GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L09404, doi:10.1029/2009GL037330, 2009

Role of S waves and Love waves in coseismic permeability enhancement

Chi-yuen Wang,[1] Yeeping Chia,[2] Pei-ling Wang,[2] and Douglas Dreger[1]

Received 16 January 2009; revised 8 April 2009; accepted 16 April 2009; published 15 May 2009.

[1] The 2008 M7.9 Wenchuan earthquake in Sichuan, China, caused water level to oscillate and undergo sustained changes in Taiwan, ~2000 km away from the epicenter. Here we use the responses in three wells recorded at high sampling rate (1 Hz) and the broadband seismograms from a nearby station to document, for the first time, that the major water-level responses associated with Rayleigh waves were preceded by small oscillations that occurred concurrently with S waves and Love waves. We also show that the groundwater flow associated with these small oscillations may be strong enough to remove blockades from sediment pores to enhance aquifer permeability and to facilitate the later major responses. **Citation:** Wang, C.-y., Y. Chia, P.-l. Wang, and D. Dreger (2009), Role of S waves and Love waves in coseismic permeability enhancement, *Geophys. Res. Lett.*, *36*, L09404, doi:10.1029/2009GL037330.

1. Introduction

[2] Large earthquakes often cause changes of water level at great distances [*Coble*, 1965; *Bower and Heaton*, 1978; *Matsumoto*, 1992; *Roeloffs*, 1998; *King et al.*, 1999; *Brodsky et al.*, 2003]. These changes correspond to rapid redistribution of pore pressure, which in turn may initiate liquefaction [*Wang*, 2007], trigger earthquakes [*Hill et al.*, 1993; *Brodsky and Prejean*, 2005; *Manga and Brodsky*, 2006] and cause transient crustal deformation [*Johnston et al.*, 1995]. Static change of stress at such distances may be too small to explain the large (~10 cm) change in water level [*Brodsky et al.*, 2003; *Manga and Wang*, 2007]. Rather, a dynamic interaction between seismic waves and aquifers is supposed to cause an enhancement of permeability [*Rojstaczer and Wolf*, 1992; *Rojstaczer et al.*, 1995; *Roeloffs*, 1998; *King et al.*, 1999; *Brodsky et al.*, 2003; *Wang and Chia*, 2008]. 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]. However, the mechanism by which the seismic waves enhance permeability has remained enigmatic. Mobilization of gas bubbles by seismic waves was proposed [*Linde et al.*, 1994; *Sturtevant et al.*, 1996; *Roeloffs*, 1998], but in most situations the amount of gaseous phase in the groundwater may be too low [*Brodsky et al.*, 2003]. Instead, a model of removing loose particles from fractures by seismic waves appears more promising [*Brodsky et al.*, 2003].

[3] The 2008 M7.9 Wenchuan earthquake in Sichuan, China, caused water level to change in Taiwan's sedimentary basins, ~2000 km away from the epicenter. Three wells (Figure 1) documented the changes at high sampling rate (1 Hz) and referenced to the same Global Positioning System (GPS) time signal received by the broadband seismometers. The high sampling rate and GPS time-base make this dataset excellent and unique for direct comparison of the water-level records with broadband seismograms from nearby stations, hence for understanding the interaction between seismic waves and water level. Here we show that the major water-level responses were preceded by small oscillations that occurred before the arrival of Rayleigh waves but concurrently with S waves and Love waves. We further show that the groundwater flow associated with the earlier, small oscillations may be strong enough to dislodge and remove blockades from sediment pores to enhance aquifer permeability and to facilitate the occurrence of the major water-level responses.

