Bulletin of the Seismological Society of America

Studies of mechanism for water level changes induced by teleseismic waves

--Manuscript Draft--

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Full Title:	Studies of mechanism for water level changes induced by teleseismic waves
Corresponding Author:	Yan Zhang, Ph.D. Institute of Geology and Geophysics, Chinese Academy of Sciences Beijing, CHINA
Corresponding Author's Institution:	Institute of Geology and Geophysics, Chinese Academy of Sciences
Corresponding Author E-Mail:	eve_041744@163.com
Order of Authors:	Yan Zhang, Ph.D.
	Li-Yun Fu
	Fuqiong Huang
	Yuchuan Ma
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. Some of those abrupt coseismic water level changes, for which the variation of the co-seismic water level, Skempton's coefficient B and the effective pressure preserve uniformity (all increase or all decrease) are found to favor the con solidation/dilatation induced by the shaking of teleseismic waves. While the other part of those coseismic water level changes, 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, and most of those wells lie in basins or in hollows, where the aquifer medium is relatively stiff.
Author Comments:	Although coseismic water level changes induced by teleseismic waves have been widely studied, the mechanism responsible for the changes are usually obscure. We invoke the Skempton's coefficient B in this paper to explore the mechanism.
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.
Opposed Reviewers:	Yaowei Liu he has a conflict with one of the author
Response to Reviewers:	I will include this information in files that will be uploaded.

BSSA-D-12-00360
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Dear Yan Zhang,

Your paper referenced above has been reviewed for publication in BSSA. In light of the referees' comments, which appear below, the Editorial Board has decided that significant revisions are required to render the paper acceptable for publication. Due to the level of revisions needed, an additional round of reviews may be required. Please consider these comments as you make your revisions, which are due by Apr 08 2013 11:59PM.

To submit a revision, go to http://bssa.edmgr.com/ and log in as an author. Under the menu item Submission Needing Revision, you will find the submission record for this paper.

--1. Submit a detailed response to reviews, including a point-by-point list of changes or rebuttals. During upload of your revised paper, you will find the step "Respond to Reviewers." Entering information in the text box on that page is required; you can enter either the complete responses to reviews or a statement that responses are in an uploaded file. The information in the text box will be available to reviewers. In the "Attach Files" step, you can upload the files labeled "Response to Reviews" and "Annotated Manuscript." Both of those files will be available to reviewers. A file uploaded as "Letter to Editor" will be seen only by the editors.

--2. Submit a clean version of your revised manuscript that includes title page; full affiliation for each author; and double-spaced text. Include a Data and Resources section before the acknowledgments. For detailed guidelines on submission, see http://www.seismosoc.org/publications/BSSA-Editorial/bssa-data-section.html.

--3. Submit figures either within the manuscript file OR as separate files OR together in a PDF file. Include the figure number on the figure itself. If your paper has color figures and you have opted for color online and gray scale in print, you must submit only the color version of each color figure AND ensure that it, its caption, and the text references will be understandable in the print journal. For information on preparing proper figures and on previewing gray-scale versions of color figures, see our guidelines and tutorial at http://www.seismosoc.org/publications/bssa/authors/bssa-art-submissions.php. If you are considering option 1 (which requires that authors pay for color in print), please review the cost of color at http://www.seismosoc.org/publications/bssa/authors/bssa-page-charges.php.

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If you have an electronic supplement, submit it as a Web site as described in our guidelines at http://www.seismosoc.org/publications/esupps.php.

I look forward to hearing from you.

Yours sincerely
Samik Sil, Ph.D.
Associate Editor
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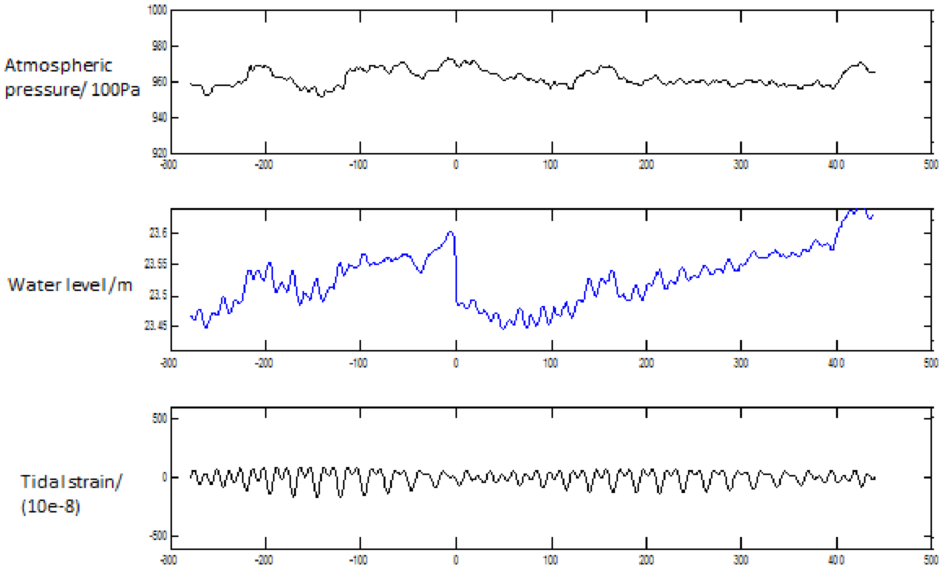

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Change of the Skempton's coefficient *B* can reflect the change of the poro-elastic medium, and the change of the local geology for each well, so we use it to analyze the mechanism of water level changes in this paper. This is the key idea of our paper.

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Some major concerns:

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1. The paper should be grammatically corrected. There are many complex sentences (e.g. page 11 line 233-237…”To our understanding…) which should be made as simple sentences.
   Reply：We have modified those sentences. See: line 186—191.

2. I don’t find any information regarding, well water level data, earthquake and about the area they have studied. Are the wells located on different fault segments with differing hydrological conditions? Although the lithology beneath the wells are given in a table but it is not discussed with reference to the value of B they obtained. Discussion part should be rewritten in view of above.
   Reply：This is a good suggestion, and another reviewer has also proposed this question, so We have added lots of the geology information into our paper, see Table 1, line 224—230, and the discussion See: line 387—405.

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4. How authors can be so sure about the fact that "The spreading of shear waves may cause dilatation of the aquifer medium…for some wells g, j and k. "

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5. A discussion should be there for the step like increase or decrease for all the wells as well as the recovery time. Is there any relation between water level changes and epicentral distance.

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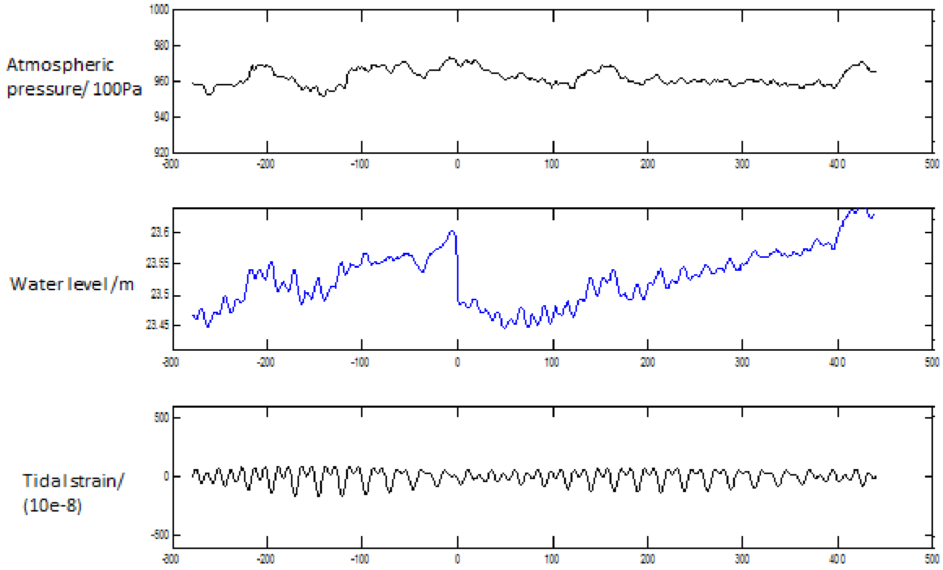

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2. China Earthquake Networks Center, No. 5, Sanlihenanheng Avenue, Beijing100036, China.

