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Studies of the mechanism for water level change induced by teleseismic waves

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Abstract:	The Ms 8.0 Wenchuan earthquake of May 12, 2008 induced 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 these changes still remain unclear. We apply Skempton's coefficient B and effective pressure in this paper to explain those coseismic water level changes documented in the intermediate and far fields. The commonly used concept of "enhanced permeability with a rapid redistribution of pore pressure induced by removing loose particles from fractures by teleseismic waves" cannot be applied to explain all of the coseismic water level changes considered in this study. From our research, we find that some of those abrupt coseismic water level changes, for which the variation of the coseismic water level and the effective pressure remain consistent (both increase or both decrease) favor the consolidation (porosity decrease) / dilatation (porosity increase) induced by the shaking of teleseismic waves. The fact that the variation of the coseismic water level is often inconsistent with the variation in effective pressure can be explained by the enhanced permeability followed by 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 have relatively high permeabilities, which is attributable to the shales in their aquifer lithologies.
Author Comments:	Although many hydrologic changes induced by teleseismic waves have been reported, the mechanisms responsible for these changes still remain unclear. We apply Skempton's coefficient B and effective pressure in this paper to explain those coseismic water level changes documented in the intermediate and far fields.
Suggested Reviewers:	Chi-yuen Wang chiyuen@berkeley.edu he's an expert in this research region
	Emily E. Brodsky ebrodsky@es.ucsc.edu She's an expert in this research region
Opposed Reviewers:	Yaowei Liu

	he has a conflict with one of the author

Ref.: Ms. No. BSSA-D-12-00360R2
Studies of mechanism for water level changes induced by teleseismic waves
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Dear Yan Zhang,

Your paper has been reviewed for publication in the Bulletin. Please note that your manuscript still contains serious problems as noted below. The editorial board has decided to not send the paper out for another round of reviews because these problems cannot be easily solved. We note that this manuscript has been submitted repeatedly and continues to be rejected, partly because of the poor organization and development, and partly because of the poor English. We do not think that the paper can become suitable for publication without significant help from an additional collaborator who is familiar with the science and who has the appropriate skills for scientific writing in English. A native speaker of English would be highly desirable. I believe the Editorial report below 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

Answer: Dear Editor-in-Chief, I am so sorry to disturb you for so many times, because of the repeat submission of my paper. This time, I have modified the paper a lot, especially for the technical concerns and the organization, also we have invited a native English speaker to check the English very carefully, and an expert in this research region has helped me to reconstruct the paper.

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Editorial comments:

Even with multiple rounds of submission, additional reviews, and feedback from knowledgeable colleagues, this manuscript is still so poorly organized and developed that it is quite unsuitable for publication. It's not just poor English, it is poor science writing and communication in a broader sense. Nonetheless, the data and possible implications are still interesting. The reviewers and associated editors who have handled this paper all tried to make numerous suggestions to move the paper in the right direction, but the authors seem unable to use this information to make the required improvements.

At this point, we suggest that the authors collaborate with a person, who has appropriate paper writing skills and understands the science well, to completely rewrite and restructure this manuscript.

Answer: Dear Editor, I am so sorry to disturb you for so much times, because of the repeat submission of my paper, I am very sorry for my careless. This time, I have modified the paper a lot, especially for the technical concerns and the organization, also we have invited a native English speaker to check the English very carefully, and an expert in this research region has helped me to reconstruct the paper.

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. We have invited a native English speaker to check the English very carefully, and an expert in this research region has helped me to reconstruct the paper.

As indicated by reviewer 3, the *B* values we calculated with the hourly data, seems very low. So we re-calculate the B values after checking the longitude and latitude carefully, and use the minute data of water level and tidal strain, and we can also get the more precise phase difference between water level and solid tide with those minute data (Table 1).

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. In addition, we have distinguished the usage of "show" and "shown".

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: Because we have modified the paper enormously, we have deleted the sentence already.

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. Please see the part of "Mechanism analysis".

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 at first, and finally we only can use 2 of those seismograms. The content has been changed a lot, see Line 375—418 "Compare with seismograms".

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: (According to the suggestion and comments of reviewer 3, we have modified the paper significantly, so as to explain the mechanism much more clearly. We have invited a native English speaker to check the English very carefully, and an expert in this research region has helped me to reconstruct the paper.)

These are good suggestions, we have done an enormous modification, including the language, the construction, and the order. 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.

As indicated by reviewer 3, the B values we calculated with the hourly data seems very low. So we re-calculate the B values after checking the longitude and latitude carefully, and use the minute data of water level and tidal strain, and we can also get the more precise phase difference between water level and solid tide with those minute data (Table 1). After those work, we find the results are much different from the previous conclusion.

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 6, that really helps us to clarify the mechanism much more deeply.

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 454—458.

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 “Well lithologic logs” Line 360—374.

- 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:

Since indicated by the reviewer, the *B* values are too low, we have checked the latitude and longitude of each well (so as to recalculate the solid tidal strain), and use the minute data of water level and tidal strain to re-calculate the *B* values for those wells, which have the minute data records. This can also help us to calculate the phase differences more precisely. After re-calculation, we find most B values are not that low.

In some wells, the values of *B* are still low. This may be attributed to the value of the shear modulus G we use (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 elastic modulus and Poisson's ratios to estimate the ranges of the shear modulus of those matrix rocks (according to the formula $G = \frac{E}{2(1+\sigma)}$.), and to choose the approximate average G values (Table 1)). [See Table 1 (Shear modulus G* see Yan Zhang and Fuqiong Huang (2011)].

It is possible that the actural G values of those wells may be smaller than the approximate average values we use, and then according to equation (A5), the actural *B* values in some wells might be larger than we calculate in this paper.

Below is Table 1 of Zhang and Huang (2011)

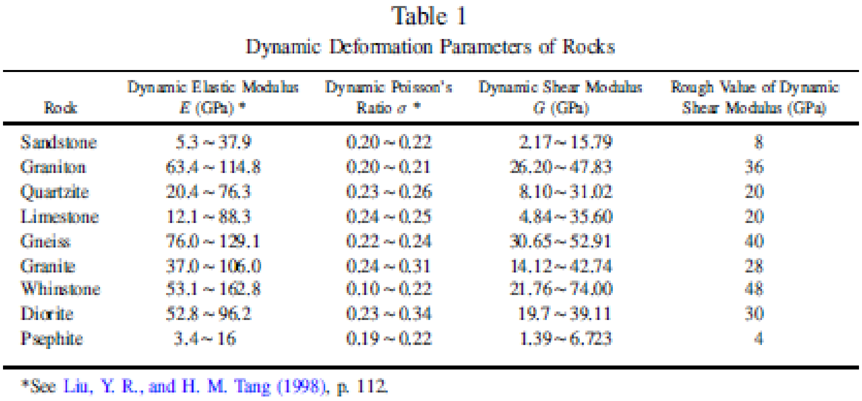

Table 1

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 458—469.

- 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 the part of "Calculation of Skempton's coefficient *B*". We use the previous results from the former researchers to justify that, compared with the variation of Skempton's coefficient *B* before and after the earthquake, the variation of shear modulus and the Poisson's ratio can be neglected. See Line 114—142 "Assumption of Poisson's ratio" and "Assumption of shear modulus".

We cite the work of Theo *et al*. (2002) is to clarify that "compared to the variation of Skempton's coefficient *B*, the change of the undrained Poisson's ratio can be neglected before and after the earthquake." See Line 123—130.

As show in Line 173: 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: 173—279 (Part of " 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 in two ways with the equation, which can help us to analyze the mechanisms much more clearly. See: Line 181—204. (and Table 4)

As indicated by this reviewer, those log analysis are very useful (Figure 6). 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 of "Well lithologic logs" Line 360-374. One thing needs to be clarified: we say those coseismic water level changes fit to be explained with the consolidation model, and those consolidation are induced by shaking of teleseismic waves: Permeability decrease (porosity decrease) is often accompanied by a consolidation of the aquifer, this mechanism is much similar with the mechanism proposed by Liu and Manga (2009). See Line 239—254

To clarify the relation between the Skempton's coefficient *B* and the effective pressure is a good suggestion, this will help us to clarify the mechanisms more clearly, we have modified it a lot. See "*Undrained Skempton's coefficient B as a function of effective pressure*" See: Line 143 -153.

Because the effective pressure range of the wells in which the co-seismic water level changes can be explained with the consolidation/dilatation model is less than 20 Mpa, during this effective pressure range, the increase of effective pressure accompanied with the decrease of Skempton's coefficient *B*. So the analysis and conclusion have changed a lot, See: Line 143-279.

