Response to Reviewer 1:

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

One drawback of this work is that it is applied to a single case study only. Why not applying to at least another case, in order to avoid that what is found is just associated to this unique case and cannot extend to other cases? If data are available, it would be interesting to compare with Wenchuan 2008 earthquake. This is done in Chi et al. 2023, but using just a single station.

By the way, regarding to this, there is another interesting paper on the comparison of the two case studies, although analysing different precursory parameters (from atmosphere): Liu et al. 2020, https://doi.org/10.3390/rs12101663.

Response:

Thanks for your suggestion.

In the process of our experiment, the data from Guza station began in 2006, the data from Xiaomiao and Luzhou station began in 2008, and the data from Zhaotong station began in 2010. Due to the lack of data on the Zhaotong station, in the case of using the same station and training data, the Wenchuan earthquake case is not suitable for comparative study with the Lushan earthquake case, so Wenchuan earthquake is not added to the submitted manuscript.

According to your suggestion, we used the same method to analyze the data before the Wenchuan earthquake and selected the data from the Guza, Luzhou, and Xiaomiao stations. Since the data began in 2008, we can only select 2010 and 2011 as the training set and validation set. The data from January to June 2008 were selected as the test set, and the method in the manuscript was used to analyze the pre-earthquake anomalies of the Wenchuan earthquake. The node diagram constructed by the distance between stations is shown in Fig. 1.

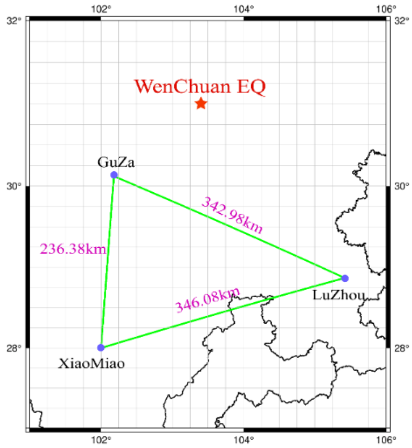

Figure 1: Node diagram of the three borehole strain observation stations. The blue circle indicates the locations of the three borehole strain stations, the green line indicates the distance between the two stations, and the red star indicates the epicenter of the Wenchuan earthquake.

We analyze the prediction results, use the definition in the manuscript to judge the abnormal days, and accumulate the abnormal days. Figure 2 shows the relationship between the accumulation of abnormal days and time at Guza, Luzhou, and Xiaomiao stations.

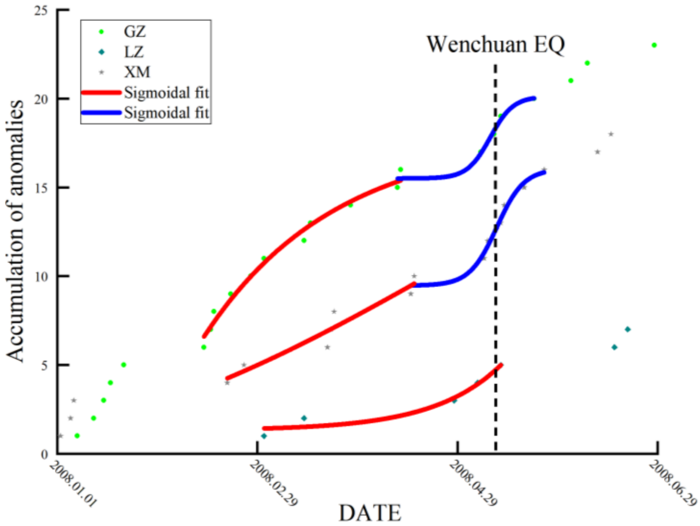

Figure 2: Accumulation results of abnormal days of borehole data at Guza, Luzhou, and Xiaomiao stations. The dashed line indicates the date of the Wenchuan earthquake, while the red and blue curves indicate the results of the S-shaped fitting before and after the earthquake, respectively

