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Research of Anomaly in Fix-Point Deformation Prior to Qinghai Menyuan Ms6.4 Earthquake in 2016

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Abstract: Based on the observation data of the fix-point deformation precursor in Gansu, Qinghai, Ningxia and Inner Mongolia, this study investigates the Qinghai Menyuan Ms6.4 earthquake which occurred in January 21, 2016, and applied the S-transform temporal-frequency analysis method to calculate and extract the short-impending high-frequency anomalies in five stations prior to this earthquake: borehole strain of Menyuan station, borehole tilt of Huangyuan station, borehole title of Sitan station, borehole strain of Haiyuan station and borehole tilt of Liangshui station. On the basis of the interference elimination and the data quality assessment, the frequency spectral characteristics and temporal-spatial distribution characteristics of high-frequency anomalies prior to the earthquake are analyzed and studied. The study results indicate that prior to the Menyuan earthquake, on the basis of the background signals, massive signals with a period of about 10-60mins emerged in multiple stations. In addition, the spatial distributions of the signals conformed to the openness and nonlinearity characteristics of the deformation anomalies while the energy amplitude expanded as the earthquake approached, and then attenuated gradually subsequent to the earthquake. Concerning the temporal characteristics, as the epicentral distance became shorter, the occurrence and duration period of the anomalies gradually shortened, and the impending earthquake anomalies gradually increased. Besides, the anomalies migrated from the peripheral region to the source region. The study conclusions are of great significance to the temporal-spatial evolutionary characteristics of short-impending anomalies prior to strong earthquakes.

1. Introduction

An Ms6.4 earthquake occurred in Menyuan, Qinghai on January 21, 2016. As a prominent earthquake in the Qilian Mountains Seismic Zone, the epicenter is located near the Lenglongling fault in the eastern segment of Qilian Mountains Seismic Zone. Since the Minle-Shandan Ms6.1 earthquake in 2003, there has been no earthquake with a magnitude higher than 6 for over 12 years in the Qilian Mountains Seismic Zone [¹]. In 1986, an Ms6.4 earthquake occurred in the same main fault zone, and the epicenter was located inside the key monitoring region of Qilian-Hexi [²]. Before this earthquake exploded, there were anomalies in the trend turnings of some fix-point deformation stations in Qinghai, Gansu and Ningxia. Therefore, it is quite necessary to analyze and study the characteristics of short-impending anomalies in the fix-point deformation before the earthquake.

The previous researches on fix-point deformation mainly adopted the trend pattern method and the tidal parametric solution algorithm. Later, the introduction of new methods, including S-transform...
temporal-frequency analysis and the overrun rate analysis, changes the previously single research methods\cite{3,4}. The S-transform temporal-frequency analysis has played an important role in the studies on the anomalies of deformation precursor. For example, anomaly signals, such as “piezotropic pulse” and “tidal distortion”, emerged frequently in the strain observation data of four-component boreholes in Guzan station, Sichuan prior to the Wenchuan earthquake in 2008. Through analysis and research, many experts believed that these distortion signals belonged to the precursors of Wenchuan \(M_{S8.0}\) earthquake; similarly, the anomaly frequency spectral characteristics of the two clusters of high-energy anomalies which emerged before the Lushan \(M_{S7.0}\) earthquake in 2013 were thoroughly studied and analyzed by applying S-transform method. The analysis of the signal characteristics has provided us with a clear understanding of the temporal-frequency evolution process of the high-frequency anomalies which emerged prior to the earthquake and its relevance to the earthquake. In this paper, the characteristics of the short-impending high-frequency anomalies prior to Menyuan \(M_{S6.4}\) earthquake are mainly analyzed and investigated.