- 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. So we have done an enormous modification, See Line: 173-279. (Part 4" 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, and according to your suggestions, we have modified the paper a lot. We have use the phase differences to estimate the variation of permeability. Since we re-calculated the phase difference with the minute data, we have obtained more accurate phase differences (in minute) for those wells. See “Well storage effects”, Line: 255—279, and Table 1.

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 Line: 262—264.

- 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 coseismic 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. See: Line 80-113 “Selection Principles and Observations ”.

Well (g) is out of our expectation, as show in Line 272—279:

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(tests on cores, sonic logs) to calibrate 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 “Well lithologic logs ” Line 360-374

- 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 to do comparisons between the arrival time of seismic waves and the occurrence time of co-seismic water level changes, and also obtain the PGV of those stations. See “Comparison with seismograms” Line: 375–418, and Table 6.

As pointed out by the reviewer, we show the seismograms in Figure 7.

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 the mechanism for water level change induced by teleseismic waves

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Abstract

The M_s8.0 Wenchuan earthquake of May 12, 2008 induced 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 these changes still remain unclear. We apply Skempton's coefficient *B* and effective pressure in this paper to explain those coseismic water level changes documented in the intermediate and far fields. The commonly used concept of "enhanced permeability with a rapid redistribution of pore pressure induced by removing loose particles from fractures by teleseismic waves" cannot be applied to explain all of the coseismic water level changes considered in this study. From our research, we find that some of those abrupt coseismic water level changes, for which the variation of the coseismic water level and the effective pressure remain consistent(both increase or both decrease)favor the consolidation (porosity decrease) / dilatation (porosity increase) induced by the

shaking of teleseismic waves. The fact that the variation of the coseismic water level is often inconsistent with the variation in effective pressure can be explained by the enhanced permeability followed by 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 have relatively high permeabilities, which is attributable to the shales in their aquifer lithologies.

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 II; Wang and Manga, 2010), and many occurred at great distances from the ruptured fault, where static stress changes were relatively small; for example, 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). These 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). 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). Chadha *et al.* (2008 I) found that wells appear to respond to regional strain variations and transient changes due to distant earthquakes. Finally, 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 coseismic changes in water level. Fracture clearing and increased permeability caused by 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). Wang *et al* (2009） found that the groundwater flow associated with S and Love waves may generate shear stresses large enough to break up the flocs in sediment pores and thereby enhance the permeability of aquifers. Others have theorized that 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 the seismically induced growth of bubbles (Linde *et al.*, 1994), and fracture of an impermeable fault (King *et al.*, 1999). In addition, Huang (2008) observed that the coseismic water level increase could be caused by the consolidation induced by the transmission of teleseismic waves in the Fuxin well. On the other hand, the experimental measurements of Liu and Manga (2009) indicate that permeability changes (either increases or decreases) owing to dynamic stresses are a reasonable explanation.

In the present study, we use Skempton’s coefficient *B*, the coseismic water level, and the inferred effective pressure to explain the coseismic water level changes in the intermediate and far fields based on datasets from the Wenchuan earthquake in the Chinese mainland. Using a poroelastic relationship 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 that consolidation/dilatation induced by shaking of teleseismic waves may explain those abrupt, coseismic water level changes, for which variations of coseismic water level and effective pressure preserve uniformity. While the other type of coseismic water level changes, for which the coseismic water level and the effective pressure change with inconformity, may be explained with the increased permeability caused by teleseismic waves, which in turn leads to the redistribution of pore pressure. Most of the wells that fall within this type have relatively high permeabilities, due to the shales in the aquifer lithologies. Comparing the occurrence time of water level change with the arrival time of surface waves in one station, we find that the coseismic water level change is induced by the long period surface waves.

Selection Principles and Observations

Data from many stations recording the coseismic water level changes induced by the M_s 8.0 Wenchuan earthquake have been collected in the intermediate and far fields (>1.5 fault-rupture lengths). Most of the water level changes in this area cannot be caused by the resulting change in static strain, which is extremely small (Zhang and Huang, 2011). We selected those coseismic water level changes with distinct amplitude (tiny or obscured coseismic water level changes have been excluded). In order to calculate the pre- and post-earthquake B values, water level data in stations could not contain large gaps in the record [e.g. there are 2-days of water level data missing (May 9th, 2008 to May 10th, 2008) in well Xiaoyi, so we excluded it], or be influenced by other factors, such as pumping and other disturbances, and the data must record a long enough time (at least 10 continuous days before and after the earthquake), so that we can use the least-square fit to calculate B (Appendix). In addition, the oceanic tides have been known to have an effect 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 not simply calculate the effect of oceanic tides by theory models. Also, there is no publicly available software that can calculate the Chinese national offshore ocean tides, so we have to delete those wells (4 wells: Hejiazhuang, Huanghua, Wafangdianloufang and Yongchun) which may be significantly influenced by the ocean tides. Bearing those restrictions in mind, we find10 stations [well (a) to well (j) (Figure 1)] that can be considered during the Wenchuan earthquake (Table 1).

Detailed basic information for each well is shown in Table 1 , including well depth, well diameter, aquifer lithology, and geological structure. However, diameter of well (f), (g), (i) and Fuxin could not be found. All of the water level recording instruments in those wells (well (a) to well (j)) are digital, they are LN-3A digital water level instruments (except for 2 wells: the Mile well uses the LN-4A digital water level instrument, and the Fuxin well uses the SQ digital water level instrument). These instruments have an observational accuracy≤0.2% F.S. and a sampling rate of 1 sample/min. The resolution ratio is 1mm. We use the Mapseis software (Lu *et al.*, 2002) to calculate the tidal strain data. Both the water level and the tidal strain use the minute data when calculating the phase difference between the water level and the solid tide.

Calculation

Calculation of Skempton's coefficient *B*

Calculations of Skempton's coefficient *B* are performed using $\rho = 1000 kg/m^3$, $g = 9.8 m/s^2$, and $\nu_u = 0.29$ with equation (A5) (see Appendix). We apply the *B*-calculation method to those selected stations. The pre-earthquake *B* values are obtained from May 1, 2008 to May 11, 2008, and the post-earthquake *B* values are obtained from May 14, 2008 to May 24, 2008 (Figure 2).

As equation (A5) shows, Skempton's coefficient *B* is related to the undrained Poisson's ratio ν_u, and the shear modulus G. In this paper, we assume both of them will not change before and after the earthquake.

Assumption of Poisson's ratio

We suppose the undrained Poisson's ratio to be $\nu_u = 0.29$ both before and after the earthquake. This kind of assumption is always used to simplify the calculations for rocks near the crust (Zeng, 1984). In addition, based on the poroelastic theory and limited to isotropic conditions, Theo *et al*.(2002) found that the variation of Skempton's coefficient *B* is much larger than that of the undrained poisson's ratio (variation extent of *B*: 6.3% ; variation extent of ν_u: 0.3%). So, compared to the variation of Skempton's coefficient *B*, the change of the undrained poisson's ratio can be neglected before and after the earthquake.

Assumption of shear modulus

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. Berryman (1999) and Berryman and Wang

(2001) found that this theory only applies at very low frequencies. At high enough frequencies (especially in the ultrasonic range), the numerical simulation of Berryman and Wang (2001) [based on an anisotropic medium, and use a complete set of poroelastic constants for drained Trafalgar shale] shows that the shear modulus is a function of Skempton's coefficient B, and with a 100% variation of Skempton's coefficient B, the shear modulus changes by about 1%. The frequencies of seismic waves are much lower than the ultrasonic frequencies, and we just consider about the undrained isotropic poroelastic media, so, we can assume that the shear modulus of well aquifer systems will not change after being affected by the seismic waves.

Derivation of effective pressure variation in each well

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

The undrained Skempton's coefficient B is considered a function of effective pressure (effective pressure $P_{eff} = P_c - P_P$, P_c confining pressure, P_P pore pressure) (Green and Wang, 1986). When the aquifer is consolidated, the effective pressure will increase, while a dilation corresponds to a decrease in effective pressure. Several previous studies (Green and Wang, 1986; Fredrich *et al.*, 1995, Blocher *et al.*, 2009) indicate that Skempton's coefficient B will decrease/ increase with an increase/ decrease in effective pressure for the well saturated aquifers, in cases where the effective pressure does not exceed a certain limitation [especially when the effective pressure is not larger than ~20 Mpa (Fredrich *et al.*, 1995)]. That effect is probably related to crack closure and to high-compressibility materials within the rock framework (Green and Wang, 1986).