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. Some of those abrupt coseismic water level changes, for which the variation of the co-seismic water level, Skempton's coefficient *B* and the effective pressure preserve uniformity(all increase or all decrease)are found to favor the con solidation/dilatation induced by the shaking of teleseismic waves. While the other part of those coseismic water level changes, 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, and most of those wells lie in

basins or in hollows, where the aquifer medium is relatively stiff.

Introduction

Various hydrologic responses to earthquakes have been documented (Kayen *et al.*, 2004; Elkhoury *et al.*, 2006; Sil and Freymueller, 2006; Chadha *et al.*,2008), many occurred at great distances from the ruptured fault where static stress changes are relatively small (Huang, 2008; 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). Liu and Manga (2009) indicate that significant water level changes can be driven at great distances by moderate-amplitude dynamic (time-varying) stresses. Chadha *et al.* (2008) find wells appear to respond to regional strain variations and transient changes due to distant earthquakes. Sil and Freymueller (2006) developed an empirical relationship between water level changes induced by teleseismic waves, epicentral distances and earthquake magnitude, and concluded that ground shaking induced by surface waves was sufficient to change far-field water levels.

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 decreases after shaking.

In the present study, we use the Skempton’s coefficient *B*, the co-seismic water level and the inferred effective pressure 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 post earthquake (which are two independent quasicstatic processes). From the research we find: Consolidation/dilatation induced by shaking of teleseismic waves, may account for the mechanism of those abrupt coseismic water level changes, for which the variations of the co-seismic water level, Skempton’s coefficient *B* and the effective pressure preserve uniformity. While, the other part of those coseismic water level changes, for which the co-seismic water level and the effective pressure change with inconformity (most of those wells stay in basins with relatively stiff aquifer matrixes) may be explained with the increased permeability caused by teleseismic waves, which in turn lead to the redistribution of pore pressure.

Selection Principles and Observation

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 (Appendix). In addition, we didn’t take into account the oceanic tides that has been known to have an effect several tens of kilometers away from the seashore (Beaumont and Berger, 1975). The deformation caused by ocean tide loading is difficult to calculate, these tides appear with the same frequencies as the solid earth effects (Khan and Scherneck, 2003), and the tides are strongly affected by the complicated topography around the seashore (Walters and Goring, 2001), so we can’t simply to calculate the ocean tides by theory models. Besides, there are no public software to calculate the China national offshore ocean tides, so we have to delete those wells (4 wells: Hejiazhuang, Huanghua, Wafangdianloufang amd Yongchun) which may be influenced by the ocean tides seriously. Bearing those rules in mind, we find 11 stations (well a to well k (Figure 1)) can be chosen during the Wenchuan earthquake (Table 1).

Detailed basic information of each well are show in Table 1 , including well depth, well diameter, aquifer lithology, and geological structure. However, diameter of well g, h and j can not be found. The detailed borehole columnar diagrams (borehole columnar diagram of well b, g, h, i, and j can not be found) are not show in this paper, which will possess so much space, but they can help us to obtain more information of the aquifer lithology. All the water level recording instruments in those wells (well a to well k) are digital, they are LN-3A digital water level instrument (except for Mile well it uses LN-4A digital water level instrument, and Fuxin well uses the SQ digital water level instrument), with the observation accuracy≤0.2% F.S. , and the sampling rate of 1/min, the resolution ratio is 1mm. We use the Mapseis software (Lu *et al.*, 2002) to calculate the tidal strain data (hourly data). In order to keep in accordance, both the water level and the tidal strain use the hourly data.

Intermediate and Far Field Analysis

Assumptions of shear modulus and Poisson's ratio and the calculation of Skempton's coefficient *B*

Calculations are performed using $\rho = 1000 kg/m^3$, $g = 9.8 m/s^2$, and $\nu_u = 0.29$ according to equation (5). 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). In addition, based on the poroelastic theory, and limited to isotropic conditions, Theo *et al.*(2002) aim to determine the elastic material constants of the solid matrix with two level of porosities. As it is not possible to experimentally determine the elastic material constants of the solid matrix at these levels, a theoretical approach is presented, based on experimental data taken from literature. They find different porosities lead to different values of elastic modulus. Their results indicate that the variation extents of Skempton's coefficient *B* and the bulk modulus are much larger than the drained and undrained poisson's ratios (variation extent of *B*: 6.3% ; variation extent of K: 7.96% variation extent of ν_u: 0.3%). So we can approximately assume that compared to the variations of the porous medium modulus (the bulk modulus and Skempton's coefficient *B*), the change of the undrained poisson's ratio can be neglected before and after the earthquake.

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 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).

We apply the *B*-calculation method (Appendix) 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).

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

When the aquifer be consolidated, the effective pressure (effective pressure = confining pressure - pore pressure) will increase, while a dilation is in accordance to the decrease of effective pressure. Blocher *et al.* (2009) measured the relationship between Skempton's coefficient *B* and effective pressure based on the laboratory experiment. The in-situ aquifer of those wells (well a～k) we studied 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 (apply more than once pressure cycles on the rock) rather than the first ramp (apply the first pressure cycle on the rock, during which a possible dissolution of gas in the fluid of an incompletely saturated sample happened) in the experiment of Blocher *et al.* (2009), 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). 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.

In order to compare with the experiment results, we have to estimate the effective pressure of each well. 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 1km. W-1 well lies in Yanchang basin of Gansu province,Yanchang basin is a deep basin with Paleozoic sediments (Wu *et al.*, 2010). The "pressure - depth" relation of well

W-1 (Figure 3a) is similar to other wells in the Chinese mainland. So we assume those results could be applied to these wells we studied (well a ~ k) since we lack the "pressure-depth" predictions of these wells. We calculate the effective pressure of W-1 well (effective pressure approximately equals to lithostatic pressure minus pore fluid pressure) (Figure 3b), and estimate the range of the effective pressure of these wells we studied according to the well-depth (Table 1).

We calculated the change of pore pressure in each well ($\Delta P_p = \rho g \Delta h$), together with the range of the effective pressure, the variation trend of Skempton's coefficient *B*, and the *B*-effective pressure relation obtained by the experiment of Blocher *et al.* (2009), we can infer the variation of the effective pressure in each well (Table 2, Table 3). When the range of the effective pressure lies in 0-3 Mpa (most of the wells), the increase/decrease of *B* accompanied with the increase/decrease of effective pressure. When the range of effective pressure >5 Mpa, the increase/decrease of *B* accompanied with the decrease/increase of effective pressure Blocher *et al.* (2009), only the effective pressure of Jurong well (well f) lies in this range (Table 3).

Mechanism analysis

Coseismic water level change induced by consolidation or dilatation

Water level increase/decrease accompanied with the increase/decrease of Skempton's coefficient *B* and the increase/decrease of effective pressure in well a, b, c, d, g, j, and k (Table 2). To our understanding, suppose the pressure not exceed a limitation (the fissures not be closed), when the aquifer be consolidated/ dilatated, the mean fracture width (the porosity and permeability) may decrease/increase with the increase/decrease of the effective pressure, then the stiff rock matrix that supports the load could with a higher/lower coupling to the fluid (Nur and Byerlee, 1971), and the value of *B* will increase/decrease.Which indicating shaking induced by the transmission of teleseismic waves may cause consolidation/dilatation of the aquifer, and lead to the increase/decrease of the water level (effective pressure). Figure 4 shows the relation between the change of Skempton's coefficient *B* and the change of effective pressure (pore pressure/water level) in well a, b, c, d, g, j, and k . Approximately, it displays a linear relation.

