Geoenvironmental Disasters

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Study on the correlation between real-time GNSS landslide acceleration monitoring and earthquake response: a case of May 2, 2023, MW = 5.2 Baoshan earthquake, Yunnan

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Abstract

Background Earthquakes and landslides pose significant threats to human safety and property, necessitating early warning systems. However, the high construction costs of earthquake early warning systems present a challenge.

Purpose Landslide warnings are more prevalent, so linking them to earthquake warnings could address cost concerns. Hence, it is crucial to validate the feasibility of utilizing GNSS landslide monitoring as assistance for earthquake early warning systems.

Methods This paper analyzes acceleration anomaly data from 31 GNSS landslide monitoring points near the epicenter of the May 2, 2023, MW = 5.2 Baoshan earthquake in Yunnan. The response time was determined as the time difference between an earthquake's occurrence and GNSS's acceleration anomalies. This calculation helps measure the time delay and sensitivity between these two events. Data were obtained from the geological disaster monitoring and early warning management system.

Results GNSS landslide monitoring showed high sensitivity to nearby earthquakes. The fastest response time among the 31 data points was 8 seconds, while the slowest was 56 seconds, all falling within the one-minute mark. A linear correlation was found between acceleration anomaly response time and distance from the epicenter, indicating the feasibility of GNSS landslide monitoring-assisted earthquake monitoring.

Conclusion A proposal is made for a GNSS landslide monitoring cluster to establish a multi-dimensional landslideearthquake disaster warning system. This approach offers new methods for combining earthquake and landslide early warning systems, leveraging existing infrastructure for cost-effectiveness and enhancing disaster preparedness.

Keywords GNSS, Landslide, Earthquake, Monitoring, Early warning, Combine

Introduction

An earthquake early warning system is an early warning system based on seismic data acquisition and processing techniques (Minson et al. 2015; Espinosa et al. 2009; Murray et al. 2018). It is a technical means to achieve early warning of possible earthquakes based on seismic data before the occurrence of seismic activity (Allen and Melgar. 2019). With the continuous development of earthquake early warning technology, the earthquake early warning system has gradually evolved from

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simple seismic instruments in the early days to highly automated, intelligent, and networked (Ide 2019; Allen 2017; Kumar et al. 2022). The physical quantities monitored have also evolved from surface displacements and seismic waves to parameters such as acceleration and geomagnetic fields (Cremen et al. 2020).

Based on the development of earthquake warning technology, countries started to establish their earthquake warning systems, such as the Japan Earthquake Alert System (J-ALERT) (Koder 2018), the United States Earthquake Alert System (ShakeAlert) (Given et al. 2014; Böse et al. 2014; Kohler et al. 2017), the seismic alert system of Mexico (SASMEX) (Espinosa et al. 1995; Cuéllar et al. 2014), the European Seismological Monitoring and Alert System (EUROSEISTEST), and the China Earthquake Networks Center (CENC) in China (Ji et al. 2019), among others. However, these earthquake early warning systems are established with huge investments (Bouta et al. 2020). Therefore, in establishing an earthquake early warning system, using the existing ground-hazard monitoring network to provide an additional source of data for the earthquake early warning system will greatly reduce the construction cost (Yang et al. 2020).

Landslide monitoring technology is an essential geological hazard monitoring tool, and its monitoring approach and development history are very similar to earthquake monitoring (Ju et al. 2020; Ahmed et al. 2018). Landslide monitoring technology to support earthquake early warning systems may greatly improve earthquake warning capabilities and reduce costs (Fan et al. 2019). Landslide monitoring has gone through several development stages, such as traditional artificial monitoring (site survey, timed measurement) (Tonnellier et al. 2013), automatic monitoring (remote control, automation) (Zhao et al. 2012), and the Internet of Things (IoT) monitoring (data collection, transmission, storage, and processing through computer technology) (Whiteley et al. 2019; Casagli et al. 2023). The use of the Global Navigation Satellite System (GNSS) for landslide monitoring has become mainstream (Shen et al. 2021). GNSS landslide monitoring has the advantages of real-time monitoring (Han et al. 2019), all-weather monitoring (Li et al. 2021), and high-precision monitoring (Wang et al. 2022). It has been widely used in landslide early warning, prevention, and management and is expected to be maturely applied in earthquake early warning (Murray et al. 2019). At the early stage of GNSS technology development, the effect of landslide warnings was mainly achieved by real-time high-precision measurement of surface deformation. With the development of lower-cost, smaller, and more accurate accelerometers, acceleration monitoring began to be gradually applied to GNSS landslide monitoring and provided more adequate information and more accurate warnings for GNSS landslide monitoring (Feng et al. 2020).

This paper verifies the feasibility of GNSS landslide monitoring for earthquake early warning assistance in the background of the May 2, 2023, $M_W = 5.2$ Baoshan earthquake. An early warning multi-dimensional monitoring method is proposed based on GNSS monitoring of acceleration changes for earthquake early warning. Through point, network, and spatial GNSS acceleration monitoring, a monitoring system is constructed to achieve the effect of regional earthquake early warning. Effectively combines GNSS landslide warning with earthquake warning in the region.

