Bulletin of the Seismological Society of America

Studies of mechanism for water level changes induced by teleseismic waves

--Manuscript Draft--

Manuscript Number:	BSSA-D-13-00246
Article Type:	Article
Section/Category:	Regular Issue
Full Title:	Studies of mechanism for water level changes induced by teleseismic waves
Corresponding Author:	Yan Zhang, Ph.D. Institute of Geology and Geophysics, Chinese Academy of Sciences Beijing, CHINA
Corresponding Author's Institution:	Institute of Geology and Geophysics, Chinese Academy of Sciences
Corresponding Author E-Mail:	eve_041744@163.com
Order of Authors:	Yan Zhang, Ph.D.
	Li-Yun Fu
	Fuqiong Huang
	Yuchuan Ma
	Lian-feng Zhao
	Bo Zhao
	Benxun Su
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. 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 have relatively high permeabilities attributing to the shales in the aquifer lithologies.
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.
Suggested Reviewers:	Chi-yuen Wang chiyuen@berkeley.edu he's an expert in this research region
	Emily E. Brodsky ebrodsky@es.ucsc.edu

Opposed Reviewers:	Yaowei Liu He has a conflict with one of the author

Ref.: Ms. No. BSSA-D-12-00360R2
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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 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 checked the English very carefully. I promise, the paper is a brand new work this time, and believe the reviewer will not be disappointed.

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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 checked the English very carefully (I have spent about 1 month on this paper, and redo this work seriously). I promise, the paper is a brand new work this time, and believe the reviewer will not be disappointed.

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.

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 because of the modification suggested by the reviewer #3. 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 303—347 "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: These are good suggestions, we have done an enormous modification (mainly in the part of "Mechanism analysis", and "Discussion"), 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).

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 4.

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 500—504.

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 and permeability" Line 290—302.

- 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, 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)

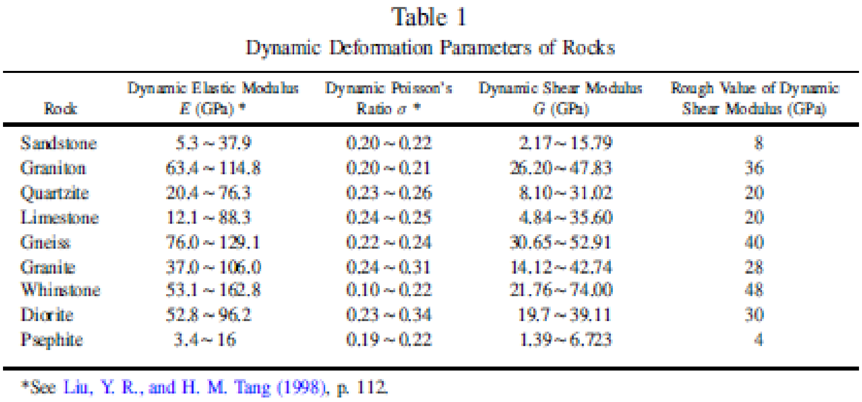

Table 1

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 504—515.

- 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 121—147 "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 122—131.

As show in Line 204-209: 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—347 (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 210—233. (and Table 4)

As indicated by this reviewer, those log analysis are very useful (Figure 5). 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 and permeability" Line 290-302. One thing needs to be clarified: we say those co-seismic 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 275—286.

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. See: Line 148 -171.

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 in 0~3 Mpa (only well (b) is in 3~5 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 148-302.

- 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: 190--347. (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, 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.

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: 445—470, and Table 1.

- 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. See: Line 82-114.

Well g is out of our expectation, as show in Line 463—470:

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 and permeability” Line 290-302.

- 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: 304–347, and Table 5.

As pointed out by the reviewer, we show the seismograms in Figure 5.

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 mechanism for water level changes induced by teleseismic waves

Yan Zhang[1], Li-Yun Fu [1], Fuqiong Huang[2], Yuchuan Ma[2], Lian-feng Zhao[1], Bo Zhao[2], and Benxun Su[1]

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

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

Abstract

The M_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. 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 have relatively high permeabilities attributing to the shales in the 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 П; 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. Experiment of Liu and Manga (2009) indicates 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 could 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. While, the other part of those coseismic water level changes, for which the co-seismic water level and the effective pressure change with inconformity, may be explained with the increased permeability caused by teleseismic waves, which in turn lead to the redistribution of pore pressures. Most of those wells have relatively high permeabilities attributing to the shales in the aquifer lithologies. Compare the occurrence time of water level change with the arrival time of surface waves in one station, we find the co-seismic water level change is 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 [e.g. there is a 2-day water level data missing (May

9th, 2008 to May 10th, 2008) in well Xiaoyi so we discarded it] 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 not simply 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 10 stations [well a to well j (Figure 1)] can be chosen during the Wenchuan earthquake (Table 1).

Detailed basic information of each well are shown in Table 1 , including well depth, well diameter, aquifer lithology, and geological structure. However, diameter of well f, g, i and Fuxin can not be found. All the water level recording instruments in those wells (well a to well j) are digital, they are LN-3A digital water level instrument (except for 2 wells: Mile well 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. 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.

Intermediate and Far Field Analysis

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 well-picked 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).

Assumption of Poisson's ratio

We suppose the undrained Poisson's ratio to be $\nu_u = 0.29$ 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) 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.

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. 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), 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. As discussed above, we can know: It is obvious that the change of shear modulus G is tiny, and even can be neglected 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).

Derivation of effective pressure variation in each well

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

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. A low value of *B* indicates the stiff rock matrix that supports the load with low coupling to the fluid (Nur and Byerlee, 1971). 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 be consolidated, the effective pressure will increase, while a dilation is in accordance to the decrease of effective pressure.