Coseismic water level change induced by increased permeability

Water level decrease/increase accompanied with the increase/decrease of Skempton's coefficient *B* and the increases/decrease of effective pressure in well e, h, and i (Table 3). Fracture clearing (unclogging) and increased permeability may be used to explain this phenomenon. 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/lower 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/increase the pore-pressure in those wells (the pore-pressure will shift to/shift from other places), and water level will decrease/increase. Then the effective pressure will increase/decrease accompanied with the decrease/increase of pore-pressure, so the Skempton's coefficient *B* increase (which indicates the stiff rock matrix could with a higher coupling to the fluid) in well e, and decrease (which indicates the stiff rock matrix could with a lower coupling to the fluid) in well h and i (Table 3).

The depth of well f (889.18 m) is larger than other wells, and the effective pressure range of this depth is 8～10 MPa (Table 3). Effective pressure decreases accompanied with the Skempton's coefficient *B* increases in this range (Blocher *et al.*, 2009). So water level increases with the decreases of effective pressure in this well, and this should be explained with the increased permeability. Pore-pressure of well f may be lower than other places before the earthquake, an enhancement of permeability will increase the pore-pressure in this well (the pore-pressure may shift from other places), and water level will increase. Then the effective pressure will decrease accompanied with the increase of pore-pressure, so the Skempton's coefficient *B* increase.

The local geological structure of each well is important (Table 1), We just find that most of those wells in which permeability increase induced by shaking of teleseismic waves, stay in basins or in hollows (well e, f, h, i and Fuxin), which may be attributed to the relatively solid formation and the stiff aquifer medium of the basin or hollow, and the deformation (consolidation or dilatation) will not easily to be incurred, then the energy of shaking may be inclined to induce the fracture clearing (unclogging) so as to increase permeability.

Examples support far field water level increases induced by consolidation

The spreading of shear waves may cause dilatation of the aquifer medium, which can broaden the porosities and give birth to new fractures, and the effective pressure will reduce (in wells: g, j and k, the effective pressure range is 0～3 MPa) leading to the decrease of Skempton's coefficient *B*. This explanation is similar to the mechanism of shaking-induced dilatancy (Bower and Heaton, 1978). So it may be easier to understand weater level decreases in the far field induced by the transmission of teleseismic waves. However, water level increases induced by consolidation in the far field is not the mainstream view. Since many cases support the theory of the increased permeability, it is necessary to give some examples which can 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, 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 (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 basalt is the bedrock and we assume the shear modulus = 60 Gpa) is induced by the increase of volume strain (consolidation) (Figure 5a). 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 show 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 5b)). (The large-step abrupt water level increase starts from 09 p.m. May 22, 2008 (Figure 5c), which may cause large impact on the detrend process and influence the calculation result, so we just discard these data). From Figure 5a, 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 (Table 3), from the change of the pre- and post- earthquake *B* (Figure 5b), 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, 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 5c). From the picture we can see it may be in a drained condition after the abrupt large-amplitude water level increase, because the water level fluctuates irregularly.

So we argue that 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.

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 strain and atmospheric pressure, and according to the <China earthquake monitoring records series> (which is written by different Subordinate units (earthquake administration of each provinces and different institutions) of China Earthquake Administration, and published in Beijing in different years by Seismological Press (in Chinese)) they are well confined. From Table 1 we can see the phase difference of water level and tidal strain of most wells are 0, which mean good correlations between the water levels and the tidal strains, 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). Phase lags ≧ 1 hour in well: b, c, e, and Fuxin, and most of them are small, except well b, which may be semi-confined. Thus, the validity of the calculated *B* values in well b may be a little questionable. 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 in accordance with the mechanism analysis of the co-seismic water level increase in Fuxin well.

Discussion

The variation of porosity

Figure 3c shows, in general, the porosity decreases with the increase of depth, however, when reach 3000m the effective pressure turns much larger (approximately equals to 35 Mpa) than that in the depth of those wells (well a～k), the porosity still persists relatively large, and changes with different depth. From Table 2 we can see, the variation of effective pressure of well a, b, c, d, g, j and k is less than 0.01Mpa, and from Figure 3b we know, variation of 0.01Mpa in effective pressure approximately equals to variation of 1 meter in depth, as Figure 3c shows, the variation of porosity is tiny during variation of 1 meter in depth. So this variation extent of effective pressure is hard to induce permanent deformation of porosity. However, in reality, the change of porosity may also connected with the formation and the state of the rock matrix.

Furthermore, phase lags of well a, b, c, d, g, j and k keep constant before and after the earthquake (change less than 1 hour) (Table (1)), so we can infer, the porosity (permeability) change little after the earthquake. Because the phase lags increase/decrease (wellbore storage effects increase/decrease) as the permeability (porosity) of the formation decreases/increase (Roeloffs, 1996; Doan *et al.*, 2006).

So we can infer, the porosity of well a, b, c, d, g, j and k can persist despite being reduced/enlarged due to the consolidation/dilatation induced by the passage of teleseismic waves of M_s 8.0 Wenchuan earthquake.

Uncertainty of *B* coefficient

In order to study the uncertainty of *B* coefficient (error related to the determination of *B* coefficient), we use Jurong well to show the variation of *B* during a relatively long – time span (50 days before and after the Wenchuan earthquake) (Figure 6). Skempton's coefficient *B* will change with the change of time. Because we use the least square fit to calculate *B*, the value may be a little different when we use diffenent length of data , but the change tendency (increase or decrease of *B*) before and after the earthquake will be constant. Furthermore, we can see the *B* value of Jurong well recover to its initial value after about 30 days (Figure 6).

So, compared with the uncertainty in *B* value, variation of *B* due to the earthquake is significant. The continuous of *B* will be influenced by lots of factors, such as power off, aftershocks, and so on, so *B*-value series at large time scale is not easy to obtain for each well.

Recovery of Water level

The recovery time of the water level is obscure, because most of those water level will not recover to the same height as the pre-earthquake level during a relatively short time span. So we should use much longer data to analyze it, and should discard all those influences: such as aftershocks, atmospheric pressure (not all those wells have the records of atmospheric pressure) , tidal strain, pumping, power off, thounder and so on, which needs lots of work, and we may study about it in future. In addition, we haven’t find any relation between water level changes and epicentral distances in those wells studied in this paper, it is possible to investigate much more wells later, to study about the relations.

The variation value of effective pressure

We calculated the change of pore pressure ($\Delta p_p = \rho g \Delta h$), and we can use the critical state to help us to analyze the variation value of effective pressure in each well.

When the aquifer be consolidated/dilated, in the critical state, the pore pressure keeps constant, the confinging pressure increase /decrease, then the effective pressure increase/decrease, and at last transfer into the increase/decrease of pore pressure (water level increase/decrease), and the system come into an equilibrium state. So the change of pore pressure can be attributed to the change of the effective pressure.

When the permeability increase, in the critical state, the confining pressure keeps constant, the pore pressure (water level) increase (the well in a relatively low pressure region before the earthquake) /decrease (the well in a relatively high pressure region before the earthquake), then the effective pressure decrease/increase, so the change of the effective pressure can be attributed to the change of pore pressure.

However , the variation value of the effective pressure of each well may be different from the value we calculate, because the critical state is an assumption ideal state, and the transfer of stress may also relate with the formation and state of the aquifer.

Impact of local geology

We just find that most of those wells in which permeability increase induced by shaking of teleseismic waves, stay in basins or in hollows (well e, f, h, i and Fuxin), which may be attributed to the relatively stiff aquifer of those basins or hollows, but we still lack direct evidence to testify that. As indicated by the reviewer, the seismograms may be helpful. There are 48 national stations recording the seismograms (event waveforms) in the Chinese mainland, however most of those stations are not in the same place with \stations which have the records of water level changes. Those stations (well a to k) analyzed in our paper (we analyze the wells in the intermediate and far fields, and those wells near the sea have been discarded) have no records of seismograms, and there are about 40 km between the nearest two stations: Qixian (112.33, 37.36) (has water level records) and Taiyuan (112.434, 37.713) (has seismogram records), so the seismogram could not reflect the real characteristics of the geology near Qixian. It is possible that, in the future, we should focus on several wells (which record both the water level and the seismogram), to reveal the connection between the local geology (some physical parameters may be deduced from the seismogram analysis, and we can see the amplitude (energy) of the waves clearly from the waveforms) and the mechanism of co-seismic water level changes deeply.

