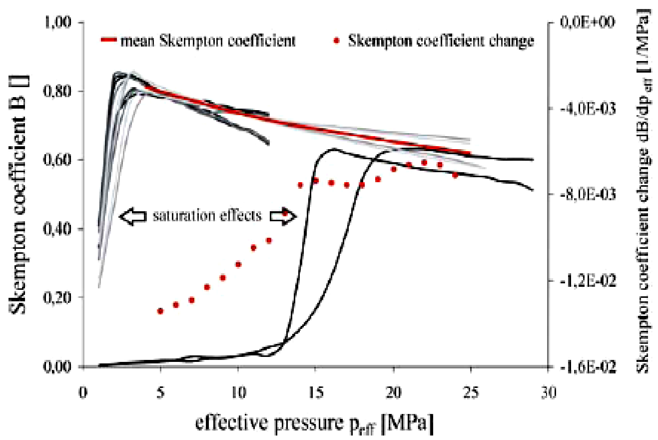


Figure 2. (A) Left y-coordinate: original water levels, the sequential number of y-coordinate depends on the type of the well, "sequential number increase from low to high" indicates an artesian well, the coordinate value means the height from the free water surface to the artesian discharge point or to the ground. "Sequential number decrease from low to high" indicates a non-artesian well, and the coordinate value means the depth from the free water surface to the ground. All the ascendant/ descendent patterns in the picture indicate water level ascending/ descending. (B) Right y-coordinate: the calculated Skempton's coefficient *B*. Red curves indicate the continuous *B* values both pre- and post- earthquake. The dashed lines indicate the mean *B* values, which are clearly shown in numbers.

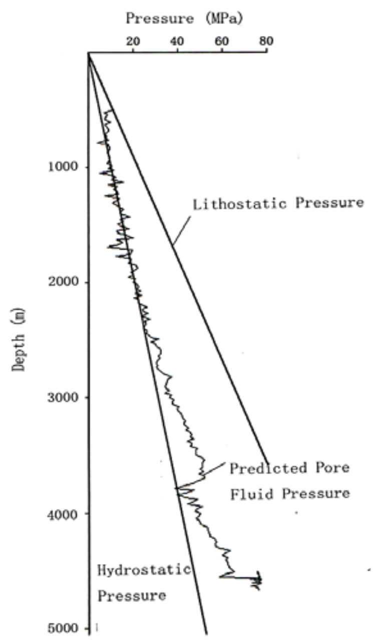


XIAXIAN (20080501--20080524)
(a)
MILE (20080501--20080524)
(b)
QINXIAN (20080501--20080524)
(c)
XIAOYI (20080501--20080524)
(d)
QIXIAN (20080501--20080524)
(e)
HEJIAZHUANG (20080501--20080524)
(f)
JURONG (20080501--20080524)
(g)
HUANGHUA (20080501--20080524)
(h)
WAFANGDIAN (20080501--20080524)
(i)
HAIYUAN (20080501--20080524)
(j)
GUYUAN (20080501--20080524)
(k)
KAIYUAN (20080501--20080524)
(l)
MEIZHOU (20080501--20080524)
(m)
ZUOJIAZHUANG (20080501--20080524)
(n)
CHAOHU (20080501--20080524)
(o)
YONGCHUN (20080501--20080524)
(p)

Figure 3. (a) Skempton's coefficient *B* measured for Flechtinger sandstone as a function of effective pressure. The color from black to light grey indicates the chronological sequence of the experiment. The vertical branches of the curves are due to a saturation deficit. The dots indicate the Skempton's coefficient change over an effective pressure interval of 1 MPa (Blocher *et al*., 2009). (b) Pressure section of well YC21-1-1 in Ying-qiong basin get from the "equilibrium depth" method, the main bedrock of Ying-qiong basin is sandstone (Wang and Luo, 2004).

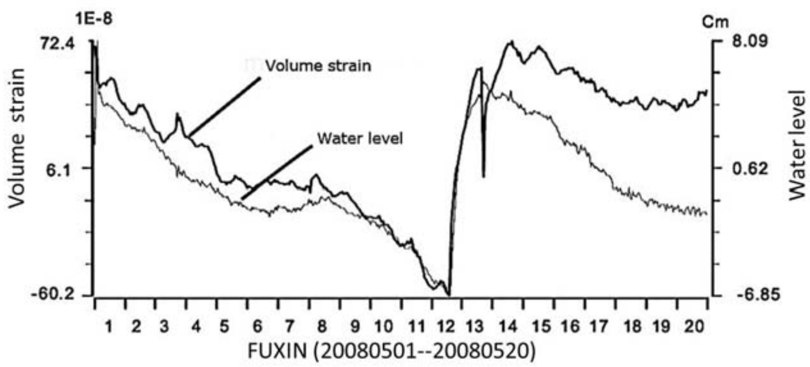


(a)

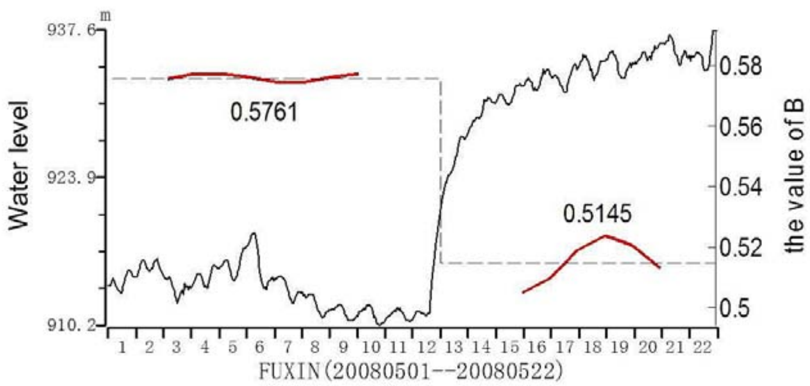


(b)

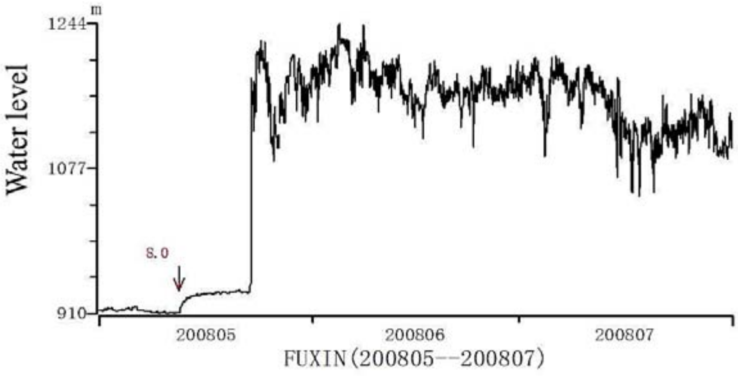
Figure 4. Fuxing well (a) Corrected water level and volume strain after removing the influence of atmospheric pressure and tidal srain (based on the harmonic analysis method). In order to avoid the interfere of thunder, there is a power cut protection on 13 May, which is in accordance with the break point of the volume strain in the figure (Huang, 2008). (b) Original water level and the pre- and post- earthquak Skempton's coefficient *B*. (c) Original water level of Fuxin well form May, 2008 to July 2008.



(a)



(b)


m
1244
1077
910
Water level
S.0
200805
200806
200807
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(c)

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