2. Analysis of the changes in the fix-point deformation of Menyuan \(M_{S6.4}\) earthquake based on S-transform method

2.1. Principle of S-transform method
There are many temporal-frequency analysis methods, such as short-time Fourier transform, wavelet transform, S-transform, Hibert transform, Hilbert Huang transform, and sine curve fitting \cite{5}. Stockwell described the S-transform method in details \cite{6}. Later, Pinnegar further promoted the method and introduced this method into the temporal-frequency analysis of earthquake signals. In essence, S-transform is the combination of the short-time Fourier transform and the wavelet transform. The former is characteristic of relatively higher temporal resolution by applying the short-time windows but lacks frequency resolution capability. When long-time windows are applied, it produces relatively higher frequency resolution but lower temporal resolution. In comparison, the wavelet transform can analyze different frequencies on different scales, reaching a relatively satisfying temporal precision. Therefore, S-transform combines the merits of the Fourier transform and the wavelet transform to obtain relatively higher precision in both temporal and frequency resolutions. Its one-dimensional continuous forward transform is expressed as:

\[
S(\tau, f) = \int_{-\infty}^{\infty} h(t) \frac{|f|}{\sqrt{2\pi}} \exp \left[ -\frac{(\tau - t)^2 f^2}{2} \right] \exp(-i2\pi ft) dt
\]

Where, \(h(t)\) is the original temporal sequence of the one-dimensional observation data, \(f\) is the frequency, \(\tau\) is the position of Gaussian window on the temporal axis, \(S(\tau, f)\) is the corresponding forward transform result of S-transform, and \(t\) is the observation time.

2.2. Overall analysis in the large-scale temporal range
In this paper, all the fix-point deformation observation data, auxiliary observation data and interference data in Qinghai, Ningxia, Gansu and Inner Mongolia are collected as shown in Figure 1. The data ranges from January 1, 2015 to December 3, 2016. Firstly, a high-pass filtering with a cutoff period of 4h was conducted on the original observation data. Then, the high-pass data with a period lower than 4h was processed by S-transform, and the pre-earthquake anomaly information were extracted to analyze and study the frequency spectral characteristics and the temporal-spatial distribution characteristics.
Figure 1 Distribution of fix-point deformation stations in Gansu, Qinghai, Ningxia and Inner Mongolia
It can be seen from Figure 2 that after the data was processed by S-transform, the short-impending anomalies (the precursory anomalies which occurred within 3 months prior to the earthquake are short-impending anomalies) prior to the Menyuan Ms6.4 earthquake in four stations were relatively prominent (the yellow area in the red frame in the figure). The high-frequency anomalies of the NS and NW components of the borehole strain in Menyuan station, Qinghai were obvious from July 20, 2015 to August 25, 2015. There were two clusters of high-frequency anomalies which emerged prior to the earthquake in the NS component of the borehole tilt in Huangyuan, Qinghai: the first cluster lasted from October 22, 2015 to December 26, 2015 while the second cluster lasted from January 3, 2016 to January 15, 2016. After a peace of six days, Menyuan Ms6.4 earthquake occurred. In addition, the high-frequency anomalies of the NS component of borehole tilt in Sitan station, Gansu, started from January 18, 2016, and gradually intensified as the earthquake approached. After the earthquake occurred, the high-frequency anomalies gradually attenuated until January 24. The pre-earthquake anomalies in the NS component of borehole tilt in Liangshui station, Gansu, lasted for a relatively long time from November 10, 2015 to January 8, 2016 (as shown in Figure 2).

2.3. Analysis of detailed characteristics in small-scale temporal range
From the small-scale analysis result, the earthquake occurrence date was selected as the center date while 15 days were adopted as the length of a window. Thus, the anomaly patterns in the frequency spectrum 7 days before and after the earthquake (from January 14, 2016 to January 28, 2016) were analyzed. It was found that the impending earthquake anomalies (the anomalies which emerge within
10 days prior to the earthquake are impending earthquake anomalies) emerged in the five extracted stations prior to the earthquake. As the epicentral distance grew farther, there were following high-frequency anomalies detected: borehole tilt of Huangyuan (Δ=120km), borehole title of Sitan (Δ=205km), borehole strain of Haiyuan (Δ=376km) and borehole tilt of Liangshui (Δ=550km). As shown in Figure 3, the red earthquake source sphere is the epicenter of Menyuan earthquake; the red triangle represents the high-frequency anomaly station.