Conclusion

Together with the variation of Skempton's coefficient *B*, the change of pore pressure and the inferred variation of effective pressure in each well, we can infer the mechanism of the co-seismic water level changes. From the study we can conclude: consolidation/dilatation induced by shaking of teleseismic waves, may account for the mechanism of those abrupt coseismic water level changes, for which the variation tendency of the co-seismic water level, Skempton's coefficient *B* and the effective pressure keep the same (all increase or all decrease). While, fracture clearing and increased permeability may be used to explain the other part of those coseismic water level changes, for which the co-seismic water level, and the effective pressure change with inconformity, and most of those wells stay in basins with relatively stiff rock matrix. 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 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 reasonable explanations for earthquake-induced hydrologic responses. 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.

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 (Blocher *et al.*, 2009)). Discard all those ideal assumptions, things may be different.

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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Appendix: 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):

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

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

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

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

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):

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

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:

$$B = -\frac{3\rho g(1-2\nu_{\mathrm{u}})}{2G(1+\nu_{\mathrm{u}})}\frac{\Delta h}{\Delta\varepsilon_t} . \tag{5}$$

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). So we can suppose 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*. 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). One thing needs to be clarified: We haven't applied the static equations directly to relate pore pressure changes to seismic waves. We use those static equations for the impact of the tidal strain on the aquifer medium before and after the Wenchuan earthquake, so as to obtain the pre- and post- earthquake Skempton's coefficient *B* (those two periods can be recognized as two independent quasi-static processes), so the poroelastic static equations can be applied.

Studies of mechanism for water level changes induced by teleseismic waves

Yan Zhang[1], Li-Yun Fu [1], Fuqiong Huang[2] and Yuchuan Ma[2]

1. Key Laboratory of the Earth's Deep Interior, Institute of Geology and Geophysics, Chinese Academy of Sciences, No. 19, Beitucheng Western Road, Beijing 100029, China. E-mail: eve_041744@163.com; lfu@mail.iggcas.ac.cn

2. China Earthquake Networks Center, No. 5, Sanlihenanheng Avenue, Beijing100036, China.

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. Some of those abrupt coseismic water level changes, for which the variation of the co-seismic water level, Skempton's coefficient *B* and the effective pressure preserve uniformity(all increase or all decrease)are found to favor the con solidation/dilatation induced by the shaking of teleseismic waves. While the other part of those coseismic water level changes, 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, and most of those wells lie in

basins or in hollows, where the aquifer medium is relatively stiff.

Introduction

Various hydrologic responses to earthquakes have been documented (Kayen *et al.*, 2004; Elkhoury *et al.*, 2006; Sil and Freymueller, 2006; Chadha *et al.*,2008), many occurred at great distances from the ruptured fault where static stress changes are relatively small (Huang, 2008; 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). Liu and Manga (2009) indicate that significant water level changes can be driven at great distances by moderate-amplitude dynamic (time-varying) stresses. Chadha *et al.* (2008) find wells appear to respond to regional strain variations and transient changes due to distant earthquakes. Sil and Freymueller (2006) developed an empirical relationship between water level changes induced by teleseismic waves, epicentral distances and earthquake magnitude, and concluded that ground shaking induced by surface waves was sufficient to change far-field water levels.

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 decreases after shaking.

In the present study, we use the Skempton's coefficient *B*, the co-seismic water level and the inferred effective pressure 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 post earthquake (which are two independent quasicstatic processes). From the research we find: Consolidation/dilatation induced by shaking of teleseismic waves, may account for the mechanism of those abrupt coseismic water level changes, for which the variations of the co-seismic water level, Skempton's coefficient *B* and the effective pressure preserve uniformity. While, the other part of those coseismic water level changes, for which the co-seismic water level and the effective pressure change with inconformity (most of those wells stay in basins with relatively stiff aquifer matrixes) may be explained with the increased permeability caused by teleseismic waves, which in turn lead to the redistribution of pore pressure.

Selection Principles and Observation

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 (Appendix). In addition, we didn't take into account the oceanic tides that has been known to have an effect several tens of kilometers away from the seashore (Beaumont and Berger, 1975). The deformation caused by ocean tide loading is difficult to calculate, these tides appear with the same frequencies as the solid earth effects (Khan and Scherneck, 2003), and the tides are strongly affected by the complicated topography around the seashore (Walters and Goring, 2001), so we can't simply to calculate the ocean tides by theory models. Besides, there are no public software to calculate the China national offshore ocean tides, so we have to delete those wells (4 wells: Hejiazhuang, Huanghua, Wafangdianloufang amd Yongchun) which may be influenced by the ocean tides seriously. Bearing those rules in mind, we find 11 stations (well a to well k (Figure 1)) can be chosen during the Wenchuan earthquake (Table 1).

Detailed basic information of each well are show in Table 1 , including well depth, well diameter, aquifer lithology, and geological structure. However, diameter of well g, h and j can not be found. The detailed borehole columnar diagrams (borehole columnar diagram of well b, g, h, i, and j can not be found) are not show in this paper, which will possess so much space, but they can help us to obtain more information of the aquifer lithology. All the water level recording instruments in those wells (well a to well k) are digital, they are LN-3A digital water level instrument (except for Mile well it uses LN-4A digital water level instrument, and Fuxin well uses the SQ digital water level instrument), with the observation accuracy≤0.2% F.S. , and the sampling rate of 1/min, the resolution ratio is 1mm. We use the Mapseis software (Lu *et al.*, 2002) to calculate the tidal strain data (hourly data). In order to keep in accordance, both the water level and the tidal strain use the hourly data.

Intermediate and Far Field Analysis

Assumptions of shear modulus and Poisson's ratio and the calculation of Skempton's coefficient *B*

Calculations are performed using $\rho = 1000 kg/m^3$, $g = 9.8 m/s^2$, and $\nu_u = 0.29$ according to equation (5). 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). In addition, based on the poroelastic theory, and limited to isotropic conditions, Theo *et al.*(2002) aim to determine the elastic material constants of the solid matrix with two level of porosities. As it is not possible to experimentally determine the elastic material constants of the solid matrix at these levels, a theoretical approach is presented, based on experimental data taken from literature. They find different porosities lead to different values of elastic modulus. Their results indicate that the variation extents of Skempton's coefficient *B* and the bulk modulus are much larger than the drained and undrained poisson's ratios (variation extent of *B*: 6.3% ; variation extent of K: 7.96% variation extent of ν_u: 0.3%). So we can approximately assume that compared to the variations of the porous medium modulus (the bulk modulus and Skempton's coefficient *B*), the change of the undrained poisson's ratio can be neglected before and after the earthquake.

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 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).

We apply the *B*-calculation method (Appendix) 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).

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

When the aquifer be consolidated, the effective pressure (effective pressure = confining pressure - pore pressure) will increase, while a dilation is in accordance to the decrease of effective pressure. Blocher *et al.* (2009) measured the relationship between Skempton's coefficient *B* and effective pressure based on the laboratory experiment. The in-situ aquifer of those wells (well a～k) we studied 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 (apply more than once pressure cycles on the rock) rather than the first ramp (apply the first pressure cycle on the rock, during which a possible dissolution of gas in the fluid of an incompletely saturated sample happened) in the experiment of Blocher *et al.* (2009), 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). 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.

In order to compare with the experiment results, we have to estimate the effective pressure of each well. 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 1km. W-1 well lies in Yanchang basin of Gansu province,Yanchang basin is a deep basin with Paleozoic sediments (Wu *et al.*, 2010). The "pressure - depth" relation of well

W-1 (Figure 3a) is similar to other wells in the Chinese mainland. So we assume those results could be applied to these wells we studied (well a ~ k) since we lack the "pressure-depth" predictions of these wells. We calculate the effective pressure of W-1 well (effective pressure approximately equals to lithostatic pressure minus pore fluid pressure) (Figure 3b), and estimate the range of the effective pressure of these wells we studied according to the well-depth (Table 1).