Background

On May 2, 2023, at 23:27:22, a 5.2 magnitude earthquake occurred at a depth of 10 km in Wayao Town, Longyang District, Baoshan City, Yunnan Province, China (25.35° N, 99.28° E), as shown in Fig. 1, according to the earthquake agency of Yunnan Province, China. The average elevation of the epicenter area is about 1863 m, which is 29 km from Baoshan City. The earthquake caused significant seismic sensations in Dali Bai Autonomous Prefecture, Lincang City, Chuxiong City, and Mangshi (Yunnan Earthquake Agency, 2023a). The Yunnan Provincial Earthquake Agency had initiated a Level 3 emergency response. In the past 10 years, there have been 43 earthquakes of magnitude 3 or higher in Baoshan City, where the epicenter is located, including 35 of magnitude 3.0 to 3.9, 6 of magnitude 4.0 to 4.9, 2 of magnitude 5.0 to 5.9, and 0 of magnitude 6.0 or higher. The largest earthquake was a 5.2 magnitude earthquake (the current earthquake) that occurred on May 2, 2023, in Longyang District, Baoshan City, Yunnan (Yunnan Earthquake Agency, 2023b).

The earthquake caused damage to the surrounding buildings and geological formations, as shown in Fig. 2. Part of the perimeter wall collapsed after the earthquake, seriously threatening the lives of people and property. The roof of the house collapsed and buried the vehicle, causing severe damage to the top of the vehicle. Some of the building structures show obvious cracks and compromised safety. The subsequent residential stability cannot be guaranteed. The earthen walls show serious cracks and risk collapsing at any time. Landslide hazards occurred on the natural slopes. Some of the landslides caused damage to the surrounding building settings, such as damage to power poles. Therefore, early earthquake warning is crucial for the safety of the area around an earthquake. Timely alerts can effectively reduce injuries to people and facilitate the transfer of property and equipment in the surrounding area, minimizing the damage caused by the earthquake as much as possible.

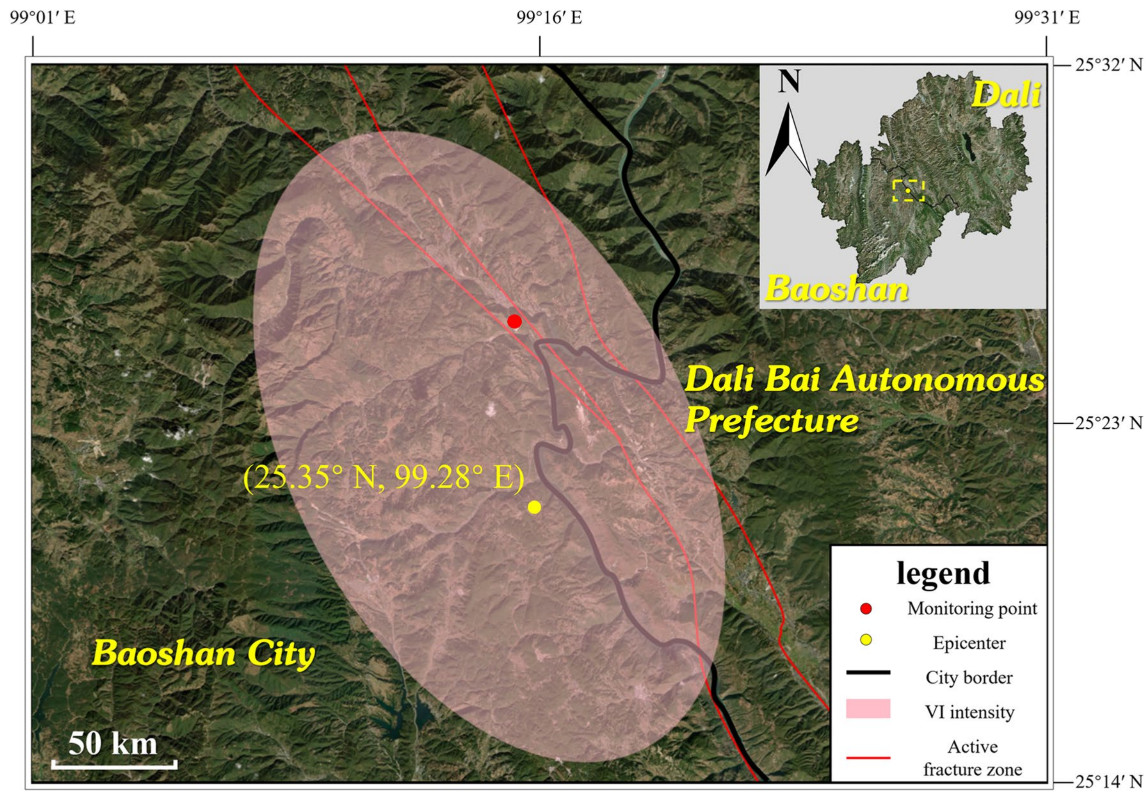

Fig. 1 Schematic diagram of the location of the May 2, 2023, MW = 5.2 Baoshan earthquake

As a common geologic hazard, monitoring and early warning of landslide hazards is crucial. Therefore, in the southwest region with complex geological conditions, landslide GNSS monitoring sites are characterized by wide distribution, simple installation, and low cost. This is diametrically opposite to the earthquake early warning system. If the landslide GNSS monitoring method can be combined with the earthquake early warning, it can realize the collaborative warning of the two, thus reducing the cost and increasing the coverage area.

