Failure process and modes of rockfall induced by underground mining: A case study of Kaiyang Phosphorite Mine rockfalls

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Abstract

The analysis of the failure processes and mechanisms of rockfalls that are associated with underground mining activities is presented. The study area is located in Kaiyang Phosphorite Mine in Southwest China, where the geological condition is dominated by anti-dip slopes with layers inclined backward into the natural slope with decreasing strength in the rock mass from the upper (dolomite-rich) to the lower (shale-rich) strata. The analysis is based on field investigation and laboratory experimental study using a gravitational simulation device. The results support the proposed failure mechanism by demonstrating the process of failure from the deformation of the roof and floor in the stopes, to the development of surface cracks near the top of slopes, and eventually to the formation of rockfalls as the surface cracks propagate along pre-existing joints. The rockfalls are classified into one of three failure modes: crack-toppling, crack-sliding, and crack-slumping, in which the failures are governed by the corresponding characteristics of the rock mass structure. The study of the failure process and their spatial and temporal correlation with the underground workings reveals warning signs or indicators of impending slope instability. Improved understanding of the failure process and indicators can aid in early identification and timely warning of geohazards in phosphorite mines.

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1. Introduction

Rockfalls are a slope process that involves the detachment and movement of rock fragments that vary in size. Typically, the detachment refers to sliding, toppling or falling, and the movement denotes bouncing, flying and rolling (Cruden and Varnes, 1996; Cruden, 1991; Evans and Hung, 1993). The most common triggering mechanisms of rock slope failure include rainfall, seismic events, volcanic activities and other environmental factors. The resulting failure processes have been well studied and presented by many researchers (Calder et al., 2002; Guzzetti et al., 2003; Hoek and Bray, 1981; Huang et al., 2011; Huang, 2009; Luckman, 1976). Ground movement in mining areas and the instability of slopes associated with underground workings has been reported throughout mining history (Carnie and Delacourt, 2000; Ewy and Hood, 1984; Hoek and Bray, 1981; Parise and Lollino, 2011; Swift and Reddish, 2002; Szwedzicki, 1999, 2001; Wyllie and Mah, 2004). However, underground mining induced rockfalls are often reported without systematic study or documentation. The analysis on the failure process and modes is not routinely presented in the literature principally because the failure often occurred after the abandonment of the mines with no records available (Szwedzicki, 2001). Research into underground mining induced rockfalls in China dates back to the 1980s from the study of the rockfalls in the Yangchi River mining area, which emphasized the critical role of underground mining as a contributing factor to rockfalls in addition to the localized geological structure of the slopes (Sun and Yao, 1983). The research was followed by many studies on underground mining induced rockfalls in China, but only limited studies have been presented to international readers (e.g. Li et al., 2004, 2006; Tang, 2009). None of these focused on the role of geologic structure on the failure processes and modes of rockfalls such as with the case study presented herein.

This paper focuses on providing an insight into the failure processes and modes of rockfall in Kaiyang Phosphorite Mine. The study area is located near the center of Guizhou Province in southwest China and was known for its high yield and good quality phosphorite prior to the 1980s. The rapid growth of small and poorly regulated mines caused severe damage to the geological and ecological environment with both underdeveloped mining technology and inadequate support measures. An extensive range of geohazards were reported including landslides, rockfalls, debris flows, surface subsidence and sinkholes in the mining area due to the adverse geological features (e.g. sharp cuts, deep valleys and steep hillslopes) and unevenly distributed seasonal rainfall. The mining area is approximately 45 km² and is incised by the Yangshui River and streams. The rockfalls along the right bank of the Yangshui River are shown in the photo in Fig. 1. More than 80 rockfalls have been reported in this area since 1958 covering a total area of approximately 2.8 million m². The majority of the rockfalls in Guizhou province have
been attributed to underground mining activities, and were often triggered by large precipitation. The failure mechanism and modes are strongly related to the localized geologic structure of the slope. A set of distinctive processes of failure are evident in the study area and found to be directly associated with the unique geological structure of the slope, i.e. the anti-dip layers inclined backward into the natural slope with decreasing strength from the upper stratum (dolomite-rich) to the lower stratum (shale-rich) with thin interbeds of phosphorite.

