Slope Stability Risk Management in Open Pit Mines

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Abstract

The stability of slopes in open pit mines is an issue of great concern because of the significant detrimental consequences instabilities can have. To ensure the safe and continuous economic operation of these mines, it is necessary to systematically assess and manage slope stability risk. This, however, has not been traditionally easy due to the fact that measuring the parameters needed to assess the stability of slopes can be laborious, expensive, and cause disruption to mining operations. This paper presents a framework based on decision theory by which risk can be systematically assessed and managed, and proposes a combination of traditional, and remote sensing techniques, both earth and satellite based, to measure certain parameters. This combination allows one to assess and update risk in a more efficient and cost-effective way than is traditionally done particularly where satellite observation data is already available. The application of such a system at the Nanfen iron open pit mine in China is presented, where a novel technique for monitoring sliding forces on pre-stressed rock bolts was developed and successfully applied. This is the first step in building an automated risk management system, which in the future will include smart sensors for warning systems and stabilization methods based on materials that can self-adjust their properties such as strength, and stiffness in response to potential instabilities.

Keywords: Risk Management, Decision Analysis, Slope Stability, Open Pit Mines, Remote Sensing.

Introduction

Open pit mines are among the largest geotechnical structures in the world and are located necessarily where ore can be extracted economically. These are frequently in inconvenient locations for the geotechnical engineer because processes such as seepage concentrate the ore along a fault, which then passes through the pit. It is not uncommon to find strata on opposite sides of the fault dipping in different directions and having different geotechnical properties.

Excavating these mines usually takes place in benches, and as such the stability of individual benches as well as that of the overall slope must be ensured. Excavating and disposing of material are typically major costs in mine operation and therefore it is economically desirable to reduce the volume that needs to be excavated. This implies that the slopes of the pit be as steep as possible, which, in turn, implies greater danger of slope failures. Slope instabilities can have detrimental consequences in terms of socio-economic damage, and sometimes even loss of life. To ensure the safe and economic operation of these mines, it is necessary to systematically access and manage slope stability risk. This paper presents a framework based on decision theory by which risk can be systematically assessed and managed.
The risk assessment involves estimating the properties of the materials in the slopes, calculating the stability of various slope geometries, and monitoring the performance of the slopes as the pit is developed. The risk management involves making decisions on the actions to mitigate these risks.

Warning systems are described with emphasis placed on monitoring systems based on traditional and remote sensed data. The application of a warning system in the Nanfen iron open pit mine in China is presented where a novel technique for monitoring sliding forces on pre-stressed rock bolts was developed and successfully applied.

In the future, risk management systems will become automated and include smart sensors and materials that have self-adjusting properties.

Decision Analytical Approach to Slope Stability Risk Assessment and Management

Definitions

Risk can be expressed in many different ways. The definitions used in this paper are based on the ISSMGE recommended Glossary of risk assessment terms (TC32).

Danger (Threat): Phenomenon, natural or manmade, that could lead to damage

Hazard: Probability that a danger (threat) occurs within a given period of time

Consequence (Damage): Result of a hazard being realized

Vulnerability: Degree of loss to a given element or set of elements within the area affected by a hazard

Risk: Measure of the probability and severity of an adverse effect on life, health, property, or the environment

Following these definitions, risk can be expressed as:

\[ R = P(T) \times \sum_i P(C_i | T) \times u(C_i) \]  

(1)

Where:

\( R \) is Risk; \( P(T) \) is the hazard, defined as the probability that a particular threat occurs within a given period;

\( \sum_i P(C_i | T) \) is the vulnerability, defined as the conditional probability that consequences \( C_i \) occur given the threat;

\( C_i \) are consequences which can include for example economic damage, as well as those that affect human lives, such as injuries and fatalities; and \( u(C_i) \) is the utility of consequences \( C_i \), defined as a function that describes a decision maker’s relative preferences between attributes.