Effective pressure variation in each well

The pore pressure response to gravitational loading is similar to that of tectonic loading and can also be treated as a poroelastic problem (Green and Wang, 1986). The 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 that this “pressure - depth” relation can be applied to the wells analyzed in this study. We calculate the effective pressure of the W-1 well (effective pressure equals lithostatic pressure minus pore fluid pressure), and obtain the “effective pressure - depth” relationship (Figure 3b). Then, we estimate the range of the effective pressure of these wells analyzed in this paper according to the well-depth. The effective pressure range of those wells are all less than 20 Mpa (Table 1), and as indicateded above, during this effective pressure range, Skempton’s coefficient B will decrease with an increase in effective pressure.

In general, the variation of pore pressure ($\Delta P_p = \rho g \Delta h$) can be used to confirm the variation value of the effective pressure (the absolute value of the effective pressure variation equals the absolute value of the pore pressure variation), and the change tendency of Skempton’s coeffieicnt B can be used to confirm the change tendency of the effective pressure in each well (effective pressure will decrease/ increase with an increase/ decrease in B for those wells) (Table 2, Table 3).

Mechanism analysis

Permeability will increase/decrease with an increase/decrease in porosity (Xue, 1986). As explained by rock mechanics, the same porosity always corresponds to the same effective pressure (Terzaghi, 1925; Magara, 1978). Porosity, permeability, and

Skempton's coefficient *B* are all directly connected with effective pressure, and they will decrease with an increase in effective pressure in the fully saturated aquifer (Blocher *et al.*, 2009). In this study, we analyze the mechanism of the coseismic water level change induced by teleseismic waves based on the deduced variation of effective pressure.

We summarize the variation of effective pressure ($P_{eff} = P_c - P_P$) in two ways (Table 4):

(A) Pore pressure P_p remains constant, and the change in effective pressure P_{eff} is induced by the change in confining pressure P_c. As shown in Table 4: (a1) P_c increases (P_p does not change), then P_{eff} increases, the porosity will decrease (a process of consolidation), and water level/ P_p will increase; (a2) P_c decreases (P_p does not change), then P_{eff} decreases, the porosity will increase (a process of dilatation), and water level/ P_p 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 (both increase or both decrease) in this case.

(B) Confining pressure P_c remains constant, the change of effective pressure P_{eff} induced by the change of pore pressure P_p. As shown in Table 4: (b1) Water level/ P_p decreases (P_c does not change), then P_{eff} increases, the porosity will decrease (a process where water flows out of the well to a place with a lower pore pressure); (b2) Water level/ P_p increases (P_c does not change), then P_{eff} decreases, porosity will increase (a process where water level flows into the well from a place with a 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 inversely with the change of effective pressure, in this case.

As shown below (part 4.1 and part 4.2), we use the two mechanisms discussed above [(A) and (B)] to explain those coseismic water level changes.

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

Water level changes inversely with the change of effective pressure in wells (b), (c), (d), (e), (f) and (j) (Table 2). We can use the mechanism of increased permeability with a rapid redistribution of pore pressure to explain this phenomena (Table 4).

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).

Coseismic water level increases and effective pressure decreases in wells (b), (c), (d) and (e) (Table 2). The pore-pressure of these wells may be lower than the close places near these wells before the earthquake, and an enhancement of permeability will increase the pore-pressure in those wells [the pore-pressure (water level) may shift into these wells from the close places with a higher pore-pressure]. Then, the effective pressure will decrease, accompanied by an increase in pore-pressure (water level), supposing that the confining pressure does not change. The Skempton's coefficient *B* increases in those wells, which indicates the stiff rock matrix could maintain a higher coupling to the fluid.

Coseismic water level decreases and effective pressure increases in wells (f) and (j). Pore-pressure of the two wells may be higher than the close proximity of them before the earthquake, and an enhancement of permeability, caused by (for example) overcoming the capillary entrapment in porous channels induced by the passage of elastic waves, will decrease the pore-pressure in the two wells [the pore-pressure (water level) will shift to the close proximity of the two wells], and water level will decrease. Then, the effective pressure will increase, accompanied by a decrease in pore-pressure (water level), supposing the confining pressure not change.

Coseismic water level change induced by consolidation or dilatation

Water level increases/decreases accompanied by the increase/decrease of effective pressure in wells (a), (h), and (i) (Table 3). We can use the mechanism of coseismic water level change induced by consolidation or dilatation to explain this phenomena (Table 4).

Coseismic water level change induced by dilatation

For wells (h) and (i), water level (pore pressure) decreases, accompanied by a decrease in effective pressure. This could be explained by the mechanism of water level change induced by dilatation. The spreading of teleseismic waves may cause dilatation of the aquifer medium, which can increase the porosity, and decrease the effective pressure, leading to an increase of Skempton's coefficient *B* (which indicates the stiff rock matrix would have a higher coupling to the fluid). This explanation is similar to the mechanism of shaking-induced dilatancy (Bower and Heaton, 1978).

Coseismic water level change induced by consolidation

Water level (pore pressure) of well (a) increased, accompanied by an increase in effective pressure. This could be explained by the mechanism of water level change induced by consolidation. This mechanism is very similar to that indicated by the laboratory experiment of Liu and Manga (2009). They find that 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. These particles are expected to accumulate and get trapped at the narrowest constrictions along flow paths, and hence allow a consolidation (contraction) of the sample. Their result supports our analysis; it implies that teleseismic waves can cause a consolidation of a well aquifer and thereby cause an increase of effective pressure (decrease of permeability and porosity). This is in accordance with the increase of coseismic water levels, accompanied by the decrease of Skempton's coefficient B (the stiff rock matrix would have a lower coupling to the fluid) in well (a).

Hence, shaking induced by the transmission of teleseismic waves may cause both consolidation or dilatation of the aquifer, and lead to both an increase or decrease of the water level (pore pressure).

Wellbore storage effects

Tidal phase lags are caused by wellbore storage. 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 differences increase) as the transmissivity (and permeability) of the formation decreases (Roeloffs, 1996; Doan *et al*., 2006).

Most of the wells in this study can record clear tidal strain and atmospheric pressure, and they are well confined. 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. From Table 1 we can see, in most wells, that the phase difference between water level and solid tide is small, which means that there are good correlations between the water levels and the tidal strains, and that those wells are well confined and under the undrained condition. Permeability/porosity will decrease (phase difference will increase) with an increase in the effective pressure in the fully saturated aquifer (Blocher *et al*., 2009). Variations of phase difference (permeability) are in accordance with the variations of effective pressure in most wells (Table 1~3).

Only well (g) (Table 5) gives unexpected results. Water level and Skempton's coefficient *B* decrease, accompanied by an increase of effective pressure in well (g). According to our expectations, this situlation should be the result of enhanced permeability, and the water level flow out of the well to the nearby area with relatively lower pore-pressure subsequently. Then, with the increase of effective pressure, the permeability should decrease. However, the permeability increases in well (g) (phase difference decreases (Table 1)), this may be attributed to the saturation deficit in well (g), and it needs to be clarified in a future study.

Discussion

The variation of porosity

Figure 3c shows, in general, that porosity decreases with the increase of depth; however, when 3000m is reached, the effective pressure becomes much larger (approximately equal to 35 Mpa) than that of the depth of those wells (wells a ~ j), the porosity still remains relatively large, and changes with depth. From Tables 2 and 3 we can see that the variations of effective pressure in wells (a)～(j) are less than 0.01Mpa. A variation of 0.01Mpa in effective pressure is approximately equal to a variation of 1 meter in depth (Figure 3b), and within this range of depth, the variation in porosity is tiny (Figure 3c). So, with this variation range of effective pressure, it is difficult to induce a permanent change in porosity. In addition, the laboratory experiment of Blocher *et al.* (2009) shows that the Skempton's coefficient B will decrease with the increase of effective pressure, and that that is a reversible process.

So, we can infer that the porosity of those wells analyzed in this paper can persist despite being reduced/enlarged due to the consolidation/dilatation induced by the passage of teleseismic waves. However, in reality, the change of porosity may also be connected with the formation and the state of the rock matrix.

Uncertainty of *B* coefficient

In order to study the uncertainty of B coefficient (error related to the determination of B coefficient), we use the Jurong well to show the variation of B during a relatively long time span (50 days before and after the Wenchuan earthquake) (Figure 4). Skempton's coefficient B will change with time. Because we use the least square fit to calculate B, the value may be a little different when we use data that extends over a different length of time , but the change tendency (increase or decrease of B) before and after the earthquake will be constant. Furthermore, we can see that the B value of the Jurong well recovered its initial value after approximately 30 days (Figure 4).

