Response to Reviewer 2:

I am very grateful to your comments for the manuscript. Thank you for your advice. All your suggestions are very important. They have important guiding significance for our paper and our research work. We have revised the manuscript according to your comments. The response to each revision is listed as following:

Comment 1

In the first part, the authors could be more specific about the different works they cite.

Response:

Thanks for your suggestion.

In response to the issues you have pointed out, we have already made the appropriate changes and additions in Part I. Specifically include:

In the original manuscript 32-34 we added a detailed description of the findings of (Seropian et al., 2021), which explicitly states that most types of volcanoes are likely to be triggered by earthquakes, thus reinforcing the scientific basis for earthquake-induced natural hazards in the context of this study. Also new is the addition of (Koshimura and Shuto, 2015), which describes the devastating tsunami triggered by the Ms 9.0 magnitude earthquake that struck Japan's North Pacific coast on March 11, 2011, completely destroying many coastal communities, further emphasizing the severity of earthquake-induced secondary disasters. Finally, we modify the paragraph to read "They can damage infrastructure such as ground, transportation, and buildings, and may lead to secondary disasters such as volcanic eruptions (Seropian et al., 2021), tsunamis (Koshimura and Shuto, 2015), and landslides (Fan et al., 2019). Meanwhile, seismic hazards not only threaten human lives (Potter et al., 2015), but also have far-reaching impacts on socioeconomic development and quality of life (Peptan et al., 2023).".

In addition, in lines 104-107 of the original manuscript, we have made the citations of (Zhu et al., 2020; Yu et al., 2021; Li et al., 2024) more specific. The addition reads "In a recent study, (Zhu et al., 2020) used harmonic analysis to eliminate the effects of solid tidal and seasonal trends on borehole strain data. (Yu et al., 2021) used state-space modeling to remove the strain response due to seasonal trends, barometric pressure, solid tides, and water level variations, thus effectively isolating non-tectonic disturbances. (Li et al., 2024) successfully extracted the pre-seismic anomalies of the 7.0 magnitude earthquake in Jiuzhaigou by removing the effects of seasonal trends and tides on the borehole observations based on the variational modal decomposition (VMD) and combining with the Graph WaveNet model to process the multi-station data.".

Comment 2

The authors should clarify the use, operation, and scope of borehole strain gauges in terms of the signals they measure.

Response:

Thanks for your suggestion.

Borehole strain observation is an important means of studying crustal deformation and changes in the earth's stress field, and can observe crustal deformation under the action of a regional stress field (Qiu and Shi, 2004). Borehole strain gauges place sensors in boreholes to observe the deformation of an extremely small part of the crust relative to the earth, which can be approximated as a point deformation observation. Inside the probe of the borehole strain gauge is the element that measures the change in internal diameter, and the probe is sealed with a sealed cylindrical sleeve and placed into the borehole, which is filled with a special cement that couples the probe to the pores of the surrounding medium.

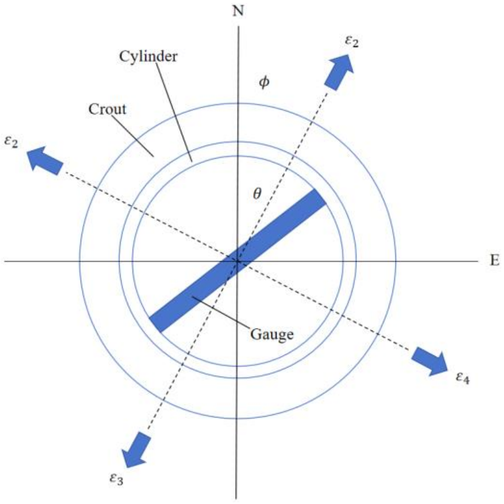


Fig. 1. Principle model of the plane strain tensor observed by a four-component borehole strain gauge.

The new YRY-4 four-component borehole strain gauge developed independently by China has a digital sampling rate of once per minute. Figure 1 gives the principle model of the plane strain tensor observed by the four-component borehole strain gauge. The schematic model assumes linear elasticity and isotropy of each medium and is used to measure the horizontal strain state of rocks. Strain gauge i in the cylinder directly measures the change in diameter of the corresponding azimuth angle θ_i caused by the change in strain state (Chi et al., 2009). The relationship equation between the measured value s_i and the strain change $(\varepsilon_1, \varepsilon_2, \varphi)$ is shown below:

$$s_i = A(\varepsilon_1 + \varepsilon_2) + B(\varepsilon_1 - \varepsilon_2)cos2(\theta_i - \varphi) \tag{1}$$

where ε_1 and ε_2 are the maximum and minimum principal strains, respectively, φ is the principal direction, and A and B are the two parameters to be determined.