Geological disaster monitoring and early warning management system

The geological disaster monitoring and early warning management system (GDMEWMS) can realize automatic, continuous, and real-time monitoring of monitoring objects in the monitoring area. Based on the information collection and forecast analysis and decision, the system can transmit the early warning information layer by layer through message, fax, wireless broadcast, and other early warning methods and the corresponding early warning process according to the warning level of the early warning information and the scope of the geological disaster. Early warning information is delivered promptly and accurately to areas that geological hazards may endanger. It enables the personnel in the receiving warning area to take timely defensive measures based on the overall safety status of the geohazard in real time to minimize casualties and property damage.

The monitoring and warning flow chart of the GDMEWMS is shown in Fig. 3. Monitoring equipment management using the IoT cloud platform. The ID of the relevant equipment at the monitoring point is set. The data is processed and transmitted in real-time with the help of platform access services, thus effectively managing the equipment. Then, the data from the newly completed IoT devices are transmitted to the monitoring and warning information system. The monitoring and early warning information system is divided into two parts: early warning analysis and monitoring points. The early warning analysis section allows you to manage and set up macro phenomena, early warning information, early warning models, and criteria. The early warning model and criteria are synchronized to the monitoring point, and the early warning backend performs the early warning calculation through the criteria formula of the device. The monitoring point makes the warning message when the warning criterion is triggered. Early warning messages are released in the management system, and early

Fig. 2 Building damage around the Baoshan earthquake

warning SMS (Short Messaging Service) and early warning horns are utilized.

The GNSS monitoring equipment at the monitoring point usually adopts model DM-GNSS A300, which can continuously, automatically, and all-weatherly monitor the real-time deformation of the monitored objects on a millimeter scale for a long time. Data is sent to remote data centers for processing and analysis