The study site is located in a region with a tropical monsoon climate and high humidity. The rainfall is concentrated in the period between May and September with an average annual precipitation of 1199.8 mm. The highest recorded monthly precipitation was 213.0 mm in July and the lowest was 32.4 mm in December. Based on rainfall records, the highest recorded daily precipitation reached 160.0 mm on June 24, 1995. The average temperature for the study area is 12.8 °C with the highest and lowest recorded average monthly temperature of 26.6 °C in July and 5.1 °C in January, respectively. The highest recorded temperature is 33.7 °C and the lowest is −10 °C.

The field investigation and analysis includes 46 rockfalls with volumes ranging from 1000 to 290,000 m³. The study of the failure mechanisms in this paper relies on an analysis of geological conditions and the mining activities through geological surveys, field investigations and measurements, and laboratory model experiments. Rock structure and lithological characteristics are discussed in the geological setting section below. Laboratory model experiments reveal the complete process of rock mass fracture and rockfall detachment. As indicated in many previous case studies, slope failures in mining areas do not occur without warning (Kaiser, 1993; Szwedzicki, 2003). Characterizing the failure mechanisms and process of rockfalls and the underlying phenomenon may be used for evaluating the stability of slopes for both active and inactive mines, and thus provide warning signs, such as excessive deformation on the slopes or inside the stopes, as indicators to aid in the early identification of geohazards.

2. Geological setting and mining activity

The mining area is located in the mid-mountainous area (between 1000 and 3500 m a.s.l.) along the Yangshui River valley as shown in the regional topographic map (Fig. 1). The steep valley sides were formed by the Yangshui River cutting into the anticline of the folded sedimentary layers with an elevation difference of approximately 1000 m. A cross section of a slope shown in Fig. 2 represents the typical strata in the vicinity of the slopes in the study site. The strata consist of mainly Cambrian and Sinian sediments. A diverse collection of lithology is found including limestone (Qing Xu Dong Group, Ed), overlying silty mudstone/quartz sandstone (Ming Xin Si Group, etm) and sandstone with laminated shale (Jing Ding Shan Group, et), underlain by the carbonate-rich mudstone with laminated shale (Niu Ti Tang Group, et), and phosphorite rock with quartz and sandstone (Dou Shan Tuo Group, Zbd), followed by the laminated shale and sandstone (Nan Tuo Group, Zbdy) with alternate layers of metasandstone and shale (Qing Shui Jiang Group, Ptmb) in sequence. Remnants of deposits from debris flows and rockfalls can be found on the surface of slopes. The slopes are characteristically formed by the combination of alternating steep (above 1350 m), mild (between 1350 m and 1100 m), and steep (below 1100 m) gradients with layers dipping into the slope (N15–30° E/SE/≤30–48°). The rockfalls concentrate in the lower steep region between 900 m and 1100 m with the average angle of the slope greater than 45° and locally greater than 80° in some areas. The formation of the alternating slope gradient in this region is mainly caused by the contrast of the weathering resistance of the strata. For example, the dolomite (Zbdy) and phosphorite rock (Zbd) group with high weathering resistance are positioned between the overlying mudstone (et) and underlying sandstone (Zbdy) with relatively low weathering resistance.

From the field geological survey, both tectonic joints and unloading joints were found in the slopes. Three dominant joint groups are identified in the dolomite (Zbdy) stratum (Fig. 2) and described using the nomenclature suggested by (Bell, 2007) as follows. J1: joint group (N50–70°E/NW/∠75–85°) steeply dipping downslope with long trace length (approx. 15 m), extremely wide space between joints (2–3 m), and visible openings (3–5 cm) without filling. These joints form the main scarp of the rockfalls in most circumstances. J2: steeply upstream-dipping joints group (N65–75°W/SW/∠75–85°) with very long trace length (max. ~50 m), extremely wide space (2–3 m), and

![Study Site](image-url)
visible openings (1–2 cm). It is difficult to depict the J2 joints in the cross section drawing due to the orientation of the joints. The J2 joints were often found on the side of rockfalls. Some localized changes in the dipping direction were observed along J2 due to the extremely steep angle of dip (~90°). J3: downstream-dipping joints group (N5–10°E/NW/∠45–65°) with moderate trace length (5–10 m), extremely wide space (2–3 m), and small openings. These dominant joints are plotted in Fig. 3 and considered very likely to form the surface of rupture. Some of the unloading joints were visible along the slope in the field investigation.

