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China's component borehole strainmeter network*

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Abstract In 2004, China's digital seismic observation network project began to deploy 40 sets YRY-4 four-component borehole strainmeters in order to monitor earthquake preparation process. The paper describes observed solid tidal strain discreteness and tidal factor anisotropy, analyzes the reliability of observational data and discusses the cause for this phenomenon. After getting rid of interferences, the network, in two years practice, has observed several pre-seismic strain anomalies at stations close to epicenters especially in the Wenchuan M_S8.0 megaquake. It shows that this borehole strainmeter network is capable of monitoring seismogenic process.

Key words: **component borehole strainmeter; tidal factor; strain anomaly; earthquake prediction**
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1 Introduction

Direct observation of crustal strain has great significance in understanding crustal movement and tectonic activities. It is a direct way to understand tectonic activities of specific landblock, and is also an important means of observation to explore shallow tectonic earthquake preparation process. However, the technique of direct measurement of crustal strain is still under development and improvement. Compared with cave extensometer, borehole strainmeter is of low-cost, relatively easy to deploy, etc. However, the very short baseline measurement of borehole strainmeter requires very high sensitivity and stability of probe. How to achieve seamless connectivity between probe and strata is a technical difficulty. Hence, modern borehole strain observing technology, to some extent, can provide reliable crustal strain data and becomes concern of geophysics researchers (Segall et al, 2003; Gladwin et al, 1991; Gwyther et al, 1996; Li, 1977; Zhang et al, 2001).

People have reasons to suspect borehole strainmeter, installed in dozens to hundreds meters in depth, but still located in the superficial crust, can record the process of strain accumulation and the earthquake preparation in the epicenter at the depth of 10–30 km. But good borehole strainmeter can record very clear tidal strain, indicating that the strain of deep activity can be delivered to the surface. Near-surface strain observation monitoring the strain changes of earthquake preparation process can be verified only by actual observation.

In 2003, the U.S. "earthscope project" slected component borehole strainmeter (GTSM) as the third major Earth observation instrument with seismograph and GPS (http://www.unavco.ucar.edu/community/publications/proposals/PBOwhitepaper.pdf). In 2004, China Earthquake Administration planed to deploy 40 sets of component borehole strainmeter (YRY-4) to build a sparse observation network. At present, the outcome has been made by the early observation.

This article describes the work and the observed crustal strain within two years after first YRY-4 has been installed and the analysis of the reliability of borehole strain data. From the quantitative analysis of strain data we find that the observed solid tidal strain discreteness and tidal factor anisotropy and discuss the cause for this phenomenon. After eliminating interferences, we observe clear strain anomalies before the Wenchuan M_S8.0 earthquake at stations near the epicenter. It shows that the borehole strainmeter network has a clear effect on monitoring earthquake preparation process.

2 Overview of YRY-4 component borehole strainmeter network

In China's digital seismic observation network, YRY-4 four-component strainmeter is the main borehole strain instrument of the network. The strainmeter was supported by the National Science Commission and the China Earthquake Administration, and the prototype has

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passed the national identification in 1984. The instrument includes a four-component strain probe, a water-level and air-pressure probe for assisted observation, EP-Ⅲ IP data acquisition and control chassis, all isolated power supply optical isolation signal output. Instrument has a strain resolution of 5×10^{-11}, response frequency range of DC-20Hz, and sampling rate of one sample per minute.

On March 24, 2006 at Sheshan station of Shanghai, the first YRY-4 instrument was installed. On December 5, 2007, the last one of the network was installed at Taian station. The network was installed 43 sets with five sets of failure installation for bad borehole reason; and success installation rate is 88%. The working 38 sets are located from east to Shanghai, west to Golmud, north to Fengman, south to Tengchong. Figure 1 shows nationwide distribution of the network.

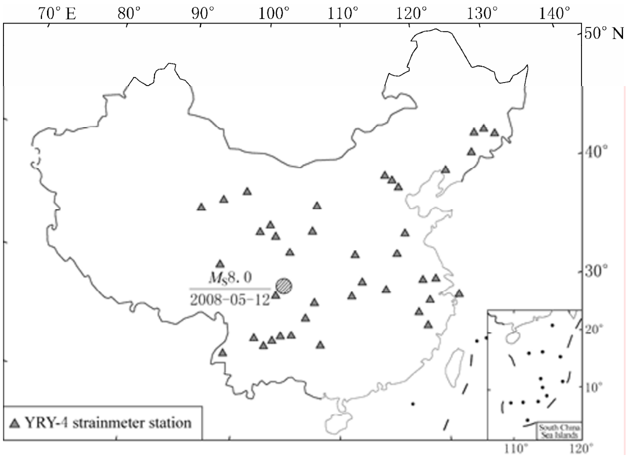

Figure 1 Nationwide distribution of YRY-4 network stations to the end of 2008.