Framework

Decision analysis provides a framework by which complex decision problems can be simplified, allowing one to more clearly make decisions based on alternatives [50, 41]. Fig. 1 Figis a graphical representation of decision making under uncertainty as proposed by [162, 61]. This process is actually also the standard decision-making process used in engineering in which one determines parameters, includes them in models and makes decisions based on the model results. Fig. 2 represents the decision analytical approach applied to natural threat risk assessment and management. The updating cycle in Figcan, amongst other things, represent the observational method in geotechnical engineering [66, 60, 14].
The steps or levels in the decision analytical approach (Fig) are described in the following. Since this paper is related to risk management, the emphasis is placed on this level whereas the other levels are briefly described.

**Level 1: Assess the State of Nature**

In decision analytical terms, this level forms part of the information collection. This information pertains to the factors that affect the stability of slopes in open pit mines. Slope instability initiation is complex and depends on a great number of factors and the interaction between them. Some of these factors are shown in Fig.

**Figure 1:** The Decision Analysis Cycle.

**Figure 2:** Decision Analytical Approach to Natural Threat Risk Assessment and Management [16].
The geology of a mine site is usually well known because the investigations that led to the establishment of the mine in the first place should provide a reasonable geological description of the site. In contrast, engineering properties of soils and rocks that affect the stability of slopes are often less well known. Gravitational loads are the most important loads affecting the stability of a slope in a mine, and the major resistance to failure is the shear strength of the ground. This is a major concern of geotechnical engineers since the strength parameters can vary significantly even in small areas. The strength of a rock mass is affected by not only the intrinsic rock strength but also the existence, and persistence of fractures and joint sets, patterns, and networks. Furthermore, the percolation of pore fluids have major effects on the stability, and subsurface flow regimes can be complex. In addition, natural events, such as rainfall and earthquakes, and man-made factors, such as blasting, can serve as triggers to slope instabilities [47,43].

Collecting information on the parameters that affect slope stability, or site characterization, is usually done through exploration schemes. Exploration is defined as information collection that involves processes of induction based on interpretations of regional geology and geologic history, as well as a deduction based on site investigations and measurements. Typically, information may comprise traditional techniques such as maps, photographs, boring logs, topographical data, weather data and visual observations. Site characterization, however, requires the allocation of resources, effort, and money, both of which are usually scarce, and therefore a tradeoff is usually made between the value of exploration and economics based on a cost-benefit analysis. Since this forms part of the cost of a mine operation, frequently not enough resources are allocated to site characterization as one would desire.
Level 2: Identify and Describe Danger

This involves both information collection and deterministic modeling. There are various techniques to assess slope stability that range in complexity from simple heuristic models to statistical models based on historical data, to more complex mechanical models which attempt to represent reality. A typical mode of slope failure in open pit mines involves a block of material sliding on two or three planes of discontinuity, known as rock wedges. The stability analysis of wedges in rock slopes involves resolution of forces in two or three-dimensional space. The problem has been extensively treated in, for example, [24, 46, 55, 36, 45, 37], Goodman [24,25,26], Hoek and Bray [37,39,70,69]. The methods used include stereographic projection technique, engineering graphics, and vector analysis.

Level 3: Determine Probabilities and Combine with Danger to Determine Hazards

Uncertainties are inherent to geology and geotechnical engineering since they deal with the underground and thus cannot be seen. Several categorizations of uncertainties have been proposed over the years that include [3, 4, 13, 8, 51]. [17] Discuss uncertainties in the context of slope stability risk assessment. It should also be noted that when formally assessing uncertainties, this can be done both by the relative frequentist or the subjective approach. These approaches and their applicability have been discussed by Baecher [3,13,15].The formal incorporation of uncertainties into the slope stability problem results in probabilities of slope instabilities or hazards. These can range in from first and second order reliability analyses [31, 68, 11,10] to full distribution probabilistic analyses based on numerical techniques [67, 56, 28]. Examples of such studies for the stability of slopes in open pit mines include for example [63, 30, 12, 22, 58] as well as others.