Figure 3 Distribution of high-frequency anomalies of Menyuan Ms6.4 earthquake in 2016

(1) NW component of borehole strain of Menyuan; (2) NS component of borehole tilt of Huangyuan; (3) NS component of borehole tilt of Sitan; (4) NS component of borehole tilt of Liangshui
It can be seen from Figure 4 that there were impending high-frequency anomalies in four stations prior to the Menyuan $M_6.4$ earthquake. In Figure 4, the blue area shows the small-scale S-transform result while the white area includes the original data curve (blue) and the interpolation curve (red). Apart from the co-seismic response caused by the earthquake, there was no impending earthquake anomaly in the borehole strain of Menyuan station. Besides, there were high-frequency interferences in the NS component of borehole tilt of Huangyuan station from January 14, 2016 to January 15, 2016 (as shown in Figure 4(2)). In addition, there was solid tidal distortion in the NS component of borehole tilt of Sitan station from January 17, 2016, and high-frequency anomalies from January 18, which lasted until the earthquake occurred and then attenuated rapidly (as shown in Figure 4(3)). Furthermore, there were high-frequency interferences in the borehole tilt of Liangshui station from January 19, 2016 to January 21, 2016 (as shown in Figure 4(4)). Finally, it can be seen that the impending earthquake anomalies in the four components of borehole strain of Haiyuan station were prominent (as shown in Figure 4(5)).

2.4. Temporal-spatial evolutionary characteristics of high-frequency anomalies in the fix-point deformation prior to Menyuan $M_6.4$ earthquake in 2016

From the analysis of Table 1, the impending earthquake anomalies (the precursory anomalies which emerge within 10 days prior to the earthquake are the impending earthquake anomalies) were mainly concentrated within the range of 100-200km. Several days prior to the earthquake, high-frequency signals began to emerge frequently and intensified. After the earthquake occurred, as the energy was released, the high-frequency signals gradually or rapidly attenuated; the short-impending anomalies were mainly found on the stations above 200km, and the pre-earthquake anomalies lasted for a relatively long time. Specifically, the epicentral distance of Menyuan station was only 30km, which makes Menyuan station the station closest to the epicenter. However, no impending earthquake anomaly was detected. There were both short-impending and impending earthquake anomalies in Huangyuan station. Besides, it can be seen that there were short-impending anomalies in Menyuan station prior to the earthquake. However, there was no impending earthquake anomaly which emerged as the earthquake approached, which might be related to that the pattern states are related to the closeness of the earthquake source zone as the station is located in the earthquake source zone. According to the previous observation results of crustal deformation in the earthquake source zone, considering that the earthquake source zone is generally under the strongly close state in the impending earthquake period, the absolute stress might be the highest while the deformation might be
the lowest. Therefore, there might be very few short-impending precursory phenomena observed in the near earthquake source zone.

Table 1 Information about high-frequency anomalies in the fix-point deformation prior to Menyuan $M_\text{S}6.4$ earthquake

| The Name Of Station | The Abnormal Items       | The Anomaly Start Time | The Anomaly End Time | Anomaly Duration Time (d) | Anomaly Types       | The Epicenter Distance(km) |
|---------------------|--------------------------|-------------------------|----------------------|--------------------------|---------------------|---------------------------|
| Menyuan             | The Four-component Borehole Strainmeter NS, NW | 20150720                | 20150820              | 31                       | Short-term Earthquake | 30                        |
| Huangyuan           | The Borehole Tilt NS      | 20151022                | 20151226              | 65                       | Short-term Earthquake | 120                       |
| Sitan               | The Borehole Tilt NS      | 20160103                | 20160115              | 12                       | Impending Earthquake  | 205                       |
| Haiyuanxiaoshan     | The Four-component Borehole Strainmeter NS, EW, NE, NW | 20151110                | 20160108              | 59                       | Short-term Earthquake | 376                       |
| Liangshui           | The Borehole Tilt NS      | 20151121                | 20160123              | 63                       | Short-term Earthquake | 550                       |