Laboratory experiments of Green and Wang (1986) find Skempton's coefficient *B* will decrease with the increase of effective pressure (effective pressure:

0～2 Mpa) for the fully saturated sandstone. As they indicate, that is probably related to crack closure and to high-compressibility materials within the rock framework. Fredrich *et al.* (1995) find Skempton's coefficient *B* will decrease with the increase of effective pressure (especially when the effective pressure is during 0～20 Mpa). For the well-indurated sandstones, *B* is highly pressure sensitive at low effective pressures due to the closure of low aspect ratio pores and microcracks. Experiment of Blocher *et al.* (2009) also indicates, the isotropic Skempton's coefficient *B* will decrease with the increase of effective pressure (when the effective pressure is larger than ～5 Mpa, while for 0～4 Mpa, there is probably a saturation deficit), and this is a reversible process.

Those previous studies indicate that, the undrained Skempton's coefficient *B* is a function of effective pressure, and it will decrease with the increase of effective pressure for the well saturated aquifers, especially when the effective pressure is less than ~20 Mpa.

Effective pressure variation in 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). In order to compare with the experiment results, we have to estimate the effective pressure range of each well. 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 the "pressure - depth" relation could be applied to these wells we studied. We calculate the effective pressure of W-1 well (effective pressure equals to 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 those wells studieded in this paper according to the well-depth. Depths of those wells analyzed in this paper are all less than 1km (Table 1).

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

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 analyze the mechanism based on the change of co-seismic water level and the deduced variation of 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 theory of consolidation or dilatation induced by teleseismic waves (about 36.36% of the 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). Porosity, permeability and Skempton's coefficient B are all directly connected with effective pressure, and they will decrease with the increase of the effective pressure in the fully saturated aquifer (Blocher *et al.*, 2009).

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

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

As shown in Table 4: (a1) P_c increases (P_p not change), then P_{eff} increases, the porosity will decrease (a process of consolidation), and water level / pore pressure will increase; (a2) P_c decreases (P_p not change), then P_{eff} 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.

As shown in Table 4: (b1) Water level/ P_p decreases (P_c not change), then P_{eff} 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) Water level/ P_p increases (P_c not change), then P_{eff} decreases, then 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 shown in 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 opposite to the change of effective pressure in well 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 those phenomenons (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).

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

Co-seismic water level decreases and effective pressure increases in well f and j. 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 the two 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), supposing the confining pressure not change. (Table 2).

Coseismic water level change induced by consolidation or dilatation

Water level increases/decreases accompanied with the increase/decrease of effective pressure in well a, h, i and Fuxin (the effective pressure range of those wells is approximately 0～3 MPa) (Table 3). As indicated by the laboratory experiment of Fredrich *et al.* (1995) and Blocher *et al.* (2009), when the effective pressure not exceed a limitation, as the aquifer be consolidated/dilatated, the mean fracture width (the porosity and permeability) will decrease/increase with the increase/decrease of the effective pressure, then the stiff rock matrix that supports the load could with a lower/ higher coupling to the fluid (Nur and Byerlee, 1971), and the value of *B* will decrease/ increase.

Coseismic water level change induced by dilatation

For well h and i, water level (pore pressure) decreases accompanied with the decrease of effective pressure. This could be explained with the mechanism of water level change induced by dilatation. The spreading of teleseismic waves may cause dilatation of the aquifer medium, which can broaden the porosities, and the effective pressure will reduce, leading to the increase of Skempton's coefficient *B* (which indicates the stiff rock matrix could with 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 and Fuxin increase accompanied with the increase of effective pressure. This could be explained with the mechanism of water level change induced by consolidation. This mechanism is very similar to the explanation of the laboratory experiment of Liu and Manga (2009). From their laboratory experiment, 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, and are expected to accumulate and get trapped at the narrowest constrictions along flow paths, and hence allow a consolidation (contraction) of the sample. Their result just supports our mechanism analysis. It implies that teleseismic waves can cause a consolidation of well aquifer and cause the increase of effective pressure (decrease of permeability and porosity), which is in accordance with the increase of co-seismic water levels accompanied with the decrease of Skempton's coefficient *B* (the stiff rock matrix could with a lower coupling to the fluid) in well a and Fuxin.

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/pore pressure.

Well lithologic logs

We show the well lithologic logs (borehole columnar diagrams) in Figure 4. 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), (j) and Fuxin (Figure 4), 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) and (j) [Although there is 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 4). Porosity (permeability) of well (c), (d) and (j) should be relatively larger, and the aquifer may even be fractured. So the pores may incline to be dilatated by the shaking of teleseismic waves, and the co-seismic water level changes in well (c), (d), (j) can be explained with the theory of increased permeability followed by a rapid redistribution of pore pressure.

Compare with seismograms

There are 48 national stations recording the seismograms (event waveforms) in the Chinese mainland, however most of those stations are not in the same place with stations which have the records of water level. Those stations (well a to j) analyzed in our paper do not record seismograms. After comparison (including seismogram quality checking), generally we may use the seismogram of 2 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 Fuxin well (there are about 102.81 km between them), and HEF (Hefei) station is corresponding to well j (there are about 91.57 km between them) (Figure 5). In addition, the geology conditions are very similar. The main matrix rocks of Fuxin well and Shengyang station are both granite, and well j 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 j to do the comparison. From the occurrence time of step in water level change and the arrival time of seismic waves of well j (Table 5), we find the co-seismic water level change should be attributed to the passage of surface waves. From that, we may infer: co-seismic water level changes of other wells are also 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 is geographic position difference between the observation of seismogram and water level, but the distance is not large enough to cuase influence on our above analysis, because the seismic waves transmit extraordinary fast.

The PGV [peak ground velocity (vertical component)] of Fuxin (SNY station) is 3.224 mm/s, and that of well (j) (HEF station) is 6.891 mm/s. The co-seismic water level change in Fuxin (Δh=0.121m) is smaller than that in well (j) (Δh=-0.455m). It seems that the change of the co-seismic water level is in accordance with the PGV in the two wells. However, they are induced by different mechanisms. Co-seismic 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 with the ratio of co-seismic water level changes.

There are aftershocks, and the one following the M_s 8.0 mainshock （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 mainshock seismogram. What’s more, the aftershocks are much smaller (the magnitude of aftershocks is less than M_s 6.0) than the mainshock. The energy will decrease by about 900 times, when the magnitude decreases 2. So the energy of those aftershocks is not large enough to induce the variations of water level in the intermediate and far fields.

