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Abnormal strain changes observed by a borehole strainmeter at Guza Station before the *Ms*7.0 Lushan earthquake

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Abstract: Several days before the *Ms*7.0 Lushan earthquake, the YRY-4 borehole Strainmeter at Guza Station recorded prominent abnormal changes. The strain anomalies are very striking on the smooth background of several years' recording after the Wenchuan earthquake. However, because construction in the town of Guza has been undergoing rapid development in recent years, many factors have interfered with observations at the station. Whether or not the observed strain changes before the Lushan earthquake were affected by any of the sources of interference becomes a question that must be answered. Among the likely sources of interference, apartment construction, sportsground reconstruction, and tunnel cutting can be excluded by analyzing the morphological characteristic of the anomalies. The two remaining most possible sources are road construction in front of the station and the water level change of the nearby Dadu River caused by water filling into and discharging from an upstream reservoir. Through field investigation, comparison of the correlation between the strain and the seismographic recordings, comparison of the correlation between the strain and the Dadu River flow recordings, and analysis of the strain anomaly characteristics, we conclude that the abnormal changes observed at Guza Station cannot be attributed to either of these two sources but should be related to the Lushan earthquake.

Key words: Lushan earthquake; earthquake precursor; borehole strain observation; YRY-4 borehole strainmeter; interference

1 Introduction

Earthquake prediction research has been active in China tens of years. Earthquake precursor research should be separated from the earthquake prediction research. Only if earthquake precursors are made clear can a reliable prediction method be proposed. The main effort of earthquake precursor research focuses on analyzing individual earthquake cases. Researchers must analyze each case carefully, trying to find reliable abnormal changes in earthquakes and further to discern their laws.

The Lushan earthquake occurring on April 20, 2013, in Sichuan Province provides a valuable earthquake case for researching earthquake precursors using borehole strain observation. In such individual case analysis, three aspects need to be considered to judge whether an observed change is an anomaly of an earthquake precursor: (1) the normal background, (2) the noninterference effect, and (3) effects related to an earthquake[1,2]. Excluding the interference effect one needs to conduct comprehensive and careful investigation and analysis.

From April 16 to 20 in 2013, before the Lushan earthquake, the YRY-4 four-gauge borehole strainme-

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ter at Guza Station had recorded prominent abnormal changes; these were the largest abnormal changes recorded since the abnormal changes related to the Wenchuan earthquake were observed at this station[3,4]. Guza Station is about 80 km away from the epicenter of the Lushan earthquake, and it is the nearest borehole strain observation station. Other borehole strain observation stations are at least 200 km away, no obvious abnormal changes were observed at those stations.

The anomalies observed by the borehole strainmeter at Guza Station have a clear normal background and good temporal and spatial correlations with the Lushan earthquake. However, in recent years, there has been many sources of interference near the station. This makes it very difficult for us to judge the nature of the observed anomalies. Clarifying whether the observed borehole strain change at Guza Station results from these interference effects is extremely important for explaining whether it is an earthquake precursor anomaly.

2 Observed anomaly

Guza Station employs a YRY-4 four-gauge borehole strainmeter. This meter was placed into service at the end of 2006 and has been in a good operational state till now. The data-sampling rate is once per minute. Figure 1 shows the epicenter of the Lushan earthquake and the position of Guza Station. It can be seen from figure 1 that Guza Station is the nearest to the epicenter of all borehole strain observation sites. To facilitate the discussion below, figure 1 also shows the azimuths of four gauges of the borehole strainmeter.