The relative change in aperture measurements of an arbitrarily selected element, denoted as S_1, is rotated clockwise by 45° in turn, and there are element measurements S_2, S_3, and S_4 (Qiu et al., 2021). According to equation (1), the four-element observations are:

$$\begin{cases} s_1 = s_{\theta_1} = A(\varepsilon_1+\varepsilon_2)+B(\varepsilon_1-\varepsilon_2)cos2(\theta_1-\varphi) \\ s_2 = s_{\theta_{1+\pi/4}} = A(\varepsilon_1+\varepsilon_2)-B(\varepsilon_1-\varepsilon_2)sin2(\theta_1-\varphi) \\ s_3 = s_{\theta_{1+\pi/2}} = A(\varepsilon_1+\varepsilon_2)-B(\varepsilon_1-\varepsilon_2)cos2(\theta_1-\varphi) \\ s_4 = s_{\theta_{1+3\pi/4}} = A(\varepsilon_1+\varepsilon_2)+B(\varepsilon_1-\varepsilon_2)sin2(\theta_1-\varphi) \end{cases} \tag{2}$$

$s_i(i = 1,2,3,4)$ are the measured values from the four instruments and the YRY-4 four-component borehole strain gauge has good data self-checking (Su, 2019). It should be available when the coupling between the probe and the surrounding rock is in ideal condition:

$$s_1 + s_3 = s_2 + s_4 \tag{3}$$

Equation (3) is the self-consistent equation for the YRY-4 four-component borehole strain gauge, which is considered reliable when the data satisfy the above results.

Borehole strain gauges observe the amount of change in strain, so the terms in the self-consistent equation are also the amount of change. In practice, due to the coupling of the borehole strain gauge with the surrounding rock layer and the instrument itself will make each component of the observed data to produce a certain drift phenomenon, that is, the annual trend in the data, $S_1 + S_3$ and $S_2 + S_4$ in the numerical value is not equal, but the two curves of the form is the same, so the self-consistency equation can be written in the form of the formula (4).

$$S_1 + S_3 = k(S_2 + S_4) \tag{4}$$

where k is the self-consistency coefficient and the data are considered to satisfy self-consistency when $k \geq 0.95$.

Due to the nature of strain observation in boreholes, it is necessary to couple the probe to the surrounding medium in order to carry out strain observations, and the medium in which the probe is installed must be continuous and uniform in order to meet the quality requirements. Because of the surface will exist from the air pressure changes and human activities and other interference, so the probe needs to be installed in a certain depth of the ground. Our four-component borehole strain gauges are installed at a depth of about 40 meters below the ground surface, and the data quality of our four-component borehole strain observations is satisfactory (Qiu et al., 2021).

Comment 3

The paragraph "By mounting strain gauges deeper in the bedrock, borehole strain gauges are able to continuously record stress and strain data, making them a key tool for monitoring crustal deformation" is unclear since it does not specify what type of borehole strain gauge they use and how they ensure the results mentioned. Furthermore, it does not specify how they physically justify the scaling suggested in the paragraph: "The high-resolution recordings provided by borehole strain gauges allow us to capture small changes in strain, thus providing accurate data to support a deeper understanding of crustal deformation processes."

Response:

Thanks for your suggestion.

(1) The paragraph “By mounting strain gauges deeper in the bedrock, borehole strain gauges are able to continuously record stress and strain data, making them a key tool for monitoring crustal deformation” is unclear since it does not specify what type of borehole strain gauge they use and how they ensure the results mentioned.

