Characteristics of coseismic water level changes at Tangshan well for the Wenchuan $M_S8.0$ earthquake and its larger aftershocks*

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Abstract Coseismic water level changes which may have been induced by the Wenchuan $M_S8.0$ earthquake and its 15 larger aftershocks ($M_S \geq 5.4$) have been observed at Tangshan well. We analyze the correlation between coseismic parameters (maximum amplitude, duration, coseismic step and the time when the coseismic reach its maximum amplitude) and earthquake parameters (magnitude, well-epicenter distance and depth), and then compare the time when the coseismic oscillation reaches its maximum amplitude with the seismogram from Douhe seismic station which is about 16.3 km away from Tangshan well. The analysis indicates that magnitude is the main factor influencing the induced coseismic water level changes, and that the well-epicenter distance and depth have less influence. M_S magnitude has the strongest correlation with the coseismic water level changes comparing to M_W and M_L magnitudes. There exists strong correlation between the maximum amplitude, step size and the oscillation duration. The water level oscillation and step are both caused by dynamic strain sourcing from seismic waves. Most of the times when the oscillations reach their maximum amplitudes are between S and Rayleigh waves. The coseismic water level changes are due to the co-effect of seismic waves and hydro-geological environments.

Key words: Wenchuan $M_S8.0$ earthquake; Tangshan well; coseismic water level variation; analog water level record

CLC number: P315.72³

Document code: A

1 Introduction

The Wenchuan $M_S8.0$ earthquake occurred at 14:28:04 on 12th May 2008 at the southeast part of the Longmenshan fold zone, Sichuan province, China. After the main shock, there occurred 15 larger aftershocks ($M_S \geq 5.4$) in a 200 km long belt within the fold zone. The 16 earthquakes from the same seismic-bearing fold zone, caused a series of coseismic changes at Tangshan well, and the data is very precious for further research on water level coseismic phenomena.

Some researchers have discussed changes of water level and water temperature at Tangshan well (Cao, 1988; Zhang et al, 1998, 2002; Che and Yu, 2004; Shi et

al, 2007; Ma et al, 2008). Zhang et al (2005b, 2007) compared coseismic recording ability of analog record with that of digital record, and suggested that there exists distortion for coseismic recording of the digital record since the sampling rate of the digital record is one minute whereas the period of the coseismic recording is by second; however, the analog water level record has the advantage for recording the amplitude and the duration of coseismic water level oscillation. As for research on coseismic water level variation to large earthquakes, some researchers analyzed coseismic water level variation characteristics and response mechanisms of Chi-Chi (Jiji) earthquake and Sumatra earthquake using the data from several wells (Huang et al, 2000; Liu et al, 2005; Zhang et al, 2005a; Kitagawa et al, 2006). However, there is no statistical coseismic research on a well responding to an earthquake sequence to the best of our

* Received 12 September 2008; accepted in revised form 13 March 2009;
published 10 April 2009.

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knowledge. Tangshan well provides us the possibility due to its high sensitivity.

The paper uses the analog water level record at the Tangshan well to analyze time and amplitude parameters of coseismic variation caused by the Wenchuan main shock and its 15 larger aftershocks. The statistical correlation between seismic parameters and coseismic amounts is calculated, and the possible mechanism of coseismic changes is discussed.

2 Observation

2.1 Water level observation of Tangshan well

The Tangshan well is located in Dazhao park in Tangshan city, which is also called Tangshan mine or Shanxi No.2 well. Dazhao park is inside Tangshan city, the altitude of which is 25.43 m. The well was drilled on October 30 in 1969 with depth 286.6 m. The hole was sealed at 207 m depth, with casing depth to 154 m. The aquifer layer consists of Ordovician limestone of about 50 m thick. The well lies between Yanshan fold zone and North China plain subsidence zone, with Tangshan

fault in NE direction and a buried fault in WNW direction going through the well. The average burying depth is about 60 m now.