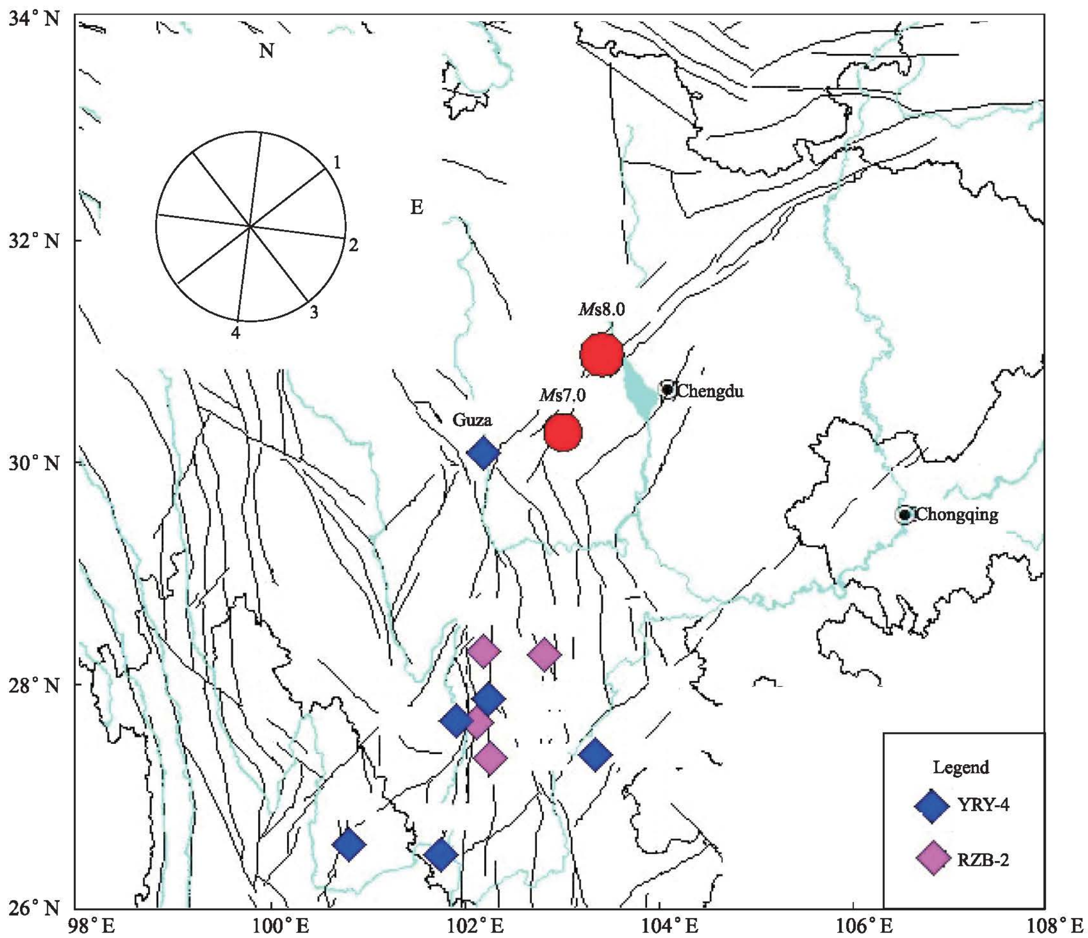


Figure 1 The epicenter of the $Ms7.0$ Lushan earthquake and the distribution of nearby four-gauge borehole strain observation sites; the inset on the upper left shows the azimuths of the four gauges of the borehole strainmeter at Guza Station

Before the M8.0 Wenchuan earthquake on May 12, 2008, the borehole strainmeter at Guza Station observed abnormal strain changes for up to about one year[4]. However, before the Lushan earthquake, the borehole strainmeter at Guza Station did not observe the same abnormal changes.

The abnormal changes related to the Lushan earthquake observed at Guza Station mainly occurred several days before the earthquake. As shown in figure 2, from April 16 till the earthquake occurrence, the plots of all four-gauge observations S_i ($i = 1, 2, 3, 4$) exhibit large-amplitude tensile (upward) jumps in succession. The morphological characteristics of the jumps include a rapid ascent, a constant period, and then a resumption to roughly the original level.

These abnormal changes basically satisfy a self-consistent equation, that is

$$\Delta S_1 + \Delta S_3 = \Delta S_2 + \Delta S_4 \qquad (1)$$

indicating that the observed changes are reliable observations[5,6]. The similarity of the two curves $S_1 + S_3$ and $S_2 + S_4$ reflects such a nature in figure 3.

3 Sources of interference

In recent years, Guza's very rapid economic development has led to numerous construction projects. In such a narrow river valley belt, construction of various types is likely to interfere with the sensitive borehole strain observation. As shown in figure 4, based on our understanding, the following sources of interference may be affecting the observation at the station shortly before and after the Lushan earthquake:

(1) Road construction in front of the station: Because of the rapid increase in the number of passing cars, the Guza government decided to build a new road to relieve the traffic burden. The planned road would pass by the door of the station (Fig. 4). Moreover, road construction in front of the station started on April 12, just shortly before the earthquake. The road construction was very close to the observation site with respect to position, and it was also very close to the anomalies occurring with respect to time. Therefore, careful investigation is especially needed. According to the increase-resume feature of the abnormal changes, a possible cause may