To ensure the quality of strain data, borehole site must avoid interference source like pump-well, etc. The probe should be installed in integral layer of hard rock. There are 23 stations with integral bedrock and low environmental interference. These stations produce high quality solid tidal strain records, with harmonic analysis of M2 tidal wave of the accuracy of 0.001–0.02, which is a great help to explore tidal factor anomaly.

3 Strain data reliability

The strain data reliability of component borehole strainmeter can be checked at separate frequency bands of data recorded by other mature instruments. In seismic wave band, classic seismograph records are used to check with. In the tidal band, YRY-4 strain data is tested by tidal theory and data from extensometer. Even lower frequence data should be compared with geodetic observation data.

More borehole strainmeters installed at the same site can prove their data reliability by comparing their data's conformity, therefore the reliability of the borehole strainmeter is also found out. Unfortunately, the digital seismic observation network project didn't plan to do such test.

3.1 Data reliability of high-frequency band

Records of seismic waves can be used to check the data reliability of high-frequency band data of borehole strainmeter. The frequency response of YRY-4 strainmeter probe is 0–20 Hz. Because the data collector's sampling rate is one sample per minute, a large number of seismic events can not be recorded. With external data collector for sampling rate of 100 sample per second, numbers of seismic records was made to prove the data reliability of high-frequency band.

Table 1 shows the comparison of seismic waves by YRY strainmeter and DD-1 pendulum seismograph at

Table 1 YRY strainmeter and DD-1 pendulum seismograph records of local quakes and explosion, P waves, S waves and magnitude for comparison

No.	Date	Instrument	Arrival of P wave	Arrival of S wave	Δ/km	A/μm	M	Note
1	1983-11-25	DD-1	19:57:52.4	19:58:11.0	157.2	0.028	2.1	quake
		YRY-2	19:57:52.4	19:58:11.0	157.2	0.042	2.3	
2	1983-12-06	DD-1	03:27:24.6	03:27:27.5	24.8	0.12	1.4	quake
		YRY-2	03:27:24.6	03:27:27.5	24.8	0.24	1.7	
3	1984-01-01	DD-1	14:55:12.6	14:55:13.9	11.1	0.056	0.6	quake
		YRY-2	14:55:12.6	14:55:13.9	11.1	0.039	0.5	
4	1984-01-04	DD-1	00:26:15.1	00:26:41.1	220.4	0.16	3.2	quake
		YRY-2	00:26:15.1	00:26:41.1	220.4	0.16	3.2	
5	1984-01-06	DD-1	12:26:32.9	12:26:50.0	144.8	0.16	2.8	quake
		YRY-2	12:26:32.9	12:26:50.0	144.8	0.20	2.8	
6	1984-01-06	DD-1	15:51:30.6	15:51:32.6	17.1	0.48	1.7	explosion
		YRY-2	15:51:30.6	15:51:33.5	24.8	0.60	2.1	

Note: A denotes earthquake displacement with unit in μm.

Xiangshan station of Beijing. Arrivals of P wave, S wave and the conversion of magnitude are listed. The result proves the two instruments are very good in consistency (Chi, 1993).

3.2 Reliability of tidal data

3.2.1 Data comparison between YRY strainmeter and extensometer

Yingkou station has installed both extensometer and borehole strainmeter. The extensometer only has N-S and E-W two component strain observation (Chi et al, 2008).

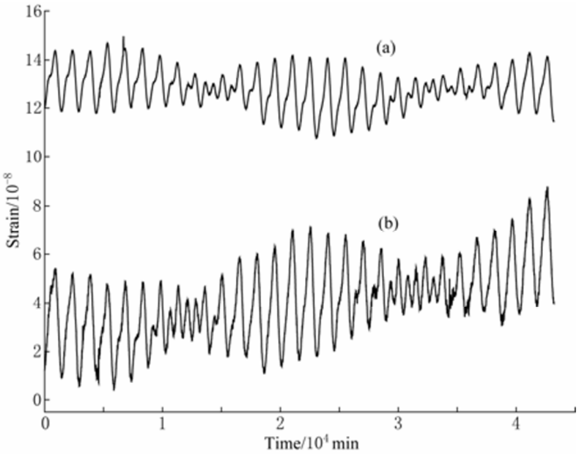

Figure 2 Yingkou station extensometer E-W component (b) and YRY-4 borehole strainmeter data converted to the same direction (a) on June, 2007

In Figure 2, two sets of tidal wave are almost completely similar, and the two sets of data's correlation coefficient reach 0.99. This means that the tidal data by short baseline strainmeter and extensometer are comparable. However, the drift direction of the two instruments are inconsistent, drift of extensometer goes to extensional direction with daily drift rate of 9.03×10^{-9}, borehole strainmeter's drift direction goes to compressional direction with a daily drift rate of 2.7×10^{-10}, 30 times smaller than that of extensometer. But this is still too high compared with the tectonic strain rate of Chinese mainland (10^{-8}–10^{-9}/a). Clearly, the strainmeter's observational data still contain a large element of non-tectonic drift of instrumental factor.