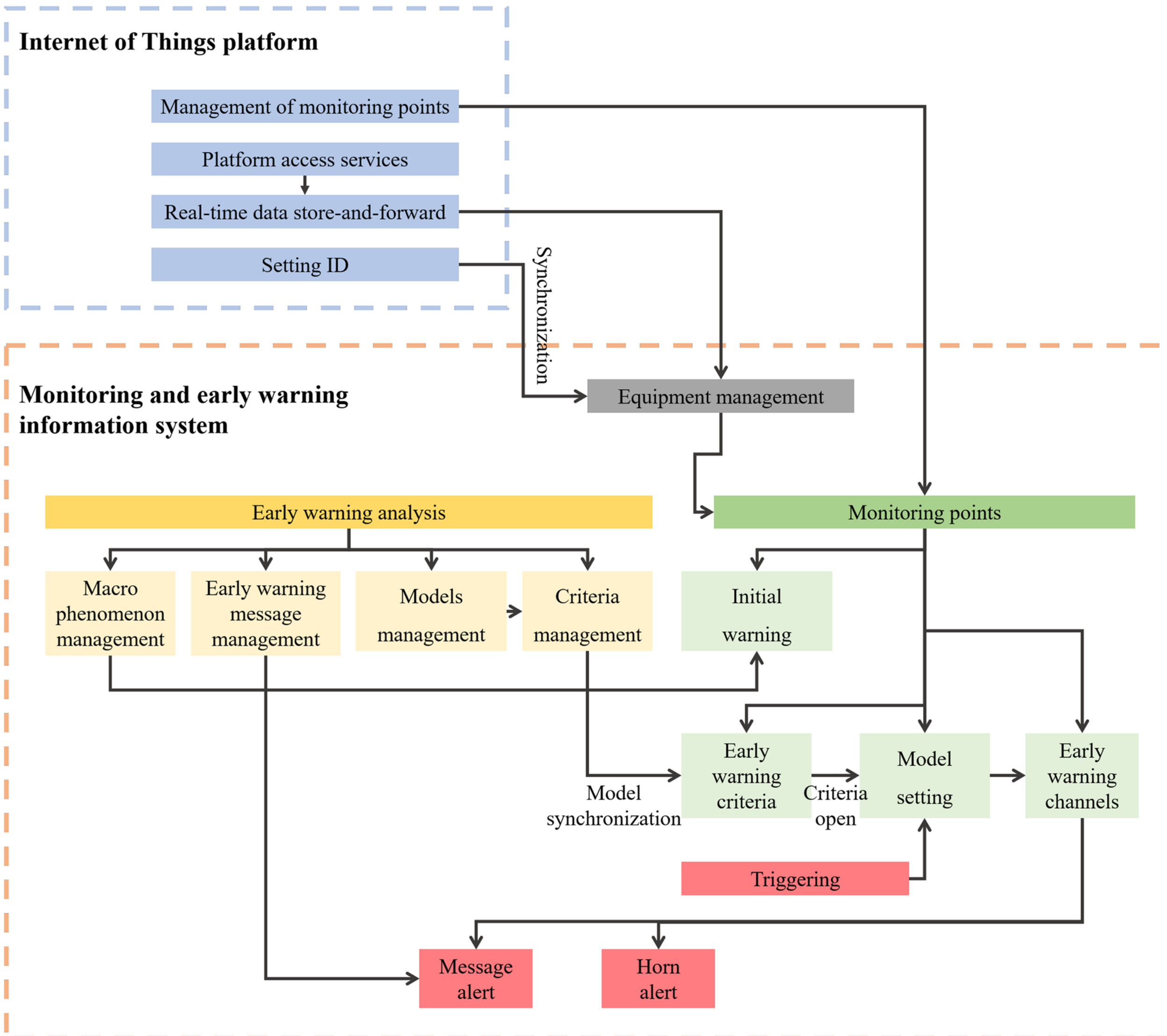

Fig. 3 Flowchart of early warning of the GDMEWMS

via the IoT. It also supports access to MEMS (Micro-electro Mechanical Systems) sensors for cross-referencing and cross-evidence when deformation occurs in the field. GNSS monitoring data provide more comprehensive and accurate data support for geological disaster monitoring and early warning. The specific parameters are shown in Table 1.

The GDMEWMS in Yunnan Province has conducted real-time monitoring of the perimeter slopes during this Baoshan earthquake. In this paper, we analyze the possibility of GNSS landslide monitoring on earthquake response based on the results of monitored data.

The theoretical basis for acceleration warning

According to the theory of double block mechanics proposed by He Manchao et al.(2017), it is known that there will be obvious sudden changes in the interaction force of the catastrophic body before the disaster occurs. When an earthquake comes, its action force F will lead to micro-deformation ΔL of the slope. However, in general, the F action time is extremely short. The deformation monitoring sensitivity decreases when the distance of the monitoring point from the epicenter increases.

As shown in Fig. 4, when an earthquake occurs, the displacements of the slope GNSS monitoring points

Table 1 Basic parameters of GNSS equipment of DM-GNSS A300 model

	Technical index	Technical parameters
GNSS receiver	Displacement accuracy	Static: Plane: ± (2.5 mm + 0.5 × 10^{-6}D), Elevation: ± (5.0 mm + 0.5 × 10^{-6}D) Dynamic: Plane: ± (8.0 mm + 0.5 × 10^{-6}D), Elevation: ± (15.0 mm + 0.5 × 10^{-6}D)
	MEMS measurement ranges	Angle: ± 90°, Acceleration: ± 8 g
	MEMS measurement accuracy	Angle: 0.1°, Acceleration: ± 0.01 g
	Frequency of data update	0.2 Hz, 0.5 Hz, 1.0 Hz, customizable
	Signal re-capture	< 1 s
Solving mode	Static solving	10 min/time
	Dynamic solving	1 min/time
Protection level	Protection level ≥ IP67, support lightning over-voltage protection	
Communication mode	Fit all kinds of networks	
Other	Environmental temperature	− 40 ℃ ~ 75 ℃
	System power consumption	< 2 W
	External interface	Power /RS485/RS232 etc., also external DTU
	Mounting bracket	