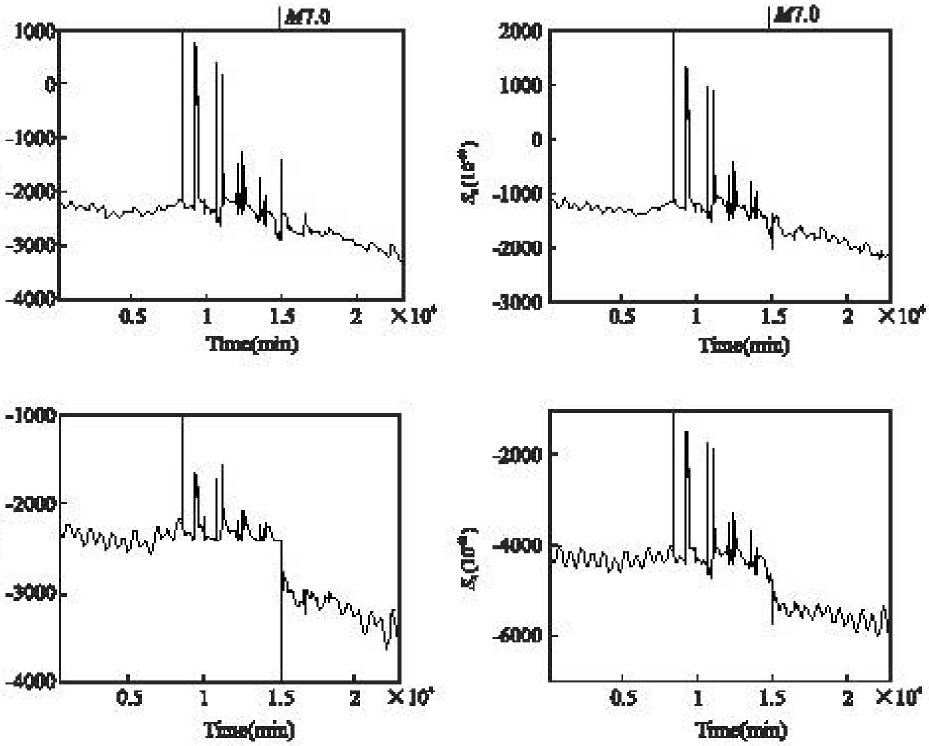


Figure 2 Direct recordings from the four-gauge borehole strainmeter at Guza Station shortly before and after the Lushan earthquake (during April 15 – 25, 2013)

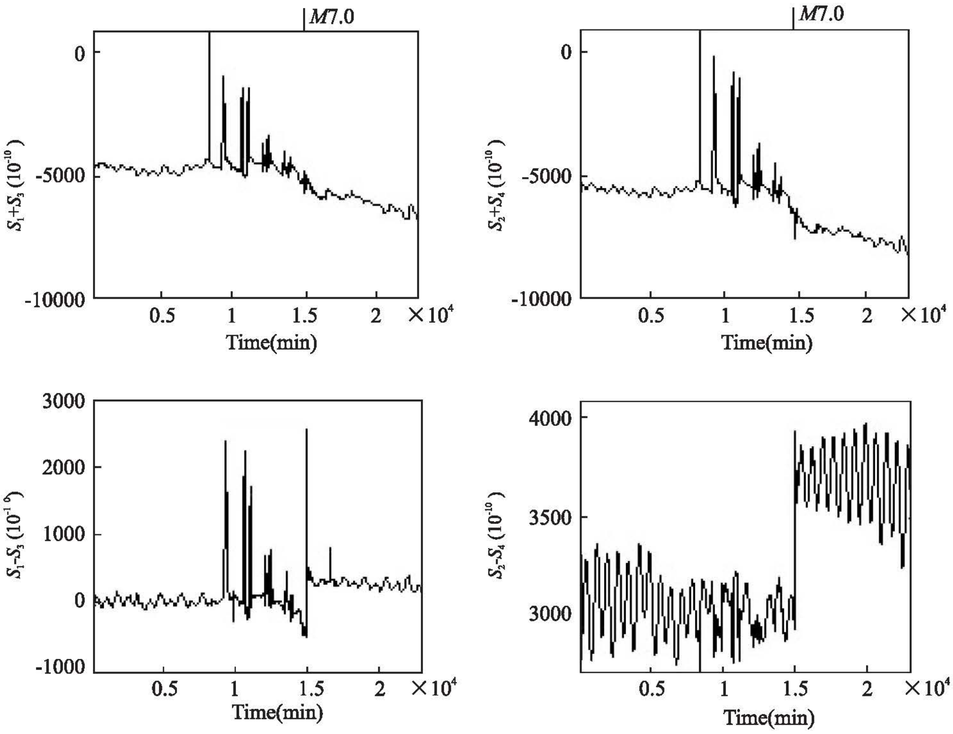


Figure 3 Substitutions of the recordings of the four-gauge borehole strainmeter at Guza Station shortly before and after the Lushan earthquake (during April 15 – 25, 2013); S_1+S_3 and S_2+S_4 represent areal strains, and S_1-S_3 and S_2-S_4 are two shear strains