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～j), the porosity still persists relatively large, and changes with different depth. From Table 2 ,3 we can see, the variations of effective pressure in well a～j are less than 0.01Mpa. Variation of 0.01Mpa in effective pressure approximately equals to variation of 1 meter in depth (Figure 3b), and during this variation range of depth the variation of porosity is tiny (Figure 3c). So this variation extent of effective pressure is hard to induce permanent deformation of porosity. In addition, the laboratory Experiment of Blocher *et al.* (2009) shows, the Skempton's coefficient *B* will decrease with the increase of effective pressure and that is a reversible process.

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

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

Recovery of water level

The recovery time of the water level is obscure, because most of those water 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 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.

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 "*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) 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 7a). 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 at first as the other wells, 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 also 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 7b)). From Figure 7a, 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). The Skempton's coefficient *B* decreases accompanied with the increase of effective pressure and the co-seismic water level (Figure 7b), that is in accordance with the mechanism analysis.

However, as we calculate, the phase difference decreases after the earthquake in Fuxin well (Table 1), which indicatres the permeability increase after the shaking of seismic waves. It is possible that, the consolidation may overcome 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 close proximity with a higher pressure, which leads to the decrease of the effective pressure, and then the water level increases more gradually. Finally with the further enhancement of the permeability (increase of the porosity), a permanent deformation could be induced, so there is an abrupt increase in the water level in 22 May, and remain in a relatively high level for several months (Figure 7c). 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 (e.g. there is a high pore pressure difference in the close proximity), 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.

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 differences 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 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 the phase difference between water level and solid tide is small, which means good correlations between the water levels and the tidal strains, and those wells are well confined and under the undrained condition. Porosity and permeability are directly connected with effective pressure, and they will decrease with the increase of the effective pressure in the fully saturated aquifer (Blocher *et al*., 2009). Variations of phase differene are in accordance with the variations of effective pressure (porosity/permeability) in most wells. Only well g (Table 6) is out of our expectation. Water level and Skempton’s coefficient *B* decrease accompanied with the increase of effective pressure in well g. In our expection, this situlation should be incurred by an ehanced permeability, and the water level flow out of the well to the close proximity with relatively lower pore-pressure. Then, with the increase of effective pressure, the permeability should decrease. However, the permeability increases in well g (phase difference decreses (Table 1)), this may be attributed to the saturation deficit in well g, and it needs to be clarified in the future study.

Conclusion

Together with the variation of Skempton's coefficient *B*, the change of water level (pore pressure) and the inferred variation of effective pressure in each well, we can deduce the mechanism of the co-seismic water level changes in the intermediate and far fields. 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 keeps the same (all increase or all decrease). 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 have relatively high permeabilities attributing to the shales in the aquifer lithologies. 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 happen 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 analysis complement 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 keeps constant, the change of effective pressure P_{eff} induced by the change of confining pressure P_c. B) Confining pressure P_c keeps constant, the change of effective pressure P_{eff} 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. The mechanism analysis of "*4.2.2 Coseismic water level change induced by consolidation*" is 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.

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 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 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 might be larger than 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 disrupt and be replaced by the drained condition soon. As described by Wang (1993) nonlinear compaction effects can be significant and they are not incorporated in the linear theory presented here. Because the well aquifers are under lithostatic pressures for a long time and withstand large numbers of seismic shaking, the irreversible deformations and the nonlinear effects have been minimized (In the laboratory experiment, in order to reduce the irreversible deformation and to minimize the nonlinear effects, repeated pressure cycles are always applied on rock samples as preconditions (Blocher *et al.*, 2009)). Discard all those ideal assumptions, things may be different.

Data and Resources

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

Acknowledgements. We thank professor Emily Brodsky, professor Chiyun-Wang, and postdoctor Jinlai Hao for discussion and help on this paper. This research was supported by the Natural Science Foundation of China (Grant No. 40925013 and 41040036). We gratefully appreciate the valuable suggestions proposed by the anonymous reviewers.

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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):

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

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

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

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

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):

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

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:

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

With equation (A5), we obtain the value of B with water level and tidal strain. However, the calculation 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 1-6

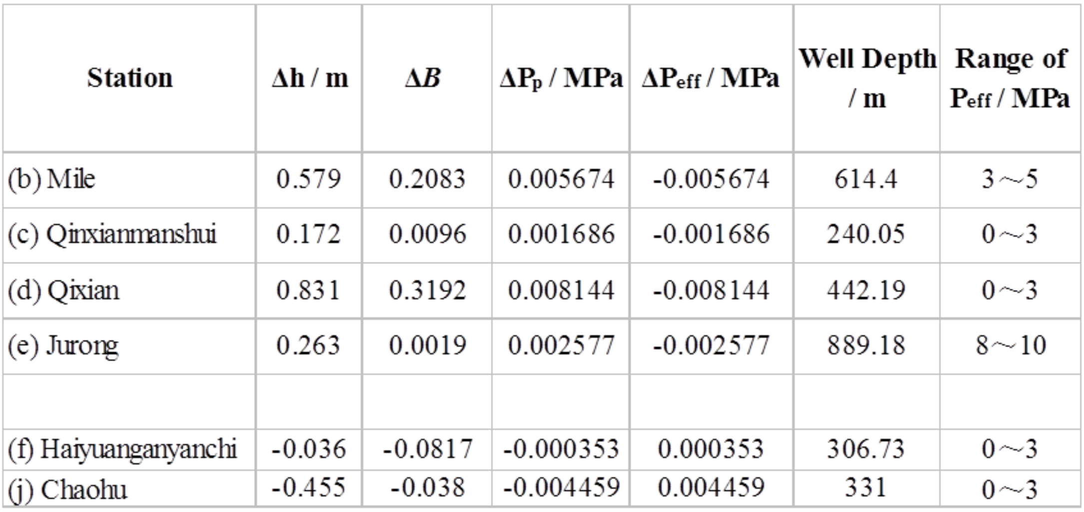
Table 1. Basic information of well a ~ k.