Level 4: Risk Assessment

In Section 2.1, risk was defined as a measure of the probability and severity of an adverse effect on life, health, property, or the environment or the product of the hazard and the potential worth of loss. Risk is therefore obtained as a combination of the quantified hazard with the quantification of consequences conditional on the hazard (eq. (1)). It is worth noting that a particular hazard can have different consequences. The quantification of consequences requires the identification of consequences and associating an expression of loss with them. This expression is usually in the form of a utility function [1, 2], which is a dimensionless transformation that describes the relative preferences of the decision maker towards different outcomes, as well as the decision maker’s attitude towards risk, i.e. risk neutral versus risk averse. For a detailed discussion on utility, reference is made to for example [50, 42, 41].

Level 5: Risk Management (Decisions)

A decision is an irrevocable allocation of resources. Decisions in the slope instability problem concern measures that can be taken to mitigate risk. These decisions, or actions, can range from construction countermeasures to administrative procedures. Typical actions include:
Passive countermeasures

Passive countermeasures reduce the vulnerability, resulting in a reduced risk $R'$:

$$R' = P[T] \times \sum_i P[C_i | T] \times u(C_i) + u(C_{\text{pas}})$$

(2)

Where:

$P[C_i | T]$ is the reduced vulnerability; $u(C_{\text{pas}})$ is the utility associated with the cost of the passive countermeasure; and other terms are as defined for Eq. (1).

Examples of passive countermeasures include galleries and nets.

Active countermeasures

Active countermeasures reduce the hazard, resulting in a reduced risk $R'$:

$$R' = P[T] \times \sum_i P[C_i | T] \times u(C_i) + u(C_{\text{act}})$$

(3)

where: $P[T]$ is the reduced probability of threat; $u(C_{\text{act}})$ is the utility associated with the cost of the active countermeasure; and other terms as defined for Eq. (1).

Examples of active countermeasures include rock bolts (anchors), tie-backs and retaining structures.

Warning systems

Warning systems mitigate risk by reducing consequences. Warning systems consist of devices capturing relevant signals, models for relating the signal to potential threats, people and procedures interpreting the modeled results, evaluating consequences and issuing warnings. Such warnings have then to be communicated to potentially affected areas and lead to passive or active countermeasures.

Warning Systems include the following components:

1. Monitoring systems (data acquisition) that track a threat such as a slope instability
2. Communication systems (data transmission) that continually transmit measurements to experts
3. Models that predict (data analysis and interpretation) the threat in the short and long terms
4. Alarm systems that transmit the warning signal(s) to the potentially affected parties efficiently and effectively when a predefined alarm threshold is exceeded
5. Specific Actions (procedures) that are implemented during the warning (evacuations routes, assembly points, others), as well as those after the warning

Error! Reference source not found. shows a flow chart for a warning system with the typical components involved.

Given the uncertainties involved in each of the components above, warning systems have a reliability associated with them. That is to say that warning systems can, on the one hand, fail to issue an alarm before a threat materializes, and on the other hand, issue false alarms. Well-designed warning systems attempt, to the extent possible, to reduce these events so as not to lose credibility, and hence effectiveness. It is also important for warning systems to be flexible and updatable both during an event/threat and as experience and technical capabilities increase.
Monitoring is the key to slope instability assessment, management, and mitigation. The objective of a landslide monitoring program is to systematically collect, record and analyze qualitative and quantitative information. Designing a monitoring program includes the following steps:

1. Define the objective of the monitoring program and select the type of measurements to be included in the program, assigning priorities to measurements.
2. On a cost-benefit basis, decide on the measurement methods to be used and select the appropriate instruments.
3. Determine the optimum number of instruments and locations; if possible, use theoretical or empirical models to optimize the number and placement of instruments.
4. Decide on the preferred method of data acquisition, e.g. manual or automatic recordings.
5. Arrange for proper installation, protection and marking of instruments and reference points in the field.
6. Plan for data flow, data management and analysis.
7. Plan for adequate maintenance of the monitoring system.