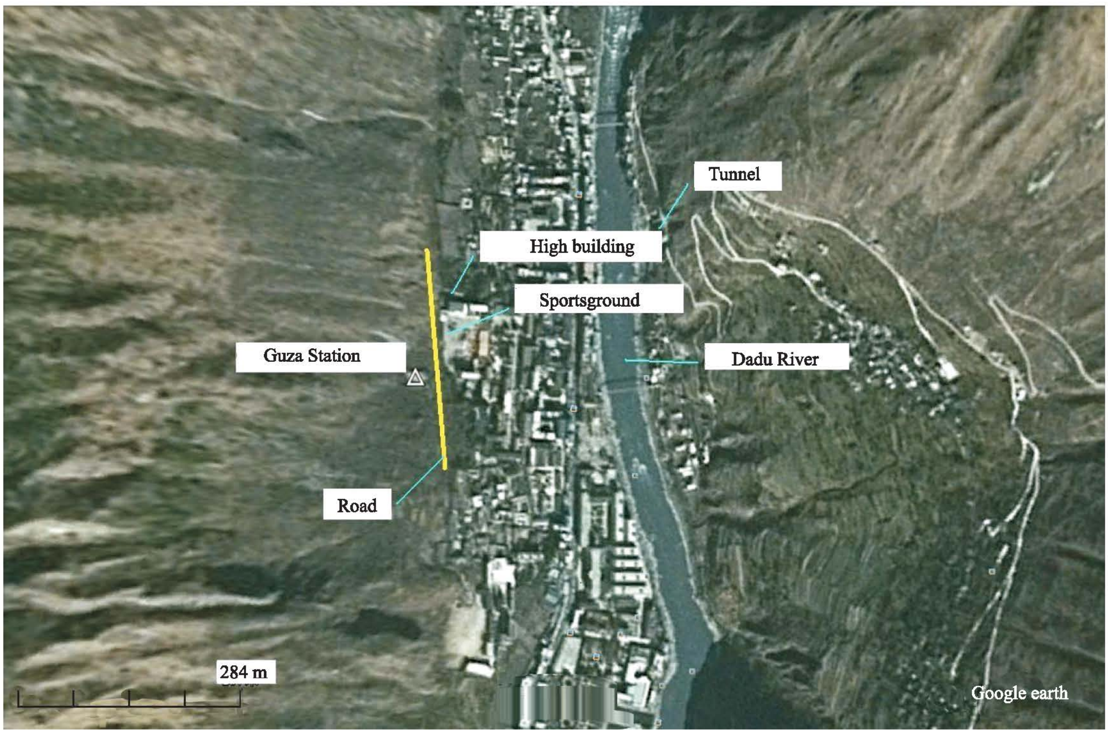


Figure 4 Distribution of construction sites around Guza Station

be the entry and exit of heavy-duty construction equipment.

(2) Sportsground construction in a health school near the station: The health school is just north of the station, and the sportsground is northeast of the observation institute (Fig. 4). The sportsground was under construction before, during, and after the earthquake, with a stand being established on the west side. A possible cause of the abnormal changes in observation may also be entry and exit of construction equipment. However, regardless of the position or the equipment, its influence is much smaller than that of the road construction in front of the station. Therefore, the influence of the sportsground construction is not taken into account.

(3) Construction of a high-rise building near the station: The high-rise building construction was to the north of the sportsground and farther from the station (Fig. 4). Even if the high-rise building itself could cause an abnormal increase in observation, it would be impossible for the observations to resume to their original state. Furthermore, the high-rise building construction was a long-term project and it could not correspond to the abnormal change in observation over several days. Therefore, the influence of the high-rise building construction is not taken into account.

(4) Tunnel cutting on the opposite bank of the Dadu River: This was also a long-term project that had been ongoing a long time, and it could not correspond to the abnormal change in observation by the borehole strainmeter at Guza Station over several days. Therefore, the influence of the tunnel cutting is not taken into account.

(5) Nearby hydropower development: The observation site at Guza Station is only about 300 m from the Dadu River. Cascade hydropower development was being conducted on the whole trunk stream of the Dadu River, and over 20 reservoirs had been put into operation or were being constructed. The upstream Houziyan Reservoir being constructed was only about 2 km from the station. Assuming for various reasons that the reservoir was suddenly filled with water or water was discharged from the reservoir, then the flow and water level of the Dadu River would suddenly decrease or increase and this might cause a change in observation; afterward, when the reservoir resumed its normal operational state so that the flow and water level of the Dadu River resumed their normal state, the observation would also return to a normal state. This must be taken into account.

In summary, according to the sudden increase-resume feature of the anomalies observed by the borehole strainmeter at Guza Station, the influences from sportsground construction, high-rise building construction, and tunnel cutting can be excluded. Therefore, there are only two possible influences: road construction in front of the station and the sudden change in flow of the Dadu River. We will analyze these two possibilities below, respectively.

4 Influence of road construction

Road construction in front of Guza Station formally began on April 12, 2013, which is close to the occurrence date of the Lushan earthquake and is closer to the period when the pre-earthquake anomalies were observed at Guza Station; therefore, careful investigation is especially needed to clarify whether this road construction has causal relations with the observed anomalies.

According to the investigation, within the period when observed anomalies occurred, the status of the road segment under construction was basically unchanged, without bedrock outcropping. The main construction activities entailed (1) demolition of yard walls and cutting of trees, (2) handling slope materials at the foot of the hill, and (3) smashing of huge rolling rocks. The main equipments employed included a Volvo EC360BLC excavator (dead weight of 38 T), a Doosan excavator (dead weight of 22 T), a SINOTRUK Howo tipper (maximum overall weight of 25 T), and Hongyan Jingang tipper (maximum overall weight of 25 T).

Did the road construction in front of Guza Station lead to abnormal changes in observed borehole strain curves? To answer this question, a simple method is to carefully compare whether the construction time synchronizes with the anomaly occurrence time. Personnel from the station took many construction photos that can be used for comparison.

At first glance, the road construction period is quite close to the anomaly occurrence period. However, through a great deal of careful comparisons, we discovered that the two periods do not precisely correspond. The following are several typical examples.

Example 1: On April 12, road construction formally began. It is important that the road construction just started in front of the station. At that moment, because the construction was the closest to the observation borehole, its influence should be the largest. However, there is no obvious abnormal change occurring on the borehole strain observation curves (Fig. 5(a)) for that time.