3.2.2 Comparison between borehole strain observational data and the theoretical solid tide

Solid Earth tide is the results of the Earth's deformation under the action of the Moon's and the Sun's overall tidal generating forces. It is an important basis to test borehole strainmeter's observational quality such as the accuracy of calibration, which can be done by making comparison between borehole strain data and theoretical tidal data. This comparison can also test the contingency of tidal theory.

In YRY-4, the sum of two component of strain perpendicular to each other represents volume strain. When using stations records of volume strain data to calculate the tidal factor of M2 tidal wave, it was found that M2 tidal wave factors have large discreteness under stations. Table 2 shows factors of M2 tidal waves of eight stations (Panzhihua, Sheshan, Menyuan, Golmud, Guzan, Jiangning, Delingha, Dunhua). Among them, Menyuan has the largest factor of 0.847 9, but still less than the theoretical value of 1.0. Delingha is 0.130 7, only 13% of the theoretical value. Largest tidal factor is six times bigger than the smallest one. Table 2 is volume strain M2 tidal wave factor calculation results.

Table 2 Tidal factor of M2 wave from eight YRY-4 strainmeter station

Station	M2 factor	e_{ms}	Phase lag/°	e_{ms}/°	O1/K1	O1/M2
Panzhihua	0.743 8	0.006 0	−2.83	0.46	1.169 4	1.026 3
Sheshan	0.737 2	0.004 7	33.81	0.36	1.195 9	0.766 0
Menyuan	0.847 9	0.011 3	−6.08	0.76	1.015 2	0.989 3
Golmud	0.403 6	0.016 2	3.23	2.28	0.866 9	2.133 6
Guzan	0.195 6	0.002 5	8.29	0.73	0.902 1	0.704 6
Jiangning	0.601 1	0.015 3	7.60	1.46	0.724 1	1.108 5
Delingha	0.130 7	0.010 6	7.33	4.66	1.159 2	0.902 9
Dunhua	0.169 1	0.016 6	7.22	5.22	0.294 0	0.767 8

Note: e_{ms} is mean square error; O1, K1, M2 are tidal waves.

Further analysis of measured data also found out those factors of different directions of the same strainmeter are also very different. Discreteness of tidal factor has a strong azimuthal anisotropy. Table 4 is the result of M2 tidal factor of linear strain of Panzhihua station, in which component-3 is three times larger than component-4. Tidal factors of four components are different in the same borehole that means tidal response at the same site has a strong anisotropy. This is very different from the isotropic earth model. Then what is the

Table 3 Four components of M2 wave tidal factor for Panzhihua station

Station	Component direction/°	M2 factor	e_{ms}	Phase lag/°	e_{ms}/°	O1/K1	O1/M2
Panzhihua	−44	0.278 6	0.004 7	22.64	0.96	0.672 8	1.304 1
	1	0.584 4	0.002 6	−3.20	0.25	1.361 3	1.013 5
	46	0.822 8	0.003 5	−1.46	0.24	1.445 4	0.885 4
	91	0.265 3	0.007 7	0.25	1.66	1.072 6	1.642 6

Note: e_{ms} is mean square error; O1, K1, M2 are tidal waves.

regularity of the anisotropic tidal factors?

In order to get the azimuthal anisotropic distribution of borehole strain tidal response, we calculate the arbitrary direction of ground strain through YRY-4 strainmeter's four-component tidal data, and then value of M2 tidal factor of a certain direction is obtained by tidal analysis, we finally can map a rose diagram of azimuthal tidal response.

Table 4 lists azimuthal tidal response of four station (Golmud, Macheng, Huangyuan, Panzhihua).

Table 4 Tidal factor values in different directions because of symmetry

Component direction/°	Tidal factor			
	Golmud	Macheng	Huangyuan	Panzhihua
0	0.089 3	0.788 3	1.262 9	0.546 2
20	0.029 7	0.988 8	1.003 0	0.644 9
40	0.072 4	1.142 1	0.607 5	0.693 9
60	0.145 8	1.184 0	0.104 6	0.650 2
80	0.255 1	1.003 7	0.408 9	0.462 2
100	0.339 1	0.673 7	0.727 3	0.254 0
120	0.298 7	0.553 2	1.070 4	0.257 0
140	0.232 9	0.516 1	1.308 9	0.322 1
160	0.162 5	0.603 2	1.370 1	0.427 9
180	0.089 3	0.788 3	1.262 9	0.546 2

Figure 3 is the azimuthal anisotropic distribution of borehole strain tidal response of Golmud, Macheng, Huangyuan, Panzhihua. In accordance with the uniform layered elastic Earth model, tidal strain response should be isotropic response, why the actual strain response is clearly anisotropic?

