Coseismic responses of groundwater levels in the Three Gorges well-network to the Wenchuan $M_S8.0$ earthquake*

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Abstract We systematically analyze coseismic responses and post-seismic characteristics of groundwater levels in the Three Gorges well-network to the $M_S8.0$ Wenchuan earthquake on 12 May 2008. The results indicate that these characteristics differ among wells. On the conditions of similar borehole configurations, the differences are associated with geological structural sites of wells, burial types of aquifers monitored, and transmissivities of aquifer systems. We explored coseismic and post-seismic step-rise and step-drop mechanical mechanisms and their implication to earthquake prediction. We validated the inference that the residual step-rise zone is a possible earthquake risk zone based on recent seismic activity on the Xiannüshan fault in the area.

Key words: well level; coseismic response; Three Gorges well-network; Wenchuan earthquake; post-seismic step

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1 Introduction

Co- and post-seismic responses of water levels provide a good way to understand the links between hydrogeological process and earthquakes. In the recent years, a lot of studies on this subject have been carried out (Huang et al, 2000; Yang et al, 2007; Fu et al, 2002). Particularly, many studies focused on the coseismic responses of water levels of several hundred wells in the groundwater dynamic observational network in Chinese mainland to the Sumatra $M_S9.0$ earthquake on 26 December 2004 (Department of Monitoring and Prediction, China Earthquake Administration, 2005), concerned the form features of coseismic responses as well as their application to earthquake prediction. Actually similar researches have been also documented abroad (Roeloffs, 1998; Kitagawa et al, 1996). It shows that this issue has attracted much attention in the field of earthquake underground fluids.

The Wenchuan $M_S8.0$ earthquake of 12 May 2008

provided another opportunity to observe the coseismic responses by the network. According to the preliminary statistics, within the range of 1 000 km away from the epicenter, 90% of the all well levels, 60% of well temperatures and 20% of radon measurements have recorded coseismic responses. They are the largest scales in the all records since the onset of observations to underground fluids in the country and offer abundant data for the study of coseismic responses.

In this paper, we present the features of coseismic responses of water levels in eight wells of the Three Gorges well-network which was constructed to monitor induced earthquakes around the reservoir. On a platform of the “field”, we analyze differences in coseismic responses among all wells and their reasons. We find that the records in the well at the Xiannüshan fault zone exhibits a residual step rise which can be explained by increasing compressive stress from the Wenchuan earthquake, implying the seismic risk of this fault. In fact, two induced shocks of $M_L3.8$ and $M_L4.1$ occurred at this fault on 27 September 2008 and 22 November 2008, respectively.

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2 Outline of the Three Gorges well-network

The Three Gorges well-network was constructed by the General Development Corporation of China Yangtze River Three Gorges which is specially for monitoring precursors of groundwater associated with induced earthquakes around the reservoir. It began to operate in 2001 and has records of eight years.

This network is composed of eight wells (named W_1 to W_8) which lie in the dam and reservoir head areas (Figure 1). In the dam area, the network ranges 20 km in

east-west and 15 km in north-south with interval of 5–10 km. And in the reservoir head area the well spacing is 10–20 km (Che et al, 2002).

The geological characteristics of the eight wells are shown in Table 1. Except slight differences in well depths, all wells have the same borehole structure. The inner diameter of the pipe for observations in the upper portion of the well is 133 mm, and that in the lower portion is 114 mm.

The primary observed items in these eight wells are water levels and water temperatures. Besides, the atmospheric pressure and rainfall are also measured at

Figure 1 Map showing distribution of observational wells of Three Gorges well-network. F_1 , Xiannüshan fault, F_2 , lukouzi fault, F_3 , Jiuwanxi fault, F_4 , Jiejiangpo fault, F_5 , Taipingxi fault, F_6 , Changmutuo fault, F_7 , Gaojiachong fault.