Example 2: On April 21, after the earthquake occurred, the local government required that road construction be temporarily halted. However, there are obvious abnormal changes occurring on the borehole strain observation curves (Fig. 5(b)) of that day.

Example 3: On May 7, we arrived at the station. There is no corresponding abnormal change occurring on the borehole strain observation curves (Fig. 5(c)) for that time.

The noncorrespondence between the road construction time and the observed anomaly occurrence time indicates that abnormal changes observed by the borehole strainmeter at Guza Station before the Lushan earthquake are not caused by the road construction in front of the station. It should be specially noted that, during all of these comparative analyses, we carefully consulted the seismographic data then, used as evidence; these cannot be shown in their entirety owing to the length of the paper.

5 Influence of flow change of the Dadu River

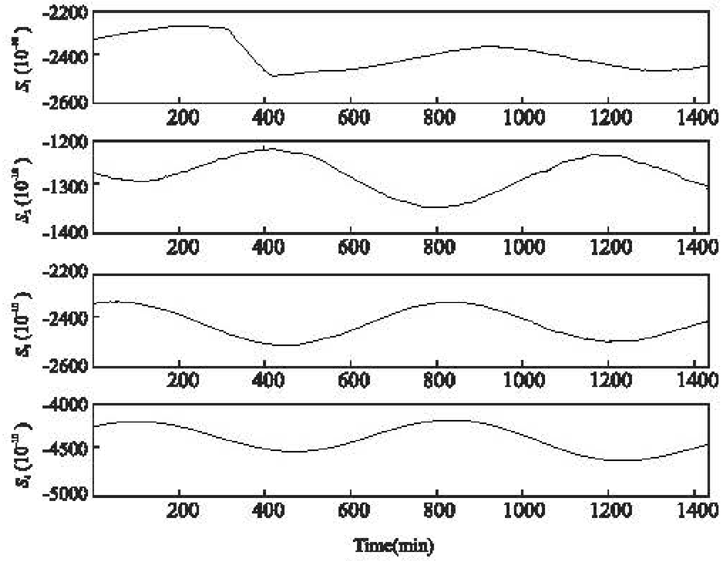
The borehole strain observation at Guza Station is obviously affected by the flow change of the Dadu River. We were assisted in our investigation by personnel from Houziyan Reservoir, the closest reservoir to Guza, at the upstream reach of the Dadu River. Figure 6 shows the flow of the Dadu River recorded at the reservoir and the curves observed within about one year by the borehole strainmeter at Guza Station. As can be seen from figure 6, from June to July, the flow of the Dadu River rose and fell greatly, and the borehole strain observation curves rose and fell greatly in an opposite and synchronous manner. The reason for this synchroneity is that the flow change of the Dadu River is accompanied by water level change, so the pressure on both banks changes accordingly and further causes a change in the rock stress state. It can be seen from figure 7 that such a change basically satisfies the self-consistent equation; in other words, the two curves $S_1 + S_3$ and $S_2 + S_4$ have similar shapes.

If before the Lushan earthquake, the upstream reservoir was suddenly filled with water or water was suddenly discharged from the reservoir for some demand in its construction, this would cause the flow change of the Dadu River and further lead to a change in borehole strain observation at Guza Station. It is obvious that, to determine whether the actual observation anomalies belong to this mechanism, one must clarify whether the flow of the Dadu River changed correspondingly several days before the earthquake. It can be seen from figure 6 that the flow recordings of the Dadu River do not exhibit any sudden change several days before the earthquake. This demonstrates that the borehole strain observation anomalies are not caused by the flow change of the Dadu River. However, such a demonstration has a defect: There are only two flow recording data points acquired each day: at 8:00 AM and 8:00 PM. Strictly, if the flow rose or fell suddenly in a short time, this might not be recorded or the record might not be obvious.

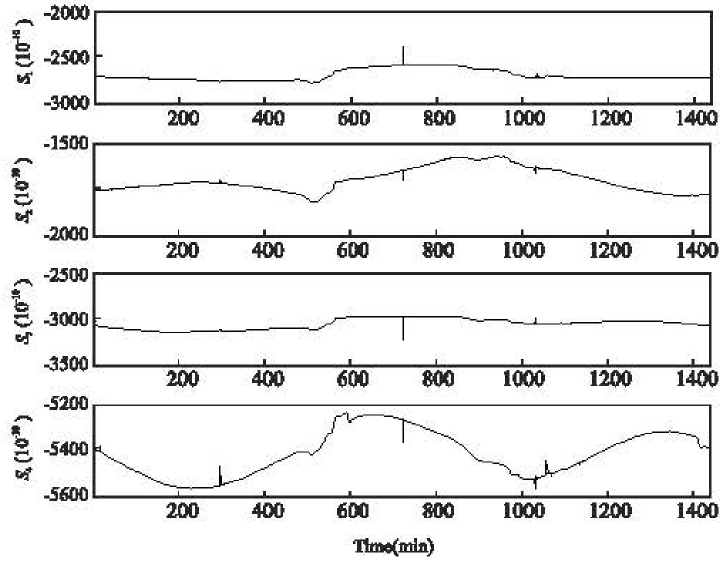
However, there is another piece of more powerful evidence that can indicate that the borehole strain observation anomalies could not possibly be caused by the flow change of the Dadu River. This evidence comes from the different characteristics between the strain anomalies observed before the earthquake and the strain changes caused by the flow of the Dadu River.