The SW40 nilometer was used to observe the ground water level from January 1981. It was upgraded to SW40-1 nilometer in 1993. Then in September 2001, a LN-3 digital nilometer was set up with the analog nilometer running simultaneously. SW40-1 nilometer is a mechanical apparatus with buoy to detect water level changes. Its mechanical clock drives an ink pen to record the water level changes on the paper around the cylinder. There are staff members replacing the starting position of the pen or changing a new piece of paper at 8 am everyday. The precision of the analog record is 1 mm, and the daily time error is about two minutes. Because the sampling rate of LN-3 digital nilometer is one minute and the period of coseismic changes is measured by second, it is impossible to record coseismic changes completely. Therefore, we use analog data to examine the coseismic changes of the 16 earthquakes (Figure 1).

Figure 1 The analog record of coseismic water level responding to Wenchuan $M_S 8.0$ earthquake and its 15 larger aftershocks at Tangshan well.

There are prominent annual tendency, earth tides and barometric effects in the water level at the Tangshan well. However, comparing with the period of seismographs, the period of these effects are much larger. Therefore, these effects have little influence on the water level changes during the short coseismic oscillation. Hence the error of using the original data to examine coseismic changes is very small. The effect on the statistical results will not be significant.

2.2 Seismic observation at Douhe station

Douhe seismic station is located on the base rock of the south hill of Douhe reservoir which lies at the northeast of Tangshan city, about 16.3 km far away from the Tangshan well. The altitude of the station is 55.42 m. The 3-components digital broad-band seismometer has a responding characteristic of 0.05–20 Hz. The dynamic range is about 120 dB. The digitalizer EDAS-C24 is made by Geodivice Inc., China. The sampling rate is 50

Hz, and the timing precision is ≤ 1 ms.

3 Parameters of the Wenchuan earthquake and water level coseismic changes at Tangshan well

3.1 Parameters of Wenchuan earthquake

The Wenchuan earthquake occurred on the southwest section of the Longmenshan fold zone. From northwest to southeast, The Longmenshan fold zone can be divided as follows: the Houshan fault extending along Wenchuan-Maowen direction, the Zhongyang fault extending along Yingxiu-Beichuan direction, and the Qianshan fault extending along Dujiangyan-Anxian direction. The three faults immersed into one shearing zone at the depth about 20–30 km (Wang et al, 2008). After the main shock, from 12th May to 27th May, there occurred 11 aftershocks ($M_S \geq 5.4$) in the main shock region. Then from 24th July to 5th August, four aftershocks ($M_S \geq 5.4$) occurred in the northeast Qingchuan region. Most of the earthquakes are thrust-fault earthquakes. The focal mechanism of most of the earthquakes near Lixian is strike-slip, whereas there are both strike-slip and thrust-fault earthquakes in the east of Qingchuan (Hu et al, 2008).

The basic parameters of the 16 earthquakes ($M_S \geq 5.4$) are listed in Table 1. Except that M_W magnitude and depth are from Harvard university CMT catalogue, all the others are from China Earthquake Networks Center (CENC) and Shaanxi earthquake networks (M_L magnitude) on the website of China Earthquake Administration. The well-epicenter distance is calculated using parameters from CENC catalogue. The arrival times of body waves and maximum amplitudes of Love and Rayleigh waves of the 16 earthquakes recorded at Douhe seismic station are also listed.

3.2 Coseismic changes of water level

The typical feature of coseismic water level oscillation at Tangshan well to the Wenchuan earthquakes is as follows. When seismic wave arrives, there is a pulse change in water level; then the water level continues oscillating, and has a water level step in the process (Figure 1). About 3 minutes after the Wenchuan $M_S 8.0$ earthquake, the water level at the Tangshan well emerged a short oscillation for about two minutes with maximum amplitude of 19 mm. After comparing with the theoretical phase arrival times calculated from the program on NEIC website, we find that the beginning time of the oscillation is nearly at the same time with the

arrival times of the P_n and P waves. The amplitude of the oscillation keeps increasing, and reaches its peak value (2.434 m, from digital record) in 10 minutes. The duration of the oscillation is about 240 minutes, and there appears an 11 mm step change in total. As for the other 15 larger aftershocks, if the magnitude is around $M_S 6.0$, there is always a pulse with maximum amplitude at first, then following an oscillation with decreasing amplitude, accompanied by a step (See EQ #3 in Figure 1). If the aftershock is around $M_S 5.5$, there always occurs a swift step change at first; then the water level keeps its changing tendency until the time when the water level arrives at the place where it should be determined according to its original tendency, accompanied by minor oscillations. We have not found significant coseismic changes which can be distinguished from the background noise in the water level for earthquakes with $M_S < 5.4$ in the analog record at Tangshan Well.