The underground working of the Kaiyang Phosphorite Mine utilizes both the Longwall Mining method and the classic Room-and-Pillar Mining method depending on the deposit characteristics, accessibility and relative cost. The Longwall Mining technique involves using carriers and shearers to extract the phosphorite ore in a straight line, whereas the classic Room-and-Pillar technique involves the excavation of underground roadways for the production of ore and leaving pillars for roof support in the stopes (Hamrin, 2001). The Longwall Mining method was found in only a few places in the study area, while the classic Room-and-Pillar was widely adopted with average size of pillars being approximately 8 × 8 m. The underground working in the Kaiyang Phosphorite Mine usually started with the excavation of an inclined shaft in the thin phosphorite layer after the preparation of the deposit. The ore production was performed by the excavation of roadways extending from both sides of the shaft. The ore production started at the back end of the shaft and progressed towards the entrance of the shaft. Part of the underground mine layout in the study site is shown in Fig. 4, in which the locations of the rockfalls and the mined-out area demonstrate a clear spatial correlation.

Localized hanging wall subsidence and floor heave were reported as the underground mining progressed, and can be attributed to the difference in the strength of the rock mass between the hanging wall (dolomite-rich) and the footwall (shale-rich). Severe deformation of the hanging wall and pillars can be identified in the shafts and stopes, which may lead to the closure of the stopes. Occasionally, pillars were blasted for ground pressure control in the mining area, which allowed the hanging wall, or the roof and the overlying rock mass to collapse into the void. Large-scale mined-out areas were often generated due to the dense distribution of shafts and stopes, which resulted in the subsidence of the hanging wall and the overlying rock mass and in
turn, large cracks and openings on the upper face and/or the crest of the slope.

3. Study methodology

3.1. Field investigation and analysis

The field investigation included the study of 46 rockfalls in the mining area. The rockfalls were all found to be located above the mined-out areas. Information pertaining to the studied rockfalls is summarized in Table 1. No records of any detailed monitoring of slope deformation and precipitation are available, as many of the rockfalls occurred more than 10 years ago with the absence of field measurement. According to the local almanac and interviews of mineworkers, cracks were found near the crest of the slopes prior to the rockfalls in the majority of the cases. Around 80% of the cracks were reported approximately 6 months after the completion of mining with some rare exceptions that were found during the underground working. The geological cross

![Fig. 4. Underground mine layout of the Kaiyang Phosphorite Mine (Shanghe mining area) and photos of selected rockfalls in the study site. Legend: 1, shaft, adits and underground roadways; 2, rockfalls and direction of the rock mass movement; 3, surface roads; 4, mining area and stopes; 5, mining building structures. The profile line A–A’ in Fig. 4 indicates the cross-section presented in Fig. 5. The stopes are surrounded by underground roadways that were excavated for ore production purposes. The pillars are distributed inside the stopes and omitted in the figure for clarity.](image-url)
section of the R-33 rockfall site is presented in Fig. 5 along with the mining infrastructure, which represents the typical cross section of the rockfalls in the mining area.

From the results of the field investigation and measurements, tension cracks were widely distributed in the mining area and many of them were found on the upper face and/or the crest of the slope above the mining infrastructure, which represents the typical cross section of the rockfall site (J3 group developed in that part of the slope as shown in Fig. 6a). It is postulated that the tension cracks are initially developed near the crest of the slope and then propagated into the rock mass until the cracks reach a set of mildly dipping joints J3 with a dip angle of 45–65°, which comprise the sliding surface. The sliding failure can only be found in the study site in the presence of J3.

3. Slumping: Rock slumping failure describes the backward rotation of blocks (Goodman and Kieffer, 2000). The process of the failure can be divided into a sequence of three steps which includes: (1) the propagation of tension cracks striking the steep joint J1 or J2; (2) the accumulation of stress at the tip of the tension crack when it reaches a certain depth, which is usually the middle part of the slope (i.e. the locking segment); and (3) the ultimate brittle failure of the slope. A typical slumping failure is presented in Fig. 6d, which shows the steeply dipping joints J2 and the estimated location of the locking segment. The locking segment is derived from the concept of the ‘three section mechanism’ that is widely adopted in the study of the failure mechanisms of landslides in China (Huang, 2011). The locking segment represents the location with accumulated stress as the cracks propagate into the slope. The high stress concentration leads to the brittle failure of the locking segment by shearing forces over an extremely short time span.