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

Recovery of the water level

The recovery time of the water level is poorly understood because most of those water levels will not recover to the pre-earthquake heights during a short time span. So, we should use data stretching over a longer time period 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, thunder, and so on, which require lots of study to understand, although we may study about them in the 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 many more wells in the future, to further study these relations.

The variation value of effective pressure

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

When the aquifer is consolidated or dilated, in the critical state, the pore pressure remains constant, the confining pressure increases or decreases, then the effective pressure increases or decreases, and finally transfers into the increase or decrease of the pore pressure (water level), and the system reaches an equilibrium state. So, the change in pore pressure can be attributed to the change in the effective pressure.

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

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

Examples support far field water level increases induced by consolidation

We analyze the mechanism of the coseismic water level changes induced by consolidation caused by teleseismic waves in "*4.2.2 Coseismic water level change induced by consolidation*". 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 this mechanism.

Huang (2008) found that the water level increase in the 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 in volume strain (consolidation) (Figure 5a). In the Chinese mainland, Fuxin is the only well in which there are observations of volume strain and water level in a specific aquifer medium, and both of them show obvious coseismic responses to the Wenchuan earthquake. Fuxin is a terrific artesian well, it was not chosen to be used at first, because there is an abrupt large-amplitude increase in the water level, which starts at 11 p.m. May 22, 2008 (we can not find any interference from this abrupt increase in the daily records of Fuxin station), and we can just use a shorter time period to calculate the post-earthquake *B* value (pre-earthquake: from May 1, 2008 to May 11, 2008, post-earthquake: from May 13, 2008 to May 22, 2008 (Figure 5b)). From Figure 5a, we can see that the coseismic water level increase is induced by the change in volume strain, which indicates that the well aquifer has been consolidated. The depth of the Fuxin well is 60.74 m, and we can assume the range of the effective pressure is 0～3Mpa. The Skempton's coefficient *B* decreases, accompanied by an increase in the effective pressure and coseismic water level (Figure 5b), which is in accordance with the mechanism analysis of coseismic water level change induced by consolidation. So, we argue that the water level increase induced by the consolidation incurred by transmission of teleseismic waves is reasonable.

Well lithologic logs

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 province and various institutions) of the China Earthquake Administration, and published in Beijing in different years by Seismological Press (in Chinese)], we can only get the lithologic logs of wells (a), (c), (d), (e), (j) and Fuxin (Figure 6), the pictures were designed previously, and some lithologic logs are explained in detail and some are not.

Shales are displayed in the lithologic logs of wells (c), (d) and (j) [Although there are no obvious records of shales in the log of well (d), according to the <China earthquake monitoring record series> there are shales (maybe a small quantity of shale) in the matrix rock of well (d) (Table 1)] (Figure 6). Porosity (permeability) of wells (c), (d) and (j) should be relatively larger, and the aquifer may even be fractured. So, the pores likely tend to be dilatated by the shaking of teleseismic waves, and the coseismic water level changes in wells (c), (d), and (j) can be explained by the theory of increased permeability, followed by a rapid redistribution of pore pressure.

Comparison with seismograms

There are 48 national stations recording seismograms (event waveforms) in the Chinese mainland, however most of those stations are not in the same place as those stations which record water level. Those stations (wells (a) to (j)) analyzed in our paper do not record seismograms. After comparison (including seismogram quality checking), we typically use the seismograms of two national stations to analyze the corresponding water level observations (the distances between the water level wells and the national seismogram stations are less than 110km). The seismogram of SNY (Shengyang) station is used to analyze the Fuxin well (there are approximately 102.81 km between them), and HEF (Hefei) station corresponds to well (j) (there are approximately 91.57 km between them) (Figure 7). In addition, the geological conditions are very similar. The main matrix rocks of the Fuxin well and the Shengyang station are both granite, and well (j) is in the Chuhe river major dislocation and Hefei-Dongguan fracture intersection.

There are only hourly water level data for the Fuxin well (minute data observation began in 2009), so we cannot use that data to do precise comparison (per minute) with the seismogram. In general, we can only use well (j) to make this comparison. From the occurrence time of water level change and the arrival time of seismic waves at well (j) (Table 6), we find that the coseismic water level change should be attributed to the passage of surface waves. From that, we may infer that the coseismic water level changes of the other wells are also attributable to the dynamic strain induced by the passage of teleseismic waves, most probably surface waves, which have a larger amplitude of oscillation, corresponding to higher energy levels. A similar conclusion has been proposed by Sil and Jeffrey (2006), West *et al.* (2005), and Chadha *et al.* (2008 Π). A more precise estimation of the timing of the change could not be made because of the low temporal resolution of the water level data. Obviously, there is geographic positional difference between the observation of seismogram and water level, but the distance is not large enough to influence our above analysis, because the seismic waves transmit extraordinarily quickly.

The PGV [peak ground velocity (vertical component)] in well Fuxin (SNY station) is 3.224 mm/s, and that of well (j) (HEF station) is 6.891 mm/s. The coseismic water level change in Fuxin (Δh=0.121m) is smaller than that in well (j) (Δh=-0.455m). It seems that the changes of the coseismic water level correspond to the PGV in the two wells; however, they are induced by different mechanisms. The coseismic water level change in well (j) is induced by increased permeability followed by a rapid redistribution of pore pressure, and that of Fuxin is induced by consolidation. So, the ratio of PGV of the two wells is not directly related to the ratio of coseismic water level changes.

The aftershock following the M_s 8.0 mainshock （Chinese time 14:27:59.5） was at 14:43:14.7 , about 15 minutes later. So, it would not have caused disturbances on the mainshock seismogram. What’s more, the aftershocks were much smaller (the magnitude of aftershocks was less than M_s 6.0). The energy will decrease by a factor of about 900, when the magnitude decreases by 2. So, the energy of those aftershocks is not large enough to induce significant variations in water level in the intermediate and far fields.

Conclusion

Till now, fracture clearing (unclogging) and increased permeability have been used to explain most of the coseismic water level changes in the far field (Brodsky *et al.*, 2003; Wang, 2007; Wang and Manga, 2010). In this study, we analyze the mechanism based on the change of coseismic water level and the deduced variation of effective pressure. However, we cannot use the enhanced permeability theory to explain all of these coseismic water level changes. And, we find that the other type of water level change may favor the theory of consolidation or dilatation induced by teleseismic waves (about 36.36% of the wells analyzed in this paper favor this explanation). From this study we can conclude that the 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 coseismic water level and the effective pressure remains the same (both increase or both decrease). Fracture clearing and increased permeability with a rapid redistribution of pore pressure may be used to explain the other type of those coseismic water level changes, for which the coseismic water level and the effective pressure change with inconformity. Most of those wells have relatively high permeabilities attributable to the shales in the aquifer lithologies. Compared to the seismograms, the coseismic water level changes are attributed to the dynamic strain induced by the passage of seismic waves, most probably long period surface waves. Our analysis does not conflict with any of those existing theories. Although those water level changes happen in the intermediate and far fields, most of those water levels present abrupt and obvious coseismic changes owing to the huge energy of the M_s 8.0 Wenchuan earthquake.

The experiments of Liu and Manga (2009) applied 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 analysis complements the limitations of their experiments. We discuss the change of effective pressure ($P_{eff} = P_c - P_P$) in two ways: A) Pore pressure: P_P remains constant, and the change of effective pressure P_{eff} is induced by the change of confining pressure P_c. B) Confining pressure P_c remains constant, and the change of effective pressure P_{eff} is induced by the change of pore pressure P_P. From the analysis of the Fuxin well, we can see that consolidation can also be incurred by teleseismic waves. The mechanism analysis of "*4.2.2 Coseismic water level change induced by consolidation*" is similar to the experimental results of Liu and Manga (2009), and our in-situ analysis may complement the limitations of the initial condition of their laboratory experiment.

