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Studies of mechanisms for water level changes induced by teleseismic waves

--Manuscript Draft--

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Abstract:	The Ms 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 and effective pressure in this paper to explain those co-seismic water level changes documented in the intermediate and far fields. The most used "enhanced permeability with a rapid redistribution of pore pressure induced by removing loose particals from fractures by teleseismic waves" can not be applied to explain all those coseismic water level changes in this study. From our research we find some of those abrupt coseismic water level changes, for which the variation of the co-seismic water level, and the effective pressure preserve consistent (all increase or all decrease) are found to favor the consolidation (porosity decrease) / dilatation (porosity increase) induced by the shaking of teleseismic waves. Most of those wells have relatively high permeabilities attributing to the shales in the aquifer lithologies. While the other part of those coseismic water level changes (the variation of the co-seismic water level keeps inconsistent with the variation of effective pressure), can be explained with the enhanced permeability with a rapid redistribution of pore pressure, which is caused by fracture clearing or overcoming the capillary entrapment in porous channels of the aquifer induced by the shaking of teleseismic waves (most probably long period surface waves). Most of those wells stay in basins or hollows, this kind of terrain inclines to lead to heterogeneous pore pressure in close proximity.
Author Comments:	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 and effective pressure in this paper to explain those co-seismic water level changes documented in the intermediate and far fields. The most used "enhanced permeability with a rapid redistribution of pore pressure induced by removing loose particals from fractures by teleseismic waves" can not be applied to explain all those coseismic water level changes in this study. From our research we find some of those abrupt coseismic water level changes, for which the variation of the co-seismic water level, and the effective pressure preserve consistent (all increase or all decrease) are found to favor the consolidation (porosity decrease) / dilatation (porosity increase) induced by the shaking of teleseismic waves. Most of those wells

	have relatively high permeabilities attributing to the shales in the aquifer lithologies.
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Opposed Reviewers:	Yaowei Liu He has a conflict with one of the auther

Ref.: Ms. No. BSSA-D-12-00360R2

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Dear Yan Zhang,

Your paper has been reviewed for publication in the Bulletin. I enclose two reviews by anonymous referees who have raised serious concerns. Reviewer #3 did not review the first draft of the manuscript but has similar criticisms to the two reviewers who reviewed the first draft. These are appended below. The editorial board has evaluated the reviews and has found the paper to be unacceptable for publication. First, the English is still poor and the paper lacks structure/organization, although you were given significant input from two reviewers and an associate editor on how to improve the grammar and organization of the manuscript. Second, you do not appear to addressed the technical concerns of the reviewers and associate editor in your revision. I believe the Editorial report and reviews adequately explain the reasons for this decision and I hope you find them useful.

Thank you for your interest in the Bulletin.

Sincerely

Diane I. Doser, PhD

Editor-in-Chief

Reviewers' and associate editor's comments:

Associate Editor:

Please see the comments from the reviewers. Try to incorporate well log data to support your view. You may need to re do this work and resubmit it.

Reviewer #2: Attached. (note this reviewer reviewed version 1 of the manuscript as well as your revised manuscript)

The authors have addressed the issues which have asked by the other reviewer. But still I feel scientifically the paper is ready to publish whereas grammatically (including structure of the sentences) it should be rechecked (The authors may take help of someone whose native language is English).

Answer: According to the suggestion and comments of reviewer 3, we have modified the paper significantly, so as to explain the mechanism much more clearly, see those modifications annotated in green colors.

e.g. Line:106 Page 5

"The detailed borehole columnar diagrams (borehole 107 columnar diagram of well b, g, h, i, and j cannot be found) are not show in this paper those information obtained from the borehole columnar diagrams together with the aquifer lithology are show in Table 1."

Answer: According to the suggestion of reviewer #3, we added those borehole columnar (well lithologic logs), so we have already deleted this sentence.

e.g. Line:236 Page 10

"The local geological structure of each well is important (Table 1), we find that most of those wells in which......"

Answer: We have modified the sentence into two sentences, See Line 272.

e.g. Line:240 Page 11

"......will not easily to be incurred, then the energy of shaking may be inclined to induce the fracture clearing (unclogging)...."

Answer: We have changed the content because of the modification suggested by the reviewer #3. Please see Line 271—276.

e.g. Line:404 Page 17

"After comparison, generally we may use the seismograms of 4 national stations to analyze the corresponding water...."

What do you mean by "may"?. You have used already. Isn't it?

Answer: Yes, your suggestion is good. However, after the suggestion of reviewer 3, we estimate the quality of those seismograms, finally we only can use 2 of those seismograms, so we still use "may". The content has been changed a lot, see Line 505—552.

Reviewer #3: The authors of this draft show water level changes due the Wenchuan Earthquake, recorded in several wells in mainland China, at distance too far to attribute these changes to poroelastic response to static stress changes. They claim these changes is due to a variation in Skempton coefficient "B", rather than changes in other poroelastic coefficients or permeability. This change in B is related to a theory of "consolidation/dilation".

The paper is difficult to read, first because of language issues, second because of the poor construction of the discussion. The consolidation/dilation theory is quite unclear, partially because of the lack of equation. Also, during their discussion, it is unclear whether the medium is fractured or porous. The relationship between porosity, elastic modulus and porosity may be quite different in these cases. The author do not take time to discuss their raw data, and comment the order of magnitude of their results. Quality control of data and analysis should be discussed in a first part of the discussion, not left to the discussion at the end of the paper.

Answer: These are good suggestions, we have done an enormous modification (see those annotated green color parts), including the construction of the discussion, the order, and the analysis of well logs. Especially, your suggestion to use equations is a terrific idea, and we summarize the variation of effective pressure ($P_{eff} = P_c - P_P$) in two ways, which can help us to analyze the mechanism much more clearly. See: Line 209—234.

There are several points which need to be clarified.

- Does the poroelastic theory used by the authors apply to the formation in their wells? For instance, lithological logs shows shales and crystalline rock. The first rock may display substantial anisotropy or a fractured network rather than a porous network. Previous reviewers asked for more log data to clarify this point, but the authors did not reply to their request.

Answer: We have added those logs, please see Figure 8.

However, there are so much wells has the fractured aquifer, and poroelastic theory is an ideal theory, it suppose the medium to be linearly elastic isotropic porous medium, Fluid saturated crust behaves as a poroelastic material to a good degree of approximation. Even if the rock is anisotropy or a fractured network rather than a porous network, we suspect that the isotropic and homogeneous poroelastic theory we used is the best available approximation. (We have consulted several experts in this research region, and they all agree with this viewpoint). Set an example: There are large distances between stations and the epicenter, and there are lots of faults (so the medium is not uniform). The Okada dislocation model (Okada, 1992; Lin and Stein, 2004; Toda et al., 2005) is based on the assumption that the whole land is isotropic and homogeneous. Therefore, there may be some differences between the calculated volume strain change and the real value, however, till now, most of us still use the Okada dislocation model to calculate the volume strains, and it might be the most useful means. We also add this discussion into the conclusion part, see Line 602—612.

As indicated by this reviewer, those log analysis are very useful. Especially the aquifer with shales, which may display a (fractured) high permeability nature, and this help us to analyze the mechanism much more deeply. See: Part "4.3 Well logs and permeability" Line 375--408 (and also Abstract, Introduction).

- The Skempton coefficients are very small for many wells (<0.1). At the recorded depths, we expect fully saturated rocks, and Skempton coefficient are expected to be larger than 0.5 (see final tables of Wang, 2010, citation of l. 585). If the medium is unsaturated, the authors should state that.

Answer: This may be attributed to the value of the shear modulus G (see Zhang and Huang (2011), since we lack the in-situ G values, we investigate the geology of each well and referred to the rock mass mechanism (Liu and Tang, 1998), using the dynamic elastic modulus and dynamic Poisson's ratios to estimate the ranges of the dynamic shear modulus of those matrix rocks (according to the formula $G = \frac{E}{2(1+\sigma)}$), and to choose the approximate mean values (Table 1)). [See Table 1 (Shear modulus G* see Yan Zhang and Fuqiong Huang (2011)].

Below is Table 1 of Zhang and Huang (2011)

Table 1

Dynamic Deformation Parameters of Rocks

Rock	Dynamic Elastic Modulus E (GPa) *	Dynamic Poisson's Ratio σ *	Dynamic Shear Modulus G (GPa)	Rough Value of Dynamic Shear Modulus (GPa)
Sandstone	5.3 ~ 37.9	0.20 ~ 0.22	2.17 ~ 15.79	8
Graniton	63.4 ~ 114.8	0.20 ~ 0.21	26.20 ~ 47.83	36
Quartzite	20.4 ~ 76.3	0.23 ~ 0.26	8.10 ~ 31.02	20
Limestone	12.1 ~ 88.3	0.24 ~ 0.25	4.84 ~ 35.60	20
Gneiss	76.0 ~ 129.1	0.22 ~ 0.24	30.65 ~ 52.91	40
Granite	37.0 ~ 106.0	0.24 ~ 0.31	14.12 ~ 42.74	28
Whinstone	53.1 ~ 162.8	0.10 ~ 0.22	21.76 ~ 74.00	48
Diorite	52.8 ~ 96.2	0.23 ~ 0.34	19.7 ~ 39.11	30
Psephite	3.4 ~ 16	0.19 ~ 0.22	1.39 ~ 6.723	4

*See Liu, Y. R., and H. M. Tang (1998), p. 112.

In addition, Sil and Jeffrey (2006) (obtained an average Skempton's coefficient B value of 0.02) and Chadha *et al*. (2008) have obtained the similar low value of *B*, which indicate that the wells are not perfectly confined and the aquifers are highly permeable. So we indicate: the assumption of undrained condition may not be strictly meet with. We have discussed this in the conclusion part, See line 606—616.

- The authors focus on the change in Skempton coefficient, dismissing any change in other coefficients. For instance, as cited in line 141, Berryman and Wang (2001) show a large variation in bulk modulus Ku in their data. Remember, that the tidal amplitude of water level changes is controlled by B x Ku. I don't understand why the author cite the work done on bone by Theo H Smit, Jacques Huyghe and Stephen C. Cowin (note that the authors cited these authors by their first name): in this paper, they discuss the dependency of the coefficient on porosity. Do the author think that porosity is changing due to shaking? In that case, it should be clarified when discussing the mechanism, because from line 352, I thought it did not.

Answer: Please see part 3.1 "Assumptions of shear modulus and Poisson's ratio and the calculation of Skempton's coefficient B"

We have use the previous results from the former researchers to justify that, compared with the pre- and post-earthquake Skempton's coefficient *B*, the shear modulus and the poisson's ratio can be neglected. See Line 116—146.

We cite the work of Theo *et al*. (2002) is to clarify that "compared to the variations of Skempton's coefficient B, the change of the undrained poisson's ratio can be neglected before and after the earthquake." See Line 116—130.

As show in Line 203: Permeability will increase/decrease, which is mostly related to the increase/decrease of porosity (Xue, 1986). So, in the mechanism analysis (which we have modified a lot), we do discuss about the porosity together with the permeability, both of which change in accordance. Line: 190--447. (" Mechanism analysis")

- The description of the consolidation/dilation model is very confusing. To be improved, it would be helpful to get a set of equations and a sketch precising the conceptual model of the medium (is it fractured? porous ?). This would replace the hand waving of lines 199-204. It would provide also an expected range for the linear relationship found between changes in effective pressure and in B. This theoretical framework would be helpful, because they do not provide any citation or evidence for why B would increase with effective pressure (the experiments of Blocher 2009 show a negative trend, but with effective pressure starting at 5MPa, and the apparent B changes in the study may be also contaminated by permeability or Ku changes).

Answer: Yes we also feel the description is confusing, your suggestion to use equations is a terrific idea, and we summarize the variation of effective pressure ($P_{eff} = P_c - P_P$) in two ways: （P_c confining pressure, P_p pore pressure, and P_{eff} effective pressure）, which can help us to analyze the mechanism much more clearly. See: Line 209—232. (Table

4)

As indicated by this reviewer, those log analysis are very useful. Especially the aquifer with shales, which may display a (fractured) high permeability nature, and this helps us to analyze the mechanism much more deeply. See: Part "4.3 Well lithologic logs and permeability" Line 375-408 (and also Abstract, Introduction)

However, one thing needs to be clarified: we say those co-seismic water level changes fit to be explained with the consolidation/dilation model, and those consolidation/dilation are induced by teleseismic waves: Permeability decrease is corresponding to the porosity decrease, and which indicates the consolidation of the aquifer, this mechanism is much similar with the mechanism proposed by Liu and Manga (2009). See Line 303—318: "From the laboratory experiment, Liu and Manga (2009) find that: in general, permeability/porosity 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, which can lead to a higher coupling between the stiff rock matrix and the fluid. Their result just supports our mechanism analysis. It implies that teleseismic waves can cause a consolidation of well aquifer and cause the increase of effective pressure (decrease of permeability and porosity), which is in accordance with the increase of co-seismic water level changes accompanied with the increase of Skempton's coefficient B in well a, b, c, and d. "

As show in equation (5): $B = -\frac{3\rho g(1-2\nu_u)}{2G(1+\nu_u)}\frac{\Delta h}{\Delta \varepsilon_t}$ B can be influenced by shear modulus G, and the poisson's ratio ν_u and we have testified that: the variation of the two parameters before and after earthquake can be neglected compared with the variation of Skempton's coefficient B. Please see "Assumptions of shear modulus and Poisson's ratio and the calculation of Skempton's coefficient B" Line 116—146.

- p 10 and all the discussion on permeability is confusing. Are there permeability changes (as p 10 says) or not (l 350-355)?

Answer: Yes, after read the whole paper, we really find it is confusing, especially as a new reader. So we have do an enormous modification, see those annotated (green color) portions in the mechanism analysis, See Line: 190--447. (" Mechanism analysis")

- The authors claim there is no issues with hydraulic coupling due to large water storage. But phase lag is not the same before and after the earthquake in some wells. This may be also the sign of change in permeability. Note finally, that your tidal analysis gives only phase with 1 hour of resolution: for M2, that is a phase lag of 30°, which is enormous. Do you have an estimate of permeability and wellbore storage to discard any issue with hydraulic coupling, using directly the equation of Hsieh, WRR, 1987 ?

- To show that only B is changing, analyzing M2 may not be enough. One can try to redo the analysis with O1 tidal component, to check that phase is not changing (phase resolution is better with ~24h, the hydraulic coupling should be also better, and the same results should be found). Also the barometric efficiency should change in the same amount as B if the other coefficients are unaffected. This independent analysis would improve the discussion on the cause of the tidal changes, by deciphering the effect of poroelasticity and hydrology in the tidal changes.