As shown in Fig. 2, the cumulative results of abnormal days at Guza station show the concavity of two parts. Some show that the abnormal accumulation accelerates from the beginning of January to April, the stress curve deviates from linearity, and the isolated area of strain release increases and extends steadily. The other part shows that the abnormal accumulation accelerated about a month before the earthquake, the strain release part on the fault accelerated expansion, and the strain level in the strain accumulation area increased rapidly. We fit the data of Xiaomiao station, and there is a similar phenomenon. It shows that the stations we selected receive more or less abnormal signals related to the Wenchuan earthquake. Our research is similar to the results of Chi et al., (2023) and Liu et al., (2020), which proves that the method in this paper is also applicable to the Wenchuan earthquake.

Comment 2

A second drawback is that it is not clearly explained the presence of the sigmoid in the results in terms of the physics of the earthquake preparation phase. Could you please interpret the results in terms of a physical model? Could it be related to a critical state of the regional crust? Could it be related to a dilatancy model of the lithosphere? How is the role of fluids?

Response:

Thanks for your suggestion.

(1) “A second drawback is that it is not clearly explained the presence of the sigmoid in the results in terms of the physics of the earthquake preparation phase. Could you please interpret the results in terms of a physical model? Could it be related to a critical state of the regional crust? Could it be related to a dilatancy model of the lithosphere?”

The findings of this study align with the theory of the synergism process of a fault. Ma and Guo, (2014) conducted a laboratory modeling study on the instability of a planar strike-slip fault, suggesting that the occurrence of an earthquake is linked to a fault's synergistic process, which encompasses three stages. In the initial stage, there's a deviation of the stress curve from linearity. The second stage is marked by the steady increase and expansion of isolated areas of strain release. In the final stage, the fault's sections of strain release accelerate and expand, alongside a rapid increase in strain levels in areas of strain accumulation. The period from September to December 2012 corresponds to the first and the second stages, where the stress curve deviates from linearity and isolated areas of strain release grow and extend steadily. From early 2013 up to the earthquake, aligns with the third stage, characterized by the accelerated expansion of strain release sections on the fault and a swift rise in strain levels in strain-accumulation areas. The multitude of anomalies observed post-earthquake, including those caused by crustal fractures and aftershocks, were also evident. Similar phenomena were recorded at the XM and LZ stations, correlating with Ma's theory. Thus, we believe that the anomalous phenomena observed prior to the Lushan earthquake are related to the earthquake's gestation process.

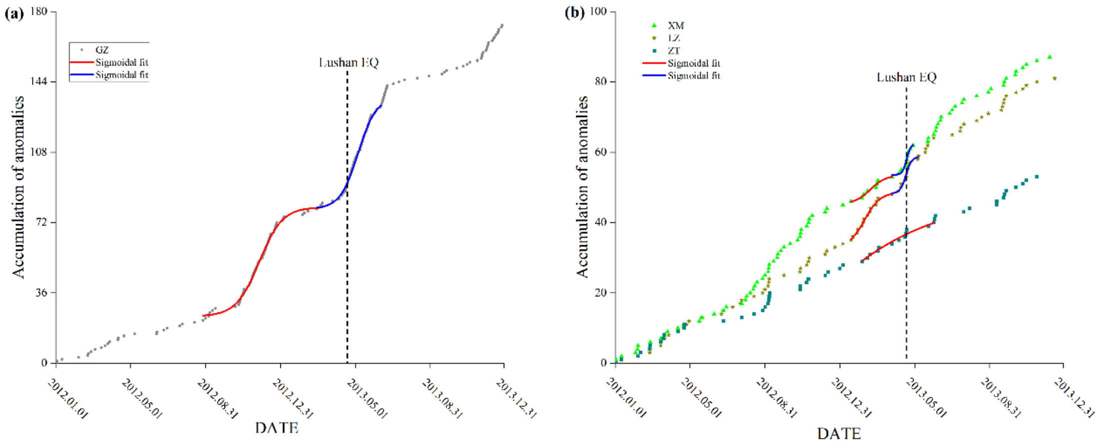

Figure 3: Accumulation results of anomalous days in borehole data from each station. The dashed line indicates the date of the earthquake, while the red and blue curves indicate the results of the S-shaped fitting before and after the earthquake, respectively. (a) Anomalous day accumulation results for Guza station; (b) Anomalous day accumulation results for Xiaomiao, Luzhou, and Zhaotong stations.