Traditionally, monitoring systems have been based on information collection using visual observations to look for evidence of instability, coupled with surface and subsurface measurements to detect movements. While these techniques still play an important role in monitoring instabilities, they suffer from various drawbacks mostly related to the fact that they can be localized. The use of remotely sensed measurements is becoming more widespread with technological advancements, and as these methods become more cost effective. The integration of Synthetic Aperture Radar (SAR) and optical images, along with interferometric SAR (InSAR) techniques, are currently being used to characterize instabilities. New techniques such as Differential Synthetic Aperture Radar (DInSAR) and high-resolution image processing are also increasingly being used in risk assessment studies. Ground-based radar devices such as Linear SAR (LISA) are capable of assessing the deformation field of an unstable slope in the areas characterized by a high radar reflectivity. Near-surface geophysical methods such as

Figure 4: Block Diagram for Warning System [9].
seismic, gravimetric, magnetic, electric and electromagnetic, can be used to monitor hydrogeological phenomena, and electric and electromagnetic survey techniques can be applied to areas with complex geology. These remote sensing tools are practical and for many of them, affordable, particularly in open pit mines where consequences can be very detrimental. Table 1 shows some of the techniques, as well as their strengths and limitations [54].

It is important to note that monitoring slope instabilities have to be coupled with continuous, and if possible real time measurements on triggering events, such as rainfall, and induced vibrations. One also needs to consider the different models of failure in interpreting the data and modes of failure in data interpretation and the setting of threshold values to issue alarms.

Traditional landslide monitoring systems have been based on measuring movements. These techniques cannot easily predict brittle slope failures or failure that change from ductile to brittle. Where a slope failure is brittle, an observation of no movement could give a false sense of security. In Section 3, a case study is presented where a warning system was successfully implemented in the Nanfen Open Pit Iron Mine in China. The warning system is based on a monitoring system that uses a novel technique to measure forces to complement displacement, as well as other, measurements.

**Level 6: Information Model**

Slope stability risk assessments, as well as standard geotechnical engineering practice involve the gathering of additional information. This involves updating prior probabilities to result in posterior probabilities that reflect the new information. This is usually done using Bayesian updating. It is possible and often desirable to check whether it is worthwhile to collect additional information through the information modeling prior to actually going out and obtaining the information. This is done through the process of pre-posterior or virtual exploration. This process has been applied in the context of tunnel exploration planning in [48, 49] and for landslides in [20].

**Early Warning System: The Nanfen Open Pit Iron Mine**

Traditional landslide monitoring systems have often been based on displacements measurements because these are easy to do, and the necessary equipment is widely available. The issue with measuring displacements is that for brittle failures, early detection of movements comes too late. Monitoring forces, or stresses, is more desirable since these reflect the kinematic characteristic of a slope. Force and stress measurements are however not very easy because they form part of a natural system and are not easy to measure often requiring sophisticated methods.

A system to measure forces was developed at the China University of Mining and Technology, Beijing (SKLGDUE) and first applied to the Three Gorges Project in China [32,35]. The basic principles of the monitoring system are shown in Fig. 5. A set of high-resolution sensors are installed at pre-selected measurement locations, which are then connected to a data acquisition and transmission system, as shown in Fig. 6. With small radio antennas mounted at the measurement locations, they are connected through a base station to a wireless receiver. The data received is transferred via satellite to a control station where data from all measurement locations is analyzed, and the stability of the entire slope system is updated based on these measurements [33].
Table 1. Remote sensing technologies: strength and limitations, after [44, 54, and 51].