6 Characteristic of abnormal strain changes

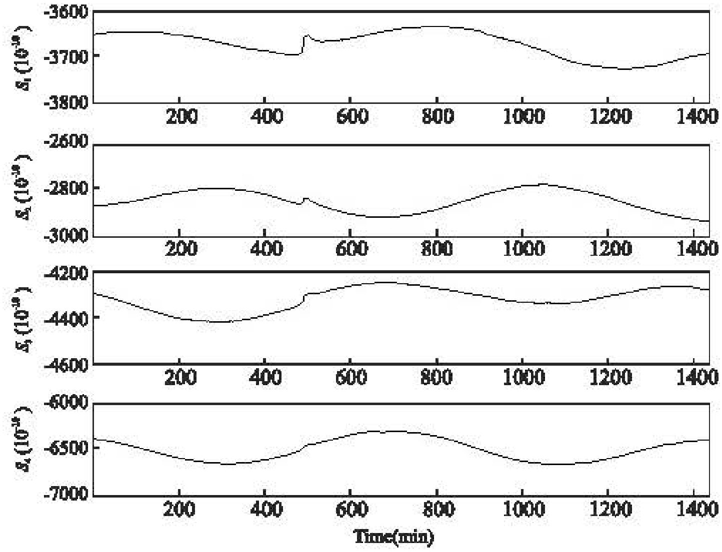
From careful observation of figure 6, we can see that the borehole strain observation changes caused by the flow of the Dadu River have an important characteristic:



(a) April 12



(b) April 21



(c) May 7

Figure 5 Recordings from the YRY-4 borehole strainmeter at Guza Station

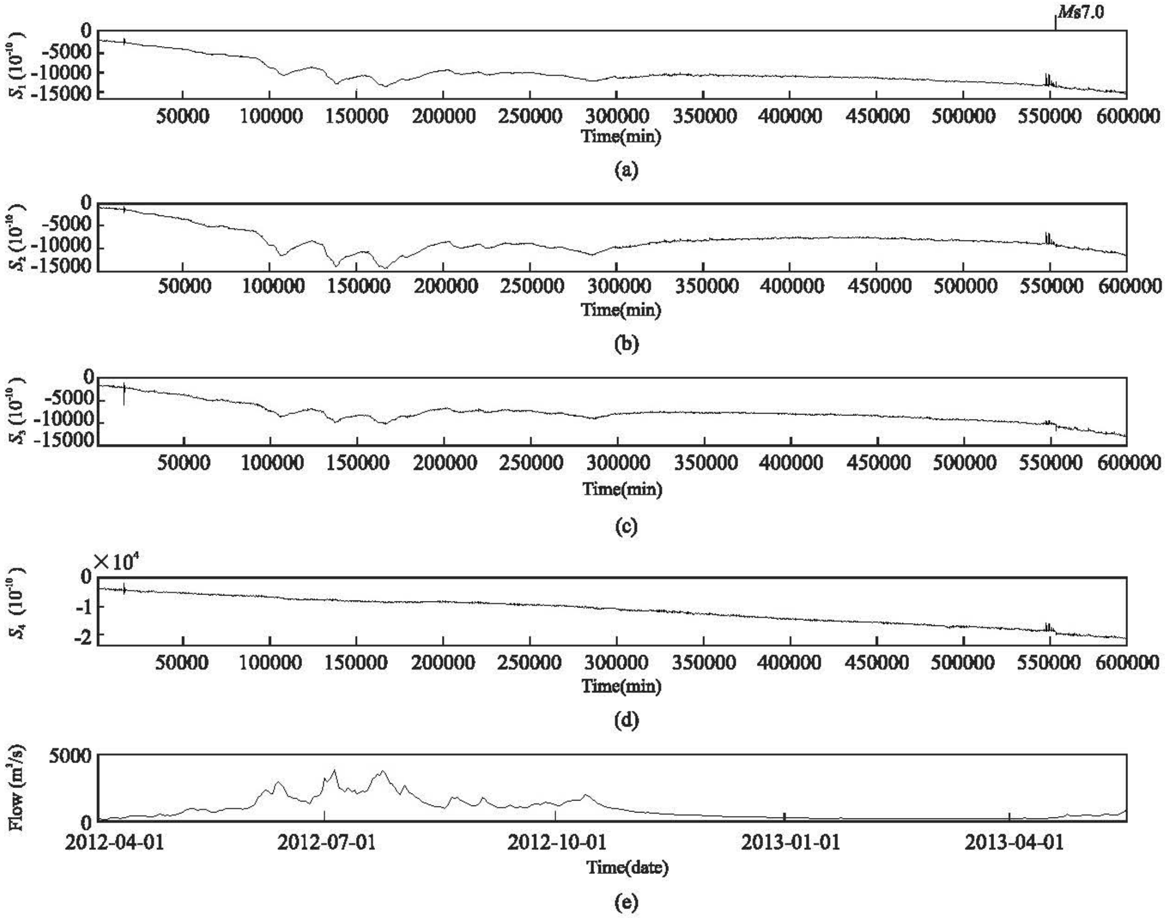


Figure 6 Recordings from the YRY-4 borehole strainmeter at Guza Station (a – d) and the flow of the Dadu River (e) for the period from April 1, 2012, to May 15, 2013