(2) “How is the role of fluids?”

Borehole strain monitoring involves the placement of strain gauges deep underground to measure changes in rock or crustal strain. Crustal strain arises from the movement of tectonic plates and seismic activity. This method provides direct insights into the rate and pattern of crustal deformation, which is extremely helpful in understanding the stress state of the Earth's crust associated with seismic activities. Strain data are often highly sensitive to impending earthquakes, offering valuable information about potential fault planes.

Underground fluid monitoring primarily refers to tracking changes in groundwater levels, groundwater pressure, or the chemical composition of subterranean fluids. Seismic activities can affect the flow and pressure of groundwater, so monitoring these changes can indirectly detect seismic activities. Variations in underground fluids may correlate with seismic activities, particularly preceding earthquakes. Anomalous fluctuations in groundwater levels and pressures can serve as precursors to earthquakes. Borehole strain data provide direct information on crustal strain, while underground fluid data offer indirect insights into fluid dynamics related to seismic activities. Both play crucial roles in earthquake precursor studies, yet they differ in their monitoring methodologies, sensitivities, and scopes of application.

Comment 3

Title. I suggest to add at the end of the title "(China)" since not all researchers know where Lushan is (especially who did not work on that earthquake).

Response:

Thanks for your suggestion.

Changed the title "Extraction of Pre-earthquake Anomalies in Borehole Strain Data Using Graph WaveNet: A Case Study of the Lushan Earthquake". Modify the title to "Extraction of Pre-earthquake Anomalies in Borehole Strain Data Using Graph WaveNet: A Case Study of the 2013 Lushan Earthquake, China".

Comment 4

Line 60. There are exceptions to the sentence "they mostly focused on single-station data": not only Liu et al. 2019 and Yu et al. 2020 (both already cited by Li et al.) but also Zhu et al. 2019 (Nonlinear Processes in Geophysics, https://doi.org/10.5194/npg-26-371-2019 not cited) to give a recent example of multi-station data analyses.

Response:

Thanks for your suggestion.

Modified "Despite the valuable insights gained from these studies, they mostly focused on single-station data, overlooking the potential correlations between multiple stations." and added " The study of seismic monitoring data based on multiple stations has been applied to many scenarios. Liu et al., (2019) analyzed the abnormal fluctuations of aerosol optical depth (AOD) before and after the 2008 Wenchuan earthquake and the 2013 Lushan earthquake, and found that the abnormal high AOD values appeared 11 days before the Wenchuan earthquake and 4 days before the Lushan earthquake. It is considered that the AOD index may be suitable as a precursor to the earthquake in the Sichuan Basin. Using borehole strain data from six stations in the Sichuan-Yunnan region, Yu et al., (2020) established a graph network and analyzed 13 earthquake cases with Es > 10^7 in the study area. It was found that the strain anomaly before the earthquake generally occurred within the first 30 days of the earthquake event. To study the abnormal strain changes before the Wenchuan earthquake, Zhu et al. (2019) introduced negative entropy analysis to the borehole data of three stations. The results show that Guza and Xiaomiao stations have similar trends and may record abnormal changes related to the Wenchuan earthquake. Renhe station failed to detect the anomalies before the earthquake due to the distance. An example of multi-station analysis is given, which shows that it is feasible to analyze seismic data with multi-station."