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.
Fuxin	1409.9764	0.121	0.5761 / 0.5145	Granite,basalt,andesite and clip tuff breccia	60	L1=120 L2=60		60.74	0~3	west and north of Fuxin fault basin

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
Fuxin	0.121	-0.0616	0.001186	0.001186	60.74	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. 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

Table 6. Well (e), an exception.

Station	**Δh / m**	**ΔB**	**ΔPp / 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).

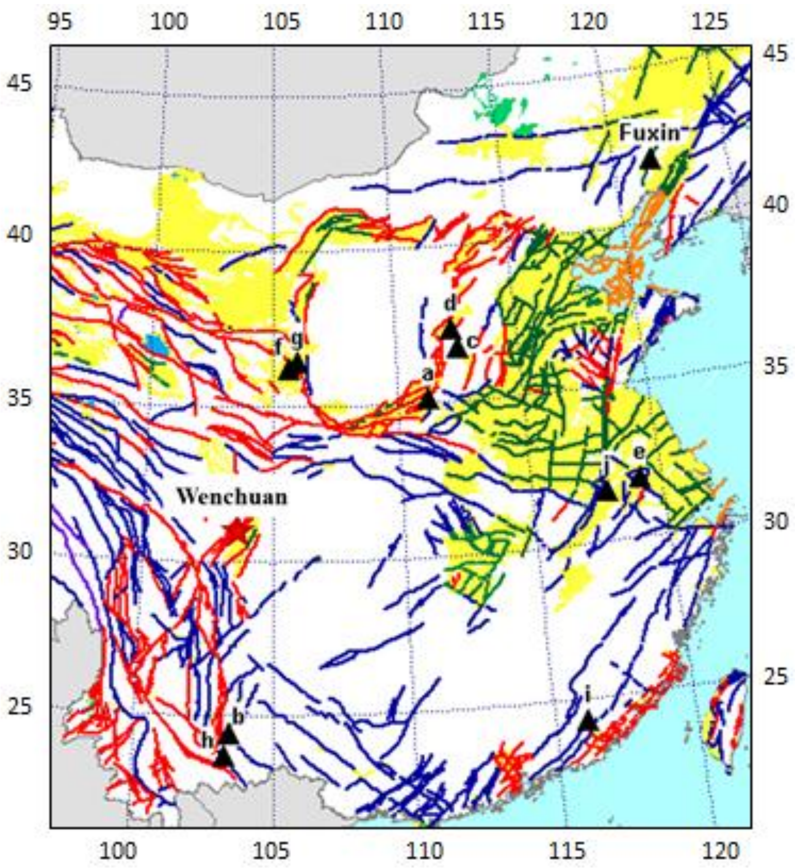
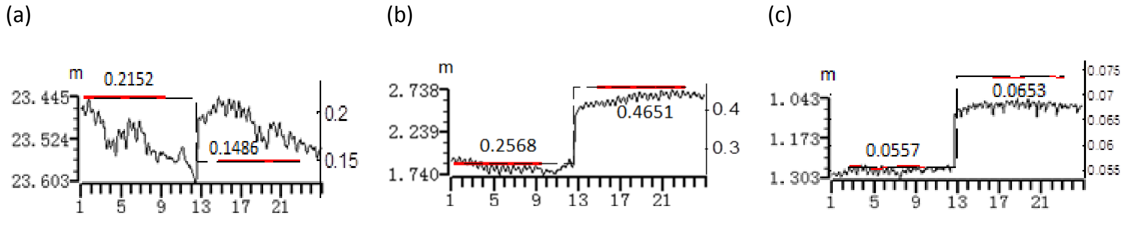


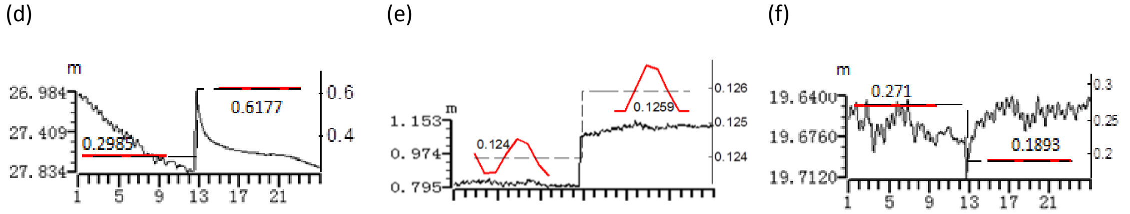
Figure 1. The selected stations with distinct amplitude co-seismic water level changes during the Wenchuan earthquake in mainland China. The well numbers are in accordance with the numbers listed in Table 1.



XIAXIAN (May 1—May 24, 2008)

MILE (May 1—May 24, 2008)

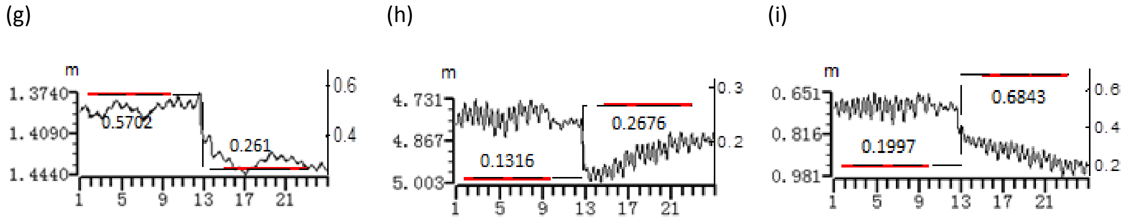
QINXIAN (May 1—May 24, 2008)



QIXIAN (May 1—May 24, 2008)

JURONG (May 1—May 24, 2008)

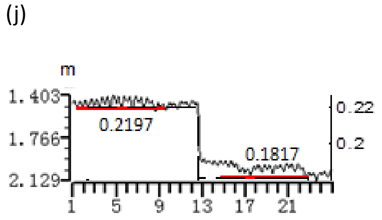
HAIYUAN (May 1—May 24, 2008)



GUYUAN (May 1—May 24, 2008)

KAIYUAN (May 1—May 24, 2008)

MEIZHOU (May 1—May 24, 2008)



CHAOHU (May 1—May 24, 2008)

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

along the dashed lines indicate the continuous *B* values both pre- and post-earthquake.