2. Water-Level Changes

[4] Following the Wenchuan earthquake, many wells in Taiwan showed water-level oscillations without sustained changes [*Chia et al.*, 2008], similar to the 'hydroseismograms' recorded since the early days of seismometer use [*Blanchard and Byerly*, 1935], while many others showed both sustained changes and oscillations [*Chia et al.*, 2008]. In the present case, the water levels in confined aquifers are measured in three open wells by using a pressure gage suspended in the well water from a cable. The high-sampling rate (1 Hz) and the GPS-based time at the three wells in Figure 1 allow a direct comparison between the water-level records with the seismograms from nearby broadband stations without any ambiguity in time. For the broadband station we choose TPUB (Figure 1) of BATS (Broadband Array in Taiwan for Seismology) for its intermediate distance from the epicenter relative to those of the wells; i.e., at an distance of 1909 km from the epicenter, it is closer by ~36 km than the Chishan well and ~15 and ~24 km further away than the Naba and Chishan wells. Assuming an average velocity of 3.7 km/s for Rayleigh waves, these differences correspond to a later arrival of ~10 s for the Chishan well and an earlier arrival by ~4 to ~7 s for the Naba and the Liujia wells, respectively, relative to the TPUB station, if other factors are equal.

[5] The water level in the Chishan well began to oscillate at ~450 s after the earthquake with small amplitudes (~3 mm) and ~10-s period, followed at ~500 s by a rapid decrease of water level of ~1 cm (see inset of Figure 2a),

[1]Department of Earth and Planetary Science, University of California, Berkeley, California, USA.
[2]Department of Geological Sciences, National Taiwan University, Taipei, Taiwan.

0094-8276/09/2009GL037330$05.00

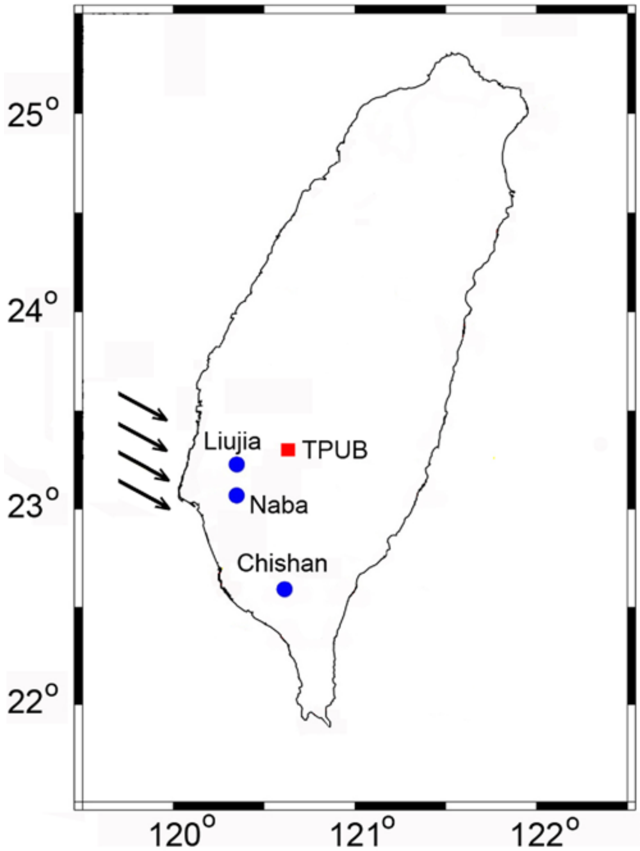

Figure 1. Diagram showing the geographic locations of the wells and the TPUB broadband seismographic station of BATS used in this study. The direction of the seismic waves from the Wenchuan earthquake is indicated by arrows on the left of the diagram.

which in turn was followed by oscillations of ~50-s period with greater amplitudes (~1 cm). Much stronger oscillations, with amplitudes up to ~5 cm, started at ~650 s. The water level in the Naba well displayed a similar sequence of events (Figure 2b), but a sustained decrease of ~3 mm occurred after the water-level oscillations.

[6] In the Liujia well, the ~50-s period oscillation is barely discernable (Figure 2a). At ~600 s, a train of ~10-s oscillations occurred with increasing amplitude (up to ~1 cm) and the water level began to decline (see inset of Figure 2c). This is followed at ~650 s by a pronounced decrease of water level that lasted long after the oscillations had stopped, with a total decrease of ~9 cm (not entirely shown in Figure 2c due to space limitation). The sequence of events suggests that the sustained decline of water level was initiated by the train of water-level oscillations.