Answer: These are good suggestions, however, as explained by Hsieh *et al*. (1987), their analysis suggests that: the computed O1 phase shift is subject to large uncertainty, while the computed M2 phase shift is substantially more accurate. So we use the M2 wave to calculated the phase shift. The enormous phase shift may be attributed to the earthquake, which induced the variation of the parameters (permeability/porosity, Skempton's coefficient *B*) in the aquifer.

From our study we find lots of factors will influence the far-field co-seismic water level changes, such as lithology, topography and geometry of the well, and it is necessary to calculate the Tranmissivity (permeability), so as to testify the mechanism. The commonly used permeability calculation [based on equations of Hsieh et al. (1987)] is based on several parameters: the dimensionless storage coefficient S, the radius of the screened or open portion of the well r_w, the radius of the well casing r_c. Because we lack the lithologic logs for all those wells, it is hard to confirm r_w or r_c for them. In our study we find the permeability increase in 4 wells (well f, h, i and Fuxin), only well f and Fuxin well have the records of well logs. However, there are no records of r_w and r_c in <China earthquake monitoring record series>, and it is hard to confirm r_w or r_c from the logging figures (Figure 6) for the two wells. We have to neglect the calculation of permeability in this paper, alternatively, we use the phase lag between water level and tidal strain to approximately estimate the variation of permeability. Later, we may focus on 1—2 wells, which have detailed records of borehole data, water level, and seismogram, and then we may do analysis of the permeability, together with the Skempton's coefficient B, so as to do comparison and to reveal the mechanism more deeply and clearly. See: Line 626—643. And see part 4.4 "Well storage effects", Line: 409—447.

- You try to apply your model to a variety of geological settings, suggesting a universal behavior. I thought the Chinese Earthquake Administration had a much larger number of monitored wells. Do you have examples of wells not evolving, or with other changes in B than what is expected in your model ? If yes, why does your model not work?

Answer: Yes the Chinese Earthquake Administration had a much larger number of monitored wells, however, as discussed in the "Selection principle", lots of wells in the far field (the epicentral distance >1000 km) has no obvious co-seismic water level changes, and some of those wells lay near the sea, which will be affected by the ocean tides, so as indicated by the first two reviewers, we neglected those wells.

Well e is out of our expectation, as show in Line 435—447: "Except for well e (Table 5), it is out of our expectation. Although there is no obvious records of shales in the lithologic logs of well e, there are shales (may be a small quantity of shale) in the aquifer lithology according to the <China earthquake monitoring record series> (Table 1), and the permeability in well e may be relatively high, so it connects well with the place outside, thus there is a low probability of connecting to a place of different pressure. Phase lag increases (which indicates a decrease in permeability) accompanied with the increase of water level in well e. In our expection, this situlation should incure an increase in Skempton's coefficient B (an increase in effective pressure), which indicates the aquifer be consolidated (squezeed). However, the effective pressure (Skempton's coefficient B) decrease in well e, this may be attributed to the fast dectrease of water level after the earthquake (Figure 2). Further researches need to be done so as to detect the mechanism more clearly."

Finally, as a 3rd reviewer, I support the request of the two first reviewers:

- the request for logs was to better characterize the aquifers. Are they porous ? Fractured ? Do the wells sample multiple aquifers? What are the constraints 制约因素 (tests on cores, sonic logs) to calibrate 校准 the elastic coefficients that are needed to extract correct values of Skempton coefficient ? These questions can be answered more precisely than by stacking raw lithological logs.

Answer: This is a good suggestion (especially as indicated by the reviewer, to consider about the shale in the aquifer). As indicated by this reviewer, those log analysis are very useful. Especially the aquifer with shales, which may display a (fractured) high permeability nature, and this helps us to analyze the mechanism much more deeply. See: Part "4.3 Well lithologic logs and permeability" Line 375--408 (and also Abstract, Introduction)

- The request for seismograms. It seems that other earthquakes, and especially the aftershocks of Wenchuan earthquakes did not trigger any changes. How do they compare ? How much less are the PGA (Peak Ground Acceleration) and PGV (Peak Ground Velocity) ? How did the shaking spectra change ?

Answer: Yes, the seismogram analysis is meaningful. Those wells are all in the far field (the aftershocks of Wenchuan earthquake did not trigger any obvious changes in water level), we use the seismograms mainly to do comparisons between the arrival time of surface waves and the occurrence time of co-seismic water level changes. See "Compare with seismograms " Line: 505–552, and Table 6.

There are aftershocks, and the one following the M_s 8.0 main shock （Chinese time 14:27:59.5）is at 14:43:14.7 , it is about 15 minutes later, so it will not cause disturbances on the main shock seismogram. What's more the after shocks are much smaller (the magnitude of aftershocks are less than M_s 6.0) than the main shock, the energy will decrease about 900 times, when the magnitude decrease 2, so the energy of those aftershocks are much smaller, which are not large enough to induce the variation of water level. See Line: 546 –552.

As pointed out by the reviewer, we show the seismograms and the PGV in Figure 8. "The PGV (peak ground velocity) of Fuxin (SNY station) is about 3.224 mm/s, and that of well (k) (HEF station) is about 6.891 mm/s. Although the co-seismic water level changes in Fuxin is smaller than that in well (k), since they are induced by different mechanisms (co-seismic water level (Δh=0.121m) in Fuxin is induced by increased permeability followed by a rapid redistribution of pore pressure, and co-seismic water level (Δh=-0.455m) in well (k) is induced by dilatation), the ratio of PGV should not directly related with the ratio of co-seismic water level changes in the two wells." See Line: 538 –545.

To conclude, given the amount of comments from my part and from the other reviewers, I suggest the paper to be rejected, and I encourage resubmission with a major reworking of the paper.

Studies of mechanisms for water level changes induced by teleseismic waves

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Abstract

The M_s8.0 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* and effective pressure in this paper to explain those co-seismic water level changes documented in the intermediate and far fields. The most used "enhanced permeability with a rapid redistribution of pore pressure induced by removing loose particals from fractures by teleseismic waves" can not be applied to explain all those coseismic water level changes in this study. From our research we find some of those abrupt coseismic water level changes, for which the variation of the co-seismic water level, and the effective pressure preserve consistent (all increase or all decrease) are found to favor the consolidation (porosity decrease) / dilatation (porosity increase) induced by the shaking of

teleseismic waves. Most of those wells have relatively high permeabilities attributing to the shales in the aquifer lithologies. While the other part of those coseismic water level changes (the variation of the co-seismic water level keeps inconsistent with the variation of effective pressure), can be explained with the enhanced permeability with a rapid redistribution of pore pressure, which is caused by fracture clearing or overcoming the capillary entrapment in porous channels of the aquifer induced by the shaking of teleseismic waves (most probably long period surface waves). Most of those wells stay in basins or hollows, this kind of terrain inclines to lead to heterogeneous pore pressure in close proximity.

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 Π; Wang and Manga, 2010), many occurred at great distances from the ruptured fault where static stress changes are relatively small. 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). Earthquake induced water level changes at distant locations were reported after the Denali earthquake (Brodsky *et al.*, 2003; Kayen *et al.*, 2004; Sil and Freymueller, 2006). Seismic oscillations, due primarily to surface waves from distant events, occur in some wells tapping highly transmissive aquifers (Liu *et al.*, 1989; Liu *et al.*, 2006). Sil and Freymueller (2006) developed an empirical relationship between water level changes, epicentral distances and earthquake magnitude in the far-field. Chadha *et al.* (2008 I) find wells appear to respond to regional strain variations and transient changes due to distant earthquakes. Liu and Manga (2009) indicate that significant water level changes can be driven at great distances by moderate-amplitude dynamic (time-varying) stresses.

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 far-field 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). Dynamic strain induced by the passage of seismic waves, most probably long period surface waves might be the cause of water level changes in the far-field (West *et al*., 2005; Sil and Jeffrey, 2006; Chadha *et al*., 2008 Π). 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), increasing pore pressure through seismically induced growth of bubbles (Linde *et al*., 1994), and fracture of an impermeable fault (King *et al*., 1999). In addition, Huang (2008) observed the co-seismic water level increase may be caused by the consolidation induced by the transmission of teleseismic waves in Fuxin well. Experimental measurements of Liu and Manga (2009) indicate that permeability changes (either increases or decreases) owing to dynamic stresses are a reasonable explanation. Wang *et al* (2009） find that the groundwater flow associated with S and Love waves may generate shear stress large enough to break up the flocs in sediment pores and to enhance the permeability of aquifers.

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 quasistatic 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 variations of co-seismic water level and effective pressure preserve uniformity. Most of those wells have relatively high permeabilities attributing to the shales in the aquifer lithologies. 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 or hollows), may be explained with the increased permeability caused by teleseismic waves, which in turn lead to the redistribution of pore pressures. Compare the occurrence time of water level changes with the arrival time of surface waves in two stations, we find the co-seismic water level changes are induced by the long period surface waves.

Selection Principles and Observations

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, the oceanic tides 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 oceanic 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 and 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. 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 when calculating the Skempton's coefficient *B*.

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 $\rho = 1000kg/m^3$, $g = 9.8m/s^2$, and $\nu_u = 0.29$ according to equation (A5) (Appendix). 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 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 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). Depths of those wells analyzed in this paper are all less than 1km (Table 1). 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 quantity 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 2).

Mechanism analysis

Till now, fracture clearing (unclogging) and increased permeability has been used to explain most of those coseismic water level changes in the far field (Brodsky *et al.*, 2003; Wang, 2007; Wang and Manga, 2010). 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). Analysis of well response to tidal forcing before and after an earthquake has provided strong evidence that earthquakes can enhance permeability (Elkhoury *et al.*, 2006). In this study, we calculate the change of Skempton's coefficient *B* and effective pressure, however, we can not use the enhanced permeability theory to explain all those coseismic water level changes. And we find the other part of water level changes may favor the consolidation or dilatation induced by teleseismic waves (about 58.3% of all those wells analyzed in this paper favor this explanation).

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).

We can summarize the variation of effective pressure ($P_{eff} = P_c - P_p$) in two ways: （P_c confining pressure, P_p pore pressure, and P_{eff} effective pressure ）

A) Pore pressure P_p keeps constant, the change of effective pressure P_{eff} induced by the change of confining pressure P_c .

There are two states (Table 4): (a1) Confining pressure increases (pore pressure not change), then effective pressure increases, the porosity will decrease (a process of consolidation or squeeze), and water level / pore pressure will increase; (a2) Confining pressure decreases (pore pressure not change), then effective pressure decreases, the porosity will increase (a process of dilatation), and water level / pore pressure will decrease. (a1), (a2) can be summarized as a mechanism of water level change induced by consolidation or dilatation, and water level changes in accordance with the change of effective pressure (all increase or all decrease) in this case.

B) Confining pressure P_c keeps constant, the change of effective pressure P_{eff} induced by the change of pore pressure P_p.

There are two states (Table 4): (b1) Pore pressure/ water level decreases (Confining pressure not change), then effective pressure increases, the porosity will decrease (a process of water level flows out of the well to a place with a relatively lower pore pressure); (b2) Pore pressure/ water level increases (Confining pressure not change), then effective pressure decreases, the porosity will increase (a process of water level flows into the well from a place with a relatively higher pore pressure). (b1), (b2) can be summarized as a mechanism of water level change induced by increased permeability with a rapid redistribution of pore pressure (this is the most used mechanism for far-field coseismic water level changes), and water level changes opposite to the change of effective pressure in this case.

As show in below (part 4.1 and part 4,2), we use two mechanisms to explain those coseismic water level changes.

Coseismic water level change induced by increased permeability followed by a rapid redistribution of pore pressure

The effective pressure range of well h, and i is 0 ~ 3 MPa (Table 2). According to the laboratory experiment of Blocher *et al* (2009), the increase of effective pressure accompanied with the increase of Skempton's coefficient *B* in this range. Water levels (pore pressure) decrease accompanied with the increase of effective pressures in well h, and i (Table 2). 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 the two wells may be higher than the close proximity before the earthquake, an enhancement of permeability incured by (for example) overcoming the capillary entrapment in porous channels induced by the passage of elastic waves will decrease the pore-pressure in wells (the pore-pressure will shift to other places), and water level will decrease. Then the effective pressure will increase accompanied with the decrease of pore-pressure (water level), so the Skempton's coefficient *B* increases (which indicates the stiff rock matrix could with a higher coupling to the fluid) in well h and i (Table 2).

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 2). According to the laboratory experiment of Blocher *et al* (2009), the decrease of effective pressure accompanied with the increase of Skempton's coefficient *B* in this range. Water level increases with the decrease of effective pressure (increase of Skempton's coefficient *B*) in well f, this should be explained with the increased permeability. Pore-pressure of well f may be lower than the close places before the earthquake, an enhancement of permeability will increase the pore-pressure in this well (the pore-pressure (water level) may shift from other places), and water level (pore pressure) will increase. Then the effective pressure will decrease accompanied with the increase of pore-pressure (water level), supposing the confining pressure not change. As explained by Blocher *et al* (2009), with the increase of effective pressure (reachers larger than 5 Mpa), the decrease of the Skempton's coefficient results from the change of the pore-geometry, which leads to a higher bulk modulus of the sample. Pore throats and microcracks were closed, and the stiff rock matrix could with a lower coupling to the fluid, so the Skempton's coefficient *B* decreases. And this is an reversible process (after they raised the confining pressure from 5 to 50 Mpa, they lowered the confining pressure form 50 to 5 Mpa, and also obtained the similar results), so when the effective pressure decreases (not lower than 5 Mpa), the closed pore throats and microcracks will be opened and turn larger under the effect of pore pressure, the stiff rock matrix could with a higher coupling to the fluid in well f, leading to the increase of Skempton's coefficient *B*.

The local geological structure of each well is important (Table 1). We find that most of those wells in which the coseismic water level changes can be explained with

" the enhanced permeability with a rapid redistribution of pore pressure" stay in basins or in hollows (well f, h, i and Fuxin). The terrains of those wells incline to lead to heterogeneous pore pressures in close proximities (possibly attributed to different altitudes).

Coseismic water level change induced by consolidation or dilatation

Coseismic water level change induced by dilatation

For well g, j and k, the effective pressure range is 0 ~ 3 MPa, effective pressure will increase/decrease accompanied with the increase/decrease of Skempton's coefficient *B* during this range (Blocher *et al.*, 2009). Water levels (pore pressures) of well g, j and k decrease, accompanied with the decrease of effective pressures [and decrease of Skempton's coefficient *B* (which indicates the stiff rock matrix could with a lower coupling to the fluid)], which can not be explained with the increased permeability followed by the rapid pore pressure redistribution between the well and the places near the well. Whereas, this could be explained with the state (a2) Confining pressure decreases (pore pressure not change), then effective pressure decreases, the porosity will increase (a process of dilatation), and water level / pore pressure will decrease.