Precipitation records (Table 1) are available at the official rainfall station of Kaiyang County located approximately 20 km from the study site. Although the distance of the rainfall station may cause the data to be less representative for this case study, a temporal relationship between the rockfall event and the rainfall intensity can still be observed. The occurrences of the recorded rockfalls are concentrated during the rainfall season between May and September, and the monthly precipitation during the period of the rockfall events was found to be significantly higher than the average for the corresponding month. Evidence of weather erosion can be observed on the surface of ruptures on the slopes at the study site, such as the slopes shown in Fig. 6b and Fig. 6d. It is very likely that the ingress of rainfall in the tension cracks developed static pore pressure and diminished the shear strength, which ultimately contributed to the overall instability of the slope.

3.2. Laboratory model experiments

The failure process was further studied using laboratory model experiments that simulated the gravitational deformation of rockfall models over a limited time span. The laboratory model experiments were designed by using the base friction principle to study the failure process of rockfalls under mining activities (Erguvanli and Goodman, 1972). The experiment was conducted in SKLGP at Chengdu University of Technology. The experiment replaces the gravity effects in a two dimensional model with the drag forces generated by the motion of a belt, while simultaneously allowing progressive excavation at the bottom of the model to simulate the underground mining.

The device contains a thin slice of model which is placed horizontally on the belt and restrained by a fixed frame at the side and the end of the platform. Based on Saint-Venant’s principle, the friction force can be considered as uniformly distributed along the underside of the model when the thickness is sufficiently small (Chen et al., 2008). The constraints of the frame represent a close analogy of the two dimensional geometric characteristics of the slope. The base friction force, $F$ is produced by the drag forces from the moving belt in the opposite direction to the resistant force produced by the fixed frame (Bray and Goodman, 1981).
Fig. 5. A typical geological cross section of the rockfalls in the mining area (R-33 as shown in Fig. 4).

Fig. 6. (a) Tension cracks/openings and rockfalls found in the study area; (b) crack–toppling failure of rockfall R-17; (c) crack–sliding failure of rockfall R-36; (d) crack–slumping failure of rockfall R-37.
The base friction is measured by a friction dynamometer. The theory of base friction modeling can be expressed mathematically in the following equation:

\[ F = \int_{0}^{l} \gamma_{m} \cdot \mu \cdot d z dw \]

where \( \gamma_{m} \) is the unit weight of the material used in the model, \( d \) is the thickness of the model, \( \mu \) is the coefficient of friction between the model material and the belt, \( z \) is the length of the model, and \( w \) is the width of the model.

### 3.3. Similitude of model materials

The two dimensional model was constructed with a mixture of barite powder, fine-grained quartz and liquid paraffin at different weight ratios. The mixtures were prepared by adding water and then oven drying them to achieve the targeted parameters as shown in Table 2. The analogues for the dolomite, phosphorite, and shale layers in the model reflect the contrast of the material properties from the upper to the lower strata in the slopes. The ratio of cohesion and internal angle of friction of the mixtures and that of the corresponding rock stratum is 1:1, which was achieved through controlling the weight ratio of the compounds in the mixtures. The cohesion and angle of friction of the corresponding stratum were obtained from uniaxial compression tests on rock specimens.

The model as shown in Fig. 7a was constructed at a scale factor, \( l_{g} = 400 \), with a length and width of 45.0 cm and 60.0 cm, respectively. The model thickness was 0.8 cm after compaction in the direction of the moving belt used to achieve uniform distribution of gravity. The structure of the model closely mimics the typical geologic structure of the slopes in the study site. The phosphorite layer is built between the overlying dolomite and the underlying shale layers. The mining process and mined-out areas (M1, M2, and M3) were simplified by conducting a progressive excavation on the model containing three stops with two pillars (P1 and P2) in the phosphorite layer. Traces were cut into the model prior to the experiment to represent the adverse joint groups of the slope. Only joint groups J1 and J3 were considered in this experiment because of the dimensional constraint of the model in creating the traces to resemble group J2 (steeply dipping towards the upstream of the Yangshui River). The angles of dip for traces in the J1 group were made between 65° and 85°, which is the same range of values in the field. The angle of dip for traces in the J3 group was the same as the actual field value of 45°.