In reality, some well aquifers are not porous and may be fractured, especially those wells with shales in the matrix rocks, which may display substantial anisotropy or a fractured property rather than a porous property. However, we suspect that the isotropic and homogeneous poroelastic theory we have used here is the best available approximation. The Skempton coefficients are small for some wells, which may be attributed to the value of the shear modulus G we use [see Zhang and Huang (2011): because 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 elastic modulus and Poisson's ratios to estimate the ranges of the shear modulus of those matrix rocks, and use the approximate mean values of G (Table 1)]. It is possible that the actual G values of those wells may be smaller than the approximate average values we use, which would mean that, according to equation (A5), the actual *B* values might be larger than those we calculate in this paper. It is also possible that those well aquifers may not be fully saturated. The discussed “undrained” condition can hardly last for a long time. As long as the fluid flow exists, the undrained condition will quickly be disrupted and replaced by the drained condition. 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 period of time and withstand large amounts 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)). If these ideal assumptions are discarded, the results will likely be different.

Data and Resources

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

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Appendix: An approach to Skempton's coefficient *B* based on the poroelastic theory

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

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

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

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

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

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

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 for water level changes in 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 that 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):

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

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:

$$B = -\frac{3\rho g(1-2\nu_{\mathrm{u}})}{2G(1+\nu_{\mathrm{u}})} \frac{\Delta h}{\Delta \varepsilon_t} \, . \tag{A5}$$

With equation (A5), we obtain the value of B with water level and tidal strain. However, the calculation is only valid when an undrained condition is assumed (the good correlation between the water level and the tidal strain), and should not be influenced by other factors.

In regards to 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 that the aquifer system is undrained (Huang, 2008). So, we can suppose that 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 we calculate that the phase lags between the water levels and the tidal strains are small, thus 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 $2.23636 \times 10^{-5} HZ$) 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) through 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 have not 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.

Table1-6

Table 1. Basic information of wells a ~ j.

Station	Epicentral Distance / km	Δh / m	Pre / Post-Earthquake *B*	Major Aquifer Lithology	G*/ Gpa	Phase Difference / min	Well Diameter / mm	Well Depth / m	Range of P_{eff} / MPa	Geological Structure
(a) Xiaxian	465.9465	0.106	0.2152 / 0.1486	Biotite plagioclase gneiss and mild clay	40	L1=9 L2=31	559	170.5	0～3	north part of Zhongtiao mountain fault
(b) Mile	726.4589	0.579	0.2568 / 0.4651	Limestone	20	L1=19 L2=2	127	614.4	3～5	Mile—Shizong fault
(c) Qinxianmanshui	983.8517	0.172	0.0557 / 0.0653	Three of Triassic sandstone	8	L1=30 L2=16	134	240.05	0～3	Guocun basin,uplift of Taihang mountain fault block
(d) Qixian	1152.6034	0.831	0.2985 / 0.6177	Limestone and shale (the Tertiary and Quaternary period loess and gravel)	20	L1=23 L2=8	146	442.19	0～3	east part of Taiyuan basin
(e) Jurong	1750.2357	0.263	0.124 0/ 0.1259	K2 Silicified sandstone and conglomerate	8	L1=2 L2=1	219	889.18	8～10	west of Maoshan mountain fault, near the top of the uplift of the buried hill of Jurong hollow
(f) Haiyuanganyanchi	606.402	-0.036	0.2710 / 0.1893	Q sandstone and conglomerate	8	L1=11 L2=32		306.73	0～3	west and south of Huashan mountain fault
(g) Guyuanzhenqi	638.7904	-0.026	0.5702 / 0.261	Mediate and fine sand	8	L1=31 L2=30		255.74	0～3	compresso-shear basin,in the east and north part of Haiyuan fault
(h) Kaiyuan	805.4263	-0.155	0.1316 / 0.2676	Triassic Falang formation limestone	20	L1=39 L2=11	273	224	0～3	south of Xiaojiang fault, east of arc structure top, in the northern part of the basin
(i) Meizhou	1345.951	-0.075	0.1997 / 0.6843	Quartzite	20	L1=18 L2=6		338.86	0～3	Heyuan—Shaowu and Chaoan—Meixian fracture intersection
(j) Chaohu	1587.6013	-0.455	0.2197 / 0.1817	The Devonian quartz and limestone	20	L1=12 L2=36	168	331	0～3	East side of the Tanlu fault,Chuhe river major dislocation and Hefei—Dongguan fracture intersection.

Epicentral Distance, Water Level Change, Pre- and Post-Earthquake *B* Values, Major Lithology of Aquifer, Shear Modulus, Phase Differences, Well Diameter, Well Depth, Range of Effective Pressure and Geological Structure of those well-picked stations. L1 and L2 represent the pre- and post-earthquake phase differences between water level and solid tide.

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

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

Station	**Δh / m**	**ΔB**	**ΔP_p / MPa**	**ΔP_{eff} / MPa**	**Well Depth / m**	**Range of P_{eff} / MPa**
(b) Mile	**0.579**	0.2083	0.005674	**-0.005674**	614.4	3～5
(c) Qinxianmanshui	**0.172**	0.0096	0.001686	**-0.001686**	240.05	0～3
(d) Qixian	**0.831**	0.3192	0.008144	**-0.008144**	442.19	0～3
(e) Jurong	**0.263**	0.0019	0.002577	**-0.002577**	889.18	8～10
(f) Haiyuanganyanchi	**-0.036**	-0.0817	-0.000353	**0.000353**	306.73	0～3
(j) Chaohu	**-0.455**	-0.038	-0.004459	**0.004459**	331	0～3

Water Level Change Δh, Change of *B* Value, Calculated Change of Pore-Pressure ΔP_p, Inferred Change of Effective Pressure ΔP_{eff}, Well Depth and Range 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**	**ΔB**	**ΔP_p / MPa**	**ΔP_{eff} / MPa**	**Well Depth / m**	**Range of P_{eff} / MPa**
(a) Xiaxian	**0.106**	-0.0666	0.001039	**0.001039**	170.5	0～3
(h) Kaiyuan	**-0.155**	0.136	-0.001519	**-0.001519**	224	0～3
(i) Meizhou	**-0.075**	0.4846	-0.000735	**-0.000735**	338.86	0～3

Water Level Change Δh, Change of *B* Value, Calculated Change of Pore-Pressure ΔP_p, Inferred Change of Effective Pressure ΔP_{eff}, Well Depth and Range 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	ΔB	ΔP_p / MPa	ΔP_{eff} / MPa	Well Depth / m	Range of P_{eff} / MPa
(g) Guyuanzhenqi	-0.026	-0.3092	-0.000255	0.0002548	255.74	0～3

Water Level Change Δh, Change of *B* Value, Calculated Change of Pore-Pressure ΔP_p, Inferred Change of Effective Pressure ΔP_{eff}, Well Depth and Range 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 waves**	**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