In the study of (Qiu et al., 2013), it was noted that the YRY-4 four-component borehole strain gauge was installed at a depth of about 40 m, and the sampling rate was 1 sample per minute. The unique design of the YRY-4 four-component borehole strain instrument allows quantitative estimation of the confidence of the data by means of a self-consistency test, without resorting to earth tides or any special signals. In addition, the study proposed a relative correction method for norm sensitivity and demonstrated its effectiveness in improving data confidence. Therefore, this confirms that the YRY-4 four-component borehole strain gauge has the ability to continuously monitor the stress-strain changes in the earth's crust, which provides reliable data support for earthquake prediction and tectonic movement studies. Also in response to your comments, we note that the statement in lines 64-65 of the original manuscript does contain a lack of specificity in that it does not specify the type of borehole strain gauges used and does not guarantee the results described above. Therefore, we modify and supplement this paragraph. It should be revised as “As the main observation equipment of China's digital seismic observation network, China's self-developed YRY-4 four-component borehole strain gauge is usually installed at the bottom of bedrock at 40 meters, and has the capability of minute-level strain sampling, which can continuously record high-resolution stress and strain changes (Qiu et al., 2013).”.

(2) Furthermore, it does not specify how they physically justify the scaling suggested in the paragraph: “The high-resolution recordings provided by borehole strain gauges allow us to capture small changes in strain, thus providing accurate data to support a deeper understanding of crustal deformation processes.”.

Borehole strain gauges have the advantages of high sensitivity, broad bandwidth, and long-term stability (Lou and Tian, 2022). Its high-resolution recordings are able to clearly observe strain solid tides, seismic strain waves, and high-frequency microseismicity from microfractures in the formation. This observational capability stems from the sensor's high sensitivity and low-noise design, allowing it to cover a wide band of signals ranging from long-term slow deformation to high-frequency seismic waves. Based on these characteristics, the borehole strain gauge can capture small strain changes and thus provide accurate data support for in-depth studies of crustal deformation processes. Therefore, we revise lines 65-67 of the original manuscript to read “The high-resolution recordings provided by borehole strain gauges allow us to capture minute strain changes, thus providing accurate data to gain insight into crustal deformation processes (Lou and Tian, 2022).”.

In addition, to ensure sentence coherence and comprehensiveness, we revised the original manuscript 62-72 to read “Borehole strain observation is superior to GPS and laser strain gauges in capturing short- and medium-term strain changes and pre-seismic anomalies (Qiu and Shi, 2004), and is an important means to study crustal deformation and stress field changes. As the main observation equipment of China's digital seismic observation network, China's self-developed YRY-4 four-component borehole strain gauge is usually installed at the bottom of bedrock at 40 meters, and has the capability of minute-level strain sampling, which can continuously record high-resolution stress and strain changes (Qiu et al., 2013). The high-resolution recordings provided by borehole strain gauges allow us to capture minute strain changes, thus providing accurate data to gain insight into crustal deformation processes (Lou and Tian, 2022). In addition, the borehole strain gauge not only provides four-component data, but also records ancillary observations such as solid tides, air temperature, and air pressure (Chi, 2009; Tang et al., 2023).”.

Comment 4

On line 80, they should specify the methodology that led to the discovery of precursors by analyzing eigenvectors and eigenvalues. Where did they get it?

Response:

Thanks for your suggestion.

(Zhu et al., 2020) conducted an anomaly extraction study on the pre-earthquake borehole strain data of Wenchuan earthquake by using principal component analysis (PCA) method to analyze the first eigenvalue and the first eigenvector of the borehole strain data, and to extract the anomalous features of the strain changes before the Wenchuan earthquake. The eigenvalue indicates the main intensity of the signal, and the anomalies may imply stress changes or earthquake precursors. The eigenvectors indicate the directional characteristics of the strain changes, and the changes in their spatial distribution can reveal the evolution of the fault from a steady state to a sub-instable state. Their results show that the borehole strain gauges recorded the preparation stage of the Wenchuan earthquake, and the principal component analysis can effectively extract the crustal strain change characteristics. Therefore, we revised lines 79-80 of the original manuscript to read "(Zhu et al., 2020) studied the anomalous characteristics of the borehole strain data before the Wenchuan earthquake by using principal component analysis. By analyzing the first eigenvalue and the first eigenvector of the borehole strain data, the characteristics of pre-earthquake crustal strain changes are revealed.".

Comment 5

Correct Maduo instead of Mado on lines 134, 140, 180, 335, and elsewhere.

Response:

Thanks for your suggestion.

We have corrected the original manuscript text from the incorrect Mado to the correct Maduo.