### 4. Model experiment results

The entire base friction experiment for one configuration requires approximately two hours with the belt moving at a speed of 1 cm/s. The experiment is divided into four stages based on the process of deformation. The case of toppling failure is presented below to illustrate the process of deformation in the experiment, and the results of sliding and slumping failure are subsequently presented.

#### 1. Pre-compaction

The trace cutting process can disturb the model, and thus pre-compaction is necessary to minimize the disturbance. The pre-compaction was performed before the initiation of the experiment by moving the belt at a speed of 0.5 cm/s to allow for the pre-compaction in the direction of the moving belt without causing any deformation of the model.

#### 2. Excavation

During the experiment, mined-out areas were excavated as shown in Fig. 7b in the order from M1 to M3 with identical sizes of 6.0 × 1.0 cm to simulate the average size (24 × 4 m) size of the actual stopes at the design scale of 1:400. By following this sequence, the excavated areas are analogues of the stopes in the study site. During the initial excava-tion, roof subsidence can be observed at M1. The magnitude of the subsidence was measured to be approximately 0.1 cm. P1 was built after the excavation of M2 in Fig. 7c. Increasing subsidence was found at the roof of both M1 and M2, while small heave can be observed at the floor caused by the stress concentration imposed from the overlying material. The maximum subsidence was measured to be 0.4 cm and 0.2 cm at the roof of M1 and M2, respectively. A crack appeared at the roof of M2 after the excavation of M3 as shown in Fig. 7d, with a length of 1.1 cm and a maximum opening of 0.2 cm. The maximum subsidence reached 0.6 cm and 0.5 cm at the roof of M1 and M2, respectively. Significant heave was noted at the floor of M1 and M2 due to the intrusion of P1.

#### 3. Deformation of Model

Underground mining was completed at this stage, yet the presence of mined-out areas induced further deformation in the model as shown in Fig. 7e. Severe subsidence (max. 0.7–0.9 cm) was found at the roof of M1 and M2 with closures at certain locations. Cracks were formed and developed at various locations in the model. The length of crack at the roof of M2 increased to 2.2 cm with an opening of 0.4 cm. A crack was formed at the roof of M3 with a length of 1.3 cm and an opening of 0.2 cm. A group of cracks (length varied between 0.8 and 2.0 cm) was formed on the face of the model slope along with the traces above the mined-out areas. Expansions were observed on P1 and P2 with maximum intrusion of 0.4 cm into the floor, which led to the formation of cracks in that area. Differential settlement of the model was induced by the deformation of mined-out areas, which caused the formation of cracks near the top of the model with a length of 6.0 cm and an opening of 0.3 cm.

The model demonstrated the bending of the slope from its original position due to lack of support in the mined-out areas as shown in Fig. 7f. The differential settlement continued as a result of the full closure of the mined-out areas. The length and the opening of the crack at different locations of the model increased as the experiment proceeded. The crack at the end of M3 reached a length of 8.0 cm and an opening of 1.0 cm. Additional cracks (C1 and C2) were formed near the top of the model, in which C1 extended 10 cm into the rock and developed at various locations in the model. The length of crack at the roof of M3 increased to 2.2 cm with an opening of 0.4 cm. A crack was formed at the roof of M3 with a length of 1.3 cm and an opening of 0.2 cm. A group of cracks (length varied between 0.8 and 2.0 cm) was formed on the face of the model slope along with the traces above the mined-out areas. Expansions were observed on P1 and P2 with maximum intrusion of 0.4 cm into the floor, which led to the formation of cracks in that area. Differential settlement of the model was induced by the deformation of mined-out areas, which caused the formation of cracks near the top of the model with a length of 6.0 cm and an opening of 0.3 cm.