We calculated the change of pore pressure in each well ($\Delta P_p = \rho g \Delta h$), together with the range of the effective pressure, the variation trend of Skempton's coefficient *B*, and the *B*-effective pressure relation obtained by the experiment of Blocher *et al.* (2009), we can infer the variation of the effective pressure in each well (Table 2, Table 3). When the range of the effective pressure lies in 0-3 Mpa (most of the wells), the increase/decrease of *B* accompanied with the increase/decrease of effective pressure. When the range of effective pressure >5 Mpa, the increase/decrease of *B* accompanied with the decrease/increase of effective pressure Blocher *et al.* (2009), only the effective pressure of Jurong well (well f) lies in this range (Table 3).

Mechanism analysis

Coseismic water level change induced by consolidation or dilatation

Water level increase/decrease accompanied with the increase/decrease of Skempton's coefficient *B* and the increase/decrease of effective pressure in well a, b, c, d, g, j, and k (Table 2). To our understanding, suppose the pressure not exceed a limitation (the fissures not be closed), when the aquifer be consolidated/ dilatated, the mean fracture width (the porosity and permeability) may decrease/increase with the increase/decrease of the effective pressure, then the stiff rock matrix that supports the load could with a higher/lower coupling to the fluid (Nur and Byerlee, 1971), and the value of *B* will increase/decrease.Which indicating shaking induced by the transmission of teleseismic waves may cause consolidation/dilatation of the aquifer, and lead to the increase/decrease of the water level (effective pressure). Figure 4 shows the relation between the change of Skempton's coefficient *B* and the change of effective pressure (pore pressure/water level) in well a, b, c, d, g, j, and k . Approximately, it displays a linear relation.

Coseismic water level change induced by increased permeability

Water level decrease/increase accompanied with the increase/decrease of Skempton's coefficient *B* and the increases/decrease of effective pressure in well e, h, and i (Table 3). Fracture clearing (unclogging) and increased permeability may be used to explain this phenomenon. 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/lower 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/increase the pore-pressure in those wells (the pore-pressure will shift to/shift from other places), and water level will decrease/increase. Then the effective pressure will increase/decrease accompanied with the decrease/increase of pore-pressure, so the Skempton's coefficient *B* increase (which indicates the stiff rock matrix could with a higher coupling to the fluid) in well e, and decrease (which indicates the stiff rock matrix could with a lower coupling to the fluid) in well h and i (Table 3).

The depth of well f (889.18 m) is larger than other wells, and the effective pressure range of this depth is 8～10 MPa (Table 3). Effective pressure decreases accompanied with the Skempton's coefficient *B* increases in this range (Blocher *et al.*, 2009). So water level increases with the decreases of effective pressure in this well, and this should be explained with the increased permeability. Pore-pressure of well f may be lower than other places before the earthquake, an enhancement of permeability will increase the pore-pressure in this well (the pore-pressure may shift from other places), and water level will increase. Then the effective pressure will decrease accompanied with the increase of pore-pressure, so the Skempton's coefficient *B* increase.

The local geological structure of each well is important (Table 1), We just find that most of those wells in which permeability increase induced by shaking of teleseismic waves, stay in basins or in hollows (well e, f, h, i and Fuxin), which may be attributed to the relatively solid formation and the stiff aquifer medium of the basin or hollow, and the deformation (consolidation or dilatation) will not easily to be incurred, then the energy of shaking may be inclined to induce the fracture clearing (unclogging) so as to increase permeability.

Examples support far field water level increases induced by consolidation

The spreading of shear waves may cause dilatation of the aquifer medium, which can broaden the porosities and give birth to new fractures, and the effective pressure will reduce (in wells: g, j and k, the effective pressure range is 0～3 MPa) leading to the decrease of Skempton's coefficient *B*. This explanation is similar to the mechanism of shaking-induced dilatancy (Bower and Heaton, 1978). So it may be easier to understand weater level decreases in the far field induced by the transmission of teleseismic waves. However, water level increases induced by consolidation in the far field is not the mainstream view. Since many cases support the theory of the increased permeability, it is necessary to give some examples which can 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, 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 (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 basalt is the bedrock and we assume the shear modulus = 60 Gpa) is induced by the increase of volume strain (consolidation) (Figure 5a). 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 show 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 5b)). (The large-step abrupt water level increase starts from 09 p.m. May 22, 2008 (Figure 5c), which may cause large impact on the detrend process and influence the calculation result, so we just discard these data). From Figure 5a, 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 (Table 3), from the change of the pre- and post- earthquake *B* (Figure 5b), 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, 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 5c). From the picture we can see it may be in a drained condition after the abrupt large-amplitude water level increase, because the water level fluctuates irregularly.

So we argue that 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.

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 strain and atmospheric pressure, and according to the <China earthquake monitoring records series> (which is written by different Subordinate units (earthquake administration of each provinces and different institutions) of China Earthquake Administration, and published in Beijing in different years by Seismological Press (in Chinese)) they are well confined. From Table 1 we can see the phase difference of water level and tidal strain of most wells are 0, which mean good correlations between the water levels and the tidal strains, 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). Phase lags ≧ 1 hour in well: b, c, e, and Fuxin, and most of them are small, except well b, which may be semi-confined. Thus, the validity of the calculated *B* values in well b may be a little questionable. 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 in accordance with the mechanism analysis of the co-seismic water level increase in Fuxin well.

Discussion

The variation of porosity

Figure 3c shows, in general, the porosity decreases with the increase of depth, however, when reach 3000m the effective pressure turns much larger (approximately equals to 35 Mpa) than that in the depth of those wells (well a～k), the porosity still persists relatively large, and changes with different depth. From Table 2 we can see, the variation of effective pressure of well a, b, c, d, g, j and k is less than 0.01Mpa, and from Figure 3b we know, variation of 0.01Mpa in effective pressure approximately equals to variation of 1 meter in depth, as Figure 3c shows, the variation of porosity is tiny during variation of 1 meter in depth. So this variation extent of effective pressure is hard to induce permanent deformation of porosity. However, in reality, the change of porosity may also connected with the formation and the state of the rock matrix.

Furthermore, phase lags of well a, b, c, d, g, j and k keep constant before and after the earthquake (change less than 1 hour) (Table (1)), so we can infer, the porosity (permeability) change little after the earthquake. Because the phase lags increase/decrease (wellbore storage effects increase/decrease) as the permeability (porosity) of the formation decreases/increase (Roeloffs, 1996; Doan *et al.*, 2006).

So we can infer, the porosity of well a, b, c, d, g, j and k can persist despite being reduced/enlarged due to the consolidation/dilatation induced by the passage of teleseismic waves of M_s 8.0 Wenchuan earthquake.

Uncertainty of *B* coefficient

In order to study the uncertainty of *B* coefficient (error related to the determination of *B* coefficient), we use Jurong well to show the variation of *B* during a relatively long – time span (50 days before and after the Wenchuan earthquake) (Figure 6). Skempton's coefficient *B* will change with the change of time. Because we use the least square fit to calculate *B*, the value may be a little different when we use diffenent length of data , but the change tendency (increase or decrease of *B*) before and after the earthquake will be constant. Furthermore, we can see the *B* value of Jurong well recover to its initial value after about 30 days (Figure 6).

So, compared with the uncertainty in *B* value, variation of *B* due to the earthquake is significant. The continuous of *B* will be influenced by lots of factors, such as power off, aftershocks, and so on, so *B*-value series at large time scale is not easy to obtain for each well.

Recovery of Water level

The recovery time of the water level is obscure, because most of those water level will not recover to the same height as the pre-earthquake level during a relatively short time span. So we should use much longer data to analyze it, and should discard all those influences: such as aftershocks, atmospheric pressure（not all those wells have the records of atmospheric pressure）, tidal strain, pumping, power off, thounder and so on, which needs lots of work, and we may study about it in future. In addition, we haven’t find any relation between water level changes and epicentral distances in those wells studied in this paper, it is possible to investigate much more wells later, to study about the relations.