<table>
<thead>
<tr>
<th>System</th>
<th>Applications</th>
<th>Resolution</th>
<th>Limitations</th>
<th>Strengths - DEM from all</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrestrial</td>
<td>Joint survey, scarp and change detection</td>
<td>cm to m, depending on the scale</td>
<td>Field of view, image resolution, requirement for surveyed positions, vegetation obscuring</td>
<td>Rapid, cheap, long term, record, stereoscopic; build DEMs and see terrain conditions</td>
<td>Digital Image-processing</td>
</tr>
<tr>
<td>Photogrammetry</td>
<td>Landslide inventory and time series analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Airborne</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LiDAR</td>
<td>Ground-based (Static)</td>
<td>mm to cm</td>
<td>Humidity, distance limitations, angular limitations, reflectivity, vegetation obscuring</td>
<td>Multi-return LiDAR allows earth model, very high accuracy, high rate of acquisition, perspective views possible</td>
<td>Cost Effective, Signal Processing Improvements, Automated feature extraction?</td>
</tr>
<tr>
<td></td>
<td>Ground-based (Mobile)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Airborne (Fixed Wing)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Airborne (Helicopter)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Standard</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Movement detection and monitoring, time series displacement, HR movement detection (ground based)</td>
<td></td>
<td>Visibility and shadowing, need reflectance, doesn't penetrate vegetation, limited to slow movements</td>
<td>Large area survey, long term monitoring, return frequency affects use, comparison or combination of ascending and descending paths, movement measurement, rapid mapping of targeted areas</td>
<td>More Frequent Satellite Passes, Monitoring of Faster Slope Instabilities</td>
</tr>
<tr>
<td>InSAR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PS</td>
<td>mm</td>
<td>As above but only works with stable reflectors, very expensive</td>
<td>As above with mm accuracy movement detection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ground-based</td>
<td></td>
<td></td>
<td>As above, and can pick up larger movements</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Optical Satellite Images</td>
<td>Landslide inventory and time series analysis</td>
<td>10's cm to 10's m</td>
<td>Expensive, image quality can be poor due to cloud cover</td>
<td>Landslide surveys, large area coverage, historical record since 1990's, change detection, rapid mapping of targeted areas</td>
<td>Higher resolution satellites to be deployed, more satellites will increase coverage and frequency</td>
</tr>
<tr>
<td>Weather Radar</td>
<td>Precipitation intensity, early warning from rainfall intensity and accumulation</td>
<td>Depending on calibration km</td>
<td>Calibration is required</td>
<td>Helps map spatial distribution of weather</td>
<td>Enhanced mapping of weather systems, cheaper systems</td>
</tr>
<tr>
<td>Others</td>
<td>Thermal, IR</td>
<td>Low Resolution</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The monitoring system was applied to the Nanfen Open Pit Iron mine in Liaoning Province, China. It is the largest open pit iron mine in Asia, covering an area of approximately 3 km long by 2 km in wide. In 2008, the mine underwent a series of expansions, and the current production capacity is about 10 million tons of iron ore per year [64, 71]. The mine consists of benches, each about 24 m high with an average slope angle of 46° on the western side (Figure 7: ). The total height of the slope is about 756 m.
The Nanfen open pit iron mine is located in the south wing of Heibei mountain inverted anticline, and geology is composed mainly of the Archean Anshan Group, Algonkian Liaohe Group, Sinian and Quaternary systems. The slopes are typically intercepted by 5 to 6 joint sets, two of which have potential impact on stability on the heading side: (1) Major Join Systems: these joints have an average attitude of 295/48, and the value of the roughness of the joints is about 2-4 according to the Barton [5], classification system. These joints form the main potential sliding surfaces on the heading side; (2) Secondary Joints Systems: these joints have an average attitude of 291/13, spreading extensively, and are characterized by small dip angles.

Twenty-eight sets of remote monitoring systems were installed at various re-selected locations in the mine as shown in Figure 8:

With continuous monitoring, the system was continually field calibrated and refined, which led to the development of a strong predictive tool. In October 2010, at monitoring location No. 334-4 (see Figure 8: ), large variations (increase) in sliding force were measured, and on October 5, 2011, a large slope failure occurred. The spatial distribution of monitoring points where the instability took place is shown in Fig.

Fig. 10a shows the monitoring stations and the geometry of the landslide that ultimately occurred. Fig. 10b shows the continuous measurements of sliding force, the cumulative amount of mining, as well as rainfall data in the days prior and post the landslide event. When combined, these provide an early warning system based on which actions, such as evacuations can be taken.
Figure 8: Outline of Nanfen open pit iron mine: sliding force monitoring points on the slope.

Figure 9: Spatial Distribution of Landslide at Nanfen Mine.
Figure 10: Early Warning System for Nanfen Open Pit Mine. a) Monitoring Stations and the Geometry of the Landslide. b) Measurements of Sliding Force, Cumulative Mining, and Rainfall Data Prior and Post Landslide.

