A new method for early warning of dangerous rock collapse based on tilt and vibration parameters

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Abstract. Dangerous rock refers to an unstable rock block that is cut by weak structural planes and gradually separates from the slope, and at present, it is challenging to effectively identify the separation degree of dangerous rock and accurately warn of its sudden failure. In this paper, a microelectromechanical system (MEMS) acceleration sensor is used in combination with the calculation principle of the included angle of the space vector to establish an integrated monitoring method of the microtilt angle and strong vibration acceleration (SVA). Through long-term field monitoring, the tilt angle and the SVA information of the whole collapse process are obtained. The analysis results show that (1) the tilt-time curve of dangerous rock is of the step-type, and the continuous and rapid increase of the tilt rate is a deformation precursor characteristic of a collapse; (2) in the absence of strong vibration source disturbance, the SVA is an early identification parameter for dangerous and stable rock, and the abnormal increase of triggering frequency of the SVA is the vibration precursor characteristic of a collapse; (3) three warning modes of dangerous rock based on the tilt rate and the SVA are obtained, i.e., stable mode, perturbation mode and alarm mode. This study provides an important early warning indicator for rock collapse.

1. Introduction

Dangerous rock refers to an unstable rock block that is cut by multiple sets of structural planes on a steep rock slope and gradually separates from the slope under the action of gravity, weathering agents, seepage pressure, and seismic forces [1]. Notably, the collapse of dangerous rock is a globally occurring geological disaster that considerably threatens the safety of infrastructure, human life and property. To reduce disaster risks and losses, it is necessary to prevent dangerous rock collapse events by effective monitoring and early warning.

For decades, displacement has been an important early warning index for slope disasters [2-3]. In experiments and engineering applications, slope instability early warning and prediction have been successfully carried out through the creep evolution law of displacement [4-14]. Different from the creep deformation evolution characteristics of large-scale landslides, dangerous rock undergoes sudden collapse under small structural deformations [15-16]. To monitor the evolution characteristics of dangerous rock deformation and realize the early warning of collapse, the monitoring sensor should have the basic requirements of high resolution, high accuracy and high sampling frequency simultaneously. The traditional use of total stations and other geodetic methods has high monitoring accuracy but requires manual and regular operations, resulting in insufficient timeliness. The method of monitoring the crack opening by connecting the extensometer to the data acquisition and transmission equipment can realize automatic monitoring, but it has the disadvantages of low terrain...
adaptability and complicated installation and maintenance. The displacement monitoring method based on the global navigation satellite system also has the shortcomings that the high-precision data calculation cycle is long and that the stability is easily affected by weather conditions. In recent years, advanced equipment such as laser radar and synthetic aperture radar has been successfully applied to millimeter-level displacement monitoring and risk zoning of rock slopes [11-14]. However, due to their high price and strong need for professional personnel, they are not suitable for long-term automatic monitoring of scattered dangerous rock masses.

To improve the applicability of dangerous rock monitoring and early warning technology, with the development of microelectromechanical system (MEMS), researchers have proposed the use of MEMS sensing technology for simple and efficient slope monitoring and early warning. Uchimura et al. [17] designed a low-cost slope warning method using a MEMS tiltmeter and a water content sensor to replace the extensometer, and through simulated rainfall experiments, they found that the abnormal behavior of the surface tilt angle can be used as an early warning sign for slopes. Uchimura et al. [18] further conducted a field monitoring test by using the method of artificial rainfall on a slope. They recommended to issue preventive measures at a tilt rate of 0.011° per hour and to issue a warning at a tilt rate of 0.11° per hour. Dikshit et al. [19] used the above method to carry out long-term monitoring of large-scale landslides and verified the effectiveness of MEMS-based sensing technology in the monitoring of rainfall-type landslides. Compared with conventional slope displacement monitoring instruments, the MEMS sensors are more precise in workmanship, smaller in size and lower in price, which greatly reduces the cost of building an early warning system [20]. Xie et al. [21] developed a slope disaster early warning system that integrates tilt and vibration parameters through MEMS acceleration sensors and narrow-band Internet of Things communication technology. In recent years, researchers have used MEMS sensing technology to study the evolution law of shallow landslide surface tilt angles [22-23], but the applicability and feasibility of this technology for early warning of collapse disasters has not yet been verified.