The variation value of effective pressure

We calculated the change of pore pressure ($\Delta p_p = \rho g \Delta h$), and we can use the critical state to help us to analyze the variation value of effective pressure in each well.

When the aquifer be consolidated/dilated, in the critical state, the pore pressure keeps constant, the confinging pressure increase /decrease, then the effective pressure increase/decrease, and at last transfer into the increase/decrease of pore pressure (water level increase/decrease), and the system come into an equilibrium state. So the change of pore pressure can be attributed to the change of the effective pressure.

When the permeability increase, in the critical state, the confining pressure keeps constant, the pore pressure (water level) increase (the well in a relatively low pressure region before the earthquake) /decrease (the well in a relatively high pressure region before the earthquake), then the effective pressure decrease/increase, so the change of the effective pressure can be attributed to the change of pore pressure.

However , the variation value of the effective pressure of each well may be different from the value we calculate, because the critical state is an assumption ideal state, and the transfer of stress may also relate with the formation and state of the aquifer.

Impact of local geology

We just find that most of those wells in which permeability increase induced by shaking of teleseismic waves, stay in basins or in hollows (well e, f, h, i and Fuxin), which may be attributed to the relatively stiff aquifer of those basins or hollows, but we still lack direct evidence to testify that. As indicated by the reviewer, the seismograms may be helpful. There are 48 national stations recording the seismograms (event waveforms) in the Chinese mainland, however most of those stations are not in the same place with \stations which have the records of water level changes. Those stations (well a to k) analyzed in our paper (we analyze the wells in the intermediate and far fields, and those wells near the sea have been discarded) have no records of seismograms, and there are about 40 km between the nearest two stations: Qixian (112.33, 37.36) (has water level records) and Taiyuan (112.434, 37.713) (has seismogram records), so the seismogram could not reflect the real characteristics of the geology near Qixian. It is possible that, in the future, we should focus on several wells (which record both the water level and the seismogram), to reveal the connection between the local geology (some physical parameters may be deduced from the seismogram analysis, and we can see the amplitude (energy) of the waves clearly from the waveforms) and the mechanism of co-seismic water level changes deeply.

Conclusion

Together with the variation of Skempton's coefficient *B*, the change of pore pressure and the inferred variation of effective pressure in each well, we can infer the mechanism of the co-seismic water level changes. From the study we can conclude: consolidation/dilatation induced by shaking of teleseismic waves, may account for the mechanism of those abrupt coseismic water level changes, for which the variation tendency of the co-seismic water level, Skempton's coefficient *B* and the effective pressure keep the same (all increase or all decrease). While, fracture clearing and increased permeability may be used to explain the other part of those coseismic water level changes, for which the co-seismic water level, and the effective pressure change with inconformity, and most of those wells stay in basins with relatively stiff rock matrix. 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 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 reasonable explanations for earthquake-induced hydrologic responses. 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.

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 (Blocher *et al.*, 2009)). Discard all those ideal assumptions, things may be different.

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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Appendix: 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):

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

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

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

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

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):

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

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:

$$B=-\frac{3\rho g(1-2\nu_{\mathrm{u}})}{2G(1+\nu_{\mathrm{u}})}\frac{\Delta h}{\Delta\varepsilon_t}\,. \tag{5}$$

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). So we can suppose 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*. 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). One thing needs to be clarified: We haven't applied the static equations directly to relate pore pressure changes to seismic waves. We use those static equations for the impact of the tidal strain on the aquifer medium before and after the Wenchuan earthquake, so as to obtain the pre- and post- earthquake Skempton's coefficient *B* (those two periods can be recognized as two independent quasi-static processes), so the poroelastic static equations can be applied.

Table 1. Basic information of well a ~ k.

Station	Epicentral Distance /km	Δh/m	Pre/Post-Earthquake *B*	Major Aquifer Lithology	G*/Gpa	Phase lag/hour	Well Diameter /mm	Well Depth/m	Range of P_{eff}/MPa	Geological Structure
(a) Xiaxian	465.9465	0.106	0.0123/0.0149	Biotite plagioclase gneiss	40	L1=L2=0	559	170.5	0~3	north part of Zhongtiao mountain fault
(b) Mile	726.4589	0.579	0.0872/0.1103	Limestone	20	L1=L2=-6	127	614.4	3~5	Mile—Shizong fault
(c) Qinxianmanshui	983.8517	0.172	0.0557/0.0653	Three of Triassic sandstone	8	L1=L2=-2	134	240.05	0~3	Guocun basin, uplift of Taihang mountain fault block
(d) Xiaoyi	1062.0768	0.398	0.1493/0.186	P2 Sandstone	8	L1=L2=0	150	520.93	0~3	Jiaocheng fault
(e) Qixian	1152.6034	0.831	0.0906/0.0153	Limestone and shale (the Tertiary and Quaternary period loess and gravel)	20	L1=0 L2=-3	146	422.19	0~3	east part of Taiyuan basin
(f) Jurong	1750.2357	0.263	0.0472/0.0519	K2 Silicified sandstone and conglomerate	8	L1=L2=0	219	889.18	8~10	west of Maoshan mountain fault, near the top of the uplift of the buried hill of Jurong hollow
(g) Haiyuanganyanchi	606.402	-0.036	0.0407/0.0395	Q sandstone and conglomerate	8	L1=L2=0		306.73	0~3	west and south of Huashan mountain fault
(h) Guyuanzhenqi	638.7904	-0.026	0.0026/0.0047	Mediate and fine sand	8	L1=L2=0		255.74	0~3	compresso-shear basin, in the east and north part of Haiyuan fault
(i) Kaiyuan	805.4263	-0.155	0.0724/0.077	Triassic Falang formation limestone	20	L1=L2=0	273	224	0~3	south of Xiaojiang fault, east of arc structure top, in the northern part of the basin
(j) Meizhou	1345.951	-0.075	0.0873/0.0823	Quartzite	20	L1=L2=0		338.86	0~3	Heyuan—Shaowu and Chaoan—Meixian fracture intersection
(k) Chaohu	1587.6013	-0.455	0.091/0.0798	The Devonian quartz and limestone	20	L1=L2=0	168	331	0~3	East side of the Tanlu fault, Chuhe river major dislocation and Hefei—Dongguan fracture intersection.
Fuxin	1409.9764	0.121	0.5761/0.5145	Granite, basalt, andesite and clip tuff breccia	60	L1=-2 L2=-1		60.74	0~3	west and north of Fuxin fault basin

Epicentral Distances, Water Level Changes, Pre- and Post- Earthquake *B* Values, Major Lithology of Aquifers, Shear Modulus, Phase Lags, Well Diameters, Well Depths, Ranges of Effective Pressure and Geological Structures 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.

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

Table 2. Coseismic water level changes induced by consolidation or dilatation incurred by shaking of teleseismic waves.

Station	Δh/m	ΔB	ΔP_p/MPa	ΔP_{eff}/MPa	Well Depth/m	Range of P_{eff}/MPa
(a) Xiaxian	0.106	**0.0026**	0.0010	**0.001**	170.5	0～3
(b) Mile	0.579	**0.0231**	0.0057	**0.0057**	614.4	3～5
(c) Qinxianmanshui	0.172	**0.0096**	0.0017	**0.0017**	240.05	0～3
(d) Xiaoyi	0.398	**0.0367**	0.0039	**0.0039**	520.93	0～3
(g) Haiyuanganyanchi	−0.036	**−0.001**	−0.0004	**−0.0004**	306.73	0～3
(j) Meizhou	−0.075	**−0.005**	−0.0007	**−0.0007**	338.86	0～3
(k) Chaohu	−0.455	**−0.011**	−0.0045	**−0.0045**	331	0～3

Water Level Changes, Changes of *B* Value, Calculated Changes of Pore-Pressure ΔP_p, Inferred Changes of Effective Pressure ΔP_{eff}, Well Depths and Ranges of Effective Pressure of those wells.

Table 3. Coseismic water level changes induced by increased permeability.