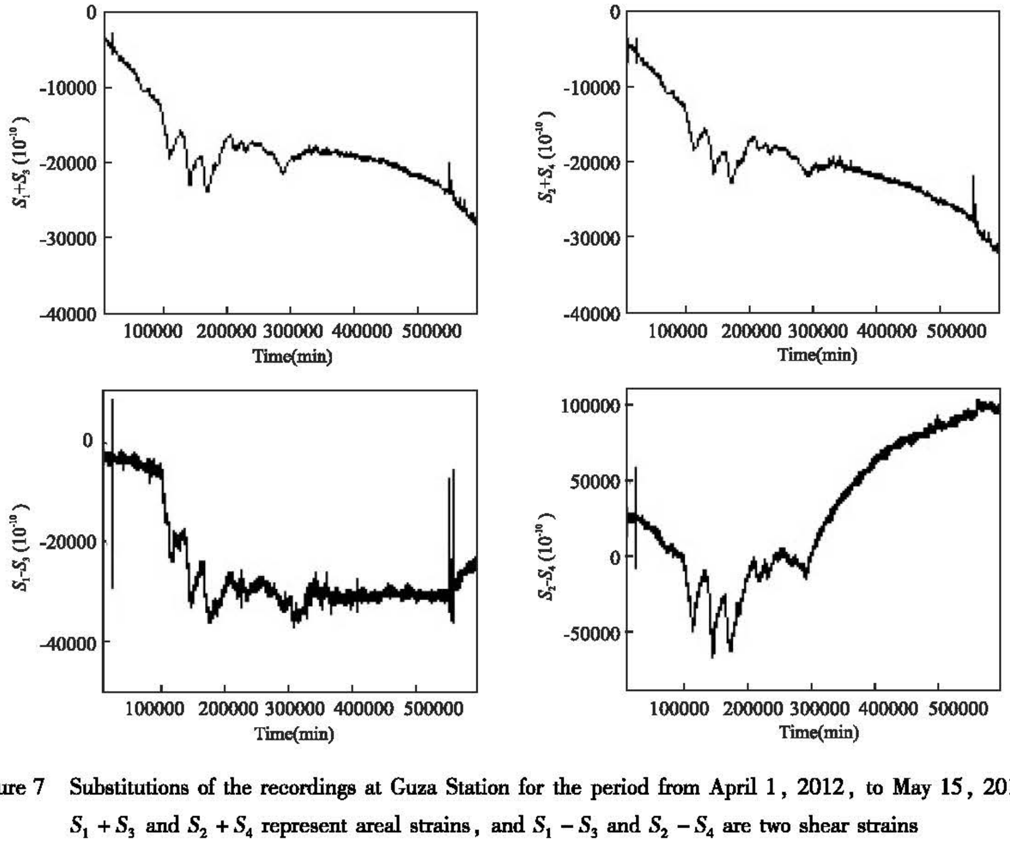


Figure 7 Substitutions of the recordings at Guza Station for the period from April 1, 2012, to May 15, 2013; S_1+S_3 and S_2+S_4 represent areal strains, and S_1-S_3 and S_2-S_4 are two shear strains

The influence on observation S_4 (Fig. 6 (d)) of the fourth component is not large. The reason for this lack of influence is that the azimuth of the fourth component roughly coincides with the extension direction of the Dadu River. The pressure on both banks by a river is perpendicular to the river, so the influence on the river direction is very small. It is evident that, in figure 6, S_2, which is directed approximately perpendicular to the Dadu River, undergoes a maximum change in amplitude with the flow change of the Dadu River. Figure 8 (a) illustrates the characteristics of the borehole strain observation changes caused by the flow of the Dadu River.

In comparison, it can be seen from careful scrutiny of the observation anomaly curves in figure 3 that the abnormal changes of $S_2 - S_4$ are relatively indefinite. This is an important characteristic of the abnormal changes observed at Guza Station before the Lushan earthquake. To interpret the nature of such a strain change, one needs to describe the analysis method of four-gauge borehole strain observation data here.

According to elastic mechanics, a planar strain state contains only three independent components. For four-gauge borehole strain observation, one needs to perform the following transform[6] before further strain conversion is conducted:

$$\begin{cases} s_{13} \equiv S_1 - S_3, \\ s_{24} \equiv S_2 - S_4, \\ s_a \equiv (S_1 + S_2 + S_3 + S_4)/2, \end{cases} \tag{2}$$

where the three variables s_a, s_{13}, and s_{24} from the transform correspond to the three independent strain components, i. e., areal strain ε_a, shear strain γ_1, and shear strain γ_2, respectively. Figure 9 shows the physical meanings of these strain components. The whole strain state change is the result of superposition of these three components.