[7] The large amplitude seismic waves that arrived at TPUB at ~600 s after the earthquake (Figure 2e), with a group velocity of 3.2 km/s and peak particle velocity of 6 mm/s, are short period Love waves. Short period Rayleigh waves arrived at TPUB at ~650 s (Figures 2d and 2f). Significant energy, however, arrived much earlier: Small amplitude (~0.5 mm/s) ~10-s waves appeared ~440 s after the earthquake, and ~50-s waves with larger amplitude (~1 mm/s) arrived at ~490 s with a group velocity of 3.9 km/s. We interpret the ~50-s waves as Rayleigh waves because of its retrograde motion, and the earlier ~10-s waves as S waves. The latter interpretation is consistent with the timing of S waves given by the IASPEI model, which arrive at TPUB at 442 s.

[8] Comparison between the water-level records and the seismograms shows that the major water-level responses were associated with the Rayleigh waves, as expected from earlier studies [*Cooper et al.*, 1965; *Liu et al.*, 1989; *Brodsky et al.*, 2003]. However, the small water-level oscillations in the Chishan and Naba wells at ~450 s were associated with S-waves, and the train of ~10-s oscillations in the Liujia well at ~600 s were associated with Love waves. These associations are documented here for the first time, even though peripheral mentioning of similar association was made before [*Brodsky et al.*, 2003].

3. Mechanism

[9] The commonly accepted mechanism for the water-level oscillation is that seismic waves may cause aquifers to expand and contract which in turn may cause pore-pressure to oscillate. If the aquifer has high enough transmissivity, groundwater may flow into and out of the well, which in turn may set up resonant motions in the water column. The lithologic logs of the wells (Figure 3) show that, while the screened aquifer at the Liujia well consists of layered fine sands, silt, mud and clay, those at the other two wells consist of either gravels or uniform sands. In the absence of accurate well tests, we may infer from the logs that the transmissivity (the product of the hydraulic conductivity of the aquifer and aquifer thickness) at the Liujia well is the lowest among the three wells, while that at the Chishan well is the highest, and that the Naba well is intermediate. The different transmissivity may account for the different oscillation characteristics of the wells, i.e., vigorous coseismic oscillations occurred in the Chishan and Naba wells but were barely discernable in the Liujia well until the arrival of the strong 10-s Love waves at ~600 s. The different transmissivity may even account for the different sustained changes of water level in the three wells, i.e., a pronounced and sustained water-level change in the Liujia well, a small sustained change in the Naba well, and no detectable sustained change in the Chishan well. High transmissivity promotes uniform pore pressure; thus there is a low probability of connecting to a reservoir of different pressure. On the other hand, poor transmissivity can support heterogeneous pore pressures in close proximity; thus there is a high probability of connecting to a reservoir of different pressure.

[10] Amplification factor, defined as the ratio between the observed well spectra and the observed vertical ground velocity spectrum, may be used to test the hypothesis of the occurrence of enhanced permeability, if the phase of the seismic waves remains unchanged before and after the permeability change [*Brodsky et al.*, 2003]. In the present case, however, the phase of the seismic waves at the TPUB station changed significantly (e.g., Figure 2f) before and after the supposed permeability changes. On the other hand, we note that the amplitude of the ~10-s water-level oscillations in the Liujia well increased significantly from 600 to 650 s (inset of Figure 2c) while the amplitude of the seismic waves during this time interval either remained constant (Figure 2f) or decreased (Figure 2e). Thus a significant