Station	Δh/m	ΔB	ΔP_p/MPa	ΔP_{eff}/MPa	Well Depth/m	Range of P_{eff}/MPa
(e) Qixian	0.831	**−0.075**	0.0081	**−0.0081**	422.19	0～3
(f) Jurong	0.263	**0.0047**	0.0026	**−0.0026**	889.18	8～10
(h) Guyuanzhenqi	−0.026	**0.0021**	−0.0003	**0.0003**	255.74	0～3
(i) Kaiyuan	−0.155	**0.0046**	−0.0015	**0.0015**	224	0～3
Fuxin	0.121	**−0.0616**	0.0012	**−0.0012**	60.74	0～3

Water Level Changes, Changes of *B* Value, Calculated Changes of Pore-Pressure ΔP_p, Inferred Changes of Effective Pressure ΔP_{eff}, Well Depths and Ranges of Effective Pressure of those wells.

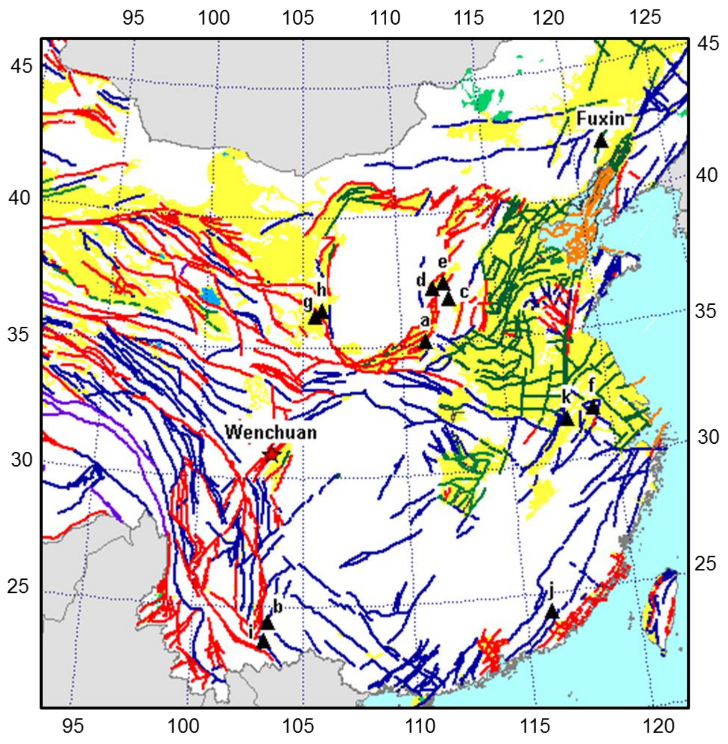
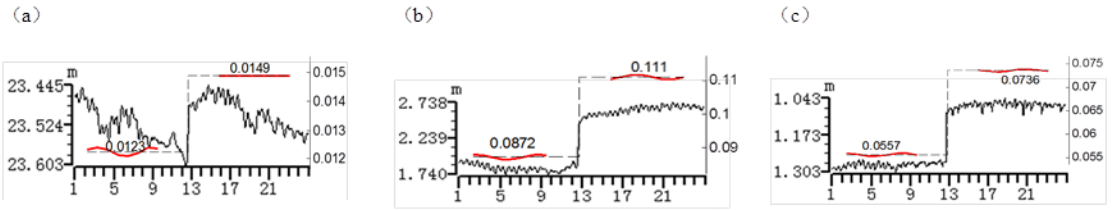
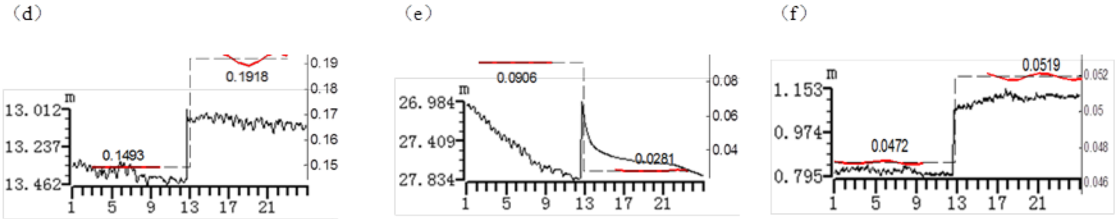


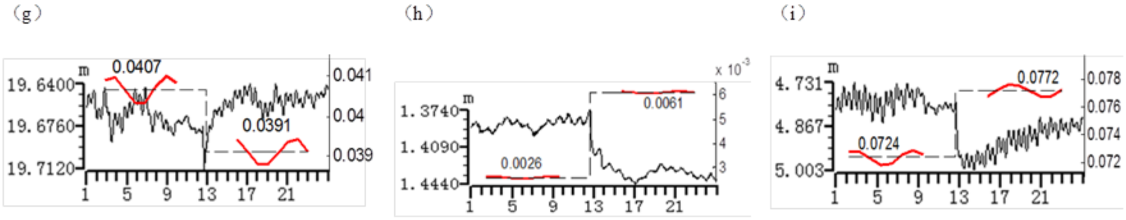
Figure 1. The selected 12 stations with distinct amplitude co-seismic water level changes during the Wenchuan earthquake in mainland China. The well numbers are in accordance with the numbers listed in Table 1.



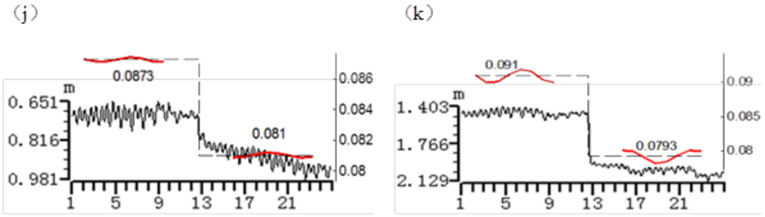
XIAXIAN (May 1—May 24, 2008)　　MILE (May 1—May 24, 2008)　　QINXIAN (May 1—May 24, 2008)



XIAOYI (May 1—May 24, 2008)　　QIXIAN (May 1—May 24, 2008)　　JURONG (May 1—May 24, 2008)



HAIYUAN (May 1—May 24, 2008)　　GUYUAN (May 1—May 24, 2008)　　KAIYUAN(May 1—May 24, 2008)



MEIZHOU (May 1—May 24, 2008)　　CHAOHU (May 1—May 24, 2008)

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*. The dashed lines

indicate the mean *B* values, which are clearly shown in numbers. While the curves along the dashed lines indicate the continuous *B* values both pre- and post-earthquake.

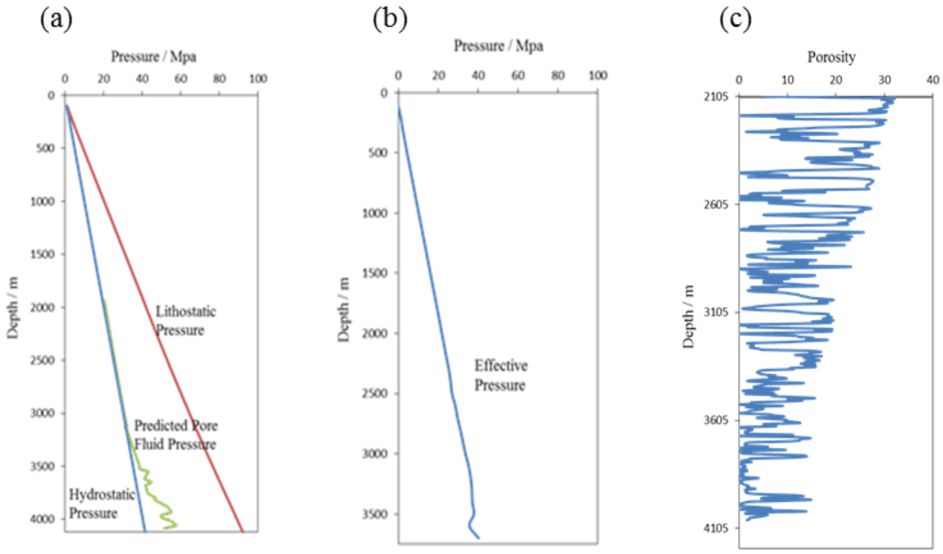


Figure 3. (a) Pressure section of W-1 well in Yanchang basin, the bedrock of W-1 well is sandstone. (b) Effective pressure section of W-1 well, we just show the depth above 3500m, so as to see the value in shallow depth more clearly. (c) Porosity section of W-1 well. The porosity records approximately starts from 2100 m, there are no records above this depth.