2.5. Comparative analysis of regional crustal deformation characteristics prior to Menyuan $M_\text{S}6.4$ earthquake in 2016

Through the three-component displacement time series analysis on the continuous observation data of GPS base station prior to Menyuan $M_\text{S}6.4$ earthquake, it is found that quasi-synchronous anomalies with a change amplitude of 6-10mm emerged in the EW component of the temporal sequence of the GPS displacement component near the epicenter about one month prior to the earthquake [7]. In addition, the high-frequency anomalies started to emerge in the borehole tilt of Huangyuan station and Sitan station about one month prior to the earthquake, and lasted until the earthquake occurred. The largest trend turning changes in the NS component and EW component of two GPS base stations, QHME (Qinghai Menyuan) and QHQL (Qinghai Qilian) occurred successively from the end of July 2015 to the end of September, 2015 [8]. The high-energy anomalies emerged in the NS component and NW component of four-component borehole strain of Menyuan station in the late July, 2015, and lasted for one month. Therefore, it can be seen that the occurrence time of high-frequency anomalies in the fix-point deformation stations near the epicenter coincides with the change time of GPS anomalies. The changes in the anomalies prior to Menyuan $M_\text{S}6.4$ earthquake were recorded simultaneously by different deformation observation means. Therefore, there were background anomaly changes prior to this earthquake, which indicates that there existed certain accumulated strain prior to the earthquake in the regions near the epicenter.

3. Discussion and conclusion

It is shown by the current research results that high-frequency anomalies emerged prior to the Wenchuan $M_\text{S8.0}$ earthquake which occurred on May 12, 2008, and prior to the Lushan $M_\text{S7.0}$ earthquake which occurred on April 20, 2013. Although their frequency spectral characteristics are the same, their anomaly patterns differ. Prior to Wenchuan earthquake, on the basis of huge background signal energy, massive signals at the specific frequency bands emerged and gradually intensified. As the earthquake occurred, the signals gradually attenuated [8]. Prior to Lushan earthquake, there were two clusters of high-energy anomalies: the first emerged six months prior to the earthquake and lasted for about four months while the second cluster started several days prior to the earthquake, in which the high-frequency signals intensified as the earthquake approached and the signal components with shorter periods emerged at a later stage, attenuating rapidly after the earthquake occurred [9]. Prior to Menyuan $M_\text{S6.4}$ earthquake, two clusters of high-energy anomalies were observed in Huanyuan station which is 120km away from the epicenter, which indicates the objectivity of the existence of short-impending high-frequency anomalies prior to medium and strong earthquakes. However,
whether these anomalies can be observed is closely related to the geological structural location, observation environment, instrument response state and interference factors of the stations.

It is found through the analysis of the fix-point deformation data before and after the Menyuan $M_s$6.4 earthquake that the high-frequency anomalies in this earthquake mainly occurred in the stations which are set up near the Haiyuan fault zone; the temporal-spatial distribution characteristics conformed to the openness and nonlinearity characteristics of deformation anomalies. In addition, as the epicentral distance became shorter (550km→376km→205km→120km), the occurrence and duration period of the anomalies gradually shortened (63d→59d→12d→3d), and there was no anomaly in the earthquake source zone, which indicates that there was large-scale movement in the peripheral fault zone in the earthquake source zone and the anomalies migrated toward the earthquake source. In addition, the earthquake source was relatively closed with highly concentrated stress. However, the stress was the lowest and very few anomalies were observed; furthermore, the high-frequency anomalies emerged several days or months prior to the earthquake, and were always accompanied by the solid tidal distortion. As the earthquake approached, the interference gradually became stronger. After the earthquake occurred, as the energy was released, the interference attenuated rapidly. Additionally, as the epicentral distance increased, the signals attenuated at a faster pace.

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