Comment 5

Figure 1 (and rest of the paper). The findings of the work are finally drawn in terms of accumulation of anomalies. This comprehensive way to express the results, in my knowledge, has been firstly proposed by De Santis et al. 2017 (https://doi.org/10.1016/j.epsl.2016.12.037) in a study of satellite magnetic field data in occasion of the large 2015 Nepal earthquake. In that paper, it was also introduced the notation "S-shape" for the first time, as it is also used in this paper (e.g. see Figure 10 caption).

Response:

Thanks for your suggestion.

Modified " In Fig. 9, it is evident that the abnormal days we defined exhibit short-period, high-frequency oscillation signals in the original waveform, suggesting that these days are associated with crustal activity. " and added " Santis et al., (2017) study the 2015 Nepal event using Swarm magnetic satellite data. For the first time, an S-shaped fitting function was proposed in the abnormal accumulation analysis, and some abnormal differences were found in the area around the EQ epicenter from the abnormal accumulation results. By comparing the S-shaped function and the linear fitting, it was found that the S-shaped fitting was significantly better than the linear fitting. In this paper, the S-type function is used to fit the abnormal accumulation results. "

Comment 6

Line 175 and following. Why did you choose the window size of 7 days? How critical could this choice be?

Response:

Thanks for your suggestion.

We choose the sliding window size standard from the equipment bearing capacity and the efficiency of data processing, through the experiment to select the optimal window size. As shown in Table 1 below, we selected the size of the sliding window for 7 days, 15 days, and 30 days, respectively. Table 1 gives the time and memory size required for the calculation process. If the size of the sliding window is too small, the correlation between the data cannot be maintained. Considering the time required for the SVMD calculation process and the memory size of the computer, we chose the size of the sliding window to be 7 days.

Table 1. The experimental results of SVMD correspond to different sliding window sizes.

Window(day)	Time(min)	Memory(MB)
7Days	22.5	85.7
15Days	51.6	171.1
30Days	125.9	308.6

Comment 7

Line 242. Are you sure that std_error is the root mean square error? From the name it looks like the standard deviation error (the two quantities are different because of a slightly different denominator).

Response:

Thanks for your suggestion.

Removed std_error. In the process of the experiment, we use the root mean square error to calculate the upper and lower bounds of the predicted value. The std_error in line 242 and formula (11) have been modified to rmse.

Comment 8

There are section 5 (Results) and section 6 (Conclusion). What is missing is a section "Discussion", that is partly present in section 5.

Response:

Thanks for your suggestion.

We have modified the structure of the manuscript. In the fifth part, we mainly include the analysis of the prediction results, the analysis of the details of the randomly selected abnormal days, and the analysis of the abnormal accumulation results. The sixth part is added as the chapter of discussion, which mainly includes the comparison and discussion of the abnormal accumulation results between different stations and the elimination of the influence of meteorological factors. The seventh section contains the conclusion. And modify the 90 lines of the original manuscript "Section five mainly includes the analysis of prediction results, the detailed analysis of randomly selected abnormal days, and the analysis of abnormal accumulation results. The sixth part is the discussion, which mainly includes the comparison and discussion of the abnormal accumulation results between different stations and the exclusion of the influence of meteorological factors. The final section presents the conclusions of the study and summarizes the key insights drawn from our analysis." And modify the 391 lines of the original manuscript "Therefore, we can exclude the influence of pressure, temperature, and rainfall on the anomalies observed in the pre-earthquake borehole data from Lushan. We have reason to believe that the anomalies we extracted before the Lushan earthquake are related to the seismogenic process."

Comment 9

There are several words interrupted by a "-": e.g. "dam-age"(Line 24), "sur-face" (line 38), "phenome-non" (line 57), etc. Please join the two parts in just one.

Response:

Thanks for your suggestion.

Delete the "-". The "dam-age" in line 24 was modified to "damage", the "sur-face" in line 38 was modified to "surface", and the "phenome-non" in line 57 was modified to "phenomenon".