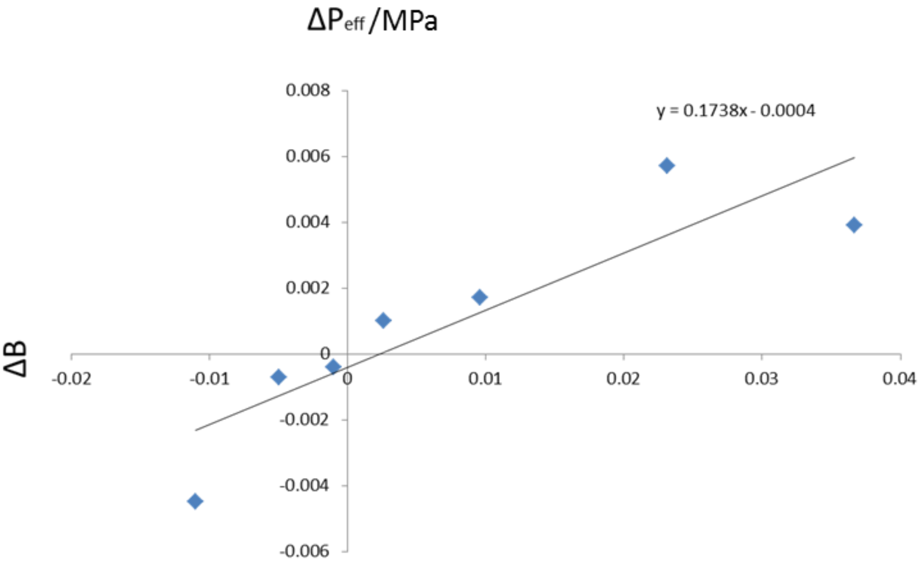
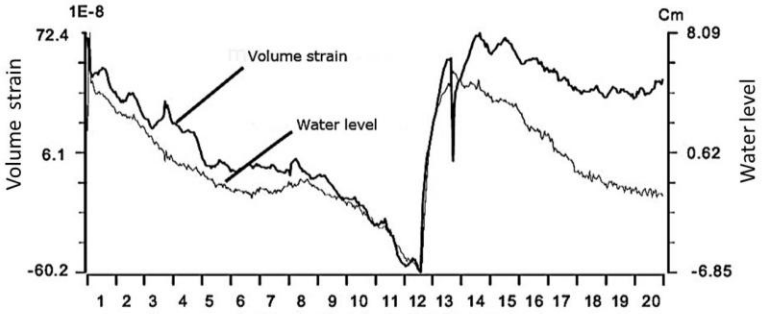


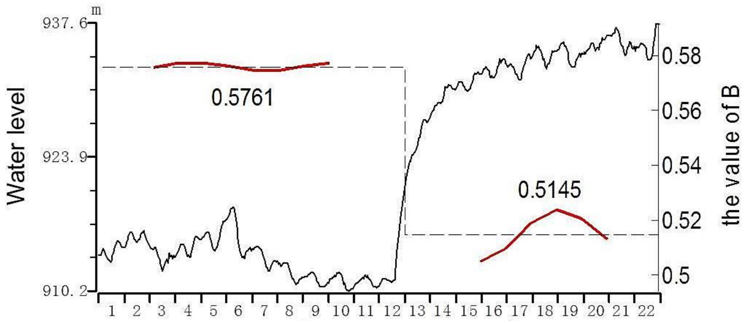
Figure 4. The relationship between the change of Skempton's coefficient *B* and the change of effective pressure Peff of those wells of which the coseismic water level changes can be explained by the consolidation or dilatation caused by teleseismic waves.

(a)



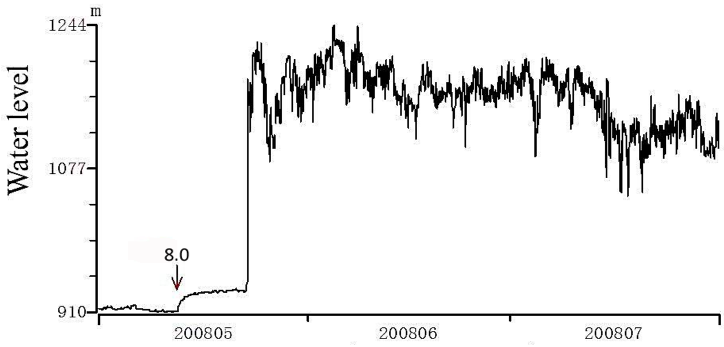
FUXIN (May 1—May 20, 2008)

(b)



FUXIN (May 1—May 22, 2008)

(c)



FUXIN (May 1—July 31, 2008)

Figure 5. Fuxin 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.

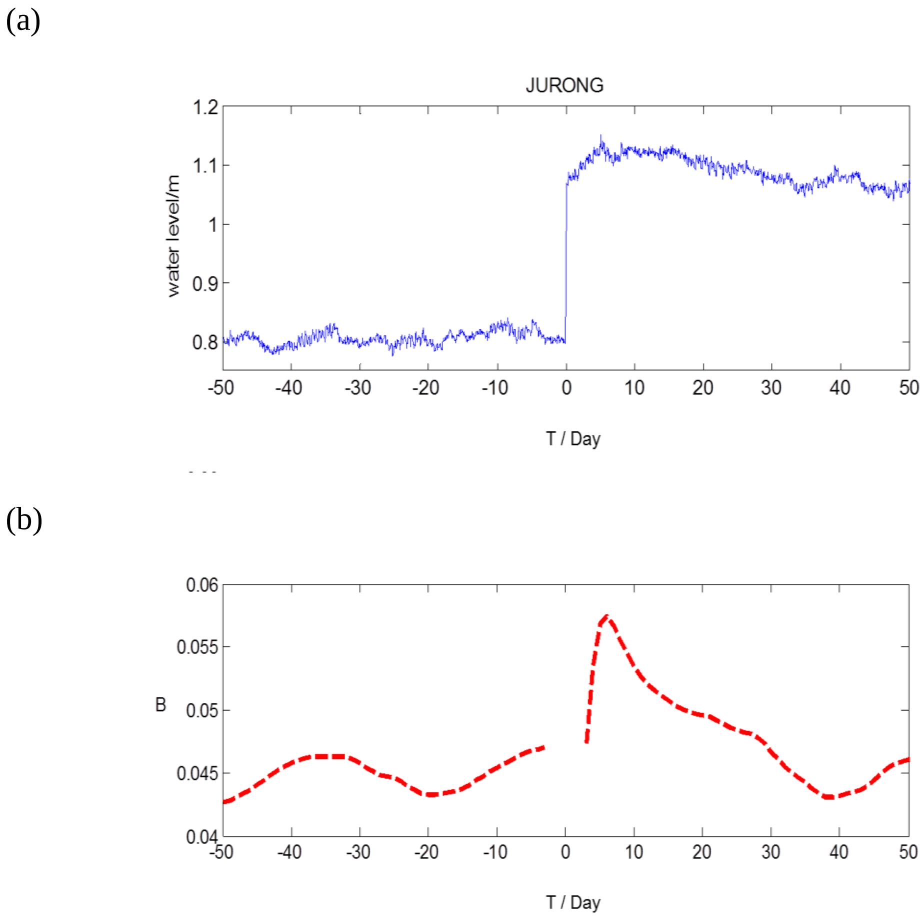


Figure 6. Jurong well (a) Original water level of Jurong station. (b) Continuous *B* value of Jurong station. (“0” depends the day when Wenchuan earthquake happened)

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