Table 1 lists maximum amplitudes of coseismic water level changes caused by the Wenchuan earthquakes, the time between seismic phase arrivals and the maximum amplitude of the coseismic oscillations, the amount of step change, and duration of oscillations, etc. (The coseismic changes of EQ #2 appears to be overlapped by that of the main shock), the time of maximum coseismic amplitude comparing to seismogram phases can be divided into four types, P-S, S- Q_m , Q_m - R_{mz} , $>R_{mz}$, they are numbered to 1–4 correspondingly, for drawings in Figures 3–6.

4 Analysis on the characteristics of coseismic water level changes

4.1 Correlations between coseismic water level changes and earthquake magnitude and well-epicenter distance using three types of magnitude scaling

Some researchers have studied correlation between earthquake magnitude and well-epicenter distance for coseismic water level changes. Matsumoto (1992) analyzed the data from Haibara well in Japan and obtained the relationship between the magnitude and well-epicenter distance $M=2.45\lg D+0.69$. Kitagawa and Matsumoto (1996) analyzed the water level at a well in Tokai area, Japan, and suggested a relationship as $M=2.62\lg D$. King et al (1999) provided a relationship of $M=2.5\lg D$ for Tono well, Japan. Yang et al (2005) analyzed coseismic phenomena at Dazhai well, Simao county, Yunnan province in China, and suggested an equation as $M=1.176\lg D+3.104$. These studies used dif-

Table 1 The parameters of the Wenchuan $M_s8.0$ and its 15 larger aftershocks, arrival time of phases of seismogram at Douhe station, and water level coseismic response at Tangshan well