Table 1 Basic characteristics of eight wells of the Three Gorges well-network

Well No.	Well name	Location	Fault strike	Well depth /m	Observed target		
					Depth/m	Rock	Groundwater
W_1	Gaojiaxi	Hanging wall of Gaojiachong fault	NNW	150	69–75	δ_0^2 Biotite-quartz diorite	Mixed water in fissures of crystalline rock
W_2	Dingjiaping	Intersection of Gaojiachong fault and Changmutuo fault	NNW	153	86–116	δ_0^2 Biotite-quartz diorite	Mixed water in fissures of crystalline rock
W_3	Maoping	Hanging wall of Changmutuo fault	NNE	200	85–130	δ_0^2 Biotite-quartz diorite	Mixed water in fissures of crystalline rock
W_4	Hanjiawan	Footwall of Taipingxi fault	NNW	100	69–72	δ_0^1 Quartz diorite	Mixed water in fissures of crystalline rock
W_5	Dahekou	Hanging wall of Xiannüshan fault	NNW	128	113–128	O ₂ Limestone	Karstic confined artesian water in fault
W_6	Qujiawan	Footwall of Jiuwanxi fault	NNW	150	73–117	S ₂ Sand shale	Mixed water in fissures of sedimentary rock
W_7	Zhouping	Footwall of Xiannüshan fault	NNW	60	Bottom of the well	K ₂ Sand gravel	Karstic confined artesian water in fault
W_8	Guojiaba	Hanging-wall of Xiannüshan fault, flank of syncline	NNW	200	124–184	J ₁₋₂ Sand shale	Mixed water in fissures of sedimentary rock

wells W_3 , W_6 and W_8 . All the observations are operated in continuous and digitalized ways. The used instrument is the integrated measurement instrument for underground fluids of type DSW-01 made by Earthquake Administration of Hubei province, which has water level resolution 1 mm, water temperature resolution 0.001°C and sampling rate 1 minute (Li et al, 2006). In the Three Gorges well-network, the measured water levels remain the real heights of water columns in wells, i.e., the vertical distance from the sensor bottom to the water top in wells, which are not normalized yet.

Observations of many years show that the long-term and annual dynamic background values of water levels in the eight wells are fairly stable. Except W_5 , the interference to other wells is primarily from rainfall. All the wells have recorded earth tides with throws 26–86 mm. They have effects of atmospheric pressure with coefficients 0.01–1.00 mm/nPa (Liu et al, 2003). Some scale coseismic responses to local shocks and great earthquakes in the world have been observed by these wells. And partial wells (within distance from the reservoir bank <1 km) are sensitive to the loading by water storage in the reservoir (Che et al, 2004).

3 Features of coseismic responses of water levels in wells

When the seismic waves of the Wenchuan earthquake arrived at the eight wells of the Three Gorges well-network, their water levels exhibited synchronous responses (Figure 2). But these records reflect the variation of the coseismic responses rather than the original real signals because of the limited sampling rate merely one time per minute. So we cannot analyze their features of the spectrum responses. Nevertheless these records contain much useful information.

As shown by Figure 2, the coseismic responses of the all wells to the Wenchuan event are characterized by a sudden drop of water level followed by different changes. They can be classified into three types: step drop-step rise, step drop-gentle rise and gentle drop. For the former two types, their subsequent features can be described by complete recovery, residual step-rise and residual step-drop. And the amplitudes of the wells differ much, ranging from over 1 m to less than 0.1 m, with differences more than 20 times (Table 2).

Figure 2 Coseismic responses of water levels to the $M_s8.0$ Wenchuan earthquake recorded by the Three Gorges well-network.