The fault near Golmud station is of NW-SE orientation which is parallel to the direction of the long axis of strain response of YRY-4 strainmeter installed at the station. Near Panzhihua station is a fault 30 degree of NE which is parallel to the long axis of the strain response of the strainmeter at the station. A NNE fault 5 km from Macheng station is also parallel to the long axis of strain response of YRY-4 strainmeter at the station. Huangyuan station is near a NW-SE strike-slip reverse fault which is roughly parallel to the long axis of strain response of the strainmeter at the station.

Based on the assumption that the Earth is a homogeneous elastic globe, the strainmeter should have observed isotropic tidal factor which is consistent with the theoretical value. As a matter of fact, at the Earth's surface, there are faults reaching a few kilometers to tens of kilometers into the Earth's crust. Upper crust is more like a mosaic of discontinuous crust blocks. Only at lower crust dozens of kilometers deep and upper mantle under the great pressure can be roughly treated as a continuum. Installed at the surface of the crust, strainmeter receives two parts of Earth strain, one part from the bottom of the crust block and the other from adjacent crust blocks through the fault contact which attenuate the tidal strain. If the strainmeter is installed close to active fault where interface has not been filled and "be welded", this could causes the strainmeter's component which is vertical to the fault alignment completely unable to receive the tidal strain, then tidal wave factor M2 will be very small. In 2001, a *M*8.0 megaquake in the Kunlun Mountains completely "loosed" the surrounding crust blocks, several years is not enough to complete bind these faults, and fault's isolation is very strong, thus tidal factor of Golmud station strainmeter's component vertical to the fault alignment is extremely small, only 0.03. It is the

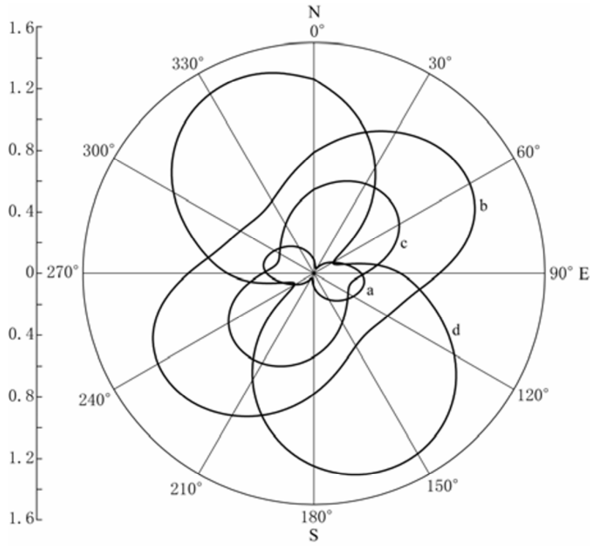

Figure 3 Tidal strain responses of Golmud (a), Macheng (b), Panzhihua (c), Huangyuan station (d).

fault that breaks the transmission path of tidal strain, and tidal strain at the direction parallel to fault alignment is almost not affected, that results in anisotropic tidal response.

In China, extensometer has history of more than 30 years. At very early history, it is found that at all extensometer stations, discreteness of measured M2 tidal wave factor is very high, and a far cry from the theoretical value. Moreover, at the same station to the different measuring orientation, the tidal factor also varies.

Tang (2006) calculated 126 sets of strain observing instruments' records, the smallest M2 wave factor was 0.07, the biggest factor 7.77, the ratio of minimum to maximum is 100.

As most extensometer only has two components of E-S and N-S, strain of arbitrary direction can not be derived through two components. That tidal factor has such a large discreteness in many cases is attributed to inaccurate instrument calibration. Thus researchers lost opportunities for the physical mechanism behind the huge deviation between measured and theoretical data (Chi et al, 2007).

In tidal observation, stability of tidal factor is widely interested by researchers. It is generally believed that changes in elastic modulus of strata are the main reason affecting the value of tidal factors. New finding shows that fault and the state of fault contact have even greater impact on tidal factor. Yushu station at Qinghai-Xizang plateau from August 2007 to April 2008, E-W tidal component factor has changed 27.4% (Figure 4). This has been a significant change that can not be explained by the change of elastic modulus. Jiangning station at the area of earthquake scarcity, the tidal factor is very stable, from November 2007 to February 2008, E-W tidal component factor changes only 0.32% (Figure 5).