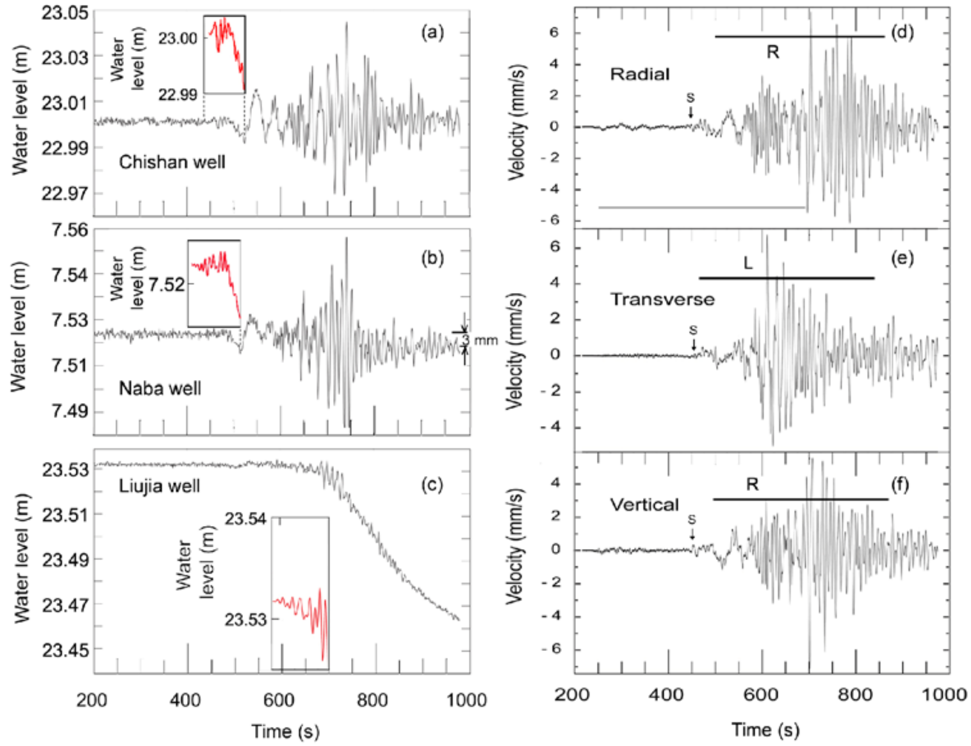

Figure 2. Water level responses to the Wenchuan earthquake in (a) the Chishan well, (b) the Naba well, and (c) the Liujia well. Markings on the vertical axis show elevations above sea-level. Insets show magnified views of the records ~100 s prior to the occurrence of major responses; a low pass filter of 0.12 to 0.15 Hz was applied to these records to reduce the high-frequency background noise. Broadband seismograms of particle velocity at the TPUB station in (d) the radial direction, (e) the transverse direction, and (f) the vertical direction (courtesy of Data Management Center of the Institute of Earth Sciences, Academia Sinica, Taiwan). Well dispersed Love waves (labeled L) are observed on the transverse component, and well dispersed Rayleigh waves (labeled R) are observed on the radial and vertical components. Superimposed on the low frequency Love and Rayleigh waves are higher frequency S body waves (labeled S). Time zero in all diagrams refers to the time of the Wenchuan earthquake.

increase in the amplification factor may indeed have occurred in the Liujia well prior to the sustained water-level decrease.

[11] It is commonly assumed that water level in the far field responds only to Rayleigh waves [*Cooper et al.*, 1965; *Liu et al.*, 1989]. While the major responses in the Chishan and the Naba wells are consistent with this hypothesis, the small water-level oscillations starting at ~450 s are associated with S-waves and the train of 10-s oscillations in the Liujia well starting at ~600 s are associated with Love waves, as noted earlier. It is not unlikely that S waves and Love waves in an anisotropic poroelastic medium do in fact generate volumetric strains [*Wang*, 2000; *Brodsky et al.*, 2003], but a demonstration of this effect, which requires the knowledge of all the three dimensional strain tensors at the wells, is currently lacking. Despite of this lack of understanding, the small water-level oscillations that occurred before Rayleigh waves must be associated with an oscillatory groundwater flow in the screened aquifer. We suggest that this groundwater flow may be strong enough to enhance aquifer permeability and to facilitate the major water-level changes associated with Rayleigh waves.