P.S.:D is the distance to the reference station; DTU: Data Transfer unit

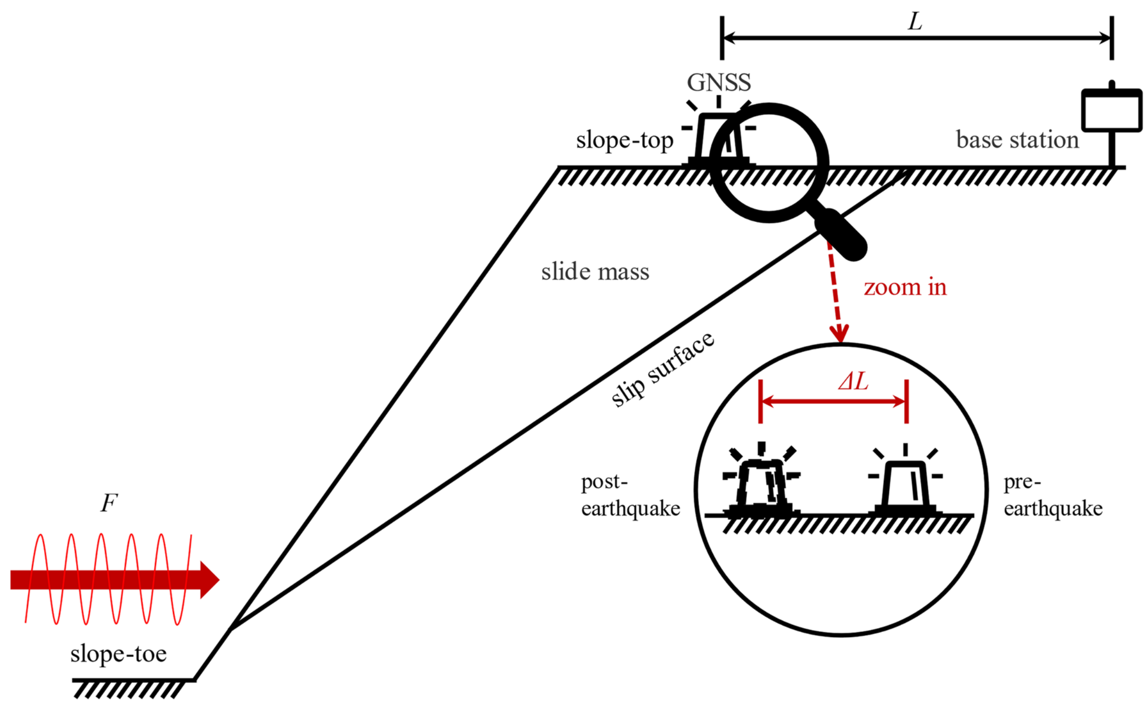

Fig. 4 Schematic diagram of the principle of GNSS acceleration cooperative seismic early warning

may be much smaller than the thresholds set for early warning, and it is not possible to realize the collaborative early warning of earthquakes. The acceleration is the second-order derivative of the micro-deformation ΔL. When acceleration is used as the threshold, its response to earthquakes is more sensitive, and the sudden change in value is obvious, which can achieve a collaborative warning effect. Therefore, collaborative early warning monitoring of earthquakes can be realized quickly and better by monitoring the acceleration anomalies of slopes as the critical coefficient.

Monitoring results and analysis

During the Baoshan earthquake, the GDMEWMS conducted real-time monitoring of monitoring points in the Yunnan area. The acceleration data of 31 surrounding monitoring points were found abnormal for a short time after the earthquake through the system data investigation. The 31 monitoring sites are in Longyang District of Baoshan City and Yunlong, and Yongping County in Dali Bai Autonomous Prefecture, as shown in Fig. 5. Acceleration surges of different degrees occurred at all 31 monitoring points, with the maximum acceleration surge of 352.14 mg and the minimum acceleration surge of 9 mg, as shown in Fig. 6a.

This monitoring result verifies the possibility of GNSS landslide monitoring for a seismic response. The Baoshan earthquake occurred on May 2, 2023, at 23:27:22.The difference between the acceleration surge time and the earthquake occurrence time, defined as the response time, was calculated from the real-time GNSS monitoring data. Since it is an earthquake warning, this paper only analyzes the GNSS monitoring points with acceleration surges after the earthquake. Analyzing the data of the distances to the epicenter and response times from 31 monitoring points, as shown in Fig. 6b, it can be found that there is a large randomness in the data as a whole, which indicates that the slope stability situation is not uniform. In order to eliminate the effect of the randomness of the data, we divided the data into regions using the distance from the epicenter location as a benchmark, and the average value was obtained. The two points in the region with the largest difference between the reaction time and the mean were removed to find the new average value and fit. After fitting, we found that the response time and distance of GNSS landslide monitoring set points showed a linear correlation.

By analyzing the response time of 31 monitoring sites in detail, we found that the fastest response time was 8 s, while the slowest response time was 56 s, indicating that the monitoring sites' response time was within 1 min. This result verifies the reliability of the GNSS landslide