The above two stations are at very different land blocks. Yushu at more active block, the state of fault contact is in strong change, resulting in large changes in tidal factor. This provides a new way to monitor the state of fault contact and the land block interaction of both sides of fault through the tidal rose map. Rose map also discloses the stability of land block (Chi et al, 2009).

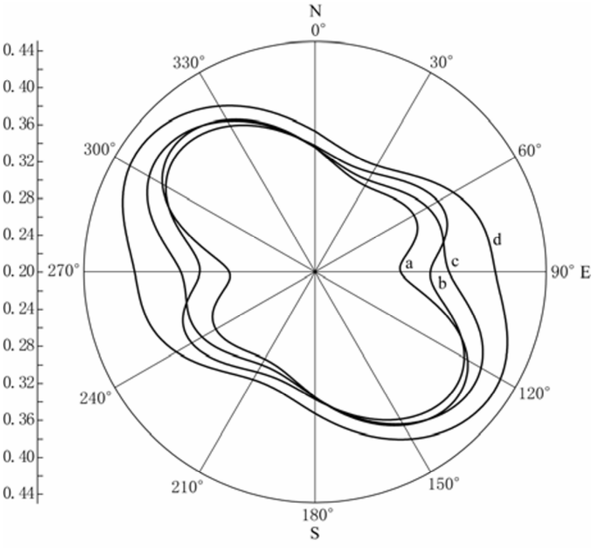

Figure 4 Rose diagram of tidal factor of Yushu station in August (a) and September (b) of 2007, January (c) and April (d) of 2008.

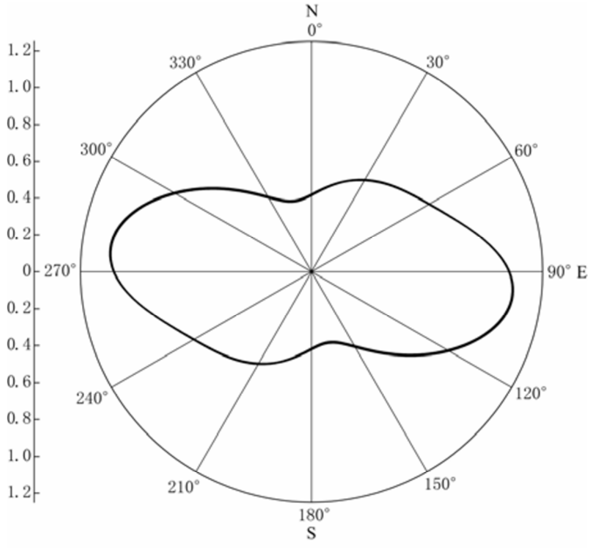

Figure 5 Rose diagram of tidal factor of Jiangning station in November and December of 2007, January and February of 2008.

3.3 Reliability of long-period data of strainmeter

From data comparison of extensometer and borehole strainmeter at Yingkou station, borehole strain data is more stable, and of less drift. However, to record tectonic strain change with very low drifting rate, borehole strain observation technique must reduce the drift of non-structural factors.

In component borehole strain observation, strain drift is caused by a number of factors.

1) Length change of base rod itself. The change can be 10^{-8}–10^{-7}/a scale.

2) Underground temperature changes. 0.01 °C temperature change will lead to changes in 10^{-7} strain.

3) Cement expansion generates significant shift (10^{-5}/a), drift rate can remain (10^{-6}–10^{-7}/a) one year after the installation.

4) Under gravity, the borehole will have a hole shrink. Shrinking scale is affected by borehole size and depth, lithology, the probe's installation stress and many other factors.

5) Electronic circuit parameter’s drift.

6) Apparatus were installed at locations such as steep slopes where unstable strata causes drift.

Drifts 1 and 2 are impossible to eliminate. Strain data of component strainmeter can be decomposed into volume strain and differential strain. Volume strain from the sum of two perpendicular radial displacement, differential strain from the substraction of two perpendicular radial displacement. Volume strain data can not be out of the effect of drifts 1 and 2. By using the same material of the base rod, differential strain can be free from drifts 1 and 2. Factors 3–6 can be lowed down as far as possible through other technical measures.

Thus, the observation strain is decomposed into two volume strains and two differential strains. Differential strain data have considerably less false strain than volume strain.

Figure 6 is the data (August 10, 2007 to April 28, 2009) of Gaotai station (installed at June 19, 2007). Figure 7 is the data (1 October, 2006 to February 28, 2009) of Golmud station (installed at September 21, 2006). Both station’s “1+3” and “2+4” plots of volume strain strike the same direction.