[12] Permeability in sedimentary basins is dominated by connected pores and fractures which are often clogged by colloidal suspensions in groundwater. Experimental studies of clogging of packed filters [e.g., *Veerapaneni and Wiesner*, 1997; *Wiesner*, 1999] show that, over a wide range of solid fractions in clay-water suspensions in slow motion, colloidal clay particles in the pore water form flocculated deposits which effectively clog pore spaces and block fluid flow. The flocculated clays generally exhibit a yield stress that arises from the bonds between the clay particles, which needs to be overcome for flow to take place [e.g., *Coussot*, 1995]. The required viscous shear to overcome the yield stress decreases with decreasing solid fraction in the colloidal suspension [*Coussot*, 1995]. For an order-of-magnitude estimate we assume a suspension with ~10% clay fraction by volume; the corresponding yield stress is ~0.03 Pa. In direct shear flow with velocity u, the viscous stress on a colloidal particle is approximately $\eta u/r$, where η is the viscosity of water (10^{-3} Pa s) and r the radius of the colloidal particle (~1 μm); thus u must be greater or equal to 0.03 mm/s in order to overcome a yield stress of ~0.03 Pa. During earthquakes, the oscillatory flow of groundwater set up an oscillatory shear stress on the interstitial colloidal particles. Using dynamic simulation of the stability of the microstructures of colloidal suspension *Yamada and Enomoto* [2007] showed that, at sufficiently low frequencies, the magnitude of strain rate required to fragment the structural chains of the suspended particles in oscillatory shear is significantly lower than that in direct shear. Thus the minimum velocity required to break up the

flocculated clay deposits in the oscillatory flow may be even smaller than that under direct shear.

[13] An order-of-magnitude estimate of the velocity of the oscillatory flow in the screened aquifer may be obtained from the observed water-level oscillations. Following [*Cooper et al.*, 1965] we assume that the vertical velocity within the cased section of the well is vertical and uniform. Thus, for a harmonic oscillation of the water level with amplitude x_o and period T, i.e., $x = x_o \sin 2\pi t/T$, where x is the vertical axis centered at the equilibrium water level, the velocity of water in the cased section, i.e., above the screened section, of the well is $v = v_o \cos 2\pi t/T$, where $v_o = 2\pi x_o/T$. We further assume that, across a horizontal section the groundwater flow in the screened aquifer is radial and uniform; thus the discharge per unit area of the screened aquifer is $q(z, t) = q_o(z)\cos 2\pi t/T$ given that the discharge must be in phase with the vertical velocity of the water in the well, where z is measured vertically down from the top of the screened section [*Cooper et al.*, 1965]. Since the total lateral influx of water to the well is equal to the total vertical flux in the cased section of the well, we have

$$\int_0^d 2\pi r_w q_o(z)dz = \pi r_w^2 v_o \tag{1}$$

where d the length of the screened section and r_w is the radius of the well, which is the same in the screened section and in the pipe in which pressure is measured. Following

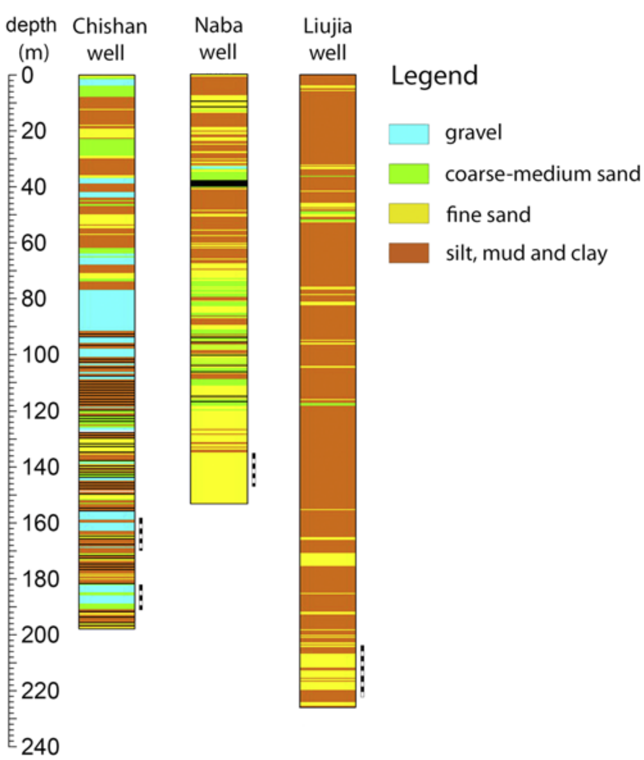

Figure 3. Lithologic logs from the Chishan, Naba and Liujia wells. Dashed lines marked on the right side of the well logs show the locations of the screened section. Note that the Chishan well opens to a gravel bed, the Naba well opens to a thick layer of uniform sand, and the Liujia well opens to layered fine sands, silt, mud and clay.