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#### 4. Failure of Model

The previously mentioned group of cracks on the model slope face continued to propagate along the joints into the model, with the lengths ranging from 4.0 cm to 7.0 cm with a maximum opening of 1.0 cm. The columnar structures in Fig. 8a were formed by the propagation of the cracks, which underwent a toppling movement with a very small amount of material detachment at different locations. Only small increments in the opening of C1 and C2 were observed at this stage without any further visible development and propagation in the direction of the moving belt. Flexural toppling occurred due to the failure at the fixed ends as the flexural deformation continued in the columnar structures in Fig. 8b. The subsequent occurrence of rockfall shown in Fig. 8c was the final outcome of the process. The rockfall materials were deposited at the slope face as kinematic energy dissipated. A cliff of approximately 5.0 cm was formed as a result of the toppling failure.

A set of experiments was conducted to simulate the failure process for different scenarios and a clear condition was reached at the final

### Table 2

The proportion and properties of the model materials.

<table>
<thead>
<tr>
<th>Corresponding rock</th>
<th>Weight ratio</th>
<th>Unit weight ( \gamma_{m} ) (kN/m³)</th>
<th>Cohesion ( c ) (kPa)</th>
<th>Friction angle ( \psi ) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barite powder</td>
<td>6.0</td>
<td>2.0</td>
<td>31</td>
<td>32</td>
</tr>
<tr>
<td>Quartz</td>
<td>6.5</td>
<td>2.5</td>
<td>34</td>
<td>41</td>
</tr>
<tr>
<td>Liquid paraffin</td>
<td>4.0</td>
<td>1.5</td>
<td>27</td>
<td>25</td>
</tr>
</tbody>
</table>

1981). The base friction is measured by a friction dynamometer. The theory of base friction modeling can be expressed mathematically in the following equation:
stage of the failure process. The sliding and slumping failure modes were validated by the base friction model using different combinations of J1, J2 and J3 joint groups. The presence of J3 governs the occurrence of sliding failure, yet it is not necessarily a prerequisite for the case of slumping failure. The angle of dip for J1 and/or J2 plays a more decisive role in the case of toppling failure. Based on the results of the experiment, the potential for toppling failure diminishes if the angle of dip is less than 75°, which result in the development of other failure modes, such as the cases shown in Fig. 9a (sliding failure) and Fig. 9b (slumping failure). The experimental results and the associated phenomena demonstrate a high agreement with the observations made in the field investigation. The proposed failure process and mode of the rockfalls in the study site are discussed in the subsequent sections.

Owing to the scale effect, the results from the base friction test cannot represent the entire failure process of the actual rockfall. The main differences are the geometrical scale, the material properties and the internal structure of the rock mass. The inherent differences between two dimensional simulations and three dimensional rockfalls remains as another barrier to fully understanding the behavior of rock slopes. The model was constructed to simulate the typical slope geometry with an average slope gradient similar to that in the mining area. The angle of friction and shear strength of the materials were prepared to be similar to the actual values of the rock. The internal structure of the slope was built by cutting traces in the model, to emulate the discontinuities in the slope. Although the base friction model may be considered rudimentary in the study of rockfalls, it offers a helpful tool to simplify and visualize the actual complex failure processes. The model results were found to be consistent with the characteristics of the failure processes interpreted from the field investigation and the results can qualitatively reflect the development of the actual failures.
5. Discussion of rockfall processes and failure modes

5.1. Failure process

A failure process for the rockfalls is proposed to encompass the comprehensive deformation process at the scale of mine slopes over a large time span. It is based on geological analysis, field investigation and laboratory model experiment results. An appropriate time period is required for the deformation to develop and proceed between the excavation in the slope and the overall instability of the slope. The failure process is divided into four stages.

1. The overlying rock mass is subject to the adjustment of stress due to the disturbance caused by the underground mining. In addition to the pre-existing adverse geological structure that cumulatively formed in the past, e.g., the decreasing compressive strength from upper to lower strata in the slope, the mining induced stress and geometrical changes collectively caused the incipient deformation of the slope.

2. The increase in the size of the mined-out area caused large deformations at the roof and floor, which in turn led to the formation of cracks on the slope face. The formation of these cracks commonly began near the top of the slope with openings ranging from 0.5 m to 5 m at this stage.

3. The deformation process of the slope remained active even after the cessation of underground mining. The closure of the mined-out area can be found at certain locations in the case of severe deformation. The development of the deformation of cracks continues vertically and/or subvertically and propagates along the existing joints in the slope. Concurrently, substantial deformation of the slope can be
observed in the horizontal direction along with the acceleration in the deformation rate of the cracks. The sporadic small-scale rock detachment of the slope together with constant rock falls can be observed at this stage. The described phenomena indicate that the slope is likely to be at a state of limiting equilibrium.