The stabilizing process of volume strain and differential strain at Figures 6 and 7 confirmed the above-mentioned analysis of different stability for volume strain and differential strain. Drifting rate of volume strain of the two stations stabilized after one year time, while differential strain drift only took one month after installation to be stable. Over time, there is annual change at differential strain, and Golmud station’s annual range is 8×10^{-8} strain. The reason for annual change in the two stations is the exposed surface of base rock of the station, no soil and vegetation cover, temperature strain of surface rock affects the underneath strainmeter. Differential strain drift in 2007 after eliminating the annual change has been 1.5×10^{-8} in magnitude, similar to tectonic strain rate. With great caution at the instrumental design, the choice of observing site, the coupling of installation, it is possible for borehole strainmeter to observe tectonic activities. Ultimately, to determine the long-period signal reliability, whether the data contain tectonic strain, a series of rigorous scientific test of multi-instrument comparison with GPS observations is also necessary.

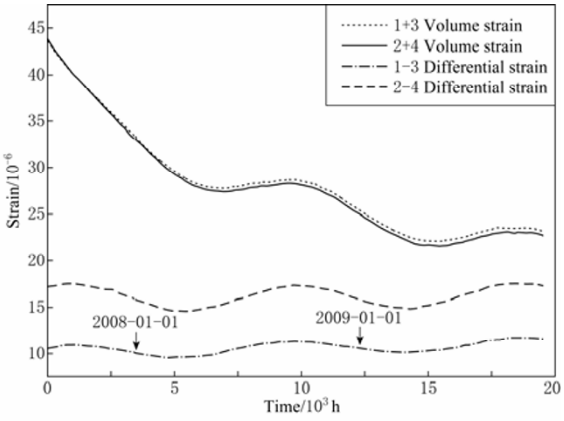

Figure 6 Gaotai station strain data from August 10, 2007 to October 31, 2009.

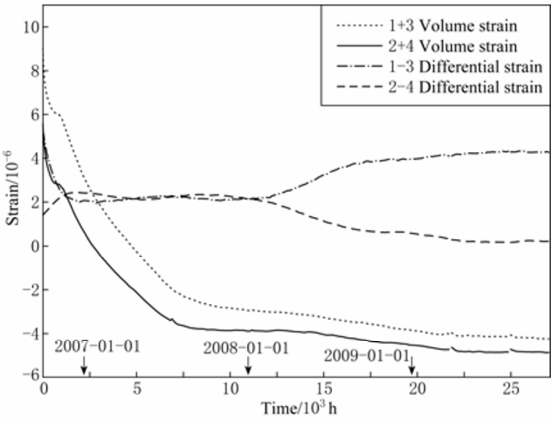

Figure 7 Geermu station strain data from October 1, 2006 to October 31, 2009.

3.4 Several interference patterns of borehole strainmeter data

Although borehole strainmeter is installed in dozens to several hundred meters under the surface, the isolation of surface temperature and anthropogenic activities is well done. However, activities such as pumping wells will interfere with the observed data. Figure 8 is Changshan station’s one day data, the marks on the map show the nearby pumping well’s interference. Solid tidal strain is completely covered by pumping interference at several stations where high-power pump well is very close to.

The additional strain generated by changes in air pressure can be mostly eliminated by the use of air pressure data. Rainfall interference, especially rainfall infiltration of rock faults and fracture will be difficult to be eliminated. Among 38 stations, about 10% has interference by rainfall. Figure 9 is Xiangfan station yearly data of 2008. It took about half year before the disruption of rainfall vanished and the normal tidal strain gradually restored.

Stations near large pond will also have the additional strain when the pond's water level changes. Figure 10 shows Tengchong station's additional strain when a fish pond 200 m away had a water exchange. The pond took 10 days to discharge and refill water, the whole process of unloading and loading was observed.

For each station, the interference factor is confirmed after careful investigation of its environmental condition and the analysis of sufficient time of data accumulation.

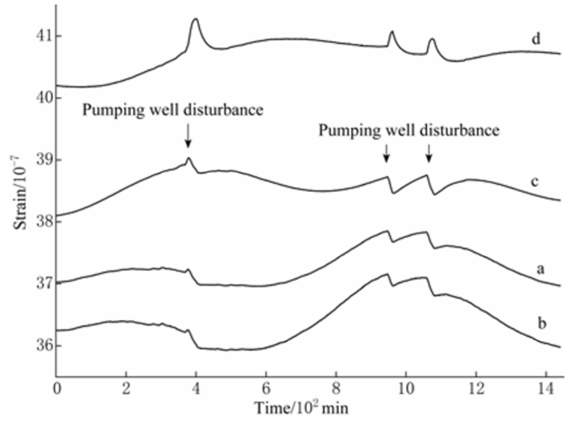

Figure 8 Changshan station strain data with pumping well disturbance in one day. a, b for body strain, c, d for differential strain.