No.	Date a-mo-d	Time h:min:s	Lat./°N	Long./°E	M_s	M_L	M_W	Depth /km	Distance /km	Location	Arrival time of seismic phases at Douhe				Maximum coseismic amplitude			Coseismic step		Dura- tion/min
											P h:min	S h:min	Qm h:min	Rmz h:min	Arrival h:min	Seismic phase	Ampli- tude/mm	Amount /mm	Variation trend	
1	2008-05-12	14:28:04	31.0	103.4	8.0	7.7	7.9	12.0	1659.5	Wenchuan	14:31.5	14:34.5	14:36.3	14:37.5	14:38	> R_{mz}	2434 [@]	-11 ^{&}	Down	240
2	2008-05-12	14:43:15	31.0	103.3	6.0	6.4	*	*	1637.5	Wenchuan	*	*	*	*	*	*	*	*	*	*
3	2008-05-12	19:10:58	31.4	103.6	6.0	6.8	5.7 ^{&}	11 [#]	1602.0	Wenchuan	19:14.5	19:17.3	19:19.2	19:20.3	19:18	S-Q _m	38	-4	Down	40
4	2008-05-13	04:08:50	31.4	104.0	5.7	6.5	5.6	28.4	1572.5	Shifang	04:12.3	04:14.8	04:16.7	04:17.8	04:16	S-Q _m	9	-2.5	Down	15
5	2008-05-13	15:07:11	30.9	103.4	6.1	6.6	5.8	14.1	1652.0	Wenchuan	15:10.7	15:13.6	15:15.7	15:16.6	15:13	P-S	10	2	Up	20
6	2008-05-14	10:54:37	31.3	103.4	5.6	5.9	5.5	12.0	1623.7	Wenchuan	10:58.2	11:01.1	11:02.8	11:03.9	11:00	P-S	4.5	0.5	Up	10
7	2008-05-16	13:25:49	31.4	103.2	5.9	6.2	5.6	24.5	1631.7	Lixian	13:29.4	13:32.3	13:34.1	13:34.9	13:33	S-Q _m	6	2.5	Up	15
8	2008-05-18	01:08:23	32.1	105.0	6.0	6.3	5.7	14.0	1450.0	Jiangyou	01:11.6	01:14.1	01:15.7	01:16.8	01:18	> R_{mz}	11.5	3.5	Up	40
9	2008-05-19	14:06:55	32.5	105.3	5.4	5.5	5.3 ^{&}	17 [#]	1400.3	Qingchuan	14:10.0	14:12.4	14:14.1	14:17.2	14:17	Q _m - R_{mz}	2	1	Up	5
10	2008-05-25	16:21:47	32.6	105.4	6.4	6.5	6.0	15.0	1386.1	Qingchuan	16:24.9	16:27.3	16:28.7	16:29.7	16:28	S-Q _m	73	-5	Down	100
11	2008-05-27	16:03:24	32.7	105.6	5.4	5.8	5.3 ^{&}	10.0	1364.5	Qingchuan	16:06.3	16:08.7	16:10.2	16:11.1	16:09	S-Q _m	2	-0.5	Down	5
12	2008-05-27	16:37:53	32.8	105.6	5.7	6.2	5.5	15.0	1357.7	Ningqiang	16:40.9	16:42.6	16:44.7	16:45.7	16:43	S-Q _m	5.5	-2	Down	17
13	2008-07-24	03:54:47	32.8	105.6	5.6	5.9	5.5	12.0	1357.7	Guangyuan	03:57.7	04:00.0	04:01.8	04:02.6	04:05	> R_{mz}	8	-1.5	Down	10
14	2008-07-24	15:09:29	32.8	105.5	6.0	6.1	5.6	12.2	1365.1	qingchuan	15:12.5	15:14.9	15:16.5	15:17.3	15:15	S-Q _m	13.5	2.5	UP	40
15	2008-08-01	16:32:00	32.1	104.7	6.1	6.2	5.7	20.2	1472.1	Beichuan	16:35.8	16:38.6	16:39.9	16:41.1	16:40	Q _m - R_{mz}	15.5	3.0	UP	20
16	2008-08-05	17:49:19	32.8	105.5	6.1	6.2	6.0	12.0	1365.1	Beichuan	17:52.1	17:54.9	17:56.3	17:57.2	17:59	> R_{mz}	122	2.5	UP	42

Notes: 1. M_L : Magnitude from Shaanxi Seismic Networks.

2. M_W : Magnitude from Harvard University CMT Catalogue, The value before \$ indicates that it is a estimated value according to similar earthquakes.

3. Focal depth: From Harvard University CMT Catalogues, the value noted by # indicates that it is from Shaanxi Seismic Networks, while having no value in Harvard Catalogues

4. * indicates there has coseismic change, but it can not be distinguished for covering by the coseismic change of the main shock.

5. @ indicates that the value is from digital recorder, for it has overflowed in the analog recording paper.

6. &:the minus value indicates the step is down, the other indicates it is up.

7. Q_m: the maximum amplitude of Love wave, R_{mz}: the maximum vertical amplitude of Rayleigh wave.

ferent earthquake catalogues and different types of magnitude scaling. The results differ from each other as well. Here, we use three types of magnitude scaling of the Wenchuan earthquakes to examine the relationship between the magnitude and well-epicenter distance for the coseismic changes at the Tangshan well.

We use M_S , M_L and M_W scaling of the earthquakes listed in Table 1 which have caused coseismic water level changes at the Tangshan well, to examine the relationship between the magnitude and well-epicenter distance (Figure 2). Comparing the three relationships we obtained, the result using M_S magnitude from CENC is similar to the result using M_W magnitude from Harvard, with nearly the same slope, though the fitted line of us-

ing M_S is slightly higher than that of using M_W magnitude as shown in the figure. The result using M_L magnitude from Shaanxi networks has a remarkable difference from the other two. The same conclusion is drawn when calculating the lower limit of the relationship between the earthquake magnitude and well-epicenter distance for coseismic changes. Comparing the equations for the Tangshan well with that of other wells mentioned above, if we use the same well-epicenter distance to calculate the lowest magnitude at which an earthquake can cause coseismic changes at a well, the Tangshan well needs the lowest magnitude to be triggered to oscillate, indicating that the Tangshan well is more sensitive.