2. Monitoring method

2.1 Field monitoring system

In response to the monitoring and early warning requirements of dangerous rock collapse disasters, we have developed a first-generation monitoring and early warning system based on MEMS sensing technology. The sensing layer of the system adopts an intelligent MEMS sensor equipped with a photovoltaic self-powered module to obtain the static-dynamic acceleration of the dangerous rock mass in real time. After the data preprocessing module of the built-in edge computing system performs data calculation and discrimination, the tilt angle, strong vibration acceleration (SVA) and temperature information are sent to the base station for data collection and transmission. The base station integrates a solar panel, camera, alarm light and rain gauge by the LoRa wireless communication module. The transmission layer uses 2G/4G mobile communication technology to send the monitoring data to the cloud platform for further storage and analysis. The application layer uses the human-computer interaction platform to dynamically display the multiple monitoring data and early warning evaluation results of dangerous rock. The IoT framework of the monitoring and early warning system is shown in Figure 1.

![Figure 1](image-url)
2.2 Tilt angle and the SVA algorithm

After the intelligent MEMS sensor is fixed on the dangerous rock mass of the slope, it actively obtains the three-axis acceleration components at a sampling frequency of 1,000 Hz, including the static acceleration (gravitational acceleration) component and the dynamic acceleration (vibration acceleration) component, which can be expressed by the following formula:

\[
\begin{bmatrix}
A_x \\
A_y \\
A_z
\end{bmatrix} = \begin{bmatrix} g_x \\
g_y \\
g_z \end{bmatrix} + \begin{bmatrix} a_x \\
a_y \\
a_z \end{bmatrix}
\]

(1)

where \(A_x, A_y,\) and \(A_z\) are the three-axis acceleration signals output of the smart MEMS sensor; \(g_x, g_y,\) and \(g_z\) are the three components of the gravitational acceleration vector in the monitoring area; and \(a_x, a_y,\) and \(a_z\) are the three components of the additional vibration acceleration vector.

When the dangerous rock mass is in a static state, the sensor acceleration signal vector after filtering and denoising and the tilt angle change obtained by the calculation principle of the space vector included angle are expressed by the following formulas [16]:

\[
\overrightarrow{OA}_0 = [g_{x0}, g_{y0}, g_{z0}]
\]

(2)

\[
\overrightarrow{OA} = [g_{x}, g_{y}, g_{z}]
\]

(3)

\[
\theta = \arccos\left(\frac{\overrightarrow{OA}_0 \cdot \overrightarrow{OA}}{|\overrightarrow{OA}_0| \cdot |\overrightarrow{OA}|}\right)
\]

(4)

where \(\overrightarrow{OA}_0\) is the initial state acceleration signal vector after the sensor is installed; \(\overrightarrow{OA}\) is the acceleration signal vector during the monitoring process; \(\theta\) is the tilt angle variation, and the average value within 1 s is taken during actual monitoring.

When the dangerous rock mass produces strong vibrations, the SVA is defined as the modulus length of the resultant vibration acceleration vector, which is expressed by the following formula:

\[
A = \sqrt{a_x^2 + a_y^2 + a_z^2}
\]

(5)

where \(A\) is the strong vibration acceleration, and the maximum value within 1 s is taken in the actual monitoring.

2.3 Acquisition and transmission mode

Dangerous rock has been static for a long time in nature, and the failure is extremely sudden. Therefore, the collection and transmission of dangerous rock monitoring information requires high frequency and low power consumption. To this end, we designed an integrated acquisition and transmission mode for the acceleration and tilt angle. Through the combination of 1000 Hz high-frequency acquisition, timing and threshold trigger wake-up transmission, it not only ensures the real-time acquisition of monitoring information but also effectively saves sensor power consumption. According to field test experience and actual application requirements, the initial timing transmission frequency of the tilt angle of dangerous rock mass monitoring is set to 1 time/hour, and the trigger transmission threshold is 5° to achieve the acquisition of the continuous tilt trends and abnormal tilt angles. The vibration trigger transmission threshold is 10 mg, which can keep the device on standby under natural environmental noise.