The spreading of teleseismic waves may cause dilatation of the aquifer medium, which can broaden the porosities (the permeability will increase) and give birth to new fractures, and the effective pressure will reduce (in wells: g, j and k) leading to the decrease of Skempton's coefficient *B*. This explanation is similar to the mechanism of shaking-induced dilatancy (Bower and Heaton, 1978).

Coseismic water level change induced by consolidation

For well a, b, c, and d, the effective pressure range is approximately 0 ~ 3 MPa, effective pressure will increase/decrease accompanied with the increase/decrease of Skempton's coefficient *B* (Blocher *et al.*, 2009). Water level (pore pressure) of well a, b, c, and d increase, accompanied with the increase of effective pressure [and increase of Skempton's coefficient *B* (which indicates the stiff rock matrix could with a higher coupling to the fluid)], which also can not be explained with the increased permeability followed by the rapid pore pressure redistribution between the well and the place near the well. Whereas, this could be explained with the state (a1) "Confining pressure increases (pore pressure not change), then effective pressure increases, the porosity will decrease (a process of consolidation or squeeze), and water level / pore pressure will increase". This mechanism is very similar to the explanation of the laboratory experiment of Liu and Manga (2009). From their laboratory experiment, they find that: in general, permeability/porosity 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, which can lead to a higher coupling between the stiff rock matrix and the fluid. Their result just supports our mechanism analysis. It implies that teleseismic waves can cause a consolidation of well aquifer and cause the increase of effective pressure (decrease of permeability and porosity), which is in accordance with the increase of co-seismic water levels accompanied with the increase of Skempton's coefficient B in well a, b, c, and d.

Examples support far field water level increases induced by consolidation

We analyze the mechanism of the coseismic water level changes induced by consolidation incurred by teleseismic waves in above. However, water level increases induced by consolidation in the far field is not the mainstream view. It is necessary to give some examples which can support far field water level increases induced by consolidation.

Huang (2008) find that: the water level increase in Fuxin well (1409.98 km away from Wenchuan, the well depth is 60.74 m， stiff Granite with a little basalt is the bedrock and we assume the shear modulus = 60 Gpa) is induced by the increase of volume strain (consolidation) (Figure 4a). 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 4b)). (The large-step abrupt water level increase starts from 09 p.m. May 22, 2008 (Figure 4c), which may cause large impact on the detrend process and influence the calculation result, so we discard these data). From Figure 4a, 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 2), from the change of the pre- and post- earthquake *B* (Figure 4b), we may infer the consolidation may be very extreme, accompanied with the coseismic water level increase it could cause an extra pressure, which 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 (corresponding to the state (b2)). 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 4c). 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 in a specific geology condition, a consolidation with large enough energy may also lead to an enhanced permeability by fracture clearing or by overcoming the capillary entrapment in porous channels.

Conclusion of coseismic water level changes induced by consolidation or dilatation

Water level increases/decreases accompanied with the increase/decrease of effective pressure (and the increase/decrease of Skempton's coefficient *B*) in well a, b, c, d, g, j, and k (the effective pressure range is approximately 0 ~ 3 MPa) (Table 3).

To our understanding, suppose the pressure not exceed a limitation (a perment derformation not happened), 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. Hence, 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. Figure 5 shows the relation between the change of Skempton's coefficient *B* and the change of effective pressure in well a, b, c, d, g, j, and k . Approximately, it displays a linear relation.

Well lithologic logs and permeability

As indicated by Wang *et al.* (2009) High transmissivity promotes uniform pore pressure, thus there is a low probability of connecting to a reservoir of different pressure. On the other hand, poor transmissivity can support heterogeneous pore pressure in close proximity, thus there is a high probability of connecting to a reservoir of different pressure. We show the well lithologic logs (borehole columnar diagrams) in Figure 6. According to <China earthquake monitoring record 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)], we can only get the lithologic logs of well (a), (c), (d), (e), (f), (k) and Fuxin (Figure 6), the pictures are designed already, some lithologic logs are explained in detail and some are in shot. Shales display in Lithologic logs of well (c), (d) , (e) [Although there is no obvious records of shales in the log of well e, according to the <China earthquake monitoring record series> there are shales (may be a small quantity of shale) in the matrix rock of well (e) (Table 1)] and (k), so the permeability of well (c), (d) , (e) and (k) may be relatively larger, and they are well connected with the close places outside the well, so there are little pressure differences between those wells and the places around them, and water level tend not to flow into or out of those wells even if the porosity/permeability increased by the shaking of telesismic waves. On the other hand, there are no shales in the logs of well (a), (f) and Fuxin, and the permeability may be relatively smaller, thus there is a high probability of connecting to a reservoir of different pressure, and water level tend to flow into or out of those wells after the porosity/permeability increased by the shaking of telesismic waves. Except for well (a), those analysises of lithologic logs are in accordance with our above mechanism analysises [well (c), (d), (e) and (k) favor the consolidation/ dilatation mechanism, while well (f) and Fuxin are induced by the increased permeability followed by a rapid redistribution of pore pressure]. Other factors may also influence the permeability, such as the geometry of the well. However, we can not make further study about that, since we lack the in situ tests and the detailed lithologic logs of other wells.

Because we use the approximately mediun value of shear modulus G (Table 1) to calculate the Skempton's coefficient B, it is hard to estimate the permeable extent of the aquifer from the absolute value of B. Whereas, the variation tendency of B before and after the earthquake is definite.

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 are a function of the transmissivity between the well and aquifer, in addition to the geometry of the well (Cooper *et al.*, 1965; Liu *et al.*, 1989; Kano and Yanagidani, 2006). 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 record series> 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. Hsieh *et al.* (1987) indicates that: the computed O1 phase shift is subject to large uncertainty, while the computed M2 phase shift is substantially more accurate. So we use the M2 wave to calculated the phase shift. Because we use the hourly data, we can not identify the phase difference when it is less than 1 hour, and we 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 changes not much (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.

Except for well e (Table 5), it is out of our expectation. Although there is no obvious records of shales in the lithologic logs of well e, there are shales (may be a small quantity of shale) in the aquifer lithology according to the <China earthquake monitoring record series> (Table 1), and the permeability in well e may be relatively high, so it connects well with the place outside, thus there is a low probability of connecting to a place of different pressure. Phase lag increases (which indicates a decrease in permeability) accompanied with the increase of water level in well e. In our expection, this situlation should incure an increase in Skempton's coefficient *B* (an increase in effective pressure), which indicates the aquifer be consolidated (squezeed). However, the effective pressure (Skempton's coefficient *B*) decrease in well e, this may be attributed to the fast dectrease of water level after the earthquake (Figure 2). Further researches need to be done so as to detect the mechanism more clearly.

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 3 we can see, the variations of effective pressure in well a, b, c, d, g, j and k are 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) changes little after the earthquake. Because the phase lags increase/decrease (wellbore storage effects increase/decrease) as the permeability (porosity) of the formation decreases/increases (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 7). 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 7).

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 levels will not recover to the pre-earthquake heights 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 calculat 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 increases/decreases, then the effective pressure increases/decreases, and at last transfers into the increase/decrease of pore pressure (water level), and the system comes into an equilibrium state. So the change of pore pressure can be attributed to the change of the effective pressure.

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

However , the variation value of the effective pressure in 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.

Compare with seismograms

There are 48 national stations recording the seismograms (event waveforms) in the Chinese mainland (we can not obtain some of the regional seismograms because of the authority limitation), 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 do not record seismograms. After comparison, generally we may use the seismograms of 4 national stations to analyze the corresponding water level observations, which are near those national stations (the distances between the water level wells and the national seismogram stations are approximately less than 100km). However, there are deficiencies in the seismograms of station TIY and LZH (TIY station is corresponding to well e (there are about 40.903 km between them); LZH station is corresponding to well g (there are about 19.82 km between them)), so we desgarded them. Finally, two seismograms can be used: the seismogram of SNY (Shengyang) station is used to analyze Fuxin well (there are about 102.81 km between them), and HEF (Hefei) station is corresponding to well k (there are about 91.57 km between them). In addition, the geology conditions are very similar (the main matrix rocks of Fuxin well and Shengyang station are both granite; Well k is in Chuhe river major dislocation and Hefei-Dongguan fracture intersection).

There are only hourly water level data in Fuxin well (minute data observation strats from 2009), so we can not use that to do precise comparison (in minute) with the seismogram. In general, we can only use well k to do the comparison between the timing of step in water level change and the arrival time of seismic waves. From the occurrence time of water level changes and the arrival time of surface waves of well k (Table 6), we find the co-seismic water level changes are attributed to the passage of surface waves. From that, we may infer: in other wells the co-seismic water level changes are attributed to the dynamic strain induced by the passage of teleseismic waves, most probably surface waves, which have relatively larger amplitude of oscillation, corresponding to relatively larger energy. The similar conclusion has been proposed by Sil and Jeffrey (2006), West *et al.* (2005), and Chadha *et al.* (2008 II). More precise estimation of the timing of the step could not be made because of the low temporal resolution of the water level data. Obviously, there are geographic position differences between the observation of seismograms and water levels, and there are also some errors on the manual amplitude readings, both of which could cause some influence on the analysis.

The PGV (peak ground velocity) of Fuxin (SNY station) is about 3.224 mm/s, and that of well (k) (HEF station) is about 6.891 mm/s. Although the co-seismic water level changes in Fuxin is smaller than that in well (k), since they are induced by different mechanisms (co-seismic water level (Δh=0.121m) in Fuxin is induced by increased permeability followed by a rapid redistribution of pore pressure, and co-seismic water level (Δh=-0.455m) in well (k) is induced by dilatation), the ratio of PGV should not directly related with the ratio of co-seismic water level changes in the two wells.

There are aftershocks, and the one following the M_s 8.0 main shock （Chinese time 14:27:59.5) is at 14:43:14.7 , it is about 15 minutes later, so it will not cause disturbances on the main shock seismogram. What's more the after shocks are much smaller (the magnitude of aftershocks are less than M_s 6.0) than the main shock, the energy will decrease about 900 times, when the magnitude decrease 2, so the energy of those aftershocks are much smaller, which are not large enough to induce the variation of water level.

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 mechanisms of those coseismic water level changes, for which the variation tendency of the co-seismic water level, and the effective pressure keep the same (all increase or all decrease), and most of those wells have relatively high permeabilities attributed to the shales in the matrix rocks (based on the obtained 7 well logs in this study). While, fracture clearing and increased permeability with a rapid redistribution of pore pressure 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. Most of those wells stay in basins or hollows (well f, h, i and Fuxin), this kind of terrain inclines to lead to heterogeneous pore pressure in close proximity. Compared with the seismorgams, the co-seismic water level changes are attributed to the dynamic strain induced by the passage of seismic waves, most probably long period surface waves. 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.

Experiments of Liu and Manga (2009) apply time varying axial stresses (confining pressure changes) whereas Elkhoury *et al*. (2011) applied time varying fluid pressure differences (pore pressure changes) across their samples. Our study complement the experiments of both of them, we discuss the change of effective pressure ($P_{eff} = P_c - P_P$) in two ways: A) Pore pressure P_P keeps constant, the change of effective pressure induced by the change of confining pressure P_c. B) Confining pressure P_c keeps constant, the change of effective pressure induced by the change of pore pressure P_P.

From the analysis of Fuxin well, we can see consolidation also can be incurred by teleseismic waves. As discussed by Liu and Manga (2009): 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. The mechanism 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 experiment.

Matrix rocks with shales always correspond to relatively high permeabilities, and those wells are well connected with the other places outside the well, so there may be little pressure differences between those wells and the places around them, and water levels tend not to flow into or out of those wells even if the porosity/permeability increased by the shaking of telesismic waves. From our study we find most of the co-seismic water level changes in those wells can be attributed to the change of confining pressures. Consolidation/dilatation induced by shaking of teleseismic waves, may account for the mechanism. According to the geological structures, all of those wells stay in faults or in fracture intersections. Meanwhile, we find that the wells in which the coseismic water level changes can be explained with "the enhanced permeability with a rapid redistribution of pore pressure", stay in basins or in hollows (well f, h, i and Fuxin). The terrains of those wells incline to lead to heterogeneous pore pressures in close proximities (possibly attributed to different altitudes).

In reality, some well aquifers are not porous and may be fractured, especially those wells with shales in the matrix rocks, may display substantial anisotropy or a fractured property rather than a porous property, however, we suspect that the isotropic and homogeneous poroelastic theory we used here is the best available approximation. The Skempton coefficients are very small for many wells, which may be attributed to the value of the shear modulus G [see Zhang and Huang (2011), since we lack the in-situ G values, we investigate the geology of each well and referred to the <rock mass mechanism> (Liu and Tang, 1998), using the dynamic elastic modulus and dynamic Poisson's ratios to estimate the ranges of the dynamic shear modulus of those matrix rocks (according to the formula $G = \frac{E}{2(1+\sigma)}$), and to choose the approximate mean values (Table 1)]. 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 (Figure 3) can be applied to all those bedrocks in those wells, 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.

From our study we find lots of factors will influence the far-field co-seismic water level changes, such as lithology, topography and geometry of the well. Later it is necessary to calculate the tranmissivity (permeability), so as to testify the mechanisms. The commonly used permeability calculation [based on equations of Hsieh *et al.* (1987)] is based on several parameters: the dimensionless storage coefficient S, the radius of the screened or open portion of the well r_w, the radius of the well casing r_c. Because we lack the logs for all those wells, it is hard to confirm r_w or r_c for all of them. In our study we find the permeability increase in 4 wells (well f, h, i and Fuxin), only well f and Fuxin well have the records of lithologic logs. However, there are no direct records of r_w and r_c in <China earthquake monitoring record series>, and it is hard to confirm r_w or r_c from the lithologic logs (Figure 6) for the two wells. We have to give up the calculation of permeability in this paper, alternatively, we use the phase lag between water level and tidal strain to approximately estimate the variation of permeability before and after the earthquake. Later, we may focus on 1—2 wells, which have detailed records of borehole datas, water level, and seismogram, and then we may do analysis of the permeability, together with the Skempton's coefficient *B*, so as to do comparison and to reveal the mechanisms more deeply and clearly.

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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Reference

Brodsky, E., E. Roeloffs, D. Woodcock, I. Gall, and M. Manga (2003). A mechanism for sustained groundwater pressure changes induced by distant earthquake, *J. Geophys. Res.* **108(B8),** 2390.