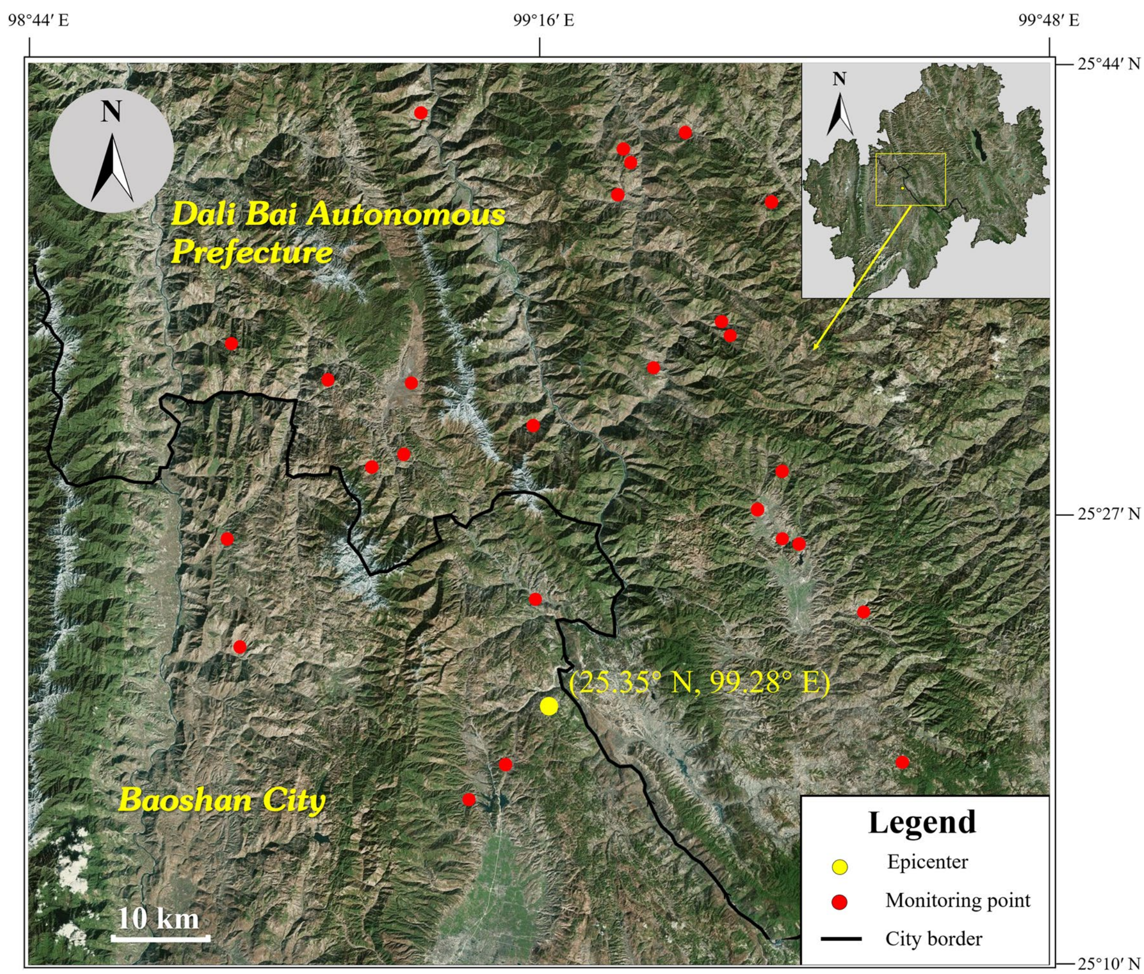

Fig. 5 Location map of GNSS landslide monitoring points

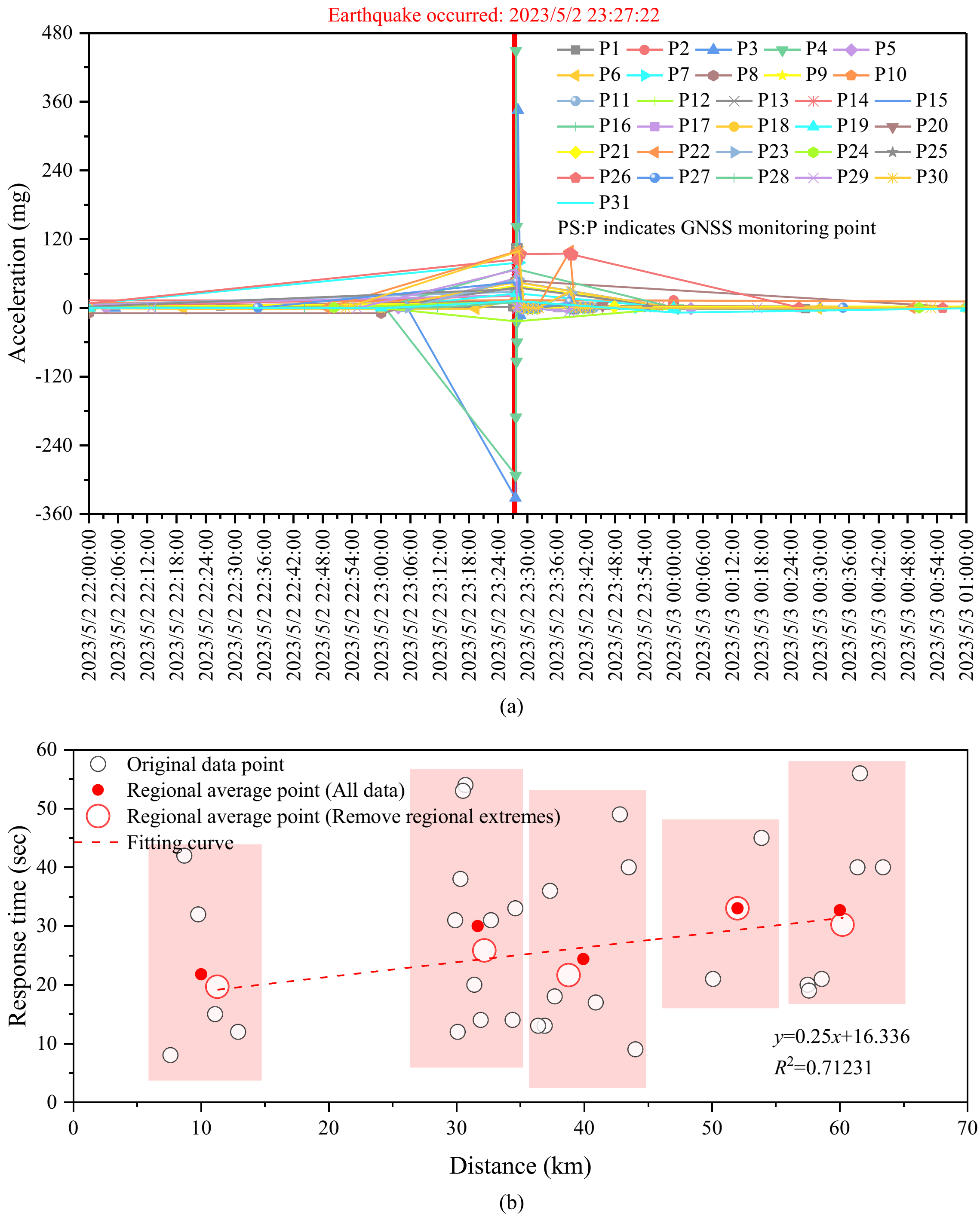

Fig. 6 Analysis of monitoring data from GNSS landslide monitoring points: **a** GNSS landslide monitoring points monitoring curve; **b** Scatter plot of the relationship between response time and distance

monitoring method in response to earthquakes. Also, it illustrates that the anomalous acceleration changes can be used to respond to the surrounding earthquakes, which provides reliable basic data support to explore further the seismic activities in the area near the epicenter.

Discussion—GNSS landslide—earthquake disaster warning combined system

According to Chen Guangqi et al. (2021), it is known that the angle between the seismic wave propagation direction and the slide mass influences the degree of slope deformation. This affects the possibility of GNSS acceleration as a coordinated earthquake disaster warning. Since GNSS acceleration monitoring uses the RTK(Real-time kinematic) relative positioning technique, the analysis of the measurement results is derived from the relative position change data of the base station concerning the slide mass monitoring point. Earthquakes can cause simultaneous displacements of GNSS monitoring points and base stations in slide mass, resulting in inaccurate data. Therefore, we need to analyze the slope monitoring points in the region to increase the feasibility of early warning.

The concept of a GNSS landslide monitoring cluster (GNSS-LMC) to assist earthquake early warning is proposed through the response made by GNSS monitoring points of the Baoshan earthquake, as shown in Fig. 7. A single GNSS landslide monitoring point monitors a small area around the point. Multiple GNSS landslide monitoring points in a small area can form a small GNSS landslide monitoring network. When multiple GNSS landslide monitoring networks collaborate, they form GNSS-LMC, which can monitor the space within the monitoring cluster for early warning.

Active faults are prone to earthquakes. The Baoshan earthquake in this paper also occurred near the fault. Therefore, it is critical to study potential landslides in their vicinity. Therefore, when establishing the GNSS-LMC, the seismic risk should be assessed jointly with the relevant local departments, and the relevant GNSS monitoring points in the region should be selected.

The location and number of monitoring points need to be considered for individual point monitoring. It is necessary to choose the part of landslide deformation as the monitoring point. At the same time, according to the different scales and nature of the landslide, different numbers of monitoring points need to be arranged in