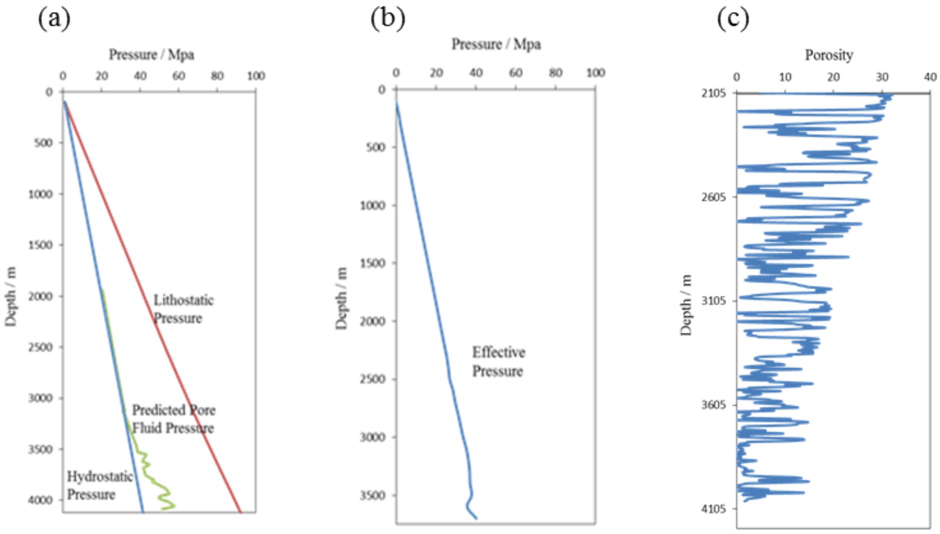
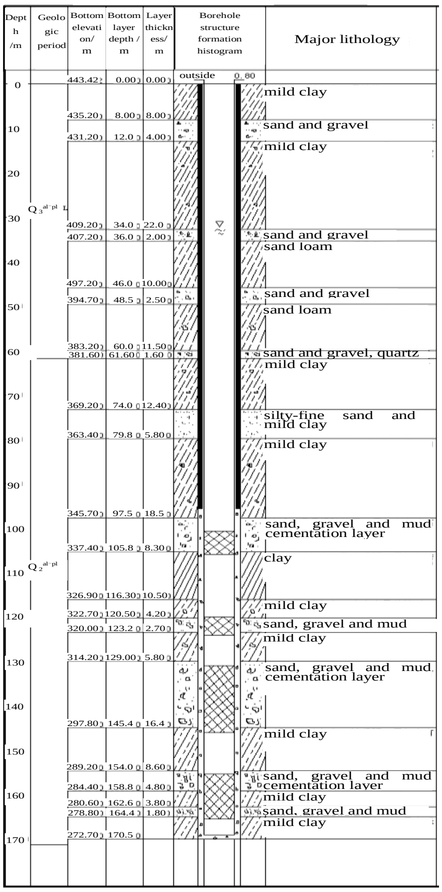


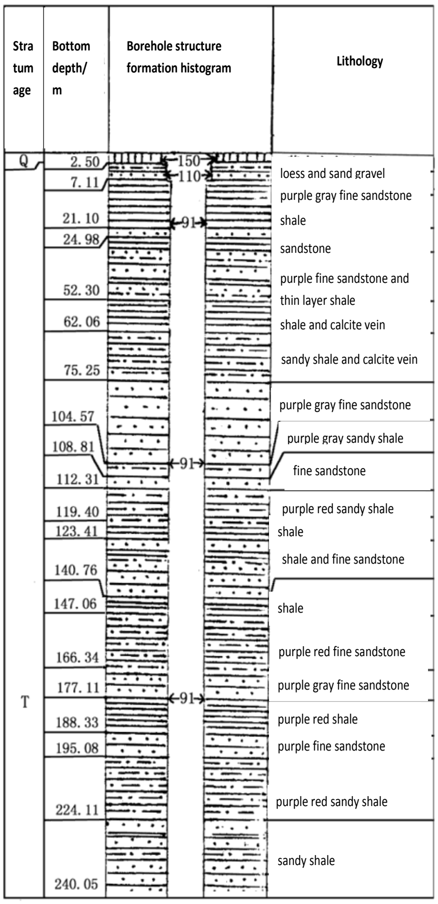
Figure 3. (a) Pressure section of W-1 well in Yanchang basin, the bedrock of W-1 well is sandstone. (b) Effective pressure section of W-1 well, we just show the depth above 3500m, so as to see the value in shallow depth more clearly. (c) Porosity section of W-1 well. The porosity records approximately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

(a) Well (a)-Xiaxian



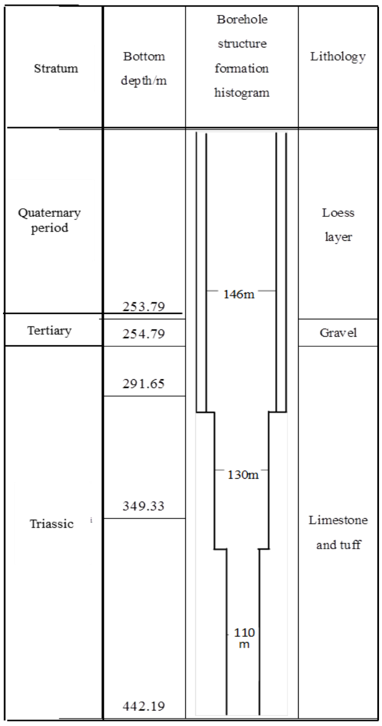
Geologic period	Bottom elevation/m	Bottom layer depth/m	Layer thickness/m	Major lithology
	443.42	0.00	0.00	
Q_3^{al-pl}	435.20	8.00	8.00	mild clay
	431.20	12.0	4.00	sand and gravel
	409.20	34.0	22.0	mild clay
	407.20	36.0	2.00	sand and gravel
	497.20	46.0	10.00	sand loam
	394.70	48.5	2.50	sand and gravel
	383.20	60.0	11.50	sand loam
	381.60	61.60	1.60	sand and gravel, quartz
Q_2^{al-pl}	369.20	74.0	12.40	mild clay
	363.40	79.8	5.80	silty-fine sand and mild clay
	345.70	97.5	18.5	mild clay
	337.40	105.8	8.30	sand, gravel and mud cementation layer
	326.90	116.30	10.50	clay
	322.70	120.50	4.20	mild clay
	320.00	123.2	2.70	sand, gravel and mud
	314.20	129.00	5.80	mild clay
	297.80	145.4	16.4	sand, gravel and mud cementation layer
	289.20	154.0	8.60	mild clay
	284.40	158.8	4.80	sand, gravel and mud cementation layer
	280.60	162.6	3.80	mild clay
	278.80	164.4	1.80	sand, gravel and mud
	272.70	170.5		mild clay