Beresnev, I., W. Gaul, and R. D. Vigil (2011). Direct pore-level observation of permeability increase in two-phase flow by shaking, *Geophys. Res. Lett.* **38,** L20302.

Blocher G., G. Zimmermann and H. Milsch (2009). Impact of poroelastic response of sandstone on geothermal power production, *Pure appl. geophys.* **166,**

1107–1123.

Bower, D. R., and K. C. Heaton (1978). Response of an aquifer near Ottawa to tidal forcing and the Alaskan earthquake of 1964, *Can. J. Earth Sci.* **15,** 331–340.

Berryman, J. G., and H. F. Wang (2001). Dispersion in poroelastic systems, *Phys. Rev. E* **64,** 011303.

Berryman, J. G. (1999). Origin of Gassmann's equations, *Geophysics* **64,** 1627–1629.

Beaumont, C. and J. Berger (1975). An analysis of tidal strain observations from the United States of America: I. The laterally homogeneous tide, *Bull. Seismol. Soc. Am.* **65,** 1613–1629.

Bodvarsson, G. (1970). Confined fluids as strainmeters, *J. Geophys. Res.* **75(14),** 49–56.

Chadha, R. K., H. J. Kuempel and M. Shekar (2008 I). Reservoir triggered seismicity (RTS) and well water level response in the Koyna-Warna region, India. *Tectonophysics* **456,** 94–102.пI

Chadha, R. K., C. Singh, and M. Shekar (2008 П). Transient changes in well-water level in bore wells in western India due to the 2004 Mw 9.3 Sumatra Earthquake, *Bull. Seismol. Soc. Am.* **98,** 2553–2558.

Cooper, H. H., Jr., J. D. Bredehoeft, I. S. Papadopulos, and R. R. Bennett (1965). The response of well-aquifer systems to seismic waves, *J. Geophys. Res.* **70,** 3915–3926.

Doan, M. L., E. E. Brodsky, R. Prioul and C. Signer (2006). Tidal analysis of borehole pressure-A tutorial, *Schlumberger Research report*, P35.

Elkhoury, J. E., E. E. Brodsky and D. C. Agnew (2006). Seismic waves increase permeability, *Nature* **411,** 1135–1138.

Elkhoury, J. E., A. Niemeijer, E. E. Brodsky, and C. Marone (2011). Laboratory observations of permeability enhancement by fluid pressure oscillation of in situ fractured rock, *J. Geophys. Res.* **116,** B02311.

Green, D. H. and H. F. Wang (1986). Fluid pressure response to undrained compression in saturated sedimentary rock, *Geophysics* **51(4),** 948–956.

Geballe, Z. M., C.-Y. Wang, and M. Manga (2011). A permeability-chang model for water-level changes triggered by teleseismic waves, *Geofluids* **11,** 302–308.

Gassmann, F. (1951). Über die elastizität poröser medien, *Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich,* **96,** 1–23.

Huang, F.-Q. (2008). *Response of Wells in Groundwater Monitoring Network in Chinese Mainland to Distant Large Earthquakes*, [Ph.D Dissertation] Institute of Geophysics, China Earthquake Administration, Beijing, pp. 47, (in Chinese).

Hsieh, P., J. Bredehoeft, and J. Farr (1987). Determination of aquifer transmissivity from earthtide analysis, *Water Resour. Res.* **23,** 1824–1832.

Khan, S. A., and H. G. Scherneck (2003). The M2 ocean tide loading wave in Alaska: vertical and horiaontal displacements, modelled and observed, *J. Geodesy* **77,** 117–127.

Kayen, R. E., E. Thompson, D. Minasian, R. E. S. Moss, B. D. Collins, N. Sitar, D. Dreger, G. A. Carver (2004). Geotechnical reconnaissance of the 2002 Denali Fault, Alaska, Earthquake. *Earthq. Spectra* **20,** 639–667.

King, C.-Y., S. Azuma, G. Igarashi, M. Ohno, H. Saito, and H. Wakita (1999).

Earthquake-related water-level changes at 16 closely clustered wells in Tono, central Japan, *J. Geophys. Res.* **104,** 13,073–13,082.

Kano,Y., Yanagidani, T., (2006). Broadband hydroseismograms observed by closed borehole wells in the Kamioka mine, central Japan: Response of pore pressure to seismic waves from 0.05 to 2 Hz, *J. Geophys. Res.*, **111,** 1 –11.

Linde, A. T., I. S. Sacks, M. J. S. Johnston, D. P. Hill, and R. G. Bilham (1994). Increased pressure from rising bubles as a mechanism for remotely triggered seismicity, *Nature* **371,** 408–410.

Liu, W. Q., M. Manga (2009). Changes in permeability caused by dynamic stresses in fractured sandstone, *Geophys. Res. Lett.* **36,** L20307.

Liu, C., M. W. Huang, and Y. B. Tsai (2006). Water level fluctuations induced by ground motions of local and teleseismic earthquakes at two wells in Hualien, eastern Taiwan, *TAO* **17,** 371–389.

Liu, L.B., E. Roeloffs, and X. Y. Zheng (1989). Seismically induced water level fluctuations in theWaliWell, Beijing, China, *J. Geophys. Res.* **94,** 9453–9462.

Liu, Y. R., and H. M. Tang (1998). *Rock Mass Mechanics*, Press of China University of Geosciences, Beijing, 214 pp.

Lu, Y. Z., S. L. Li, Z. H. Deng, H. W. Pan, S. Che, and Y. L. Li (2002). *Seismology Analysis and Prediction System Based on GIS (Mapseis Software)*, Chengdu Map Press, Chengdu, China, 232.

Magara, K. (1978). Compaction and fluid migeation, *Practical petroleum geology*. Ameterdam: Elsevier Scientific Publishing Company, 1–319.

Nur, A., and J. Byerlee (1971). An exact effective stress law for elastic deformation of rocks with fluids, *J. Geophys. Res*. **76,** 6414–6419.

Rice, J. R., and M. P. Cleary (1976). Some basic stress diffusion solutions for fluid-saturated elastic porous media with compressible constituents, *Rev. Geophys.* **14,** 227–241.

Roeloffs, E. A. (1996). Poroelastic techniques in the study of earthquakes-related hydrologic phenomena, *Adv. Geophys.* **37,** 135–195.

Roeloffs, E. A. (1998). Persistent water level changes in a well near Parkfield, California, due to local and distant earthquakes, *J. Geophys. Res*. **103,** 869–889.

Sil, S. (2006). Response of Alaskan wells to near and distant large earthquakes, Master's Thesis, University of Alaska Fairbanks, pp. 8−11.

Sil, S. and J. T. Freymueller (2006). Well water level changes in Fairbanks, Alaska, due to the great Sumatra-Andaman earthquake, *Earth Planets Space* **58**, 181–184.

Terzaghi, K. (1925). Principles in soil mechanics, III. Determination of the permeability of clay, *Engineering News Record.* **95,** 832−836.

Theo, H. S., M. H. Jacques, and C. C. Stephen (2002). Estimation of the poroelastic parameters of cortical bone, *J. Biomech.* **35,** 829–835.

Wang, H. F. (2000). *Theory of linear poroelasticity with application to geomechanics and hydrogeology.* Princeton University Press, Princeton, pp. 5−6.

Wang, H. F. (1993). Quasi-static poroelastic parameters in rock and their geophysical applications, *PAGEOPH* **141,** 269–286.

Wang, C.-Y. (2007). Liquefaction beyond the near field, *Seismol. Res. Lett.* **78,**

512–517.

Wang, C.-Y., Y. Chia, P. L. Wang and D. Dreger (2009). Role of S waves and Love waves in coseismic permeability enhancement, *Geophys. Res. Lett.* **36,** L09404.

Wang, C.-Y., and M. Manga (2010). *Earthquakes and Water, Series: Lecture Notes in Earth Sciences.* Springer Press, Berlin, pp. 18−24.

Wang, C.-Y., and Y. Chia (2008). Mechanism of water level changes during earthquakes: Near field versus intermediate field, *Geophys. Res. Lett.* **35,** L12402.

Walters, R. A. and D. G. Goring (2001). Ocean tides around New Zealand, *New. Zeal. J. Mar. Fresh.* **35**, 567−579.

Wu, H, Z., L. Y. Fu and H. K. Ge (2010). Quantitative analysis of basin-scale heterogeneities using sonic-log data in the Yanchang Basin, *J. Geophys. Eng.* **7,** 41–50.

West, M., J. Sanchez, and S. McNutt (2005). Periodically-triggered seismicity at Mt. Wrangell volcano following the Sumatr earthquake, *Science*, **308,**1144–1146.

Xue, Y.-Q. (1986). *Groundwater dynamics*. Geology Press, Beijing, pp. 16, (in Chinese).

Zhang, Y., F. Q. Huang, and G. J. Lai (2009). Research on Skempton's coefficient *B* based on the observation of groundwater of Changping station, *Earthq. Sci.* **22,** 631−638.

Zhang, Y., and F. Q. Huang (2011). Mechanism of Different Coseismic Water-Level Changes in Wells with Similar Epicentral Distances of Intermediate Field, *Bull.*

Seismol. Soc. Am. **101,** 1531–1541.

Zeng, R. S. (1984). *Solid Geophysics Introduction*, Press of Science, Beijing, pp. 9, (in Chinese).

Zhao L. F., X. B. Xie, W. M. Wang, and Z. X. Yao (2008). Regional Seismic Characteristics of the 9 October 2006 North Korean Nuclear Test, *Bull. Seismol. Soc. Am.* **98,** 2571–2589.

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):

$$2G\varepsilon_{ij} = \sigma_{ij} - \frac{\nu}{1+\nu}\sigma_{kk}\delta_{ij} + \frac{3(\nu_u - \nu)}{B(1+\nu)(1+\nu_u)} p\delta_{ij}, \qquad \text{(A1)}$$

$$m - m_0 = \frac{3\rho(\nu_u - \nu)(\sigma_{kk} + 3p/B)}{2GB(1+\nu)(1+\nu_u)}. \qquad \text{(A2)}$$

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 (A1) as a stress balance equation and equation (A2) 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 (A2) to obtain

$$p = -B\sigma_{kk} / 3 \text{ or } \Delta p = -B\Delta\sigma_{kk} / 3. \quad \text{(A3)}$$

Equation (A3) 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 (A3), 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 (A3) can be expressed in terms of tidal strain as well (Roeloffs, 1996):

$$\Delta h = -\frac{2GB(1+\nu_u)}{3\rho g(1-2\nu_u)}\Delta\varepsilon_t. \quad \text{(A4)}$$

Equation (A4) 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 (A4) we obtain:

$$B = -\frac{3\rho g(1-2\nu_u)}{2G(1+\nu_u)}\frac{\Delta h}{\Delta \varepsilon_t}. \quad (A5)$$

With equation (A5), 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 (A5)), 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 mechanisms for water level changes induced by teleseismic waves

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Abstract

The M_s 8.0 Wenchuan earthquake of May 12, 2008 induces large-amplitude water level changes at intermediate and far fields (epicentral distance >1.5 fault rupture length) in Chinese mainland. Although many hydrologic changes induced by teleseismic waves have been reported, the mechanisms responsible for the changes still remain unclear. We invoke Skempton's coefficient *B* and effective pressure in this paper to explain those co-seismic water level changes documented in the intermediate and far fields. The most used "enhanced permeability with a rapid redistribution of pore pressure induced by removing loose particals from fractures by teleseismic waves" can not be applied to explain all those coseismic water level changes in this study. From our research we find some of those abrupt coseismic water level changes, for which the variation of the co-seismic water level, and the effective pressure preserve consistent (all increase or all decrease) are found to favor the consolidation (porosity decrease) / dilatation (porosity increase) induced by the shaking of

teleseismic waves. Most of those wells have relatively high permeabilities attributing to the shales in the aquifer lithologies. While the other part of those coseismic water level changes (the variation of the co-seismic water level keeps inconsistent with the variation of effective pressure), can be explained with the enhanced permeability with a rapid redistribution of pore pressure, which is caused by fracture clearing or overcoming the capillary entrapment in porous channels of the aquifer induced by the shaking of teleseismic waves (most probably long period surface waves). Most of those wells stay in basins or hollows, this kind of terrain inclines to lead to heterogeneous pore pressure in close proximity.

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 Π; Wang and Manga, 2010), many occurred at great distances from the ruptured fault where static stress changes are relatively small. 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). Earthquake induced water level changes at distant locations were reported after the Denali earthquake (Brodsky *et al.*, 2003; Kayen *et al.*, 2004; Sil and Freymueller, 2006). Seismic oscillations, due primarily to surface waves from distant events, occur in some wells tapping highly transmissive aquifers (Liu *et al.*, 1989; Liu *et al.*, 2006). Sil and Freymueller (2006) developed an empirical relationship between water level changes, epicentral distances and earthquake magnitude in the far-field. Chadha *et al.* (2008 I) find wells appear to respond to regional strain variations and transient changes due to distant earthquakes. Liu and Manga (2009) indicate that significant water level changes can be driven at great distances by moderate-amplitude dynamic (time-varying) stresses.

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 far-field 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). Dynamic strain induced by the passage of seismic waves, most probably long period surface waves might be the cause of water level changes in the far-field (West *et al*., 2005; Sil and Jeffrey, 2006; Chadha *et al*., 2008 Π). 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), increasing pore pressure through seismically induced growth of bubbles (Linde *et al*., 1994), and fracture of an impermeable fault (King *et al*., 1999). In addition, Huang (2008) observed the co-seismic water level increase may be caused by the consolidation induced by the transmission of teleseismic waves in Fuxin well. Experimental measurements of Liu and Manga (2009) indicate that permeability changes (either increases or decreases) owing to dynamic stresses are a reasonable explanation. Wang *et al* (2009）find that the groundwater flow associated with S and Love waves may generate shear stress large enough to break up the flocs in sediment pores and to enhance the permeability of aquifers.

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 quasistatic 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 variations of co-seismic water level and effective pressure preserve uniformity. Most of those wells have relatively high permeabilities attributing to the shales in the aquifer lithologies. 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 or hollows), may be explained with the increased permeability caused by teleseismic waves, which in turn lead to the redistribution of pore pressures. Compare the occurrence time of water level changes with the arrival time of surface waves in two stations, we find the co-seismic water level changes are induced by the long period surface waves.

Selection Principles and Observations

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, the oceanic tides 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 oceanic 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 and 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. 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 when calculating the Skempton's coefficient *B*.

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 (A5) (Appendix). 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 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 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). Depths of those wells analyzed in this paper are all less than 1km (Table 1). 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 quantity 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 2).