Table 2 Comparison of coseismic responses of water levels in Three Gorges well-network

Well No.	Response type	Subsequent process	Amplitude of step-drop /cm	Note
W_1	Step drop-gentle rise	Residual step drop	116	
W_2	Gentle drop		>122	
W_3	Gentle drop		>17.8	
W_4	Step drop-step rise	Residual step rise	6.7	
W_5	Step drop-step rise	Residual rise	79.8	
W_6	Step drop-step rise	Residual step drop	44.6	
W_7	Step drop-step rise	Residual step rise	40.6	
W_8	Step drop-?	?	>172	Incomplete record due to instrument breakdown at shock time

4 Analysis of different coseismic responses of well water levels

The eight wells of the Three Gorges well-network lie in an area of 20 km in east-west and 15 km in north-south direction. Although they have roughly same structures of boreholes, their coseismic responses of water levels, both in forms and amplitudes, as well as the subsequent behaviors are quite different. What factors determines these differences? Our analysis shows that the geological locations of wells and transmissivity T ($T=K \times M$, K is hydraulic conductivity, M is thickness of aquifer) of aquifers are the primary factors which are presented in detail below.

The tectonic settings determine the forms of the coseismic responses. As shown in Figure 2 and Table 2, the coseismic responses of wells W_2 and W_3 , which lie on the NNE trending Changmutuo fault, are all of gentle drop type, while those of the wells on the NNW trending fault are all of step drop-step rise type. Meanwhile, the coseismic responses of the wells on the faults of same trend also differ from each other to some extent. For example, the wells W_5 , W_7 and W_8 on the NNW trending Xiannüshan fault are largely of step drop-step rise type (except W_8 without step-rise recorded), while the wells W_1 on the NNW trending Gaojiachong fault and W_6 on the NNW trending Jiuwanxi fault are of step drop-gentle rise for their coseismic responses. Apparently, firstly the strike of a fault determines the form of the coseismic responses, secondly the wells on faults with same strike have varied features in coseismic responses.

The amplitudes of coseismic step drops of water levels in wells are primarily associated with their locations and transmissivity of aquifers (Table 3). For instance, for the wells W_5 , W_7 and W_8 on the NNW trending Xiannüshan fault, their amplitudes of coseismic step drop of water levels become larger with increasing

transmissivity of well-aquifers. This case holds true for the wells W_2 and W_3 on the NNE trending Changmutuo fault. However, for the wells with mixed water in diorite fissures, which have higher transmissivity of aquifers, the amplitudes of coseismic responses seem to be much larger.

Table 3 Comparison of coseismic response recovery time and aquifer transmissivity in the Three Gorges well-network

Well No.	Recovery time of coseismic response/h	Transmissivity of aquifer/ m^2d^{-1}
W_1	2	0.075
W_2	>10	0.15
W_3	>10	0.02
W_4	<0.5	0.04
W_5	<0.5	10.4
W_6	3	0.012
W_7	1	0.085
W_8	?	11.17

The amplitudes of coseismic step drops of water levels in wells are also dependent upon rocks of aquifers, burial types of groundwater and transmissivity of aquifers. Specifically, the amplitudes of coseismic step drops of water levels in the wells in limestone karst are obviously larger than those in the wells with aquifers in diorite fissures. For the wells with aquifers in diorite fissures, those wells of higher transmissivity of aquifers have larger coseismic responses. For the three wells with aquifers in detrital rock, their coseismic responses of water levels differ very much. The response amplitude of the well W_8 with strong confined aquifers is considerably larger than the well W_6 with weaker confined aquifers. Overall, the step drop amplitudes of water levels in coseismic responses become larger with growing transmissivity of aquifers (Figure 3).

Figure 2 and Table 3 also demonstrate that the subsequent effects of coseismic responses of wells are different. First, they have varied recovery time of water levels (Table 3), with shortest time less than half an hour (W_4 , W_5), intermediate time 1 hour (W_7), longer time

Figure 3 Relation of response amplitudes and transmissivity of aquifers in the Three Gorges well-network.