For the abnormal changes observed at Guza Station before the earthquake, is approximately zero, so the changes come from the superposition of only and. Thus, the change characteristics in figure 8(b) is obtained. Such a characteristic is significantly different from that of the strain change caused by the flow change of the Dadu River (Fig. 8(a)), so the changes observed cannot possibly be caused by the flow change of the Dadu River.

Through comparison with the source mechanism solution of the *Ms*7.0 Lushan earthquake, it can be seen that the principal strain (tensile) orientation of the abnormal changes observed at Guza Station roughly coincides with the direction of the main tensile axis in the source mechanism. This is an important piece of evidence, indicating that such abnormal changes have a genetic association with the earthquake.

In addition, is approximately zero, indicating that is approximately the maximum shear strain. From careful observation of $S_1 - S_3$ in figure 3, we can see an obvious accelerated change several hours before the earthquake. This is another piece of important evidence to demonstrate that such anomalies are close correlated with the Lushan earthquake.

7 Conclusions

The *Ms*7.0 Lushan earthquake occurring in Yaan, Sichuan, on April 20, 2013, provides a new individual case for earthquake precursor research. Several days

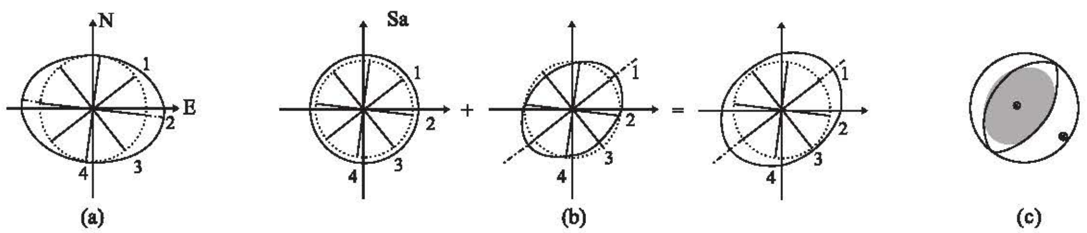


Figure 8 (a) Characteristics of the strain observation change caused by the flow change of the Dadu River; (b) characteristics of the strain anomalies observed before the Lushan earthquake; (c) source mechanism solution of the *Ms*7.0 Lushan earthquake (from Institute of Geophysics, China Earthquake Administration, and China Seismic Information Website)

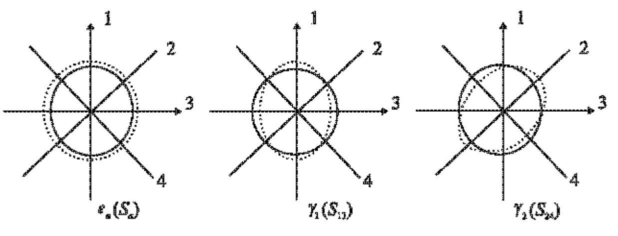


Figure 9 Physical meanings of transform components in the four-gauge borehole strain observation; solid lines represent original situations before deformation, and dashed lines represent the situations after deformation

before the earthquake, obvious abnormal changes were observed at Guza Station. They have a clear background and have a strong correlation with the earthquake. Different from the past, this observation site was subjected to many obvious sources of interference shortly before and after the earthquake. The most likely sources of interference causing such observation anomalies are the road construction in front of the station and the flow change of the nearby Dadu River.

By conducting field investigation of the construction status and comparing the changes observed by seismograph and borehole strainmeter, we excluded the possibility that the road construction caused the abnormal changes occurring several days before the Lushan earthquake. Comparing the water level change of the Dadu River and the borehole strain changes and analyzing the characteristic of the abnormal changes, we excluded the possibility that the flow change of the Dadu River caused the abnormal changes occurring several days before the Lushan earthquake.

In-depth analysis of the borehole strain observation anomalies before the earthquake reveals that the anomalies are obviously different from those caused by the flow change of the Dadu River, but they are consistent with the source mechanism solution of the $Ms7.0$ Lushan earthquake. This further indicates that such abnormal changes should have a genetic association with the Lushan earthquake.

As early as 1976 when the Tangshan earthquake occurred, the borehole stress (inductance method) observation sites at Douhe Station and Zhaogezhuang Station located at the epicenter synchronously recorded abnormal changes[8]. In 1985, when the $M7.4$ Wuqia earthquake occurred in Xinjiang, the soil stress meter at Kashi station also recorded abnormal changes[9]. In 2008, when the Wenchuan earthquake occurred, the YRY-4 four-gauge borehole strainmeter at Guza Station, which is the closest station to the epicenter, recorded abnormal changes up to a period of one year[4]. The anomalies recorded at Guza Station before the Lushan earthquake added another case, indicating that there is a precursor for the occurrence of an earthquake and that such precursors for different earthquakes have similar characterisitcs that are comparable to acoustic emission before rock breaking.

The borehole strainmeter at Guza Station can record the precursor change of nearby major earthquakes, perhaps because of its location at a place of tectonic stress concentration. Why is the station at a place with tectonic stress concentration? This is a question worthy of further research and will provide important guidance for establishing observation stations in the future.

Acknowledgments

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