Mechanism analysis

Till now, fracture clearing (unclogging) and increased permeability has been used to explain most of those coseismic water level changes in the far field (Brodsky *et al.*, 2003; Wang, 2007; Wang and Manga, 2010). 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). Analysis of well response to tidal forcing before and after an earthquake has provided strong evidence that earthquakes can enhance permeability (Elkhoury *et al.*, 2006). In this study, we calculate the change of Skempton's coefficient *B* and effective pressure, however, we can not use the enhanced permeability theory to explain all those coseismic water level changes. And we find the other part of water level changes may favor the consolidation or dilatation induced by teleseismic waves (about 58.3% of all those wells analyzed in this paper favor this explanation).

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).

We can summarize the variation of effective pressure ($P_{eff} = P_c - P_p$) in two ways: （P_c confining pressure, P_p pore pressure, and P_{eff} effective pressure ）

A) Pore pressure P_p keeps constant, the change of effective pressure P_{eff} induced by the change of confining pressure P_c .

There are two states (Table 4): (a1) Confining pressure increases (pore pressure not change), then effective pressure increases, the porosity will decrease (a process of consolidation or squeeze), and water level / pore pressure will increase; (a2) Confining pressure decreases (pore pressure not change), then effective pressure decreases, the porosity will increase (a process of dilatation), and water level / pore pressure will decrease. (a1), (a2) can be summarized as a mechanism of water level change induced by consolidation or dilatation, and water level changes in accordance with the change of effective pressure (all increase or all decrease) in this case.

B) Confining pressure P_c keeps constant, the change of effective pressure P_{eff} induced by the change of pore pressure P_p.

There are two states (Table 4): (b1) Pore pressure/ water level decreases (Confining pressure not change), then effective pressure increases, the porosity will decrease (a process of water level flows out of the well to a place with a relatively lower pore pressure); (b2) Pore pressure/ water level increases (Confining pressure not change), then effective pressure decreases, the porosity will increase (a process of water level flows into the well from a place with a relatively higher pore pressure). (b1), (b2) can be summarized as a mechanism of water level change induced by increased permeability with a rapid redistribution of pore pressure (this is the most used mechanism for far-field coseismic water level changes), and water level changes opposite to the change of effective pressure in this case.

As show in below (part 4.1 and part 4,2), we use two mechanisms to explain those coseismic water level changes.

Coseismic water level change induced by increased permeability followed by a rapid redistribution of pore pressure

The effective pressure range of well h, and i is 0 ~ 3 MPa (Table 2). According to the laboratory experiment of Blocher *et al* (2009), the increase of effective pressure accompanied with the increase of Skempton's coefficient *B* in this range. Water levels (pore pressure) decrease accompanied with the increase of effective pressures in well h, and i (Table 2). 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 the two wells may be higher than the close proximity before the earthquake, an enhancement of permeability incured by (for example) overcoming the capillary entrapment in porous channels induced by the passage of elastic waves will decrease the pore-pressure in wells (the pore-pressure will shift to other places), and water level will decrease. Then the effective pressure will increase accompanied with the decrease of pore-pressure (water level), so the Skempton's coefficient *B* increases (which indicates the stiff rock matrix could with a higher coupling to the fluid) in well h and i (Table 2).

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 2). According to the laboratory experiment of Blocher *et al* (2009), the decrease of effective pressure accompanied with the increase of Skempton's coefficient *B* in this range. Water level increases with the decrease of effective pressure (increase of Skempton's coefficient *B*) in well f, this should be explained with the increased permeability. Pore-pressure of well f may be lower than the close places before the earthquake, an enhancement of permeability will increase the pore-pressure in this well (the pore-pressure (water level) may shift from other places), and water level (pore pressure) will increase. Then the effective pressure will decrease accompanied with the increase of pore-pressure (water level), supposing the confining pressure not change. As explained by Blocher *et al* (2009), with the increase of effective pressure (reachers larger than 5 Mpa), the decrease of the Skempton's coefficient results from the change of the pore-geometry, which leads to a higher bulk modulus of the sample. Pore throats and microcracks were closed, and the stiff rock matrix could with a lower coupling to the fluid, so the Skempton's coefficient *B* decreases. And this is an reversible process (after they raised the confining pressure from 5 to 50 Mpa, they lowered the confining pressure form 50 to 5 Mpa, and also obtained the similar results), so when the effective pressure decreases (not lower than 5 Mpa), the closed pore throats and microcracks will be opened and turn larger under the effect of pore pressure, the stiff rock matrix could with a higher coupling to the fluid in well f, leading to the increase of Skempton's coefficient *B*.

The local geological structure of each well is important (Table 1). We find that most of those wells in which the coseismic water level changes can be explained with

“ the enhanced permeability with a rapid redistribution of pore pressure” stay in basins or in hollows (well f, h, i and Fuxin). The terrains of those wells incline to lead to heterogeneous pore pressures in close proximities (possibly attributed to different altitudes).

Coseismic water level change induced by consolidation or dilatation

Coseismic water level change induced by dilatation

For well g, j and k, the effective pressure range is 0 ~ 3 MPa, effective pressure will increase/decrease accompanied with the increase/decrease of Skempton's coefficient *B* during this range (Blocher *et al.,* 2009). Water levels (pore pressures) of well g, j and k decrease, accompanied with the decrease of effective pressures [and decrease of Skempton's coefficient *B* (which indicates the stiff rock matrix could with a lower coupling to the fluid)], which can not be explained with the increased permeability followed by the rapid pore pressure redistribution between the well and the places near the well. Whereas, this could be explained with the state (a2) Confining pressure decreases (pore pressure not change), then effective pressure decreases, the porosity will increase (a process of dilatation), and water level / pore pressure will decrease.

The spreading of teleseismic waves may cause dilatation of the aquifer medium, which can broaden the porosities (the permeability will increase) and give birth to new fractures, and the effective pressure will reduce (in wells: g, j and k) leading to the decrease of Skempton's coefficient *B*. This explanation is similar to the mechanism of shaking-induced dilatancy (Bower and Heaton, 1978).

Coseismic water level change induced by consolidation

For well a, b, c, and d, the effective pressure range is approximately 0 ~ 3 MPa, effective pressure will increase/decrease accompanied with the increase/decrease of Skempton's coefficient *B* (Blocher *et al.*, 2009). Water level (pore pressure) of well a, b, c, and d increase, accompanied with the increase of effective pressure [and increase of Skempton's coefficient *B* (which indicates the stiff rock matrix could with a higher coupling to the fluid)], which also can not be explained with the increased permeability followed by the rapid pore pressure redistribution between the well and the place near the well. Whereas, this could be explained with the state (a1) "Confining pressure increases (pore pressure not change), then effective pressure increases, the porosity will decrease (a process of consolidation or squeeze), and water level / pore pressure will increase". This mechanism is very similar to the explanation of the laboratory experiment of Liu and Manga (2009). From their laboratory experiment, they find that: in general, permeability/porosity 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, which can lead to a higher coupling between the stiff rock matrix and the fluid. Their result just supports our mechanism analysis. It implies that teleseismic waves can cause a consolidation of well aquifer and cause the increase of effective pressure (decrease of permeability and porosity), which is in accordance with the increase of co-seismic water levels accompanied with the increase of Skempton's coefficient *B* in well a, b, c, and d.

Examples support far field water level increases induced by consolidation

We analyze the mechanism of the coseismic water level changes induced by consolidation incurred by teleseismic waves in above. However, water level increases induced by consolidation in the far field is not the mainstream view. It is necessary to give some examples which can support far field water level increases induced by consolidation.

Huang (2008) find that: the water level increase in Fuxin well (1409.98 km away from Wenchuan, the well depth is 60.74 m， stiff Granite with a little basalt is the bedrock and we assume the shear modulus = 60 Gpa) is induced by the increase of volume strain (consolidation) (Figure 4a). 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 4b)). (The large-step abrupt water level increase starts from 09 p.m. May 22, 2008 (Figure 4c), which may cause large impact on the detrend process and influence the calculation result, so we discard these data). From Figure 4a, 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 2), from the change of the pre- and post- earthquake *B* (Figure 4b), we may infer the consolidation may be very extreme, accompanied with the coseismic water level increase it could cause an extra pressure, which 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 (corresponding to the state (b2)). 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 4c). 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 in a specific geology condition, a consolidation with large enough energy may also lead to an enhanced permeability by fracture clearing or by overcoming the capillary entrapment in porous channels.

Conclusion of coseismic water level changes induced by consolidation or dilatation

Water level increases/decreases accompanied with the increase/decrease of effective pressure (and the increase/decrease of Skempton's coefficient *B*) in well a, b, c, d, g, j, and k (the effective pressure range is approximately 0 ~ 3 MPa) (Table 3).

To our understanding, suppose the pressure not exceed a limitation (a perment derformation not happened), 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. Hence, 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. Figure 5 shows the relation between the change of Skempton's coefficient *B* and the change of effective pressure in well a, b, c, d, g, j, and k . Approximately, it displays a linear relation.

Well lithologic logs and permeability

As indicated by Wang *et al*. (2009) High transmissivity promotes uniform pore pressure, thus there is a low probability of connecting to a reservoir of different pressure. On the other hand, poor transmissivity can support heterogeneous pore pressure in close proximity, thus there is a high probability of connecting to a reservoir of different pressure. We show the well lithologic logs (borehole columnar diagrams) in Figure 6. According to <China earthquake monitoring record 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)], we can only get the lithologic logs of well (a), (c), (d), (e), (f), (k) and Fuxin (Figure 6), the pictures are designed already, some lithologic logs are explained in detail and some are in shot. Shales display in Lithologic logs of well (c), (d) , (e) [Although there is no obvious records of shales in the log of well e, according to the <China earthquake monitoring record series> there are shales (may be a small quantity of shale) in the matrix rock of well (e) (Table 1)] and (k), so the permeability of well (c), (d) , (e) and (k) may be relatively larger, and they are well connected with the close places outside the well, so there are little pressure differences between those wells and the places around them, and water level tend not to flow into or out of those wells even if the porosity/permeability increased by the shaking of telesismic waves. On the other hand, there are no shales in the logs of well (a), (f) and Fuxin, and the permeability may be relatively smaller, thus there is a high probability of connecting to a reservoir of different pressure, and water level tend to flow into or out of those wells after the porosity/permeability increased by the shaking of telesismic waves. Except for well (a), those analysises of lithologic logs are in accordance with our above mechanism analysises [well (c), (d), (e) and (k) favor the consolidation/ dilatation mechanism, while well (f) and Fuxin are induced by the increased permeability followed by a rapid redistribution of pore pressure]. Other factors may also influence the permeability, such as the geometry of the well. However, we can not make further study about that, since we lack the in situ tests and the detailed lithologic logs of other wells.

Because we use the approximately mediun value of shear modulus G (Table 1) to calculate the Skempton's coefficient B, it is hard to estimate the permeable extent of the aquifer from the absolute value of B. Whereas, the variation tendency of B before and after the earthquake is definite.

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 are a function of the transmissivity between the well and aquifer, in addition to the geometry of the well (Cooper *et al.*, 1965; Liu *et al.*, 1989; Kano and Yanagidani, 2006). 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 record series> 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. Hsieh *et al*. (1987) indicates that: the computed O1 phase shift is subject to large uncertainty, while the computed M2 phase shift is substantially more accurate. So we use the M2 wave to calculated the phase shift. Because we use the hourly data, we can not identify the phase difference when it is less than 1 hour, and we 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 changes not much (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.

Except for well e (Table 5), it is out of our expectation. Although there is no obvious records of shales in the lithologic logs of well e, there are shales (may be a small quantity of shale) in the aquifer lithology according to the <China earthquake monitoring record series> (Table 1), and the permeability in well e may be relatively high, so it connects well with the place outside, thus there is a low probability of connecting to a place of different pressure. Phase lag increases (which indicates a decrease in permeability) accompanied with the increase of water level in well e. In our expection, this situlation should incure an increase in Skempton's coefficient B (an increase in effective pressure), which indicates the aquifer be consolidated (squezeed). However, the effective pressure (Skempton's coefficient B) decrease in well e, this may be attributed to the fast dectrease of water level after the earthquake (Figure 2). Further researches need to be done so as to detect the mechanism more clearly.

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 3 we can see, the variations of effective pressure in well a, b, c, d, g, j and k are 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) changes little after the earthquake. Because the phase lags increase/decrease (wellbore storage effects increase/decrease) as the permeability (porosity) of the formation decreases/increases (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 7). 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 7).

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 levels will not recover to the pre-earthquake heights 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 calculat 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 increases/decreases, then the effective pressure increases/decreases, and at last transfers into the increase/decrease of pore pressure (water level), and the system comes into an equilibrium state. So the change of pore pressure can be attributed to the change of the effective pressure.

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

However , the variation value of the effective pressure in 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.

Compare with seismograms

There are 48 national stations recording the seismograms (event waveforms) in the Chinese mainland (we can not obtain some of the regional seismograms because of the authority limitation), 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 do not record seismograms. After comparison, generally we may use the seismograms of 4 national stations to analyze the corresponding water level observations, which are near those national stations (the distances between the water level wells and the national seismogram stations are approximately less than 100km). However, there are deficiencies in the seismograms of station TIY and LZH (TIY station is corresponding to well e (there are about 40.903 km between them); LZH station is corresponding to well g (there are about 19.82 km between them)), so we desgarded them. Finally, two seismograms can be used: the seismogram of SNY (Shengyang) station is used to analyze Fuxin well (there are about 102.81 km between them), and HEF (Hefei) station is corresponding to well k (there are about 91.57 km between them). In addition, the geology conditions are very similar (the main matrix rocks of Fuxin well and Shengyang station are both granite; Well k is in Chuhe river major dislocation and Hefei-Dongguan fracture intersection).

There are only hourly water level data in Fuxin well (minute data observation strats from 2009), so we can not use that to do precise comparison (in minute) with the seismogram. In general, we can only use well k to do the comparison between the timing of step in water level change and the arrival time of seismic waves. From the occurrence time of water level changes and the arrival time of surface waves of well k (Table 6), we find the co-seismic water level changes are attributed to the passage of surface waves. From that, we may infer: in other wells the co-seismic water level changes are attributed to the dynamic strain induced by the passage of teleseismic waves, most probably surface waves, which have relatively larger amplitude of oscillation, corresponding to relatively larger energy. The similar conclusion has been proposed by Sil and Jeffrey (2006), West *et al.* (2005), and Chadha *et al.* (2008 Π). More precise estimation of the timing of the step could not be made because of the low temporal resolution of the water level data. Obviously, there are geographic position differences between the observation of seismograms and water levels, and there are also some errors on the manual amplitude readings, both of which could cause some influence on the analysis.