3. Application case

3.1 Description of the monitoring site

The first application case is in Guangdong Province, China. Due to the living customs of local residents, it is common to build houses by cutting slopes, which affects the stability of the slopes. According to a site survey, the dangerous slope is approximately 15 m high, with a slope of approximately 75°, and the lithology is fully weathered granite. The excavation of the rock mass destroys the stress balance of the original mountain mass, resulting in unloading fissures in the upper part of the slope and formation of dangerous rocks with steeply inclined fissures, the size of which is approximately 3.3×1.2×2.6 m, and there is a high risk of collapse. We installed 3 MEMS sensors on site, fixed them on the upper slope of the excavation area and the surface of the dangerous rock, and set up rainfall and video monitoring stations for long-term automatic monitoring. Figure 2 is an image
of the dangerous slope. Figure 3 is an image of the dangerous rock. Figure 4 is a cross-sectional sketch of the dangerous rock.

![Figure 2. Image of the dangerous slope.](image)

![Figure 3. Image of the dangerous rock.](image)

![Figure 4. Dangerous rock cross-sectional sketch.](image)

3.2 Monitoring results

The monitoring system started to operate stably at 10:00:00 on January 12, 2020, and the dangerous rock collapsed at approximately 6:55:00 on April 24, 2020. Figure 5 shows the image after the collapse of the dangerous rock. Figure 6 shows the time history of the monitoring information from the MEMS sensor and the rainfall station during this monitoring period. Figure 6(a) shows that the average hourly rainfall during the period is 0.16 mm, the average three-day rainfall is 11.61 mm, and there is no short-term heavy rainfall. The collapse of the dangerous rock is the result of the joint action of self-gravity, excavation unloading and long-term rainfall infiltration. Figure 6(b) shows that the monitoring information of sensor 1 and sensor 3 only includes the tilt angle, and no SVA signal is obtained. Due to the influence of noise and environmental temperature differences, the tilt angle fluctuates slightly in the range of approximately ±0.06°, a continuous and stable trend, which is consistent with the stable state of the monitoring position. From Figure 6(c), it can be seen that sensor 2 placed on the surface of the dangerous rock shows a "step-type" tilt curve with a stepped ascent characteristic, which is consistent with the monitoring results in Ref. 16. Before 01:00:00 on March 17, the change in the tilt angle of the dangerous rock stabilized at approximately 0.23° and then increased at an average rate of 0.014°/hour, reaching 0.56° at 00:00:00 on March 18 and maintaining long-term stability. It entered the accelerated growth phase at 12:00:00 on April 21. After the acceleration lasted for 66 hours, it increased to 2.318° at 6:00:00 on April 24. At 6:55:03 on April 24, the threshold triggers the acquisition. The tilt angle signal suddenly changed to 97.645°, indicating that the dangerous rock collapsed.

It is noteworthy that, unlike the stable monitoring position, sensor 2 has collected 5 threshold-triggered SVA signals. When the first two SVA signals (1.784 g, 1.428 g) appear, the tilt angle monitoring curve remains stable, and it has been confirmed that there is no artificial vibration disturbance at the site, which indicates that the SVA signal that appears before the accelerated deformation of the dangerous rock may be due to changes in the stress field, i.e., the resulting rock fracture signal. Therefore, the SVA can be used as a characteristic parameter for the early identification of dangerous rock and stable rock. In addition, three strong vibration signals (0.935 g, 0.746 g, and 1.811 g) were obtained within 23 hours before the collapse. Therefore, in the absence of a strong vibration source disturbance, the SVA is an early identification parameter for dangerous rock and stable rock, and the increase in triggering frequency of the SVA can characterize the strong vibration behavior caused by fissure extension, which is the precursor of collapse. According to the abnormal behavior of the tilt and vibration of the dangerous rock, we issued a hazard avoidance reminder one hour before the collapse.
Figure 5. Image after the rock collapse.

Figure 6. Field monitoring information.