Table 1. Well Parameters

Well Parameter	Chishan	Naba	Liujia
Well bore diameter (m)	0.15	0.15	0.15
Screen length (m)	21	12	18
Distance from the epicenter (km)	1945	1894	1885
Water-level oscillation amplitude at ~450 s (mm)	3	1	NA
Water-level oscillation period at ~450 s (s)	~10	~10	NA

Liu et al. [1989] we assume that the amplitude of the volume rate of flow decreases exponentially with depth from a maximum at the top of the screen to zero at the base of the screen; i.e.,

$$q_o(z) = q_m \frac{e^{\mathrm{d}-z} - e^{-(\mathrm{d}-z)}}{e^{\mathrm{d}} - e^{-\mathrm{d}}}. \tag{2}$$

Replacing equation (2) in equation (1) we have, for screened lengths ≥ 2 m as in the present case (Table 1),

$$q_m = \frac{\pi x_o r_w}{T}. \tag{3}$$

Given the well parameters in Table 1 and a range of porosity of 20 to 30% for the aquifer [e.g., *Fetter*, 2001], we estimate a maximum linear velocity u of 0.6 to 0.9 mm/s in the Chishan well and 0.2 to 0.3 mm/s in the Naba well. Both are an order of magnitude greater than the threshold velocity required to break up the colloidal suspension with 10% clay fraction. We can thus conclude that the groundwater flow associated with S waves and Love waves may generate shear stress large enough to break up the flocs in sediment pores and to enhance the permeability of aquifers.

[14] While direct evidence for breaking the flocculated structure of colloidal clays by seismic waves and removing them from sediment pores is not yet available, earthquake-induced turbidity in well water has been commonly reported. After the 2002 M7.9 Denali earthquake, for example, groundwater flow in Iowa (some 5,000 km away) increased, and flushed out colloidal particles from local aquifers, so much as to discolor well waters [*Prior et al.*, 2003]. We suggest that pore fluid in sedimentary basins may be repeatedly redistributed and mixed after large earthquakes even at remote distances.

[15] **Acknowledgments.** We thank Barbara Bekins, William H. Lee, Wen-Tzong Liang, Michael Manga and Lee-Ping Wang for useful comments. We also thank Steve Ingebritsen for reviewing the paper and providing helpful suggestions. Seismic data were from Data Management Center of the Institute of Earth Sciences, Academia Sinica, Taiwan. Research is supported in part by the National Science Council of Taiwan (NSC-96-2116-M002-005) and the Water Resources Agency (MOEAWRA0970042).

References

Blanchard, F. G., and P. Byerly (1935), A study of a well gage as a seismograph, *Bull. Seismol. Soc. Am.*, *25*, 313–321.

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

Brodsky, E. E., and S. G. Prejean (2005), New constraints on mechanisms of remotely triggered seismicity at Long Valley Caldera, *J. Geophys. Res.*, *110*, B04302, doi:10.1029/2004JB003211.

Brodsky, E. E., E. Roeloffs, D. Woodcock, I. Gall, and M. Manga (2003), A mechanism for sustained groundwater pressure changes induced by distant earthquakes, *J. Geophys. Res.*, *108*(B8), 2390, doi:10.1029/2002JB002321.

Chia, Y., P. Wang, K. Hsu, R. Lee, and T. Lee (2008), Changes of groundwater level in Taiwan following the 2008 Wenchuan Earthquake, *Eos Trans. AGU*, *89*(53), Fall Meet. Suppl., Abstract U23B-0064.