The PGV (peak ground velocity) of Fuxin (SNY station) is about 3.224 mm/s, and that of well (k) (HEF station) is about 6.891 mm/s. Although the co-seismic water level changes in Fuxin is smaller than that in well (k), since they are induced by different mechanisms (co-seismic water level (Δh=0.121m) in Fuxin is induced by increased permeability followed by a rapid redistribution of pore pressure, and co-seismic water level (Δh=-0.455m) in well (k) is induced by dilatation), the ratio of PGV should not directly related with the ratio of co-seismic water level changes in the two wells.

There are aftershocks, and the one following the M_s 8.0 main shock (Chinese time 14:27:59.5) is at 14:43:14.7 , it is about 15 minutes later, so it will not cause disturbances on the main shock seismogram. What's more the after shocks are much smaller (the magnitude of aftershocks are less than M_s 6.0) than the main shock, the energy will decrease about 900 times, when the magnitude decrease 2, so the energy of those aftershocks are much smaller, which are not large enough to induce the variation of water level.

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 mechanisms of those coseismic water level changes, for which the variation tendency of the co-seismic water level, and the effective pressure keep the same (all increase or all decrease), and most of those wells have relatively high permeabilities attributed to the shales in the matrix rocks (based on the obtained 7 well logs in this study). While, fracture clearing and increased permeability with a rapid redistribution of pore pressure 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. Most of those wells stay in basins or hollows (well f, h, i and Fuxin), this kind of terrain inclines to lead to heterogeneous pore pressure in close proximity. Compared with the seismorgams, the co-seismic water level changes are attributed to the dynamic strain induced by the passage of seismic waves, most probably long period surface waves. 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.

Experiments of Liu and Manga (2009) apply time varying axial stresses (confining pressure changes) whereas Elkhoury *et al*. (2011) applied time varying fluid pressure differences (pore pressure changes) across their samples. Our study complement the experiments of both of them, we discuss the change of effective pressure ($P_{eff} = P_c - P_P$) in two ways: A) Pore pressure P_P keeps constant, the change of effective pressure induced by the change of confining pressure P_c. B) Confining pressure P_c keeps constant, the change of effective pressure induced by the change of pore pressure P_P.

From the analysis of Fuxin well, we can see consolidation also can be incurred by teleseismic waves. As discussed by Liu and Manga (2009): 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. The mechanism 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 experiment.

Matrix rocks with shales always correspond to relatively high permeabilities, and those wells are well connected with the other places outside the well, so there may be little pressure differences between those wells and the places around them, and water levels tend not to flow into or out of those wells even if the porosity/permeability increased by the shaking of telesismic waves. From our study we find most of the co-seismic water level changes in those wells can be attributed to the change of confining pressures. Consolidation/dilatation induced by shaking of teleseismic waves, may account for the mechanism. According to the geological structures, all of those wells stay in faults or in fracture intersections. Meanwhile, we find that the wells in which the coseismic water level changes can be explained with “the enhanced permeability with a rapid redistribution of pore pressure”, stay in basins or in hollows (well f, h, i and Fuxin). The terrains of those wells incline to lead to heterogeneous pore pressures in close proximities (possibly attributed to different altitudes).

In reality, some well aquifers are not porous and may be fractured, especially those wells with shales in the matrix rocks, may display substantial anisotropy or a fractured property rather than a porous property, however, we suspect that the isotropic and homogeneous poroelastic theory we used here is the best available approximation. The Skempton coefficients are very small for many wells, which may be attributed to the value of the shear modulus G [see Zhang and Huang (2011), since we lack the in-situ G values, we investigate the geology of each well and referred to the <rock mass mechanism> (Liu and Tang, 1998), using the dynamic elastic modulus and dynamic Poisson’s ratios to estimate the ranges of the dynamic shear modulus of those matrix rocks (according to the formula $G = \frac{E}{2(1+\sigma)}$), and to choose the approximate mean values (Table 1)]. 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 (Figure 3) can be applied to all those bedrocks in those wells, 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.

From our study we find lots of factors will influence the far-field co-seismic water level changes, such as lithology, topography and geometry of the well. Later it is necessary to calculate the tranmissivity (permeability), so as to testify the mechanisms. The commonly used permeability calculation [based on equations of Hsieh *et al.* (1987)] is based on several parameters: the dimensionless storage coefficient S, the radius of the screened or open portion of the well r_w, the radius of the well casing r_c. Because we lack the logs for all those wells, it is hard to confirm r_w or r_c for all of them. In our study we find the permeability increase in 4 wells (well f, h, i and Fuxin), only well f and Fuxin well have the records of lithologic logs. However, there are no direct records of r_w and r_c in <China earthquake monitoring record series>, and it is hard to confirm r_w or r_c from the lithologic logs (Figure 6) for the two wells. We have to give up the calculation of permeability in this paper, alternatively, we use the phase lag between water level and tidal strain to approximately estimate the variation of permeability before and after the earthquake. Later, we may focus on 1—2 wells, which have detailed records of borehole datas, water level, and seismogram, and then we may do analysis of the permeability, together with the Skempton's coefficient *B*, so as to do comparison and to reveal the mechanisms more deeply and clearly.

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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Reference

Brodsky, E., E. Roeloffs, D. Woodcock, I. Gall, and M. Manga (2003). A mechanism for sustained groundwater pressure changes induced by distant earthquake, *J. Geophys. Res.* **108(B8),** 2390.

Beresnev, I., W. Gaul, and R. D. Vigil (2011). Direct pore-level observation of permeability increase in two-phase flow by shaking, *Geophys. Res. Lett.* **38,** L20302.

Blocher G., G. Zimmermann and H. Milsch (2009). Impact of poroelastic response of sandstone on geothermal power production, *Pure appl. geophys.* **166,**

1107–1123.

Bower, D. R., and K. C. Heaton (1978). Response of an aquifer near Ottawa to tidal forcing and the Alaskan earthquake of 1964, *Can. J. Earth Sci.* **15,** 331–340.

Berryman, J. G., and H. F. Wang (2001). Dispersion in poroelastic systems, *Phys. Rev. E* **64,** 011303.

Berryman, J. G. (1999). Origin of Gassmann's equations, *Geophysics* **64,** 1627–1629.

Beaumont, C. and J. Berger (1975). An analysis of tidal strain observations from the United States of America: I. The laterally homogeneous tide, *Bull. Seismol. Soc. Am.* **65,** 1613–1629.

Bodvarsson, G. (1970). Confined fluids as strainmeters, *J. Geophys. Res.* **75(14),** 49–56.

Chadha, R. K., H. J. Kuempel and M. Shekar (2008 I). Reservoir triggered seismicity (RTS) and well water level response in the Koyna-Warna region, India. *Tectonophysics* **456,** 94–102.пI

Chadha, R. K., C. Singh, and M. Shekar (2008 Π). Transient changes in well-water level in bore wells in western India due to the 2004 Mw 9.3 Sumatra Earthquake, *Bull. Seismol. Soc. Am.* **98,** 2553–2558.

Cooper, H. H., Jr., J. D. Bredehoeft, I. S. Papadopulos, and R. R. Bennett (1965). The response of well-aquifer systems to seismic waves, *J. Geophys. Res.* **70,** 3915–3926.

Doan, M. L., E. E. Brodsky, R. Prioul and C. Signer (2006). Tidal analysis of borehole pressure-A tutorial, *Schlumberger Research report*, P35.

Elkhoury, J. E., E. E. Brodsky and D. C. Agnew (2006). Seismic waves increase permeability, *Nature* **411,** 1135–1138.

Elkhoury, J. E., A. Niemeijer, E. E. Brodsky, and C. Marone (2011). Laboratory observations of permeability enhancement by fluid pressure oscillation of in situ fractured rock, *J. Geophys. Res.* **116,** B02311.

Green, D. H. and H. F. Wang (1986). Fluid pressure response to undrained compression in saturated sedimentary rock, *Geophysics* **51(4),** 948–956.

Geballe, Z. M., C.-Y. Wang, and M. Manga (2011). A permeability-chang model for water-level changes triggered by teleseismic waves, *Geofluids* **11,** 302–308.

Gassmann, F. (1951). Über die elastizität poröser medien, *Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich,* **96,** 1–23.

Huang, F.-Q. (2008). *Response of Wells in Groundwater Monitoring Network in Chinese Mainland to Distant Large Earthquakes*, [Ph.D Dissertation] Institute of Geophysics, China Earthquake Administration, Beijing, pp. 47, (in Chinese).

Hsieh, P., J. Bredehoeft, and J. Farr (1987). Determination of aquifer transmissivity from earthtide analysis, *Water Resour. Res.* **23,** 1824–1832.

Khan, S. A., and H. G. Scherneck (2003). The M2 ocean tide loading wave in Alaska: vertical and horiaontal displacements, modelled and observed, *J. Geodesy* **77,** 117–127.

Kayen, R. E., E. Thompson, D. Minasian, R. E. S. Moss, B. D. Collins, N. Sitar, D. Dreger, G. A. Carver (2004). Geotechnical reconnaissance of the 2002 Denali Fault, Alaska, Earthquake. *Earthq. Spectra* **20,** 639–667.

King, C.-Y., S. Azuma, G. Igarashi, M. Ohno, H. Saito, and H. Wakita (1999).

Earthquake-related water-level changes at 16 closely clustered wells in Tono, central Japan, *J. Geophys. Res.* **104,** 13,073–13,082.

Kano,Y., Yanagidani, T., (2006). Broadband hydroseismograms observed by closed borehole wells in the Kamioka mine, central Japan: Response of pore pressure to seismic waves from 0.05 to 2 Hz, *J. Geophys. Res.*, **111,** 1 –11.

Linde, A. T., I. S. Sacks, M. J. S. Johnston, D. P. Hill, and R. G. Bilham (1994). Increased pressure from rising bubles as a mechanism for remotely triggered seismicity, *Nature* **371,** 408–410.

Liu, W. Q., M. Manga (2009). Changes in permeability caused by dynamic stresses in fractured sandstone, *Geophys. Res. Lett.* **36,** L20307.

Liu, C., M. W. Huang, and Y. B. Tsai (2006). Water level fluctuations induced by ground motions of local and teleseismic earthquakes at two wells in Hualien, eastern Taiwan, *TAO* **17,** 371–389.

Liu, L.B., E. Roeloffs, and X. Y. Zheng (1989). Seismically induced water level fluctuations in theWaliWell, Beijing, China, *J. Geophys. Res.* **94,** 9453–9462.

Liu, Y. R., and H. M. Tang (1998). *Rock Mass Mechanics*, Press of China University of Geosciences, Beijing, 214 pp.

Lu, Y. Z., S. L. Li, Z. H. Deng, H. W. Pan, S. Che, and Y. L. Li (2002). *Seismology Analysis and Prediction System Based on GIS (Mapseis Software),* Chengdu Map Press, Chengdu, China, 232.

Magara, K. (1978). Compaction and fluid migeation, *Practical petroleum geology*. Ameterdam: Elsevier Scientific Publishing Company, 1–319.

Nur, A., and J. Byerlee (1971). An exact effective stress law for elastic deformation of rocks with fluids, *J. Geophys. Res*. **76,** 6414–6419.

Rice, J. R., and M. P. Cleary (1976). Some basic stress diffusion solutions for fluid-saturated elastic porous media with compressible constituents, *Rev. Geophys.* **14,** 227–241.

Roeloffs, E. A. (1996). Poroelastic techniques in the study of earthquakes-related hydrologic phenomena, *Adv. Geophys.* **37,** 135–195.

Roeloffs, E. A. (1998). Persistent water level changes in a well near Parkfield, California, due to local and distant earthquakes, *J. Geophys. Res*. **103,** 869–889.

Sil, S. (2006). Response of Alaskan wells to near and distant large earthquakes, Master's Thesis, University of Alaska Fairbanks, pp. 8−11.

Sil, S. and J. T. Freymueller (2006). Well water level changes in Fairbanks, Alaska, due to the great Sumatra-Andaman earthquake, *Earth Planets Space* **58**, 181–184.

Terzaghi, K. (1925). Principles in soil mechanics, III. Determination of the permeability of clay, *Engineering News Record.* **95,** 832−836.

Theo, H. S., M. H. Jacques, and C. C. Stephen (2002). Estimation of the poroelastic parameters of cortical bone, *J. Biomech.* **35,** 829–835.

Wang, H. F. (2000). *Theory of linear poroelasticity with application to geomechanics and hydrogeology.* Princeton University Press, Princeton, pp. 5−6.

Wang, H. F. (1993). Quasi-static poroelastic parameters in rock and their geophysical applications, *PAGEOPH* **141,** 269–286.

Wang, C.-Y. (2007). Liquefaction beyond the near field, *Seismol. Res. Lett.* **78,**

512–517.

Wang, C.-Y., Y. Chia, P. L. Wang and D. Dreger (2009). Role of S waves and Love waves in coseismic permeability enhancement, *Geophys. Res. Lett.* **36,** L09404.

Wang, C.-Y., and M. Manga (2010). *Earthquakes and Water, Series: Lecture Notes in Earth Sciences.* Springer Press, Berlin, pp. 18−24.

Wang, C.-Y., and Y. Chia (2008). Mechanism of water level changes during earthquakes: Near field versus intermediate field, *Geophys. Res. Lett.* **35,** L12402.

Walters, R. A. and D. G. Goring (2001). Ocean tides around New Zealand, *New. Zeal. J. Mar. Fresh.* **35**, 567−579.

Wu, H, Z., L. Y. Fu and H. K. Ge (2010). Quantitative analysis of basin-scale heterogeneities using sonic-log data in the Yanchang Basin, *J. Geophys. Eng.* **7,** 41–50.

West, M., J. Sanchez, and S. McNutt (2005). Periodically-triggered seismicity at Mt. Wrangell volcano following the Sumatr earthquake, *Science*, **308,**1144–1146.

Xue, Y.-Q. (1986). *Groundwater dynamics*. Geology Press, Beijing, pp. 16, (in Chinese).

Zhang, Y., F. Q. Huang, and G. J. Lai (2009). Research on Skempton's coefficient *B* based on the observation of groundwater of Changping station, *Earthq. Sci.* **22,** 631−638.

Zhang, Y., and F. Q. Huang (2011). Mechanism of Different Coseismic Water-Level Changes in Wells with Similar Epicentral Distances of Intermediate Field, *Bull.*

Seismol. Soc. Am. **101,** 1531–1541.

Zeng, R. S. (1984). *Solid Geophysics Introduction*, Press of Science, Beijing, pp. 9, (in Chinese).

Zhao L. F., X. B. Xie, W. M. Wang, and Z. X. Yao (2008). Regional Seismic Characteristics of the 9 October 2006 North Korean Nuclear Test, *Bull. Seismol. Soc. Am.* **98,** 2571–2589.