2–3 hours (W_1 , W_6), and longest time over 10 hours (W_2 , W_3) to restore or approach the original water levels. The reasons for these differences are rather complicated. The fast recovery of W_5 is associated primarily with its very large transmissivity of aquifers, secondarily with its artesian aquifers in the fault. The short recovery time of W_4 is probably related with its least step drop amplitude of the coseismic response. W_7 recovered fairly fast, likely because it is artesian aquifers in the fault, and its transmissivity of aquifers is large. And the relatively slow or very slow recovery of W_1 , W_2 , W_3 and W_6 are likely related with their confined water and mixed groundwater, because the recovery mechanisms of these two kinds of water are different. For the confined aquifers, pressure transmission makes well water levels restore after the coseismic response. For the water table aquifers, the recovery of well water levels relies on water flow. And the pressure propagation in confined aquifers is much faster than water flow. It means that the different recovery processes of water levels after the coseismic responses are primarily dependent on the transmissivity of aquifers, secondly related with types of subsurface water, ordinary underground water or in confined aquifers.

In the aftermath of the coseismic responses, the residual step change is particularly noteworthy. For instance, after the coseismic step drops of water levels in W_1 and W_6 , they did not restore completely to the original levels, instead having residual step drops. While the residual step rises of water levels were left in wells W_5 and W_7 . W_4 has almost no residual change. W_2 and W_3 did not restore their levels before the earthquake. These different aftermaths seem to be related with locations of wells. Because only the wells W_5 and W_7 on the Xiannüshan fault (except W_8 unclear) have residual step rise, while other wells have residual step drops or restored completely.

Analysis of the relationship between rise and drop

of well water levels and mechanical state of aquifers indicates that compressive stress makes aquifer water rise and extensional stress makes it drop (Che and Yu, 2006). Thus, different aftermaths of coseismic responses in the wells likely mean varied effects of the seismic waves of the Wenchuan earthquake on the Three Gorges area. Specifically, the compressive stress on the Xiannüshan fault was enhanced, while that on other faults was reduced (extensional stress was increased) or did not change.

In the view of earthquake prediction, the abnormal variation mentioned above likely means increasing seismic hazard on the Xiannüshan fault by the Wenchuan $M_{\text{L}}3.8$ (epicenter $30^{\circ}56'N$, $110^{\circ}46'E$) and $M_{\text{S}}4.1$ (epicenter $31^{\circ}00'N$, $110^{\circ}47'E$) occurred at the northernmost of this fault on 27 September 2008 and 22 November 2008, respectively. Although both shocks are interpreted as induced events by the reservoir, they are still associated with geological structure as evidenced by thrust nature revealed by the focal mechanism solutions. Therefore they should be attributed to the enhanced compressive stress on the fault mentioned above.

5 Discussion and conclusions

1) Observations demonstrate that the eight wells of the Three Gorges well-network can generate remarkable responses to earth tides, atmosphere pressure as well near- and far-field earthquakes. It means that water levels are very sensitive to changes of stress or strain on varied frequency bands. Thus this well-network can detect precursors to earthquakes.

2) Even if in a small range, capabilities and features of responses of well water levels to seismic waves are different between wells. Hence the characters of coseismic responses in a well cannot characterize the entire area where this well lies. The dependence of responses of well water levels on the conditions of well-aquifers is an important issue to be studied.

3) Coseismic responses of well water levels are associated with the tectonic settings, types of observed aquifers and their transmissivity. In general, faults with varied strikes can produce different coseismic responses and aftermaths. The wells in confined aquifers with large transmissivity have larger amplitudes of coseismic responses and shorter recovery times.

4) The observed residual step variations of coseismic responses in well water levels probably indicate the effects of one large shock on the fault where the well is

situated. The remaining step rise of water levels is likely indicative of enhanced compressive stress which implies increasing earthquake risk. This inference is supported by the fact that two mediate-sized induced earthquakes by the reservoir occurred on the Xiannüshan fault in September–November 2008.

The study results presented in this article are preliminary. The coseismic responses of well water levels in the Three Gorges well-network to the Wenchuan $M_S 8$ event require further research. Particularly, we need make comparison with the case studies of other $M \geq 7$ events on coseismic responses of water levels and well temperatures at home and abroad to test the inferences made in this work.

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