Comment 6

The authors used the SVMD-Informer network to extract preseismic anomaly signals from the Mado earthquake from well deformation data at Mengyuan Station. The authors state that anomalies associated with the earthquake were recognized when the raw data exceeded the corresponding upper or lower limits. The question is: What is the physical basis for determining the criteria described in paragraphs 366 to 368?

Response:

Thanks for your suggestion.

The anomaly criteria presented in paragraphs 366-368 of the original manuscript build on prediction intervals constructed using the SVMD-Informer model. Although the form of these criteria is statistical in nature, we believe that they reflect to some extent the processes associated with earthquake gestation and have some physical significance.

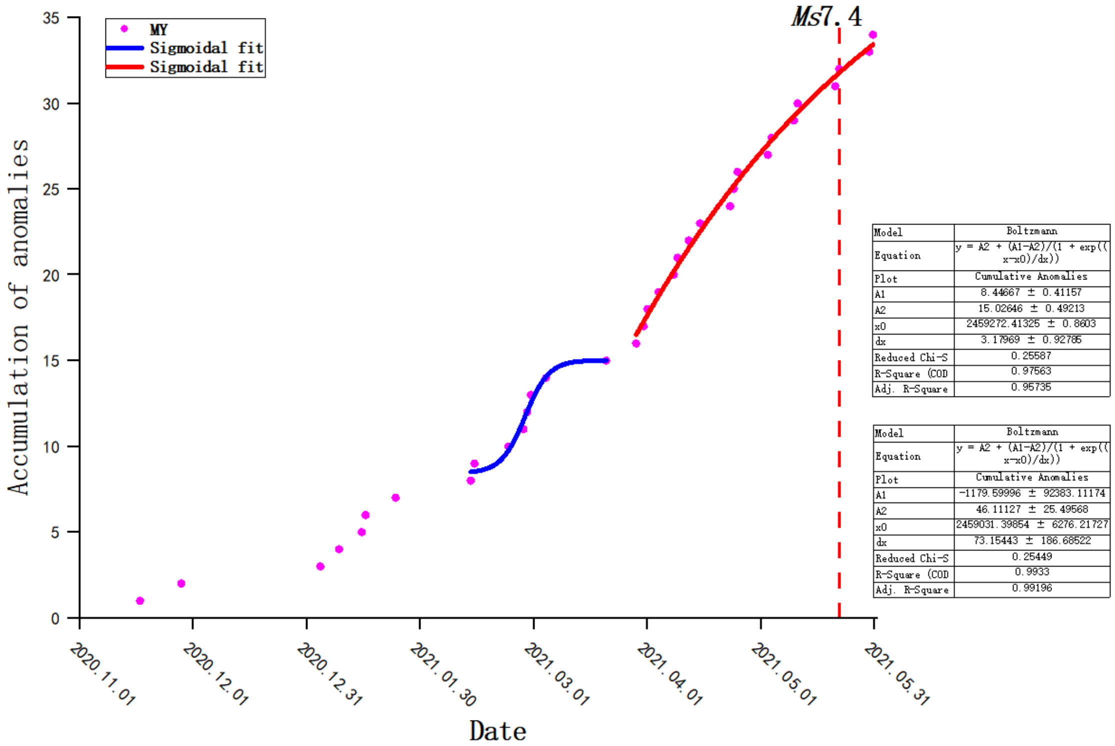
1. Physical interpretation of the prediction intervals: The 85% confidence intervals that we have constructed represent the range of normal fluctuations in crustal strains of the tectonic system under steady-state conditions. This range essentially describes the strain behavior "under normal tectonic evolution". Observations outside this range indicate that the crustal system may have deviated from elastic equilibrium, which may be caused by processes such as microfracture extension, localized stress concentrations, or

pre-seismic nonlinear evolution.

2. Physical significance of the anomalous day criterion: We define two criteria for anomalies: (a) ≥15 anomalies outside the prediction interval in a 30-minute time window; and (b) ≥3 points where the actual value deviates from the center of the prediction interval by more than one and a half times the width of the interval in the same time window. These criteria are used to identify strain deviation behaviors with temporal aggregation, persistence, and nonlinear characteristics that are closely related to pre-seismic system destabilization and rapid energy aggregation. When the crustal system is close to rupture, it tends to exhibit nonlinear dynamics such as increased fluctuations and enhanced system response.