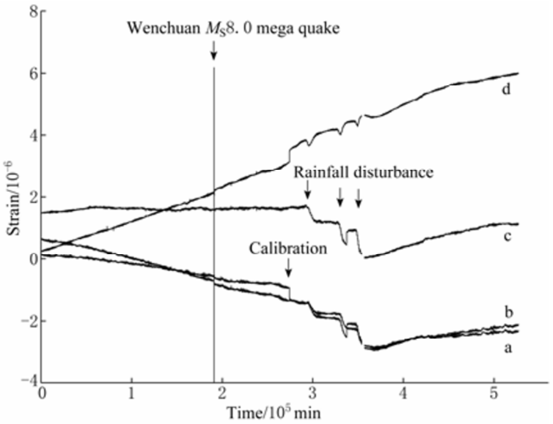

Figure 9 Xiangfan station data of 2008. a, b for volume strain, c, d for differential strain.

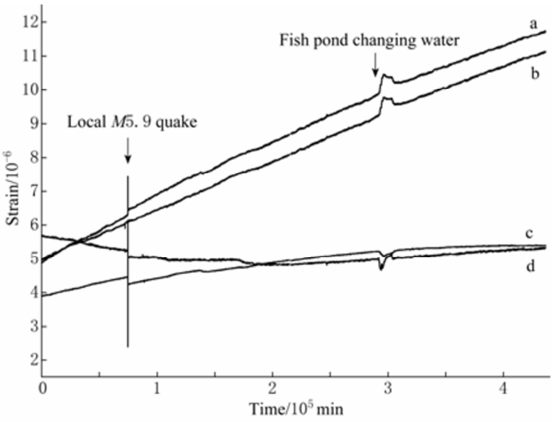

Figure 10 Tengchong station's strain disturbance when a fish pond 200 m away had water exchange. a, b for body strain, c, d for differential strain.

4 Observed seismogenic strain anomalies by component borehole strainmeter network

After the removal of interferences, strain anomalies before earthquakes at some stations near epicenter were recorded (Chi et al, 2009; Qiu et al, 2005; Qiu and Shi, 2004). The following descriptions are about pre-quake strain anomalies of seismogenic process of Wenchuan M_S8.0 megaquake on May 12, 2008 recorded by Guzan station, which is the nearest YRY-4 strainmeter station to the quake's epicenter.

Guzan station, 150 kilometers away from Wenchuan, is the closest one to Wenchuan among all YRY-4 strainmeter stations (Figure 1). Underneath the station is granite baserock, drill sample disclosed the strata is of good integrity and hardness. Installed at October 28, 2006, clear and continuous records of solid tide appeared few days after the installation. Figure 11 is two day's smooth and regular solid tide from February 1 to February 3 in 2007. However, since mid-April 2007, on the smooth curve of Earth tide, "pulse of pressure" and "tidal distortion" appeared from time to time. Over time the development of pulse of pressure and tidal distortion is more and more serious. Until the May 12 Wenchuan megaquake occurred, this phenomenon has lasted for 13 months. Figure 12 is three day tidal curve with pulse of pressure and tidal distortion.

YRY-4 strainmeter tests data with its self-test function. Self-test conditions are as follows (Chi et al, 2007).

(component 1) + (component 3) = (component 2) + (component 4) + (arbitrary constant)

Because tidal distortion and pulse of pressure are simultaneous on volume strain (1+3) and (2+4), the strain data response real Earth strain.

Figure 13 is (1+3) and (2+4) volume strain curves, the two curves of the correlation coefficient reached 0.99.

The strain anomaly at Guzan station was concerned since July 2007. On March 16, 2008 we went to Guzan station to check the equipment, and to investigate the anomaly. It's a great regret before the second YRY-4 was planed to install at the station, Wenchuan mega quake has occurred on May 12, 2008.

To date, we still do not know the relationship between pulse of pressure abnormal strain and earthquake mechanism. After the Wenchuan earthquake, pulse of pressure has not yet disappeared, but the pulse number is of some relevance with aftershocks and their transference. And as time goes on, pulse of pressure are less and less. Figure 14 is one year and a half after the Wenchuan earthquake, from 2009 October 6 to 8, a record for three consecutive days. Tidal records have largely returned to normal.

Qiu and Zhou (2009) has concluded the strain anomaly at Guzan station was precursory signal of Wen-

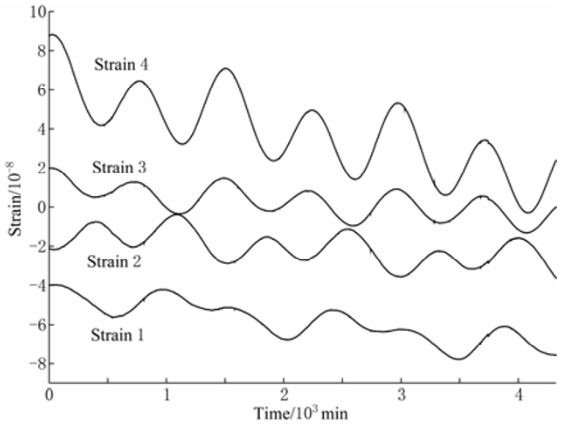

Figure 11 Guzan station clean and smooth strain data after the strainmeter was stable from February 1 to February 3, 2007.