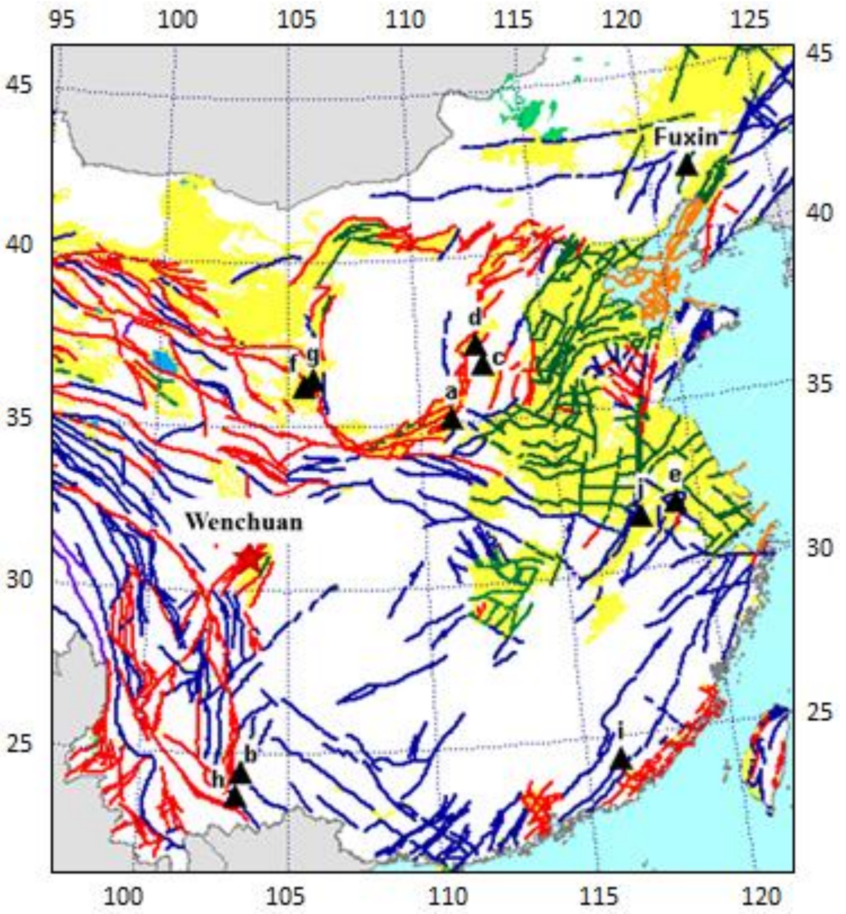
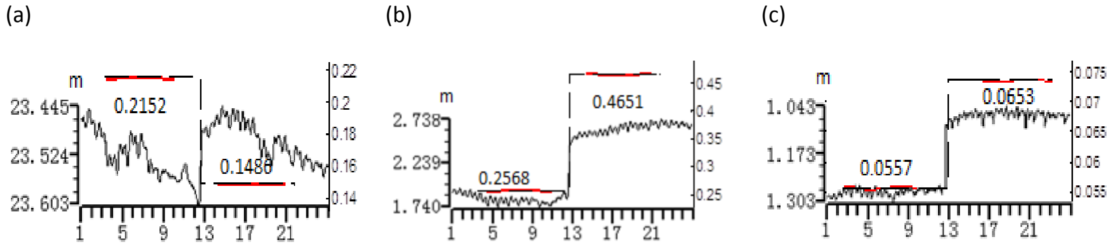
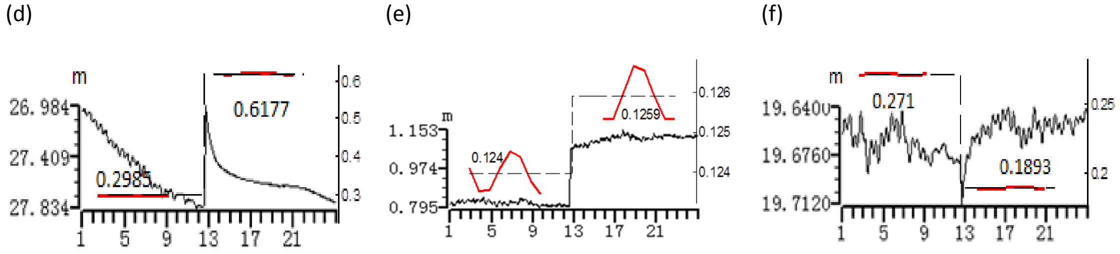


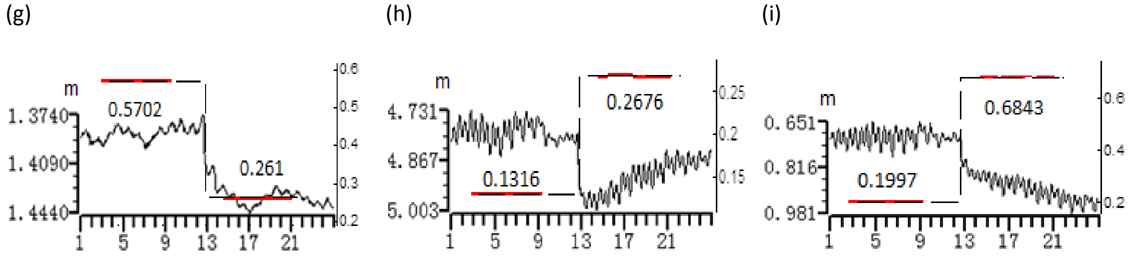
Figure 1. The selected stations with distinct amplitude coseismic water level changes during the Wenchuan earthquake in mainland China. The well numbers are in accordance with the numbers listed in Table 1.



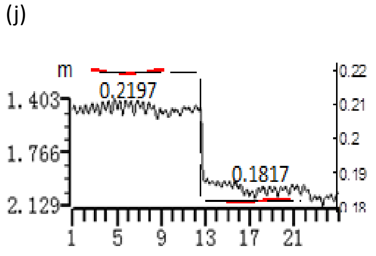
XIAXIAN (May 1—May 24, 2008) MILE (May 1—May 24, 2008) QINXIAN (May 1—May 24, 2008)



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



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



CHAOHU (May 1—May 24, 2008)

Figure 2. (a) Left y-coordinate: original water levels, the sequential number of y-coordinate depends on the type of the well, "sequential number increase from low to high" indicates an artesian well, the coordinate value means the height from the free water surface to the artesian discharge point or to the ground. "Sequential number decrease from low to high" indicates a non-artesian well, and the coordinate value means the depth from the free water surface to the ground. All the ascendant/ descendent patterns in the picture indicate water level ascending/ descending. (b)

Right y-coordinate: the calculated Skempton's coefficient *B*. The dashed lines indicate the mean *B* values, which are clearly shown in numbers. While the curves along the dashed lines indicate the continuous *B* values both pre- and post- earthquake (most of those curves seem like straight lines, because the variations are not obvious compared to the pre- and post-earthquake *B* value changes).

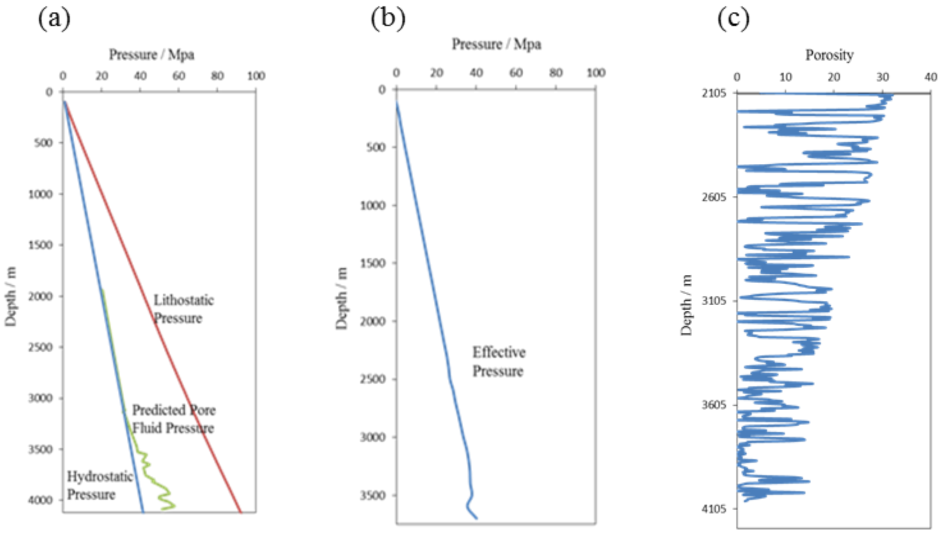
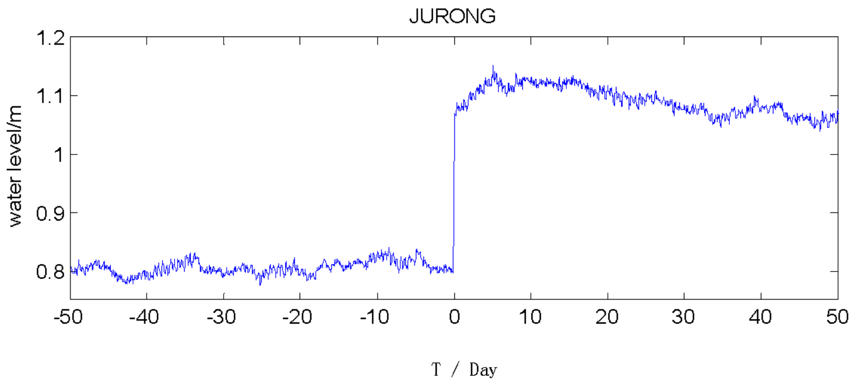


Figure 3. (a) Pressure section of W-1 well in Yanchang basin, the bedrock of W-1 well is sandstone. (b) Effective pressure section of W-1 well, we just show the depth above 3500m, so as to see the value in shallow depth more clearly. (c) Porosity section of W-1 well. The porosity records approximately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

(a)



(b)