4. Characteristic analysis of the tilt rate-time curve

To obtain the effective tilt warning indicators of dangerous rock collapse, we tried to analyze the tilt rate-time curve characteristics. Figure 7 shows the tilt rate-time curves of two cases, which are the monitoring results in this paper (Figure 7(a)) and Ref. 16 (Figure 7(b)). It can be intuitively found that
due to the slow deformation of dangerous rocks and influenced by the environment and equipment noise, the tilt rate fluctuates slightly around 0 for a long time, but there inevitably are gross errors due to large perturbations such as sudden changes in ambient temperature or site vibration, for example, in Case II at 03:00:00 on May 9, the tilt rate reached 0.029°/h and then immediately fell back. Before the approaching collapse, the tilt rate shows a continuous and rapid increase. After eliminating the gross error, there is a threshold $\lambda$ before the rapid increase in the tilt rate. After the tilt rate exceeds $\lambda$, it enters a continuous increase stage. In Case I, $\lambda=0.020°/h$, and in Case II, $\lambda=0.013°/h$, and all appear in the step process of the tilt angle. In the two cases, when the tilt rate exceeded $\lambda$, collapse occurred after 24 hours and 21.5 hours, and collapse occurred after 13 hours and 7.5 hours after exceeding $2\lambda$. Since $\lambda$ is an indicator that continuously adjusts in the monitoring process, we recommend using $\lambda$ as a high-risk warning indicator and $2\lambda$ as a critical collapse warning indicator.

![Figure 7. Dangerous rock tilt rate-time curve of the two cases.](image)

5. Warning mode analysis based on the tilt rate and the SVA

The dangerous rock monitoring parameters used in this paper include the dip angle, SVA and rainfall. As shown in Figure 6 (a), whether hourly precipitation or 3-day precipitation occurred, the tilt and precipitation were weakly correlated. The precipitation in the 3 days before the collapse was the maximum during the monitoring period, indicating that precipitation is an important inducing factor for the collapse of dangerous rock, which is consistent with the monitoring results obtained in Ref. 16. At present, it is difficult to obtain an accurate precipitation warning threshold. Therefore, the following only analyzes the dangerous rock warning mode on the coupling curve of the tilt rate and SVA.

(1) Stable mode
- The tilt rate fluctuates slightly around 0, there may be a sudden change at a certain moment caused by sudden changes in ambient temperature or site vibration, and the SVA signal is not triggered, as shown in Figure 8(a). The rock mass is in a stable state.

(2) Perturbation mode
- The tilt rate gradually increases in a short period of time and then stabilizes, as shown in Figure 8(b). The dangerous rock has undergone a slow separation process.
- In the absence of a strong vibration source disturbance, an SVA appears, as shown in Figure 8(c). A dangerous rock mass may exhibit fracture behavior.
Under the above two types of conditions, the rock mass is in a substable state, and there is a potential risk of collapse.

(3) Alarm mode
- The tilt rate continuously and rapidly increases, as shown in Figure 8(d). At this time, the dangerous rock accelerates its deformation.
- The tilt rate increases rapidly, and there is an SVA signal, as shown in Figure 8(e). At this time, the dangerous rock is accelerating its separation and has strong vibration behavior.

In the above two types of situations, the rock is at risk of near collapse, and a warning evaluation should be carried out in time, and emergency rescue work should be deployed.

![Figure 8. Warning mode based on the tilt rate and SVA](image)

6. Conclusions
A monitoring and warning system for dangerous rock based on MEMS sensing technology has been developed. The tilt angle and SVA data of the whole process of collapse were obtained through long-term field monitoring. The main research conclusions are as follows:

(1) The tilt angle can indicate the separation degree of the dangerous rock, and the tilt-time curve of dangerous rock is of the step-type.

(2) Affected by equipment and environmental noise, the changing trend of the tilt rate during the slow separation of dangerous rock may be concealed by random errors, causing the tilt rate-time curve to remain fluctuating around 0 for a long time, while the tilt rate has a continuous and rapid increase trend only in the near collapse stage. An early warning index $\lambda$ based on the tilt rate is proposed. It is recommended to use $\lambda$ as a high-risk warning threshold and $2\lambda$ as a critical collapse warning threshold.

(3) In the absence of a strong vibration source disturbance, the SVA is an early identification parameter for dangerous rock and stable rock, and the abnormal increase in the triggering frequency of the SVA can characterize the continuous strong vibration behavior caused by fissure extension, which is the precursor of collapse.

(4) Three types of dangerous rock monitoring and early warning modes through the dip rate and the SVA curve are obtained. The stable mode indicates that the rock is in a stable state, the perturbation mode indicates that the rock has a potential risk of collapse, and the alarm mode indicates that the rock is near collapse.

Data Availability
The data used to support the findings of the study are included in the article.

Conflicts of Interest
The authors declare no conflicts of interest.

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