(b) Well (c)-Qinxianmanshui



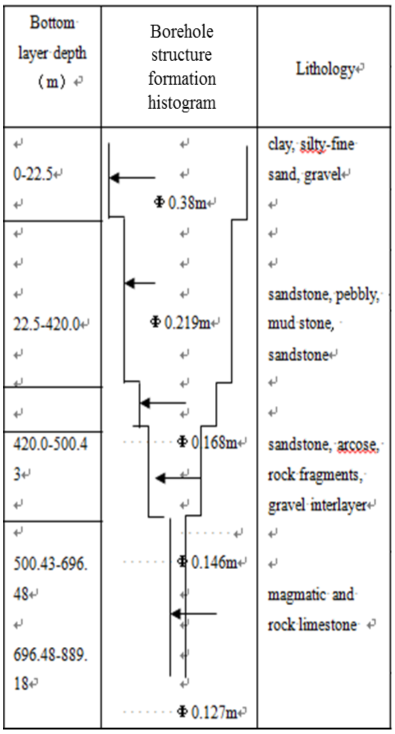
Stratum age	Bottom depth/m	Lithology
Q	2.50	loess and sand gravel
T	7.11	purple gray fine sandstone
	21.10	shale
	24.98	sandstone
	52.30	purple fine sandstone and thin layer shale
	62.06	shale and calcite vein
	75.25	sandy shale and calcite vein
	104.57	purple gray fine sandstone
	108.81	purple gray sandy shale
	112.31	fine sandstone
	119.40	purple red sandy shale
	123.41	shale
	140.76	shale and fine sandstone
	147.06	shale
	166.34	purple red fine sandstone
	177.11	purple gray fine sandstone
	188.33	purple red shale
	195.08	purple fine sandstone
	224.11	purple red sandy shale
	240.05	sandy shale

(c) Well (d)-Qixian



Stratum	Bottom depth/m	Lithology
Quaternary period	253.79	Loess layer
Tertiary	254.79	Gravel
Triassic	291.65 349.33 442.19	Limestone and tuff

(d) Well (e)-Jurong



Bottom layer depth (m)	Borehole structure formation histogram	Lithology
0-22.5	Φ 0.38m	clay, silty-fine sand, gravel
22.5-420.0	Φ 0.219m	sandstone, pebbly, mud stone, sandstone
420.0-500.43	Φ 0.168m	sandstone, arcose, rock fragments, gravel interlayer
500.43-696.48	Φ 0.146m	magmatic and rock limestone
696.48-889.18	Φ 0.127m	

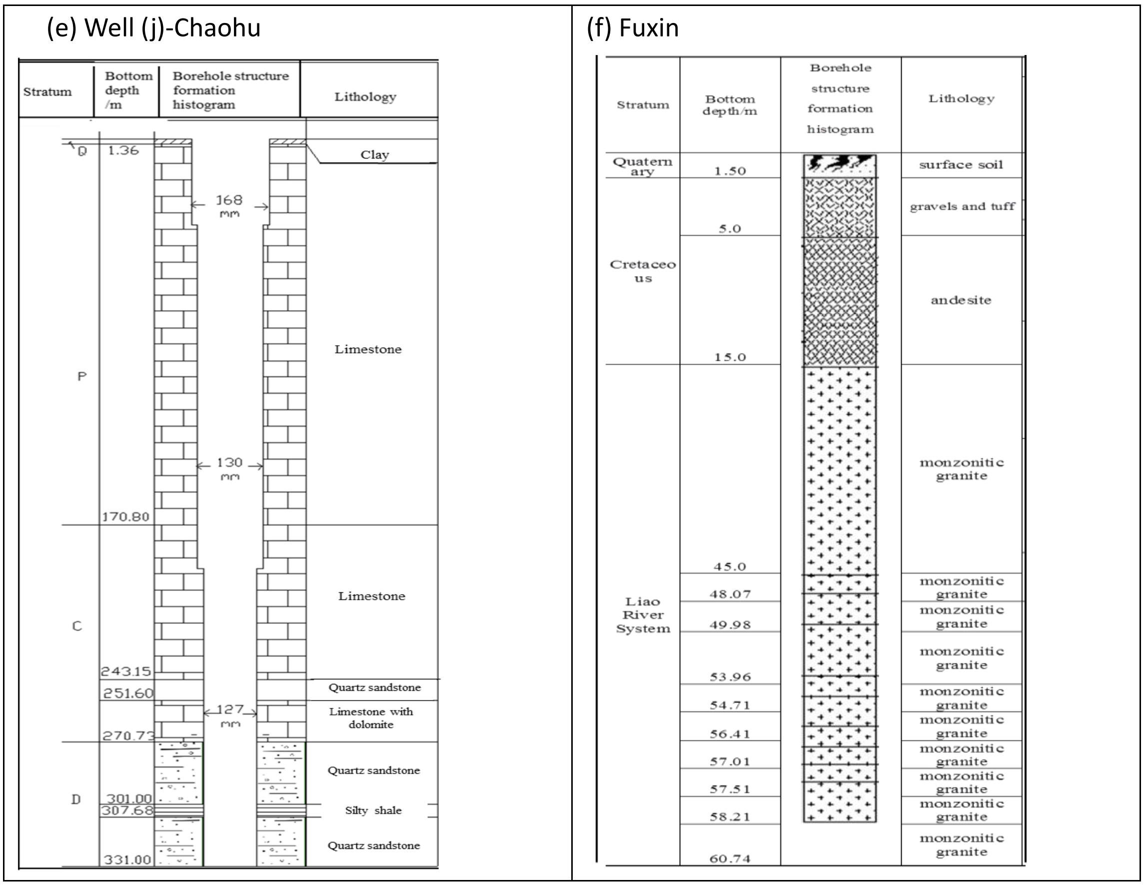


Figure 4. Lithologic logs (borehole structure histogram) of well (a), (c), (d), (e), (j), and Fuxin.