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):

$$2G\varepsilon_{ij} = \sigma_{ij} - \frac{\nu}{1+\nu}\sigma_{kk}\delta_{ij} + \frac{3(\nu_u - \nu)}{B(1+\nu)(1+\nu_u)} p\delta_{ij}, \tag{A1}$$

$$m - m_0 = \frac{3\rho(\nu_u - \nu)(\sigma_{kk} + 3p/B)}{2GB(1+\nu)(1+\nu_u)}. \tag{A2}$$

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 (A1) as a stress balance equation and equation (A2) 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 (A2) to obtain

$$p = -B\sigma_{kk} / 3 \text{ or } \Delta p = -B\Delta\sigma_{kk} / 3. \quad \text{(A3)}$$

Equation (A3) indicates that, in the undrained condition, the change in fluid pressure (Δp) is proportional to the change in mean stress ($\Delta\sigma_{kk} / 3$). This is the mechanism of water level changes for poroelastic material. ($p = \rho g h$, where h is the water column height, g is the acceleration due to gravity and ρ is the density of water).

According to equation (A3), 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 (A3) can be expressed in terms of tidal strain as well (Roeloffs, 1996):

$$\Delta h = -\frac{2GB(1+\nu_u)}{3\rho g(1-2\nu_u)} \Delta\varepsilon_t. \quad \text{(A4)}$$

Equation (A4) 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 (A4) we obtain:

$$B = -\frac{3\rho g(1-2\nu_u)}{2G(1+\nu_u)}\frac{\Delta h}{\Delta \varepsilon_t}. \quad \text{(A5)}$$

With equation (A5), 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 (A5)), 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

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 and mild clay	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	502.93	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	442.19	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 Zhang and Huang (2011).

Table 2. Coseismic water level changes induced by increased permeability.

Station	**Δh / m**	**Δ*B***	**ΔP_p / MPa**	**ΔP_{eff} / MPa**	**Well Depth / m**	**Range of P_{eff} / MPa**
(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 Δh, 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 consolidation or dilatation incurred by shaking of teleseismic waves.

Station	**Δh / m**	**Δ*B***	**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 Δh, 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 4. Sketch of mechanism analysis.

State	Confining pressure *Pc*	Pore pressure *Pp*	Effective pressure *Pp* =*Pc* -*Pp*	Coseismic water level change Δh	Deduced Mechanism
(a1)	↑	–	↑	↑	Consolidation
(a2)	↓	–	↓	↓	Dilatation
(b1)	–	↓	↑	↓	Increased permeability followed by a rapid redistribution of pore pressure (water level flow out of the well to a place with a relatively lower pore pressure)
(b2)	–	↑	↓	↑	Increased permeability followed by a rapid redistribution of pore pressure (water level flow into the well from a place with a relatively higher pore pressure)

"↑"depends increase, "↓"depends decrease, and "–"depends invariance.

Table 5. Well (e), an exception.

Station	Δh / m	Δ*B*	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

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 well (e).

Table 6. Occurrence time of water level changes, arrival time of surface waves and peak ground velocities of well (k) and Fuxin well.

Well (water level) **/ Station** (seismogram)	**Occurrence time of water level change**	**Arrival time of surface wave**	**PGV (Z-component)**
(k) Chaohu / HEF	14:32:00, May 12, 2008	14:31:29.5, May 12, 2008	6.891 mm/s
Fuxin (only hour data) / SNY	14:??, May 12, 2008	14:35:34.5, May 12, 2008	3.224 mm/s

Figure

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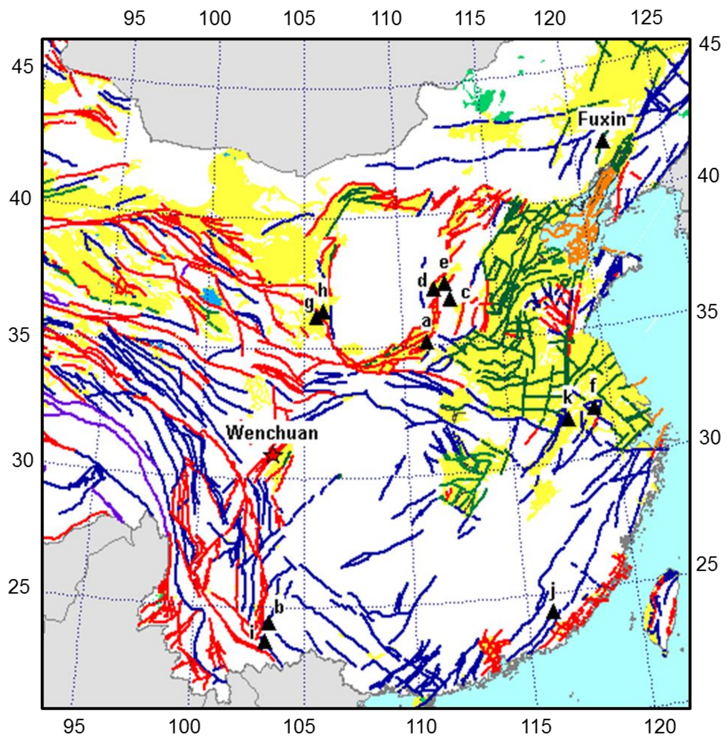


Figure 1. The selected 12 stations with distinct amplitude co-seismic water level changes during the Wenchuan earthquake in mainland China. The well numbers are in accordance with the numbers listed in Table 1.

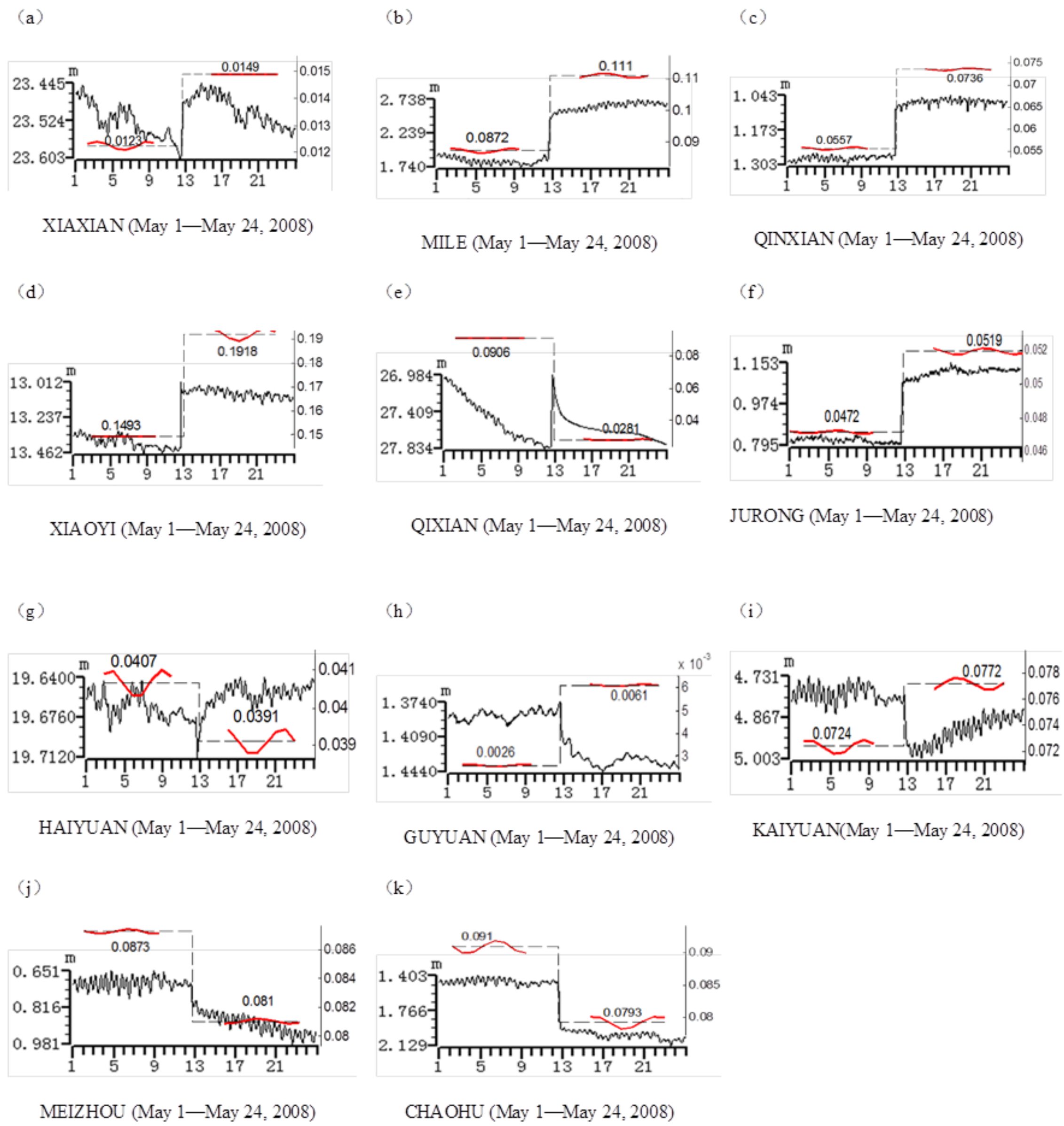


Figure 2. (a) Left y-coordinate: original water levels, the sequential number of y-coordinate depends on the type of the well, “sequential number increase from low to high” indicates an artesian well, the coordinate value means the height from the free water surface to the artesian discharge point or 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.

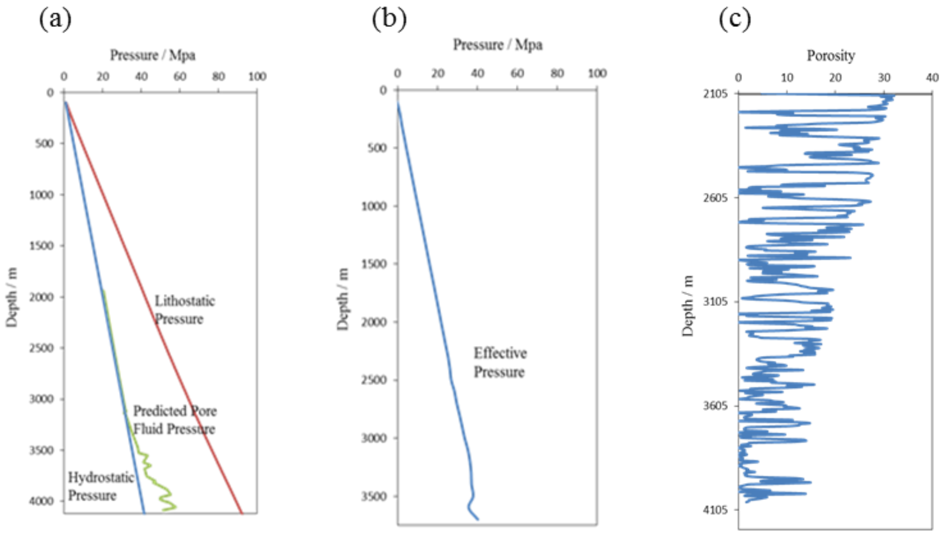
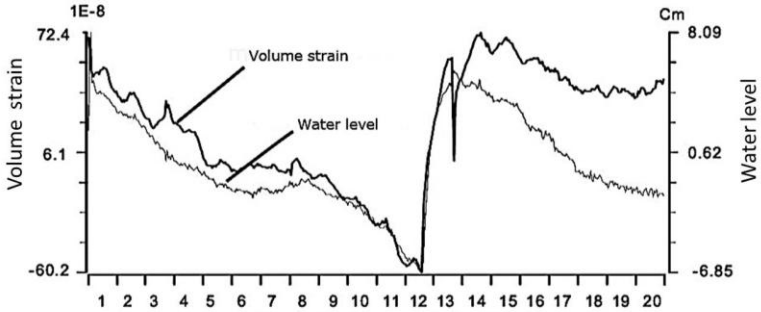


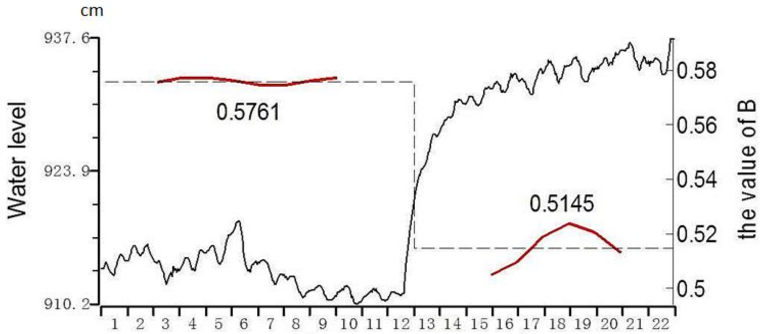
Figure 3. (a) Pressure section of W-1 well in Yanchang basin, the bedrock of W-1 well is sandstone. (b) Effective pressure section of W-1 well, we just show the depth above 3500m, so as to see the value in shallow depth more clearly. (c) Porosity section of W-1 well. The porosity records approximately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

(a)



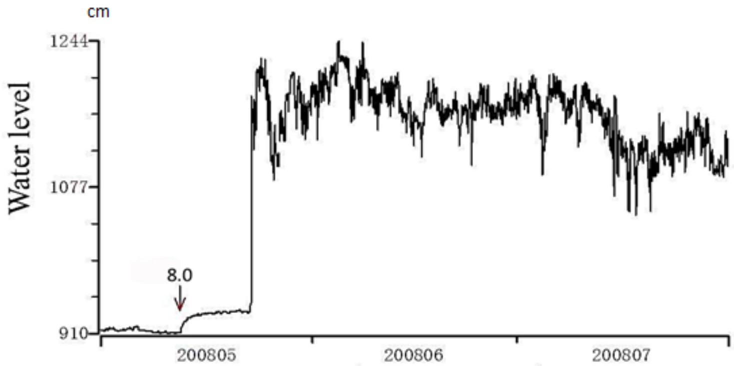
FUXIN (May 1—May 20, 2008)

(b)



FUXIN (May 1—May 22, 2008)

(c)



FUXIN (May 1—July 31, 2008)

Figure 4. 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.