Comment 10

Line 86. "two sections": do you mean "next section"?

Response:

Thanks for your suggestion.

The "two sections" were deleted. The meaning you want to express here is the next section, and line 86 is changed to "next section".

Comment 11

Line 200 (equation (9)). Which is the "sigmod" function? Is it actually "sigmoid" as introduced in the line before?

Response:

Thanks for your suggestion.

Delete tanh and sigmod in equation (9). The tanh and sigmod in Equation (9) of line 200 are the activation functions of the neural network, tanh is the activation function of the output, and sigmod is the activation function that determines the information ratio transmitted to the next layer. The sigmod function in equation (9) is different from the sigmod function mentioned in the previous row. To avoid ambiguity in the symbol, the equation (9) in line 200 is modified to $T = \boldsymbol{g}(W_1 * x + b_1) \bullet \boldsymbol{\sigma}(W_2 * x + b_2)$, and in line 202 is added "where $\boldsymbol{g}$ is the activation function of the output, $\boldsymbol{\sigma}$ is the activation function that determines the ratio of information passed to the next layer."

Comment 12

Figure 9. The numbers at the axes are too small. Please enlarge them in order to let them more visible.

Response:

Thanks for your suggestion.

The value of the coordinate axis in Fig. 9 has been modified.

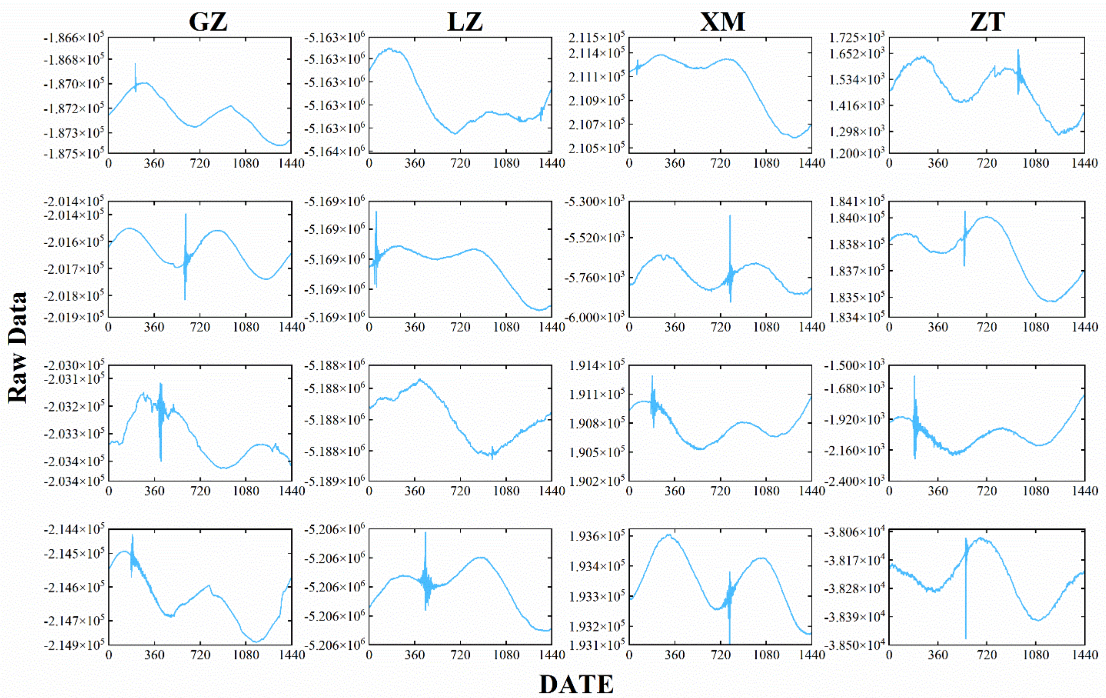

Figure 9: Plots of raw data from four randomly selected anomalous days at each station.

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