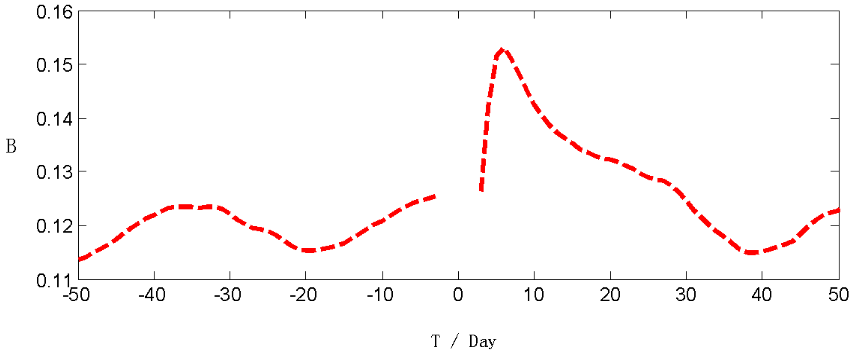
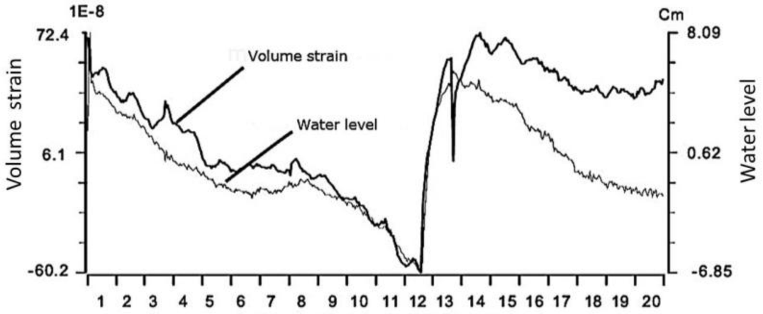


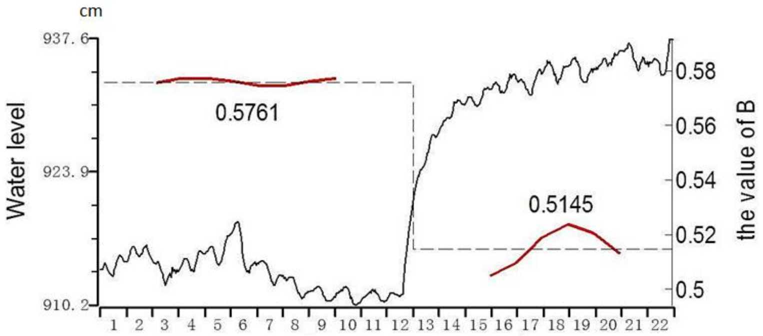
Figure 4. Jurong well (a) Original water level of Jurong station. (b) Continuous *B* value of Jurong station. (“0” indicates the day when Wenchuan earthquake happened)

(a)



FUXIN (May 1—May 20, 2008)

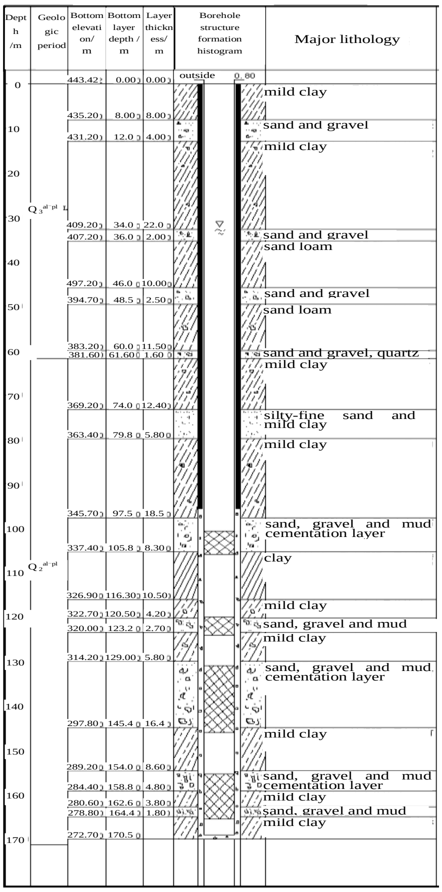
(b)



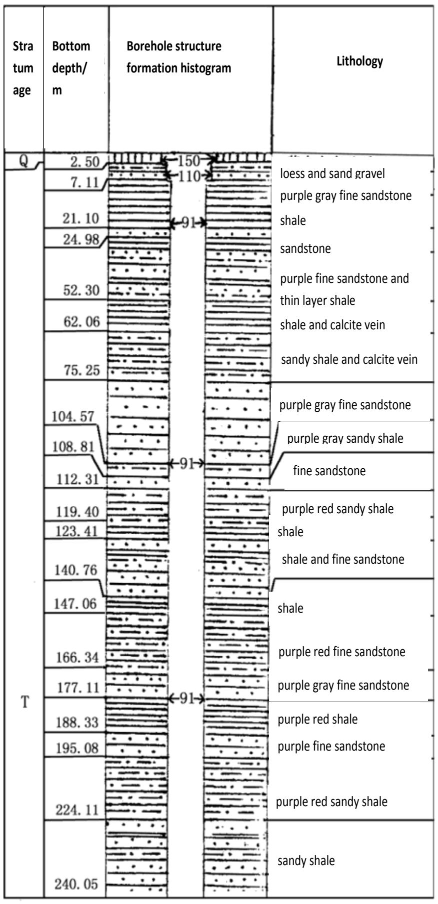
FUXIN (May 1—May 22, 2008)

Figure 5. Fuxin well (a) Corrected water level and volume strain after removing the influence of atmospheric pressure and tidal srain (based on the harmonic analysis method). In order to avoid the interfere of thunder, there is a power cut protection on 13 May, which is in accordance with the break point of the volume strain in the figure (Huang, 2008). (b) Original water level and the pre- and post-earthquak Skempton's coefficient *B* in Fuxin well.