3. The pre-seismic anomaly accumulation process presented in Fig. 8 of the original manuscript shows a typical “S-type two-phase acceleration” pattern, which further suggests that these anomalies are not noise, but may reflect key evolutionary stages in the proseismic process. This phenomenon has been recognized in several studies on seismic phase transition theory (e.g., (De Santis et al., 2017; Fan et al., 2024)).

Therefore, although these anomaly detection criteria are set on the basis of statistical modeling, we believe that they reflect, to some extent, the processes associated with earthquake gestation and have some physical significance.



Model	Boltzmann
Equation	y = A2 + (A1-A2)/(1 + exp((x-x0)/dx))
Plot	Cumulative Anomalies
A1	8.44667 ± 0.41157
A2	15.02646 ± 0.49213
x0	2459272.41325 ± 0.8603
dx	3.17969 ± 0.92785
Reduced Chi-S	0.25587
R-Square (COD	0.97563
Adj. R-Square	0.95735

Model	Boltzmann
Equation	y = A2 + (A1-A2)/(1 + exp((x-x0)/dx))
Plot	Cumulative Anomalies
A1	-1179.59996 ± 92383.11174
A2	46.11127 ± 25.49568
x0	2459031.39854 ± 6276.21727
dx	73.15443 ± 186.68522
Reduced Chi-S	0.25449
R-Square (COD	0.9933
Adj. R-Square	0.99196

Figure 8 of the original manuscript. Cumulative results of anomalous days of borehole data at Mengyuan station (MY). The red dashed line indicates the date of the earthquake, and the blue and red curves indicate the results of the S-fit function for the first and second phases, respectively.

Comment 7

If an earthquake is considered to correspond to a phase transition, are the results shown in this analysis associated with the critical state or preparation mechanism of the seismic process?

Response:

Thanks for your suggestion.

The two-stage accelerated growth of the borehole strain accumulation results may reveal two preparatory mechanisms prior to the mainshock. This is consistent with the theory of fault synergistic process of (Ma et al., 2014). They found that the occurrence of earthquakes is closely related to the three-stage synergistic evolution of faults through an indoor experimental study of plane-walk-slip faults. In the first stage, the initial stress nonlinear divergence leads to localized weakening and the formation of discrete strain release zones. The second stage is characterized by an increase in stress and a widening of the strain release zone. In the final stage, the expansion of the strain-release region and the rapid increase of the strain level in the strain-accumulation region. The anomalous cumulative acceleration about 3 months before the Maduo earthquake corresponds to the first and second stages in the theory, which is manifested by the deviation of the stress curve from linearity and the beginning of the formation and slow expansion of the discrete release zone. The acceleration 2 months before the earthquake reflects the characteristic changes of the third stage, which is characterized by the accelerated expansion of the release zone and the sharp increase of the strain in the accumulation zone. Therefore, we believe that the anomalies observed before the Maduo earthquake are related to the process of earthquake incubation.

Comment 8

The conclusion section must be improved

Response:

Thanks for your suggestion.

The conclusion of the original manuscript lacks a sense of hierarchy, has redundant sentences and lacks synthesis. Therefore, we modify the conclusion to read “In this study, a SVMD-Informer network-based anomaly detection method for borehole strain data is proposed, and the 2021 Maduo Ms7.4 earthquake is used as an example for pre-seismic anomaly extraction. The method optimizes the problems of slow computation speed and memory limitation existing in the traditional VMD by SVMD, and significantly improves the accuracy and stability of long series time series prediction by combining with Informer network. By analyzing the borehole strain data from Mengyuan station, we successfully extracted the anomalous cumulative acceleration phenomenon in the two stages before the Maduo earthquake, which appeared about 3 months and 2 months before the earthquake, respectively, and the anomalous cumulative curves showed a typical S-shape growth trend, and this result is consistent with the theory of fault synergistic process of (Ma et al., 2014). In addition, our results are highly consistent with the time windows of other seismic precursor anomalies, such as the index of microwave radiation anomalies (IMRA), outward long-wave radiation (OLR), and geoelectric field, which further validates the correlation between the borehole strain anomalies and the Maduo earthquake. With the continuous progress of machine learning technology and the continuous accumulation of seismic observation data, this method is expected to provide a higher precision technical support for earthquake prediction and help reduce the risk of seismic disasters.”. The above modifications effectively reduce repetitive descriptions, making the conclusions more coherent and concise.

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