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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 Hungr, 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 (Carnec 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 km^2 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 m^2. The majority of the rockfalls in Guizhou province have

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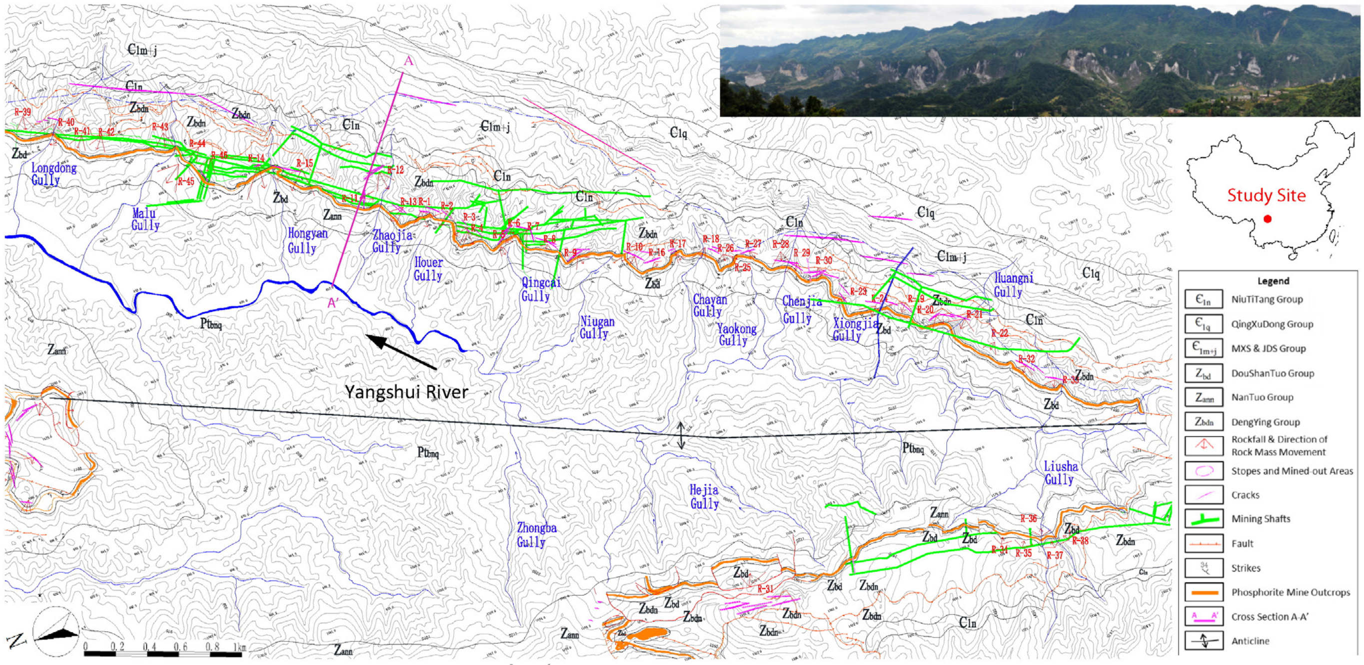

Fig. 1. Regional topographic and geological map with reported locations of rockfall. The regional map is showing the central part of Kaiyang Phosphorite Mine. The photo shows part of the rockfall belt along the Yangshui River. The location of the study site is indicated on the map of China and the geological profile of cross section A–A′ is presented in Fig. 2 below.

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 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 m^3. 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, $Є_{1q}$) overlying silty mudstone/quartz sandstone (Ming Xin Si Group, $Є_{1m}$) and sandstone with laminated shale (Jing Ding Shan Group, $Є_{1j}$), underlain by the carbonate-rich mudstone with laminated shale (Niu Ti Tang Group, $Є_{1n}$). The underlying Sinian sediments which contain dolomite (Deng Ying Group, Z_{bdy}) are on top of the phosphorite mining area, i.e. phosphorite rock with quartz and sandstone (Dou Shan Tuo Group, Z_{bd}), followed by the laminated shale and sandstone (Nan Tuo Group, Z_{ann}), with alternate layers of metasandstone and shale (Qing Shui Jiang Group, Pt_{bnq}) 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 (Z_{bdy}) and phosphorite rock (Z_{bd}) group with high weathering resistance are positioned between the overlying mudstone ($Є_{1n}$) and underlying sandstone (Z_{ann}) 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 (Z_{bdy}) 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

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