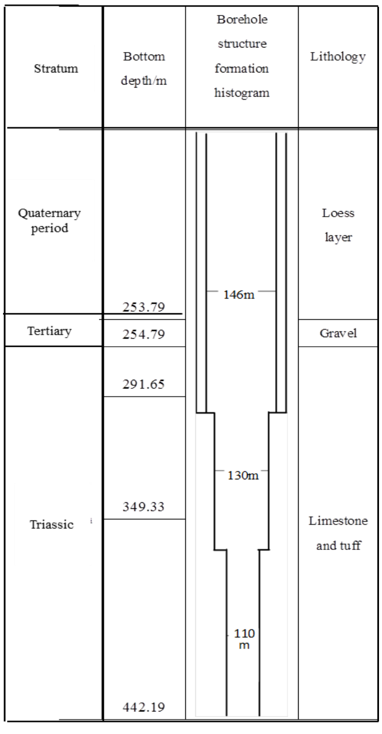
(a) Well (a)-Xiaxian



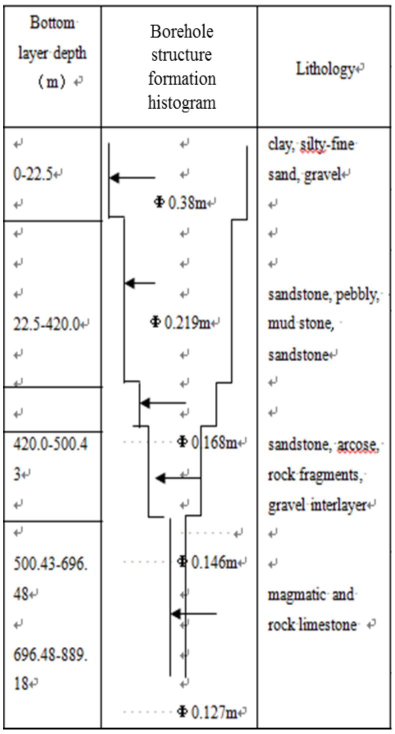
(b) Well (c)-Qinxianmanshui

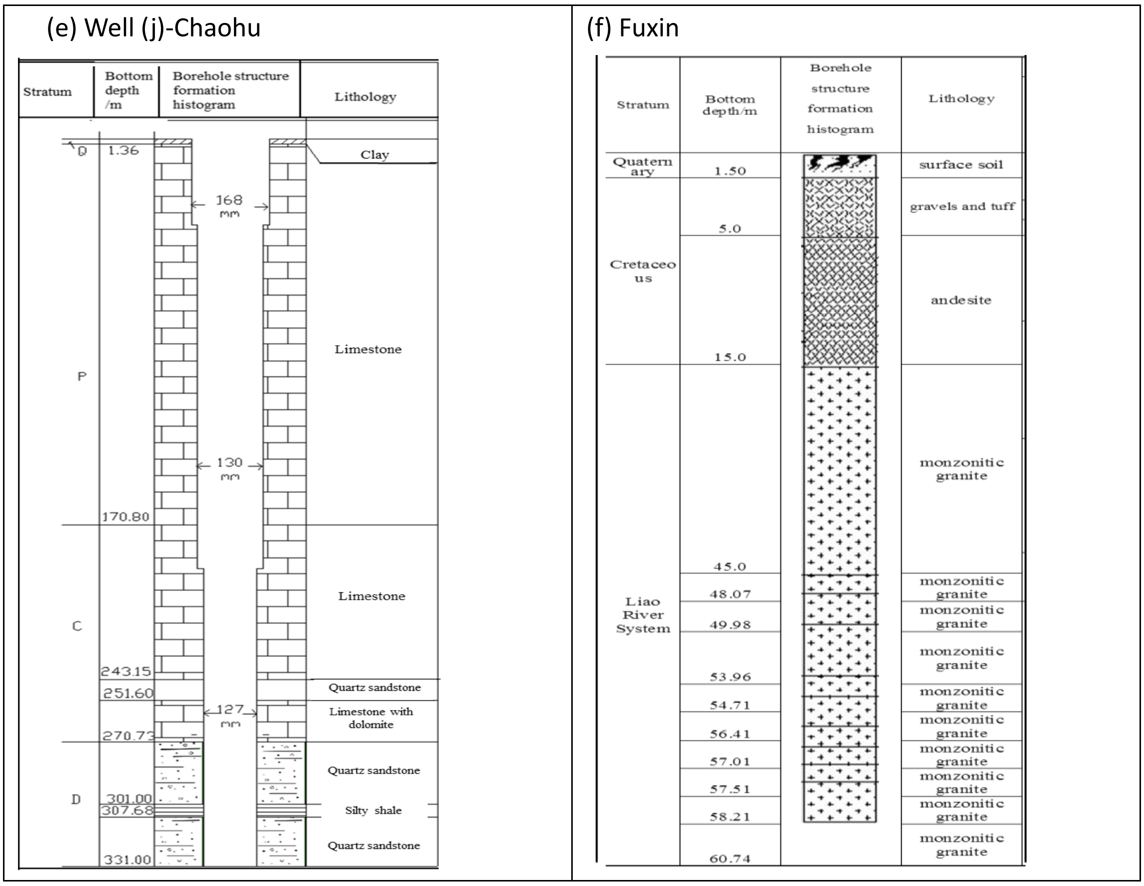


(c) Well (d)-Qixian



(d) Well (e)-Jurong




(e) Well (j)-Chaohu

(f) Fuxin

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

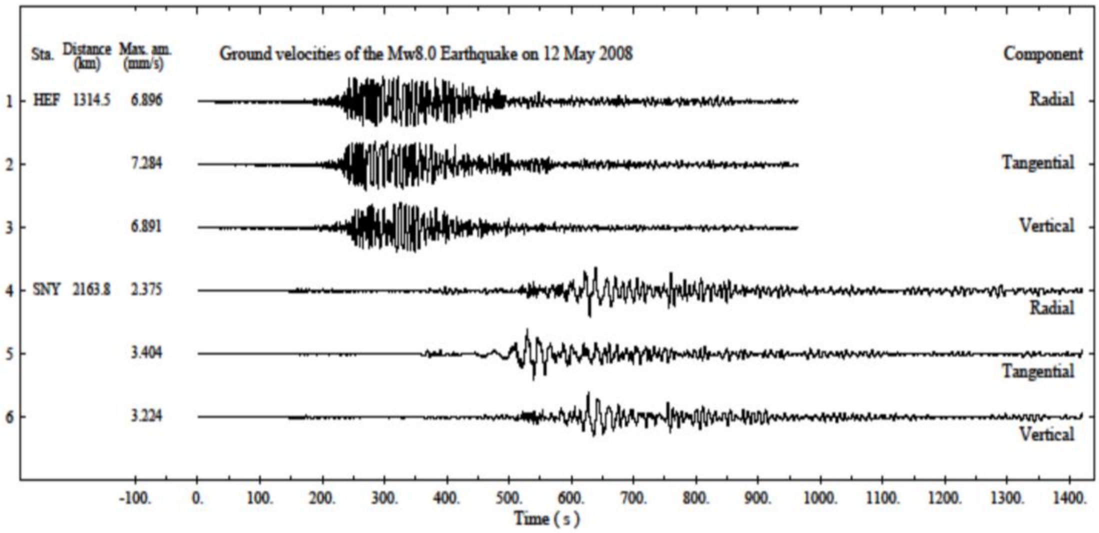


Figure 7. Seismograms of HEF and SNY national stations for the M_s 8.0 Wenchuan earthquake. The stations are ordered according to their epicentral distances. The station names and maximum amplitudes are listed on the left-hand side and are measured in millimetres per second. “0” is the time of Wenchuan 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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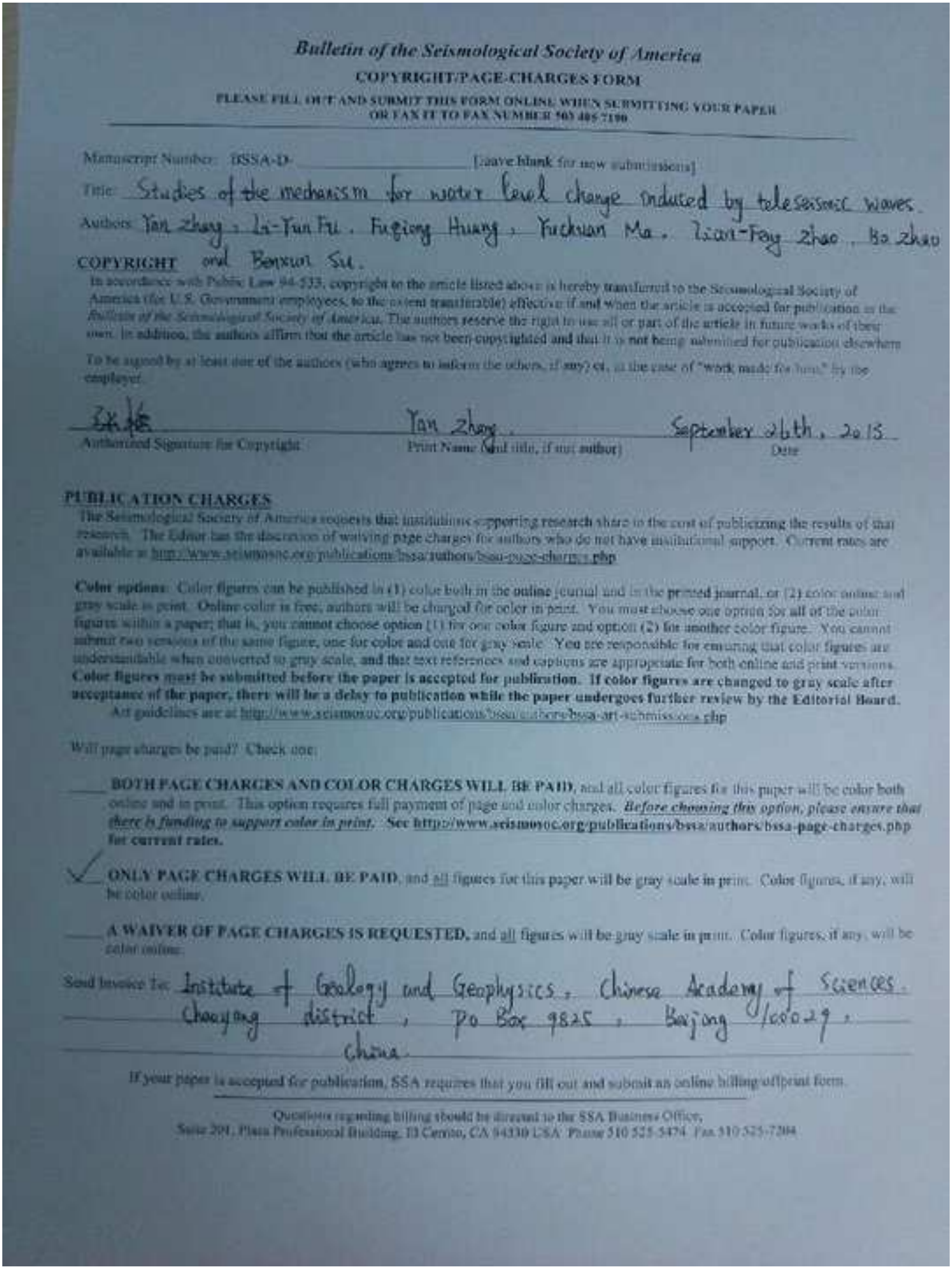

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