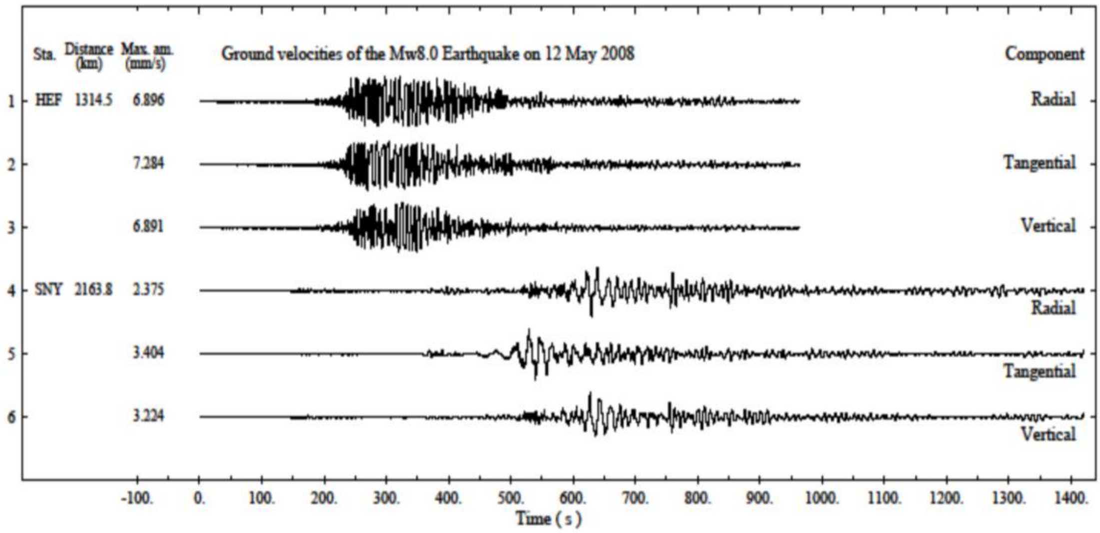
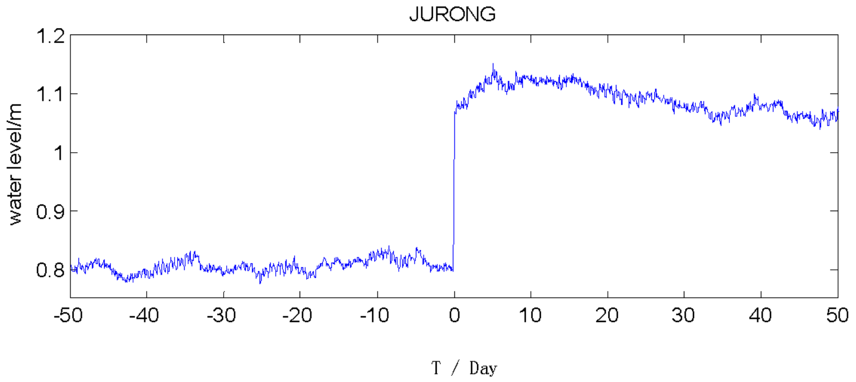


Figure 5. Seismograms of HEF and SNY national stations for the M_s 8.0 Wenchuan earthquake. The stations are ordered according to their epicentral distances. The station names and maximum amplitudes are listed on the left-hand side and are measured in millimetres per second. “0” is the time of Wenchuan earthquake: at 14:27:59.5, May12, 2008 (Chinese time). (This plotting pattern of seismograms are coined by Zhao *et al.*(2008)).

(a)



(b)

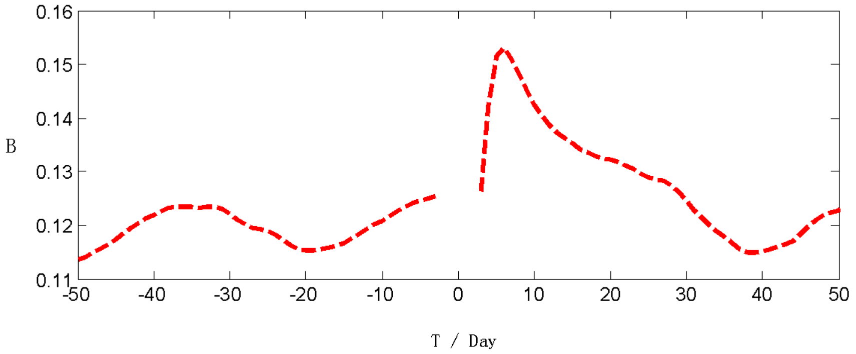
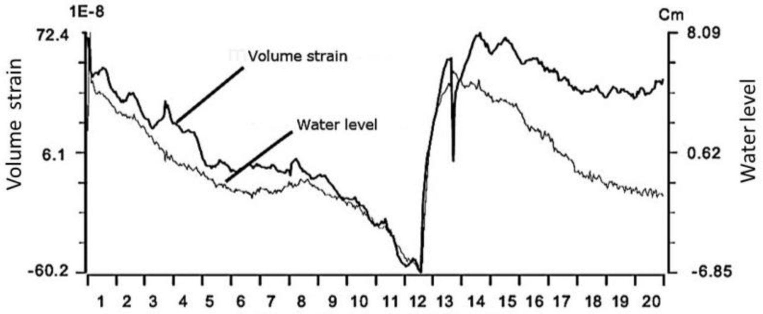