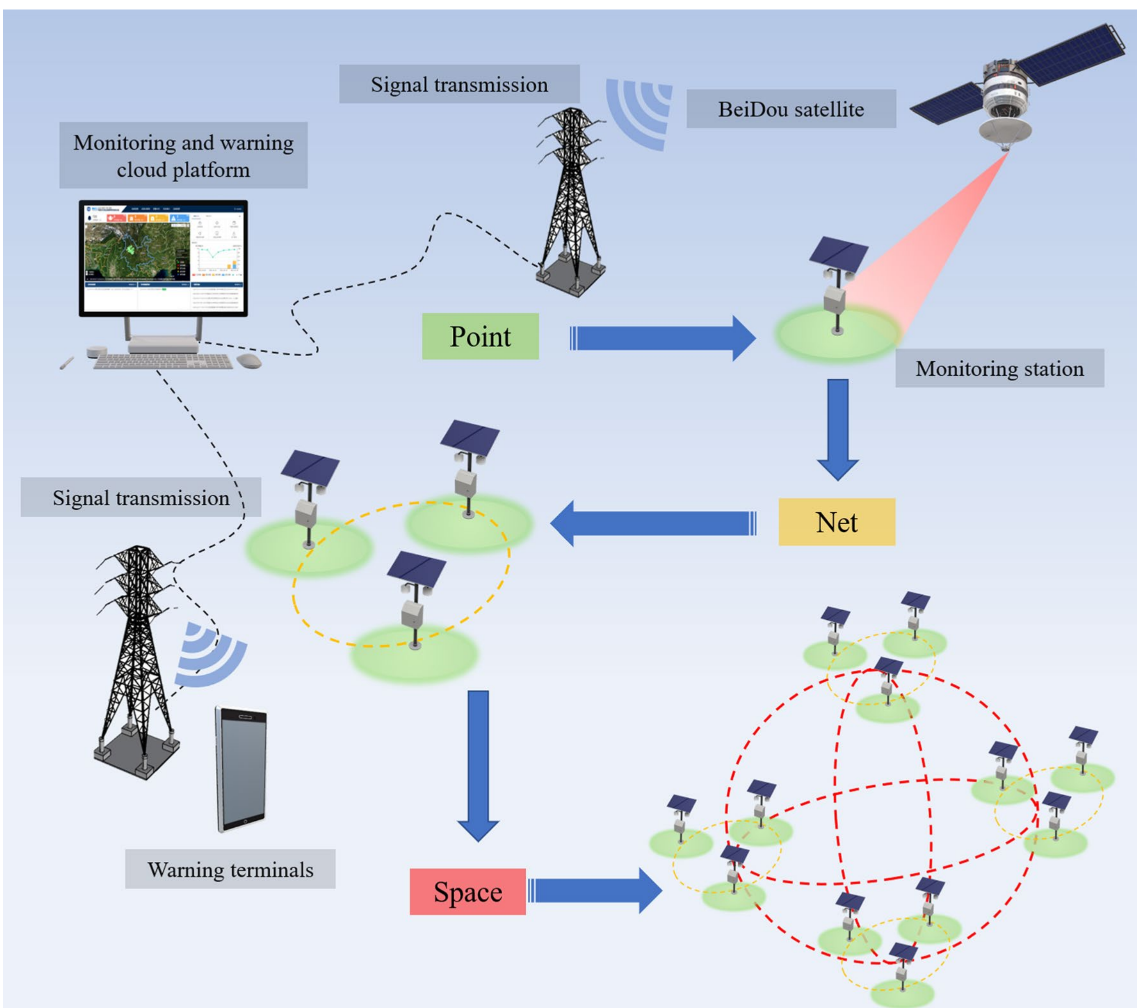

Fig. 7 Schematic diagram of GNSS-LMC relationship

different areas to realize real-time monitoring of individual landslide surfaces.

In network monitoring, a monitoring grid containing multiple monitoring points needs to be established to determine signs of landslide deformation or earthquake occurrence within the monitoring grid by collecting the location information of all monitoring points at regular intervals. The slope directions within the grid should be as rich as possible to increase the probability that the slope monitoring points will respond to seismic waves coming from all directions. When the monitoring data of multiple monitoring points in the grid are abnormal, it indicates that a serious geological disaster has occurred within the grid and realizes the early warning of geological disaster assistance in the monitoring grid.

Regarding space monitoring, the landslide area needs to be taken as the monitoring area, and a full-coverage monitoring system needs to be established. This system should contain several monitoring grids, and each grid should contain several monitoring points. In data processing, the time and spatial span of data analysis must be taken into account to comprehensively analyze the geological hazards in the monitoring space.

If an earthquake occurs in the GNSS-LMC space and multiple monitoring points have acceleration anomalies exceeding the threshold value within a short period, the monitoring and warning cloud platform is used as a medium to generate warning messages to people in the monitoring cluster space through the warning terminal. The GNSS-LMC realizes the multi-dimensional landslide-earthquake disaster warning combined system, net, and space. It achieves the purpose of increasing monitoring parameters and reducing monitoring and warning costs, which integrates landslide and earthquake monitoring. Therefore, for GNSS landslide monitoring systems, point, net, and space monitoring are all critical monitoring methods. Different monitoring methods complement each other, which can comprehensively grasp the deformation of landslides and, at the same time, have a certain auxiliary early warning effect on the earthquake in the region.

Conclusion

The May 2, 2023, $M_W = 5.2$ Baoshan earthquake in Yunnan was used as a background. The correlation between GNSS landslide monitoring and seismic response is studied based on the geological hazard monitoring management system in Yunnan Province. The following conclusions are drawn:

(1) After the May 2, 2023, $M_W = 5.2$ earthquake in Baoshan, Yunnan Province, 31 GNSS monitoring points around the epicenter monitored acceleration anomalies. After analyzing the data, it can be seen that the acceleration of all 31 monitoring points increased abruptly within one minute after the earthquake, and the fastest response time was 8 s. This case proves that the GNSS landslide monitoring system has a highly sensitive response to earthquakes occurring in the surrounding area.

(2) The acceleration anomaly data of 31 monitoring points show dispersion as a whole. The data were divided into regions for more accurate analysis using the distance from the epicenter location as the benchmark. The data were fitted by regionally culling out the outliers and averaging them. After fitting, it was found that the response time was a linear correlation with the distance.

(3) GNSS-LMC is proposed to assist earthquake prediction. Multiple GNSS landslide monitoring points form GNSS-LCM, which can respond to earthquakes occurring in the corresponding space and assist the earthquake early warning system. The GNSS-LMC is a multi-dimensional monitoring system from point, net, and space to realize the integration of landslides and earthquake early warning.

Author contributions

ZT: Funding acquisition; Supervision; Project administration. ML: Investigation. QS: Conceptualization; Methodology; Formal Analysis; Validation; Visualization; Investigation; Writing – original draft; Writing – review & editing. YM: Investigation; Visualization. MH: Funding acquisition; Supervision. YJ: Resources.

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Data availability

Data sets generated during the current study are available from the author (Yuebin Jiang, E-mail: 727413969@qq.com) on reasonable request. The data are available from the geological disaster monitoring and early warning management system in Yunnan province, but restrictions apply to the availability of these data, which were used under license for the current study and so are not publicly available.

Declarations

Competing interests

The authors declare no competing interests.

Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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