Figure 2 The correlations between well-epicenter distances and magnitudes of Wenchuan earthquakes which cause coseismic response at Tangshan well. M_L1 , M_S1 , M_W1 are correlative results of all the earthquakes, while M_L2 , M_S2 , M_W2 are correlative results of minimum limit of causing coseismic change.

4.2 Correlations between coseismic water level statistics and the three types of magnitude scaling

Figure 3 shows the correlations between three types of magnitude scaling and coseismic parameters for the Tangshan well. For the four coseismic parameters, the strongest correlations are between the maximum amplitude and the three types of magnitude scaling, and between the amount of step change and the magnitudes, the all is larger than 0.85. The correlations between the duration of coseismic changes and the magnitudes are all larger than 0.8. However, the time when coseismic oscillation reaches its maximum amplitude has less correlation with the magnitudes. Comparing the correlations respectively for the three types of magnitudes, M_S magnitude always has the strongest correlation with the coseismic parameters except for the time when coseismic oscillation reaches its maximum amplitude. The

results for M_W magnitude are close to that of M_S magnitude, whereas M_L magnitude always has the weakest correlation.

4.3 Correlations between coseismic water level statistics and well-epicenter distance

Figure 4 shows the correlations between well-epicenter distance and parameters of coseismic changes caused by the Wenchuan earthquakes. The coseismic parameters are the maximum amplitude of coseismic water level changes, coseismic step, coseismic duration and the time when coseismic oscillation reaches its maximum amplitude. In general, the correlations are poor, and the correlation tendencies are not consistent with the commonly known tendency. This is probably due to the small differences of well-epicenter distances of these earthquakes, and big differences of magnitudes of the main shock and the aftershocks.

Figure 3 The correlations between coseismic parameters at Tangshan well and three types of magnitude scaling.

Figure 4 The correlations between coseismic parameters for Tangshan well and well-epicenter distances.

4.4 Correlations between coseismic water level statistics and focal depth

Figure 5 shows correlations between focal depth and coseismic parameters at the Tangshan well. Even though the correlation is not strong, the changing tendencies of the fitted curves are consistent. It is very clear that the coseismic maximum amplitude, coseismic step change, and the duration decrease as the depth increases. It also shows that when the focal depth is larger than 15 km, the time when coseismic oscillation reaches its maximum amplitude is close to the surface wave arrival time. For those reaching their maximum amplitudes between the P and S wave arrivals, the focal depths are always shallower than 15 km.

4.5 Correlations between coseismic water level parameters

Figure 6 shows that the correlations between maximum amplitude of coseismic water level changes

and coseismic step change, and between maximum amplitude and duration are larger than 0.9, indicating that they are strongly correlated. There exists relatively weaker correlation between maximum amplitude and the time when coseismic oscillation reaches its maximum amplitude.

5 Discussion and conclusions

The Wenchuan $M_S8.0$ and its 15 larger aftershocks caused prominent coseismic water level changes at the Tangshan well. From the relationship between the magnitude and well-epicenter distance, we can conclude that the Tangshan well is very sensitive to detect coseismic changes. The correlations between coseismic parameters (coseismic maximum amplitude, coseismic step, coseismic duration) and earthquake statistics (magnitude, well-epicenter distance and focal depth) shows that there

Figure 5 The correlations between coseismic parameters for Tangshan well and focal depth.