4. The deformation rate of cracks in the vertical and/or subvertical direction increases dramatically with more frequent small-scale (volume < 10 m³) rock detachments on the slope. Rockfalls occur under suitable triggering mechanisms, such as precipitation, which causes the state of limiting equilibrium to be exceeded.

5.2. Failure modes

The failure modes for the rockfalls in the study site are proposed and discussed in this section. The study of the failure modes is based on the investigation of 46 rockfalls in the study site by considering their geological conditions and the characteristics of the rockfall types. Three hypothesized failure modes are summarized below.

1. Crack–toppling failure

The conceptual mode for this failure is shown in Fig. 10. The formation of crack–toppling failure is highly dependent on the angle of dip of the steeply dipping joint groups, i.e. J1 and J2. The excavation in the phosphorite mine is followed by deformation of the slope. The increase in the size of the stopes enlarges the deformation and leads to the formation of cracks near the top of the slope. The cracks propagate vertically and/or subvertically along the direction of the joints due to the continuous progress of the deformation. The opening of the cracks creates voids that can be filled by rock fragments and rainwater. Consequently, the rainfall induced static pore water pressures and seepage forces cause the rock mass to bend forward and in turn, the toppling failure to occur.

2. Crack–sliding failure

The conceptual mode of this failure is shown in Fig. 11. The formation of crack–sliding failure requires the presence of the mildly dipping joint group J3, in addition to the joint group J1 and/or J2 in the slope. Cracks with rough surfaces are formed near the top of the slope following the excavation. These cracks propagate vertically and/or subvertically along the direction of J1 and/or J2. Subsequently, the presence of the J3 joint group permits the propagation of cracks along the mildly-downstream dipping direction, which leads to the formation of a crack–sliding failure mode. This failure mode is often associated with large volumes of rockfall deposit.

3. Crack–slumping failure

The conceptual mode of this failure is shown in Fig. 12. The process of the failure mode is similar to the previous modes in the early stages, in which the cracks are formed near the top of the slope and propagate vertically and/or sub-vertically along J1 and/or J2. However, the crack–slumping failure commonly occurs in the absence of J3, which, as previously noted, plays a decisive role in the occurrence of the crack–sliding failure. The distance between the slope face and the cracks that retrogress from the top of the slope is crucial to the final outcome of the failure mode. The small distance between the slope face and the cracks is likely to cause the bending motion of the rock mass towards the toe of slope, which consequently leads to the crack–toppling failure mode. In contrast, the bending motion is not promoted in the case of cracks that are located far away from the slope face. The crack–slumping failure mode is governed by the locking segment formed in the slope. The locking segment is the intact rock mass located between the cracking segment near the top and the compressing segment close to the phosphorite mine. The brittle failure of the locking segment results in the instantaneous release of the energy and ultimately leads to the crack–slumping failure, which is commonly triggered by large precipitation.

Some critical phenomena are found in common for all failure modes. For example, all of the failure modes initiate from the crest or upper part of steep slopes with structurally decreasing strength from the upper to the lower strata. The existence of cracks and large mined-out area are a prerequisite for the slope deformation with all failure modes. The final outcome of the failure modes is governed by the geological structures of the slope, e.g. the pre-existing vertical and/or subvertical joints. The understanding of the geological structures provides a means for identifying the most likely failure mode for a potential rockfall during the early stage.
5.3. Failure conditions

A steep slope with the absence of support in three spatial orientations and the presence of discontinuities are geologically fundamental to the rockfalls in the Kaiyang Phosphorite Mine. The decreasing strength of the dolomite-rich upper strata and the shale-rich lower strata is the mechanical foundation of the rockfalls at the study site. The occurrence of the rockfall is induced by the underground mining and commonly triggered by the ingress of rainfall into the cracks on the face and/or near the crest of the slope. The failure conditions can be summarized into both the internal and the external factors. The main internal factors are: 1) The combination of strata is structurally adverse to the stability of the slope; 2) The rockfalls are not associated with regional faults, but constrained by the pre-existing joints in the rock mass of the slope. The failure process of the slope is essentially a deformation process, which begins with the vertical and/or subvertical propagation of cracks in the direction of J1 and J2. The type of existing joints is vital to the final configuration of the failure mode. For example, the formation of columnar structures in the crack–toppling failure and the development of locking segments in the crack–slumping failure can be attributed to the presence of J1 and J2, respectively, whereas the crack–sliding failure is a result of the propagation of cracks along the