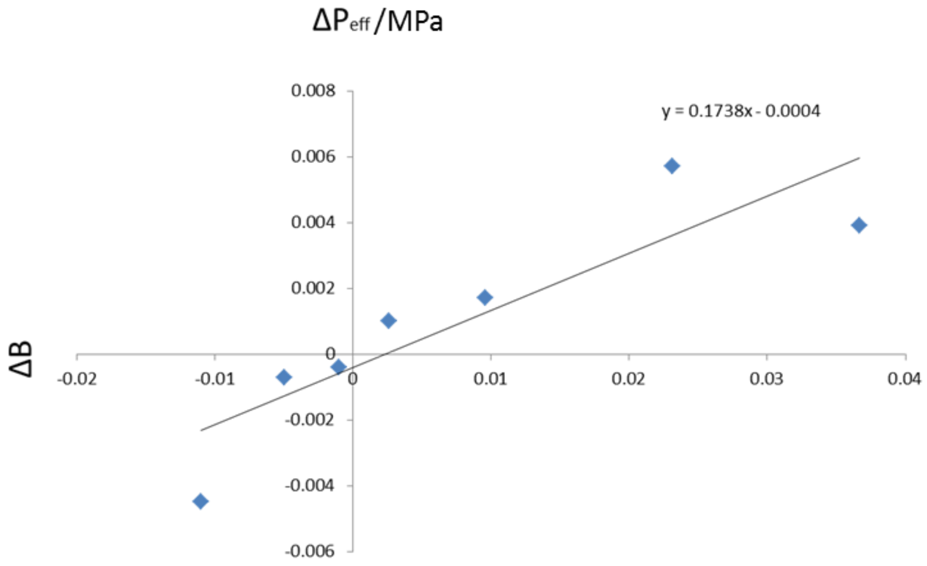
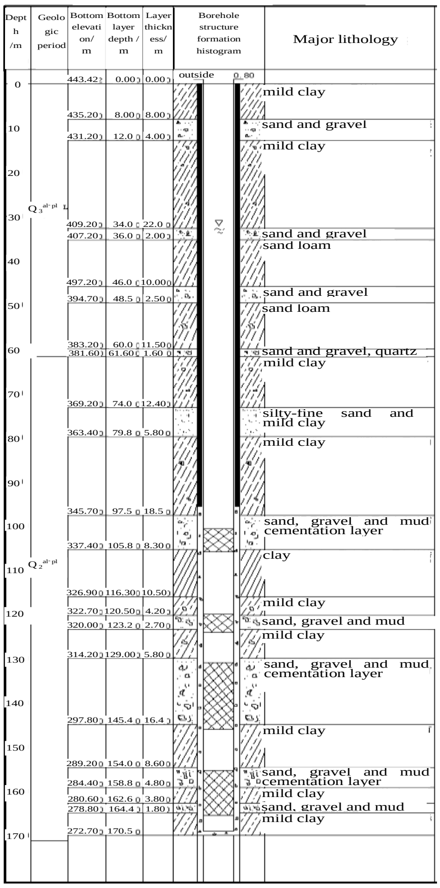
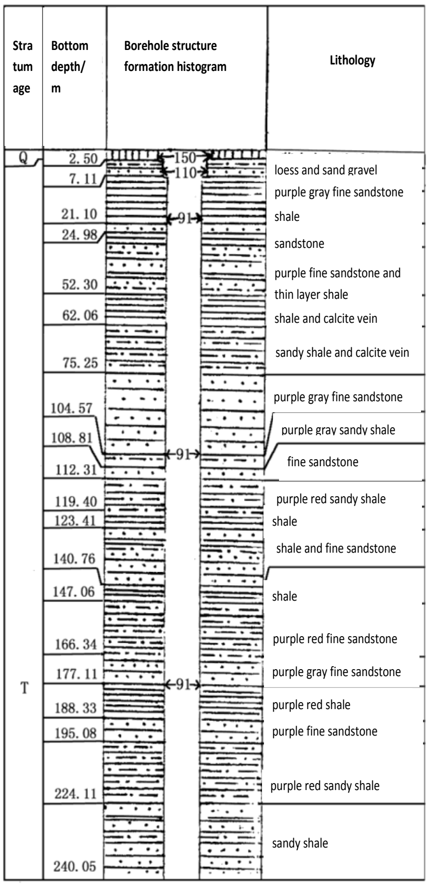


Figure 5. The relationship between the change of Skempton's coefficient *B* and the change of effective pressure P_{eff} of those wells of which the coseismic water level changes can be explained by the consolidation or dilatation caused by teleseismic waves.

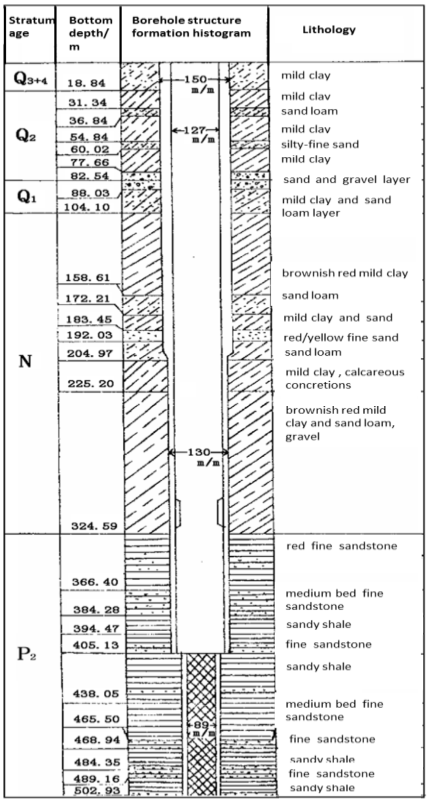
(a) Well (a)-Xiaxian



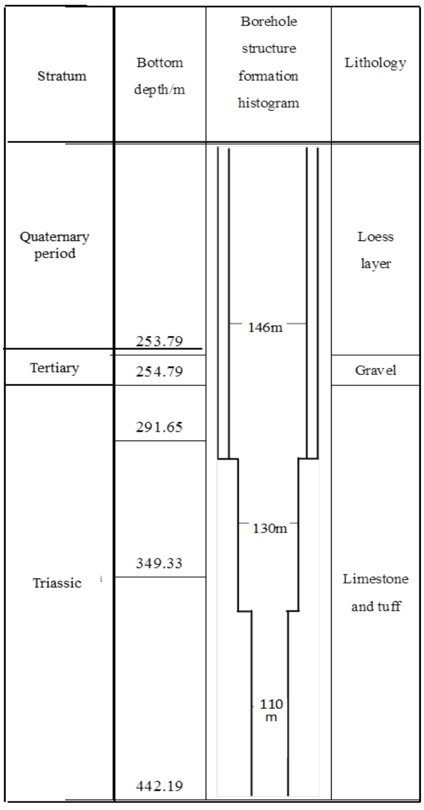
(b) Well (c)-Qinxianmanshui



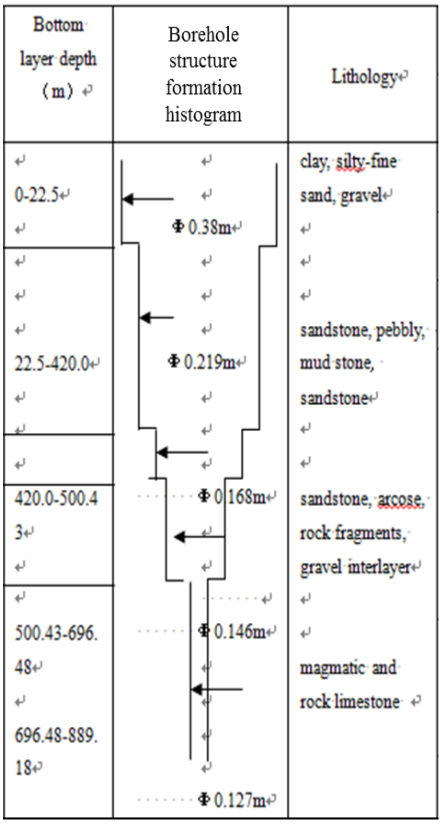
(c) Well (d)-Xiaoyi



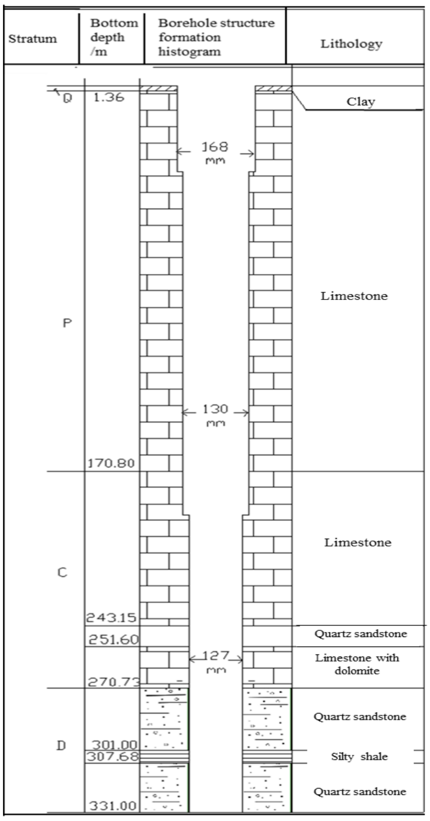
(d) Well (e)-Qixian



(e) Well (f)-Jurong



(f) Well (k)-Chaohu



(g) Fuxin

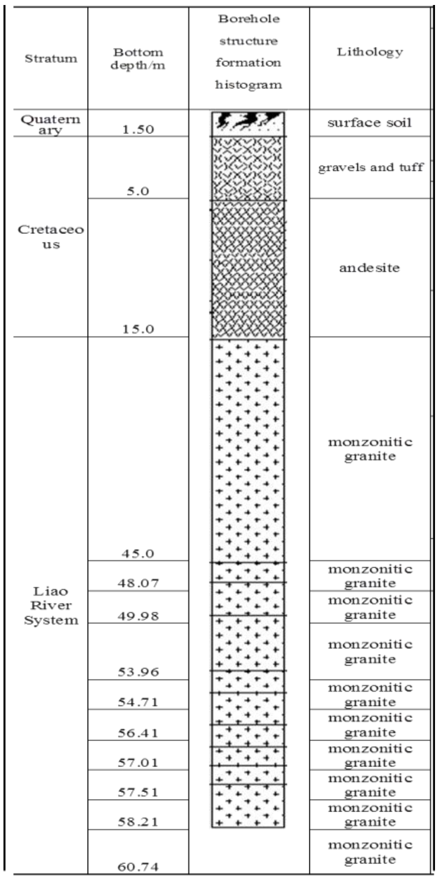
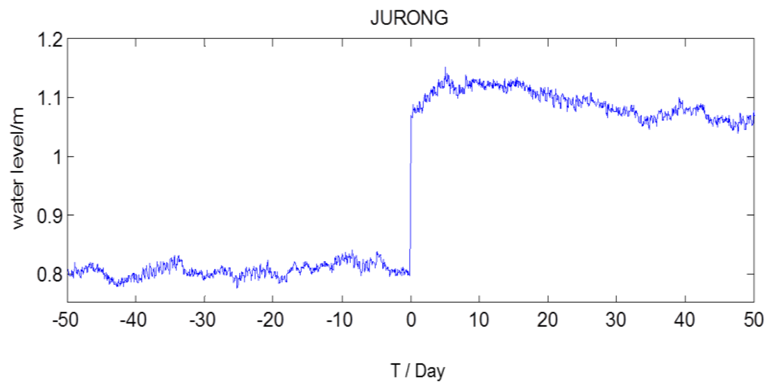


Figure 6. Lithologic logs **(**borehole structure histogram) of well (a), (c), (d), (e), (f), (k) and Fuxin.

(a)



(b)

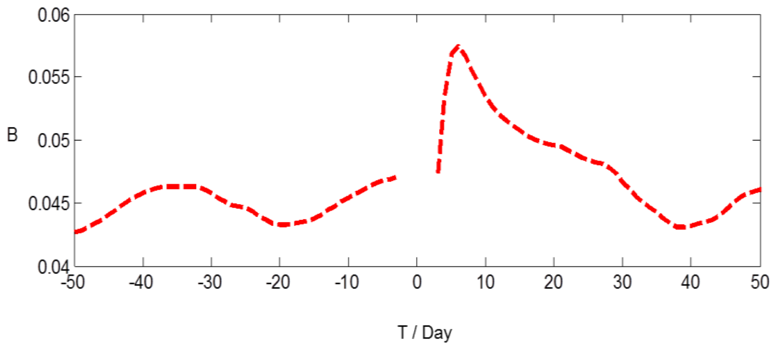


Figure 7. Jurong well (a) Original water level of Jurong station. (b) Continuous *B* value of Jurong station. (“0” depends the day when Wenchuan earthquake happened)

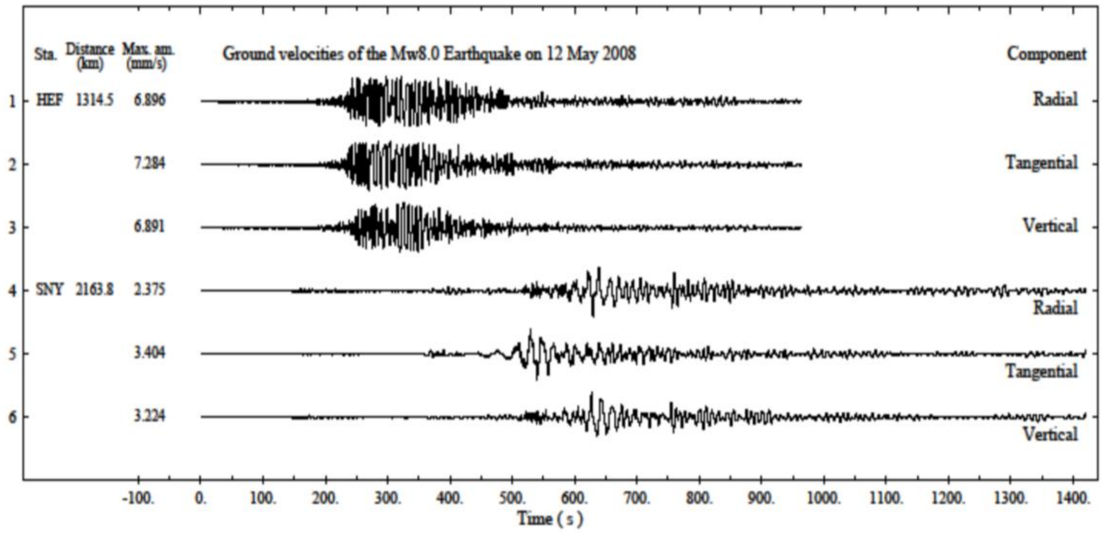


Figure 8. Seismograms of HEF and SNY national stations for the M_s 8.0 Wenchuan earthquake. The stations are ordered according to their epicentral distances. The station names and maximum amplitudes are listed on the left-hand side and are measured in millimetres per second. "0" is the time of Wenchuan earthquake: at 14:27:59.5, May12, 2008 (Chinese time). (This plotting pattern of seismograms are coined by Zhao *et al.*(2008)).

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