Figure 6 The correlations between coseismic parameters for Tangshan well.

are strong correlations between the coseismic parameters and earthquake magnitude, whereas the correlations between the coseismic parameters and the other two earthquake statistics, the focal depth and well-epicenter distance, are relatively weaker. This is because that the Wenchuan earthquakes are driven from the same source area, and that the well-epicenter distance and focal depth have relatively smaller differences. Therefore, magnitude is the main factor affecting the coseismic responses. Furthermore, comparing the relationship of M_W , M_S , and M_L magnitudes versus coseismic water level responses, it shows that the correlation of M_S magnitude is the strongest, whereas that of M_L magnitude is the weakest. This indicates that the surface wave magnitude has more effect on the coseismic changes caused by medium to tele-seismics. The maximum amplitude of coseismic water level changes has very strong correlation with coseismic step and duration. The three coseismic variables may have been affected by dynamic strain produced by the propagation of seismic waves, and may have little relation with the static strain deriving from focal fault fracture.

Analysis on the temporal process of coseismic water level changes shows ① the Wenchuan $M_S 8.0$ earthquake causes oscillation lasting for four hours. After comparing it with the seismogram at Douhe seismic station, we get the same cognition as that of Woodcock and Roeloffs (1996) and Shu et al (2006), i.e., the well-aquifer system is equivalent to a broad-band seismometer. It also shows that not only the Rayleigh wave can cause coseismic water level, P and S wave can also cause coseismic changes (Zhang et al, 1998); ② Comparing the time when coseismic oscillation reaches its maximum amplitude with seismic phase arrivals of the Wenchuan aftershocks, there are maximum amplitudes occurring after the P wave arrivals and near the surface wave arrivals. The maximum amplitudes of the coseismic water level changes of EQ#5、EQ#6 are very close to the S wave arrivals. There are seven earthquakes (#3、#4、#7、#10、#11、#12) the coseismic changes caused by which have maximum amplitudes between S and Love wave arrivals. The coseismic changes of six earthquakes (#1、#8、#9、#13、#15、#16) reach their

maximum amplitudes near the Rayleigh wave arrivals. Considering the time error of analog water level, which is about 2 minutes, it is reasonable that the maximum amplitudes of coseismic water level changes are distributed between S and Rayleigh wave arrivals. This suggests that the Rayleigh wave is not the only factor causing the maximum amplitude of water level. On the one hand the coseismic water level changes can be affected by the features of well-aquifer system for some characteristic period of which may will magnify the oscillation amplitude of water level changes, (Cooper et al, 1965; Kunugi et al, 2000); on the other hand, coseismic changes may relate to the environmental state of the borehole when seismic waves arrive. The dynamic strain caused by seismic waves at the borehole is related to the features of seismic waves and their propagation, seismic phases coupling, and hydro-geological settings around the borehole. It is the coefficient of these elements.

As for coseismic step of water level, because the well-epicenter distances of Wenchuan earthquakes are between 1 350 km and 1 650 km, and because the earthquakes are driven from the same earthquake-gestating fault, the static strain produced by the fault cracking is tiny at those distances, and can not be used to interpret the coseismic step. The strong correlations between the amount of coseismic step and earthquake magnitude, maximum amplitude and duration may suggest that those changes have the same force source, which is derived from seismic waves. The relationship between the step direction of coseismic water level changes and focal mechanism indicates that there is no obvious correlation. However, it shows consistency between step direction and water level changing tendency (Table 1). This indicates that coseismic step has stronger correlation with the propagation of seismic waves and the hydro-geological environment around the borehole. This result is similar to that of some other researchers. Koizumi et al (2004) suggested that using focal mechanism to explain coseismic changes has big discrepancy with the fact. Wang et al (2005) suggested that the causation of coseismic variation is the movement of ground surface and its aftereffect caused by seismic waves. Lai et al (2006) concluded that coseismic steps are affected by dynamic strain and hydro-geological environments. If the time serving system and the sampling rate of digital water level can be improved in the future (Shu et al, 2006), using broad-band seismograph, strainmeter and considering the hydrological environment around borehole simultaneously can make further progress in the

mechanism study of coseismic water level changes.

Acknowledgements This study is supported by National Natural Science Foundation of China (No. 40574020) and Basic Research item of Institute of Earthquake Science, China Earthquake Administration (No. 0207690236). The authors are grateful to the staff members at Tangshan Well who supplied the high standard data, and pay great thanks to the constructive comments and suggestions from the anonymous reviewers.

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