Coble, R. (1965), Effects of the Alaskan earthquake of March 27, 1964, on groundwater in Iowa, *Proc. Iowa Acad. Sci.*, *72*, 323–332.

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

Coussot, P. (1995), Structural similarity and transition from Newtonian to non-Newtonian behavior for clay-water suspensions, *Phys. Rev. Lett.*, *74*, 3971–3974.

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

Fetter, C. W. (2001), *Applied Hydrogeology*, 4th ed., Prentice Hall, Upper Saddle River, N. J.

Hill, D. P., et al. (1993), Seismicity remotely triggered by the magnitude 7.3 Landers, California, earthquake, *Science*, *260*, 1617–1623.

Johnston, M. J. S., D. P. Hill, A. T. Linde, J. Langbein, and R. Bilham (1995), Transient deformation during triggered seismicity from the 28 June 1992 M = 7.3 Landers earthquake at Long Valley volcanic caldera, California, *Bull. Seismol. Soc. Am.*, *85*, 787–795.

King, C. Y., S. Azuma, G. Igarashi, M. Ohno, and H. Wakita (1999), Earthquake-related water-level changes at 16 closely clustered wells in Tono, central Japan, *J. Geophys. Res.*, *104*, 13,073–13,082.

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

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

Manga, M., and E. E. Brodsky (2006), Seismic triggering of eruptions in the far field: Volcanoes and geysers, *Annu. Rev. Earth Planet. Sci.*, *34*, 263–291.

Manga, M., and C.-Y. Wang (2007), Earthquake hydrology, in *Treatise on Geophysics*, vol. 4, edited by G. Schubert, pp. 293–320, Elsevier, Amsterdam.

Matsumoto, N. (1992), Regression-analysis for anomalous changes of groundwater level due to earthquakes, *Geophys. Res. Lett.*, *19*, 1193–1196.

Prior, J. C., J. L. Boekhoff, M. R. Howes, R. D. Libra, and P. E. VanDorpe (2003), *Iowa's Groundwater Basics*, 92 pp., Iowa Dep. of Nat. Resour., Iowa City, Iowa.

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

Rojstaczer, S., and S. Wolf (1992), Permeability changes associated with large earthquakes: An example from Loma Prieta, California, 10/17/89 earthquake, *Geology*, *20*, 211–214.

Rojstaczer, S., S. Wolf, and R. Michel (1995), Permeability enhancement in the shallow crust as a cause of earthquake-induced hydrological changes, *Nature*, *373*, 237–239.

Sturtevant, B., H. Kanamori, and E. E. Brodsky (1996), Seismic triggering by rectified diffusion in geothermal systems, *J. Geophys. Res.*, *101*, 25,269–25,282.

Veerapaneni, S., and M. R. Wiesner (1997), Deposit morphology and head-loss development in packed bed filters, *Environ. Sci. Technol.*, *31*, 2738–2744.

Wang, C.-Y. (2007), Liquefaction beyond the near field, *Seismol. Res. Lett.*, *78*, 512–517.

Wang, C.-Y., and Y. Chia (2008), Mechanism of water level changes during earthquakes: Near field versus intermediate field, *Geophys. Res. Lett.*, *35*, L12402, doi:10.1029/2008GL034227.

Wang, H. (2000), 2000*Theory of Linear Poroelasticity*, Princeton Univ. Press, Princeton, N. J.

Wiesner, M. R. (1999), Morphology of particle deposits, *J. Environ. Eng.*, *125*, 1124.

Yamada, Y., and Y. Enomoto (2007), Effects of oscillatory shear flow on chain-like cluster dynamics in ferrofluids without magnetic fields, *J. Physica A*, *387*, 1–11.

Y. Chia and P.-l. Wang, Department of Geological Sciences, National Taiwan University, 1 Sec 4, Roosevelt Road, Taipei 106, Taiwan.

D. Dreger and C.-y. Wang, Department of Earth and Planetary Science, University of California, McCone Hall, Berkeley, CA 94720, USA. (chiyuen@berkeley.edu)