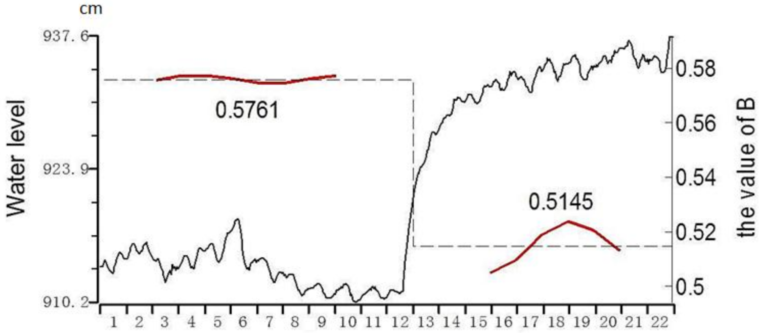
Figure 6. Jurong well (a) Original water level of Jurong station. (b) Continuous *B* value of Jurong station. ("0" depends the day when Wenchuan earthquake happened)

(a)



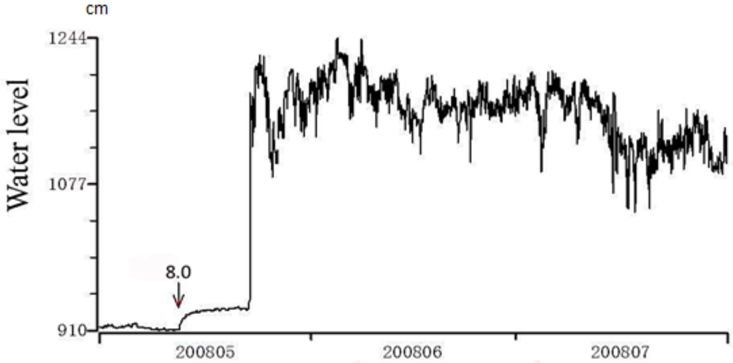
FUXIN (May 1—May 20, 2008)

(b)



FUXIN (May 1—May 22, 2008)

(c)



FUXIN (May 1—July 31, 2008)

Figure 7. 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.

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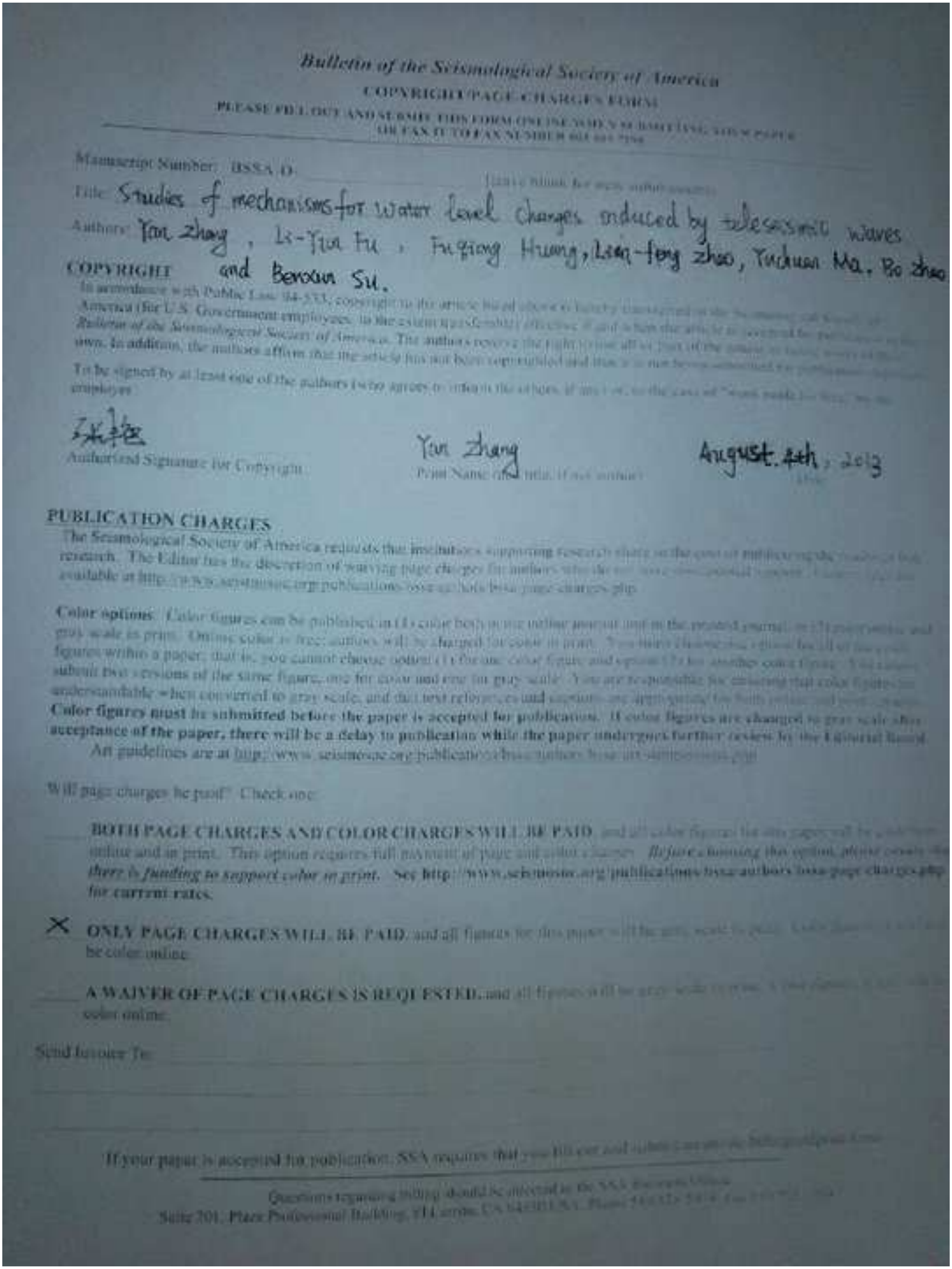

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