A more detailed timeline of events prior to the occurrence of the 5 October 2011 landslide is shown in Table 2.

Table 2. Timeline and Observations Prior to 5 October 2011 Landslide at Nanfen Mine.

<table>
<thead>
<tr>
<th>Date</th>
<th>Laboratory Observations</th>
<th>Field Observations</th>
<th>Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 September 2011</td>
<td>Monitored forces at location No. 334-4 are very small, and monitoring curve tends to a straight horizontal line, indicating that the slope was relatively stable</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>1 October 2011</td>
<td>Sliding forces show a clear upward trend.</td>
<td>Field investigations did not find any surface cracks and other signs of slippage</td>
<td>None</td>
</tr>
<tr>
<td>2 October 2011</td>
<td>Sliding forces show a significant increase particularly at locations No. 322-334</td>
<td>Micro-fissures and cracks appear on the surface of the rock slope surface with a width of 15-40 cm and a length 1.5-5 m</td>
<td>None</td>
</tr>
<tr>
<td>3 October 2011</td>
<td>Sliding forces continue to increase</td>
<td>Cracks developed to become longer and wider, with a width of 25-60 cm and a length of 3-9 m.</td>
<td>Mining activities were stopped, and personnel and equipment were evacuated. These measures are reflected in the reduction of the cumulative mining (Fig. 10).</td>
</tr>
<tr>
<td>4 October 2011</td>
<td>Sliding forces, particularly at location No. 334-4 continue to rise although at a lesser rate</td>
<td>Cracks continue to extend and propagate</td>
<td>Mining activities continue to be halted as the slope is still deemed unstable</td>
</tr>
<tr>
<td>5 October 2011</td>
<td>Sliding forces at location No. 334-4 reduce abruptly from 1700 kN to 1400 kN indicating slope rupture with height 36m and length 50m</td>
<td>Intense rainfall event, (accumulated rainfall 31.8 mm in 3 hours)</td>
<td>None</td>
</tr>
</tbody>
</table>

The measurement of sliding force in the rock mass served, successfully, as a timely warning system in the case of the October landslide at the Nanfen Mine. Because of the continuous monitoring system, it was possible to
take decisive measures and present casualties and property losses. While it is true that there are economic opportunity costs to the cessation of mining activities, losses from the landslide occurring during mining operations would have been far greater, possibly including loss of lives.

The high-resolution sliding force monitoring system developed at SKLGDU provides a rapid and accurate early warning system for open pit mines. Monitoring sliding forces can better reflect the complex systems mines exist in which include natural systems, such as rainfall, erosion, and others, as well as manmade systems, such as excavation and blasting as the mine is developed.

**Future Trends**

With increasing global satellite coverage and access to open and in many occasions free data, remote sensing techniques are bound to play a more significant role in slope stability risk assessments in the future. Technological advancements will lead to the development of cheaper and more reliable sensors that can be deployed as part of monitoring systems. Increasing computing power and cheap storage are also likely to play more significant roles in the future enabling the acquisition, storage, and analysis of big data. In the future, the risk assessment and management procedure described in this paper may become fully automated. Smart sensors can issue alarms based on the results of the risk assessment. The properties of materials used in countermeasures can also become self-adjusting based on the risk assessment. For example, the strength and stiffness of rock bolts can vary in response to potential instabilities.

**Conclusions**

Decisions regarding mine operations, even which mines to open and close, are typically based on a cost to benefit analysis. Increasing urgency for economical, technological and environmental mining operations have placed unprecedented demand on engineers to design mines on a scale not attempted before. Modern management methods, such as the one described in this paper, can and should be used to systematically access and manage the risks associated with slope instabilities. Warning systems are effective tools to mitigate slope instability risks in mines. As remotely sensed data become more widely available and cheaper to collect, these techniques are bound to play a more significant role in monitoring systems of the future. The Nanfen Iron Ore case study showed that warning systems can be successfully used to prevent substantial economic losses, and possibly save lives.

**References**