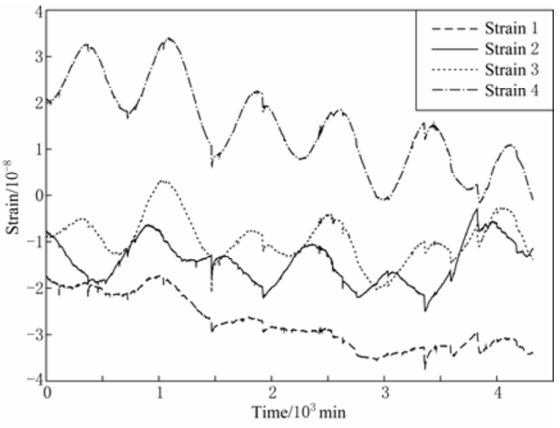

Figure 12 Guzan station strain data from June 22 to 24, 2007, clear disturbance of 'pressure pulse' and 'tidal distortion'.

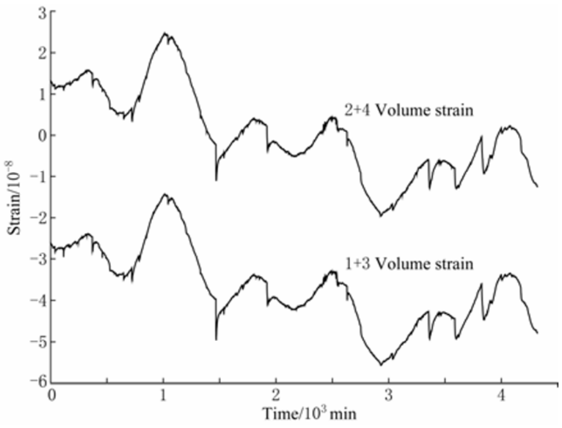

Figure 13 'Pressure pulse' and 'tidal distortion' on (1+3) and (2+4) volume strain. The correlation coefficient is 0.99.

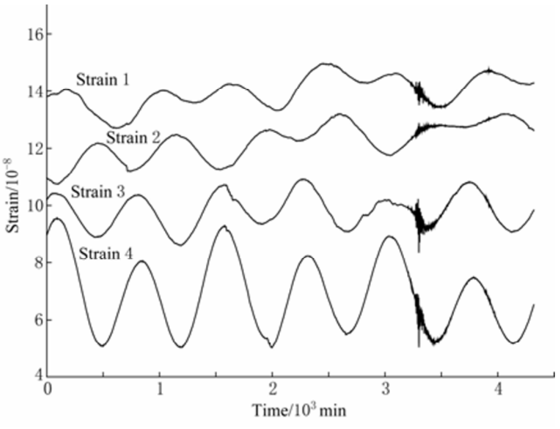

Figure 14 Three days tidal strain of Guzan station one year after Wenchuan $M_S8.0$ megaquake.

chuan M_S8.0 mega quake, the observed changes in seismic precursory anomalies at Guzan station were comparable to rock rupture phenomenon of acoustic emission and they may reflect small scale of rock rupture before the megaquake.

5 Discussion and conclusions

Borehole strainmeter used for direct measurement of crustal strain, is of importance to understanding of crustal movement and tectonic activities, and is also an important means of observation to explore shallow tectonic earthquake preparation process.

From the network's observational data we discovered the observed solid tidal strain discreteness and tidal factor anisotropy and the cause for this phenomenon. We have solved the mystery of discrete tidal factor that have confused tidal deformation observation over years. The discovery of tidal response anisotropy linked solid tide and fault structure.

China's borehole strain observations from the beginning emphasized the importance of the four components. The greatest advantage of the four components observation is to carry out self-test, which provides a simple method to exam the reliability of observational data.

The very low yearly drift rate reaching 10^{-8} indicates the necessity of multi-instrument comparison with geodetic observations, such as scientific experiments has been put on the agenda.

Seismology is a science of observation. Whether the precursory seismic observation can forecast the quake to a certain extent will only be answered by the observation in the practice of testing ground. Last two years observation of YRY-4 strainmeter network has proved that borehole strainmeter stations within a close distance (50–150 km) to earthquake epicenter is able to discover pre-earthquake strain anomalies. Earthquake preparation and strain changes have a direct relationship. In-depth exploration on physical and mechanical links between pre-earthquake strain anomaly and seismogenic process should be an important direction of earthquake prediction research.

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