Mechanism of Co-seismic Water-Level response to 2015 Nepal earthquake

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Abstract Two adjacent wells -Mangshi (MS) and Lijiang (LJ), are located in the southeast margin of the Tibet Plateau The 2015 Mw 7.8 Nepal earthquake induced different far field (>1000 km) co-seismic water level responses that range from 0.16 to 0.76m We confirm that the seismic wave influences the water level greatly in a high-frequency band (f > 8 cpd) by coherence analysis Furthermore we use the tidal-response variations (M2 tide) to explain this hydrological response The results show that the co-seismic water level response to the distant earthquake may be explained by aquifer permeability or transmissivity enhancements caused by the passage of seismic waves through the mobilization of the colloidal particles Horizontal groundwater flow can be induced in a confined aquifer system as in the MS well While in the LJ well vertical groundwater flow can be further induced by a switch to semiconfined aquifers which may be caused by preexisting vertical fractures The post-seismic tidal-response relax which also means a healing of the aquifer after great earthquakes.

1. Introduction
It has been widely reported that earthquakes can cause various hydrological responses such as changes in groundwater level\textsuperscript{[1,2]} stream flow\textsuperscript{[3-6]} water temperature\textsuperscript{[7-10]} and chemical composition\textsuperscript{[11,12]} which may be caused by ground water transport\textsuperscript{[13]} Different mechanisms have been proposed to explain these phenomena including changes in aquifer parameters (permeability or storativity)\textsuperscript{[14]}, uncooling of deep fractures\textsuperscript{[15]} Research of the co-seismic change in permeability\textsuperscript{[16,17]} usually attaches to horizontal flow in wells since permeability of a layered groundwater system in the horizontal direction is normally larger than that in the vertical direction But recent study shows that earthquakes may also breach the hydraulic barriers between aquifers and increase vertical permeability.

In this work we have examined the water-level data at the Mangshi (MS) and Lijiang (LJ) well the two adjacent wells in Yunnan in the southeast margin of Tibet Plateau The 2015 Mw 7.8 Nepal earthquake induced distinct co-seismic water-level responses in these two adjacent wells in a teleseismic distance Using the phase shift of tidal response as the characterization the change of permeability after earthquake is analyzed which is helpful to better understand the possible mechanisms of co-seismic water level change The results show that earthquakes may change both the horizontal and vertical permeabilities of the aquifer systems switching the aquifer from confined to semiconfined.
2. Observation and data

We collected data from two adjacent wells with distinct co-seismic water level responses to the 2015 Nepal earthquake (Figure 1) The MS well is located in Luxi Basin at 24.2°N 98.6°E whose elevation is 924 m According to the drilling data the well is 200.17 m deep cased with pipe to 95.57 m The LJ well is drilled to 310 m cased with pipe to 240 m.

The water level was recorded by LN-3A digital water level meter developed by the Institute of Seismic Science China Earthquake Administration (CEA) The sampling length (rate) is 1 minute The resolution is 1 mm and the accuracy is 0.2% Along the wells broad-band seismometers with sampling rate of 0.01 s were laid We chose water level and seismic data from April 14 to May 9 in 2015 of the two wells After preprocessing the data (interpolation demeaning and detrending) we used Baytap-G software[18] to calculate the synthetic tidal strain data (solid earth tides).

Figure 1. Map showing the locations of the MS well and LJ well (red solid triangles) 'Beach ball' shows the epicenter and focal mechanism of the 2015 Mw 7.8 Nepal earthquake (from Global CMT) Black lines denote the location of surface faults on the Chinese mainland[19] The blue and purple lines indicate the variation amplitude and duration of water level responses to the Nepal earthquake respectively.

3. Co-seismic response in water level

Co-seismic and post-seismic water level changes caused by the Nepal earthquake are clearly identified The water level responses show oscillation changes with sustained post-seismic variation The amplitudes of the co-seismic water-level changes are shown in Figures 1 and 3 The approximate durations of the co-seismic water-level changes (the relax time) are also measured (see Figure 1).
Figure 2. Z-component seismic wave records at the MS (a) and LJ (b). The red dotted lines represent the earthquake origin time.

Figure 3. Water levels at the MS (a) and LJ (b). The red dotted lines represent the earthquake origin time.

Compared the seismic waves (Figure 2) with the water levels (Figure 3), it is easy to distinguish the co-seismic water level responses in MS and LJ wells induced by the earthquake whose amplitudes are 0.76 m and 0.16 m respectively. The relax times of the co-seismic water level changes are 109 min and 97 min. It is easy to suggest that the co-seismic water level changes are associated with seismic wave propagation.

To estimate how seismic waves influence the water level, we regard the a seismic wave as the input signal and the water level as the output signal. We calculate the ordinary coherence functions among the water level and seismic wave for each station to obtain transfer functions [20].

Figure 4. Changes of water level and seismic coherence before (a) and after (b) the Nepal earthquake in the MS well.

Figure 5. Changes of water level and seismic coherence before (a) and after (b) the Nepal earthquake in the LJ well.
Figures 4 and 5 show the changes of water level and seismic cross coherence before and after the Nepal earthquake in the MS and LJ wells. Before the earthquake, the coherence fluctuates around 0.5, which means the transfer relationship is not so strong. However, after the earthquake, the coherence at most frequencies, especially in the high-frequency band (f > 8 cpd), for two wells are greater than 0.9. It can be confirmed that seismic waves influence the co-seismic water level response greatly, especially in the high-frequency band (f > 8 cpd).

4. Tidal response analysis
The amplitude and phase responses of the water level to Earth tides can be used to monitor aquifer storativity and permeability, respectively.[21-23] In a confined system, high permeability usually causes small phase lags, whereas low permeability results in large phase lags. The amplitude response is primary to measure specific storage.[24]. According to Cooper et al.[25] and Hsieh et al., we get the phase shift changes caused by the Nepal earthquake in the two wells (Figures 6 and 7).

5. Mechanisms of co-seismic aquifer property changes
The co-seismic phase shift of the MS well is negative, and the horizontal fluid flow model is applicable. In this model, the well response depends on the flow of water through the porous medium in the water table. The permeability or transmissivity of the system is generally related to its water level phase lags. As Figure 7 shows that phase response of the LJ well changes across 0 with time. A combination of the horizontal fluid flow and the vertical pore-pressure diffusion model can explain the phase ahead. The flow in the confining formation is vertical. The diffusion of pore pressure with a term due to the tidal forcing. The corresponding time-dependent transmissivities of the two wells are obtained (Figures 8 and 9).
Figure 8. Transmissivity changes of the MS well. The dotted line shows the origin time of the 2015 Nepal earthquake. The transmissivity calculated using the horizontal flow model.

Figure 9. Transmissivity changes of the LJ well. The dotted line shows the origin time of the 2015 Nepal earthquake. The transmissivity calculated using the horizontal flow model and $T_v$ calculated using the vertical pore-pressure diffusion model.

6. Conclusions

The water levels at the MS and LJ wells can respond to far field (>1000 km) large earthquakes such as the Nepal earthquake. We applied the water-level to seismic-wave transfer functions at different frequency ranges and the amplitude-ratio and phase-shift response to the M2 tide to confirm and further explain the co-seismic water-level changes in the MS and LJ wells.

Permeability enhancements were observed both in the far-field aquifer systems caused by the passage of seismic waves through the mobilization of colloidal particles. What’s more, it depends on the local aquifer properties to decide whether the seismic waves change the aquifer into semiconfined or not. The post-seismic healing represents the high-frequency response characteristics which is in accord to the seismic to wave level transfer functions.

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