![Fig. 11. Conceptual mode of crack-sliding failure.](image)

![Fig. 12. Conceptual mode of crack-slumping failure.](image)
mildly dipping J3. The main external factors are: 1) The underground working changes the stress distribution in the slopes mainly because of the dynamic disturbance directly associated with the excavation and the large mined-out area with insufficient support. The accelerated propagation of cracks can only be observed in the rock mass above the mined-out area. The deformation of the slope was found to deteriorate faster in the poorly regulated mines with improper ground pressure control; 2) Precipitation is the triggering factor for geohazards in many cases. Although the deformation is likely to be induced by the underground mining, the failure of the slope commonly occurs in conjunction with large precipitation. The bending movement of the rock mass towards the toe of the slope is compounded by the static pore pressure in the cracks. The ingress of rainfall reduces the shear strength of the joints, which yields the necessary mechanical condition for sliding and slumping failures.

5.4. Early warning

The internal factors can hardly be altered in practice to reduce the possibility of rockfalls, and thus regulation and monitoring of the external factors are crucial to the early warning of rockfalls in mines. The retreat mining applied in Kaiyang Phosphorite Mine requires regular maintenance and support measures for the roadways in addition to the pillars that are reinforced and preserved in the stopes. The development of tension cracks on the face and/or near the crest of the slope is a key indicator of the instability of the slope based on the analysis of the failure process. In the presence of tension cracks, field monitoring should be conducted for slope deformation as well as precipitation. However, a quantitative threshold for rainfall cannot be established from the available data. Therefore, a locally installed field monitoring is vital for recording the long-term deformation and monitoring any sudden acceleration in the displacement rate as they may advise of any imminent danger to the safety of the miners (Szwedzicki, 2001). Based on this study of the Kaiyang Phosphorite Mine, miners are advised to evacuate immediately to prevent potential life loss in the case of small-scale rock detachments from the slopes with accelerated deformation.

6. Conclusions

In this case study, the failure processes and modes of the rockfalls in Kaiyang Phosphorite Mine were observed and analyzed in light of the results from field investigations and laboratory experimental studies using a gravitational simulation device. The rockfall is a typical example of anti-dip slope failure with structurally decreasing strength from upper to lower strata in conjunction with mining activities. The failure conditions, process and modes are summarized as follows:

1. The rockfalls are associated with the unique geological conditions in the mining area. The rockfalls occurred in steep slopes with the absence of support in three spatial orientations. The decreasing strength of the dolomite-rich upper strata and the shale-rich lower strata provides the mechanical basis for the rockfall. The rockfalls are induced by underground mining and are commonly triggered by the ingress of rainfall in the mining induced cracks.

2. A sufficient time period is required in the deformation process that occurs between the initial excavation and the overall instability of the slope. The deformation process includes the incipient deformation (e.g. subsidence of the roof in the stopes and the formation of cracks near the crest of slope), the development of deformation (e.g. the propagation of cracks along pre-existing joints in the slope and the closure of stopes), and the gradual deterioration of the rock mass stability (e.g. the acceleration of deformation with frequent small scale detachment of rocks with volume less than 10 m³). The failure modes of the rockfalls are summarized as crack–toppling failure, crack–sliding failure, and crack–slumping failure and depend on the rock mass structure of the slope.

3. The safety and future development of Kaiyang Phosphorite Mine requires the improvement of mining methods and the understanding of the failure process of rockfalls. The reduction in the amount and the size of the pillars in the stopes in exchange for better recovery rates decreases the overall stability of the slopes by allowing the subsidence of the upper rock mass and introducing tension cracks in the slope. The occurrence of rockfalls invariably involves the formation of tension cracks on the upper face and/or near the crest of the slope and reveals a clear relationship between tension cracks and rockfalls in the study site. Consequently, the formation of tension crack can be treated as an early warning sign for potential instability of slopes in mining areas based on this case study.

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