Rockfall Hazard Assessment for a Railway Line in Western Shanxi Province, China

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Abstract

Rockfalls can cause serious damage to people, property, facilities and transportation corridors. Therefore, the detachment of large size boulders and their fall track represent issues that should be evaluated for the construction of lifelines or transportation corridors. In this paper, we illustrate the assessment of the rockfall hazard along a small area of the railway line (Yinghuo railway) and three profiles selected in different rockfall models. In the area, we have carried out detailed field surveys and software simulations that allow generating simple rockfall hazard trajectories at each profile. From the fieldwork, location and size of detached blocks having potential to fall were described. The aim of this study was a preliminary assessment of rockfall hazard for this railway site. We evaluate this hazard potential and perform a series of rockfall analyses and discuss the results. RocFall V.4.0 software has been used to calculate bounce heights, total and translational kinetic energies, and translational velocities of the falling blocks of different masses. The results were exploited to evaluate the rockfall hazard along the threatened element at risk. Finally, to reduce the rockfall hazard, remedial measures including rock bolts and placement of flexible restraining nets are suggested.

Keywords: Rockfall hazard, Assessment, RocFall, Trajectories, Kinetic energies

1. Introduction

Rockfall is one of the major concerns along different urban areas and transportation routes all over the world (Bunce et al., 1997; Huang, 2011; Topal et al., 2012). And also, the rockfall can cause injuries and death to roadway users, traffic delays and diversions, damage of road surface in transportation corridors (Hungr et al., 1999; Budetta, 2004). A rockfall is a fragment of rock detached by sliding, toppling or falling that falls along a vertical or sub-vertical cliff, proceeds down slope by bouncing and flying along ballistic trajectories (Ansari et al., 2012). The occurrence and magnitude of rockfall depends on many influencing factors, which include chemical weathering, freezing-thawing, earthquake effects, train vibration, and anthropogenic effect or a combination (Krautblatter and Dikau, 2007; Haas et al., 2012). The behavior of rockfalls is affected by a high degree of uncertainty. The energy lost by blocks during impact or rolling is a complex function of the geomechanical properties, e.g., the shape, the size of the block, and the local geometry and roughness of the slope (Frattini et al., 2008). Several researchers made experiments and simulations to evaluate the kinematic parameters of falling rocks at specific locations and translational velocities of the unstable rocks (e.g., Giani et al., 2004; Dorren et al., 2006; Bourrier et al., 2009, 2012; Youssef et al., 2015). When rockfall promoters have prepared the cliff for rockfalls, then visible detachments of rock fragments are induced by the rockfall triggers. Finally, to prevent the rockfall hazard, a prime concern is to assess the possibility of rockfall path, energy, and velocity associated with it.

In this work, we present the results of an attempt to evaluate rockfall hazard in a railway line, western Shanxi province, China. Based on extensive field work focusing on the characteristics of dominant discontinuities controlling the stability of blocks, the locations of three types of rockfall model were identified. Rockfall hazard in this corridor is determined through numerical simulations of rockfall trajectories. More specifically, the study is aimed is delineating different rockfall model in railway corridor, tracing of the ballistic trajectory, evaluating the rebound height, total and translational kinetic energies, and translational velocities in different rockfall model, and proposing protection measures.

2. Regional and site setting

The study area is located on the southern Hequ County, western Shanxi province (Fig. 1). The study area is part of the Loess Plateau with loess tableland, loess hill and loess gully landforms, with 850 ~ 1250 m above sea level. The terrain lowered gradually from the Shaquan Town (southeast) to the Yellow River (northwest). The study area has a temperate continental monsoon climate. The mean annual temperature is approximately 8.8 °C and average annual rainfall is 460 mm. The Yellow River flows from the north through the south in the western boundary of study area. A railway constructed from Yingta Village (Shaquan Town) to Huoshan Village in study area (Fig. 1). The strata are covered in study area can be divided into five geological ages, as follow:

(i) Quaternary in age, covered by yellowish loess.

(ii) Baode Formation, Pliocene in age, consisting of sandstone and conglomerate.

(iii) Shihezi Formation, Lower Permian in age, consist of sandstone, siltstone, shale, mudstone and thin coal. The color of Shihezi Formation in the study area is purplish red, grayish yellow and yellowish green.

(iv) Taiyuan Formation, Upper Carboniferous in age, including clay rock, mudstone, sandstone, limestone and mineable coal. The color of this member is grayish white to purplish red.

(v) Majiagou Formation, Middle Ordovician in age, consist of limestone, argillaceous limestone, dolomite and dolomite limestone. The color of this stratum is gray to grayish white.

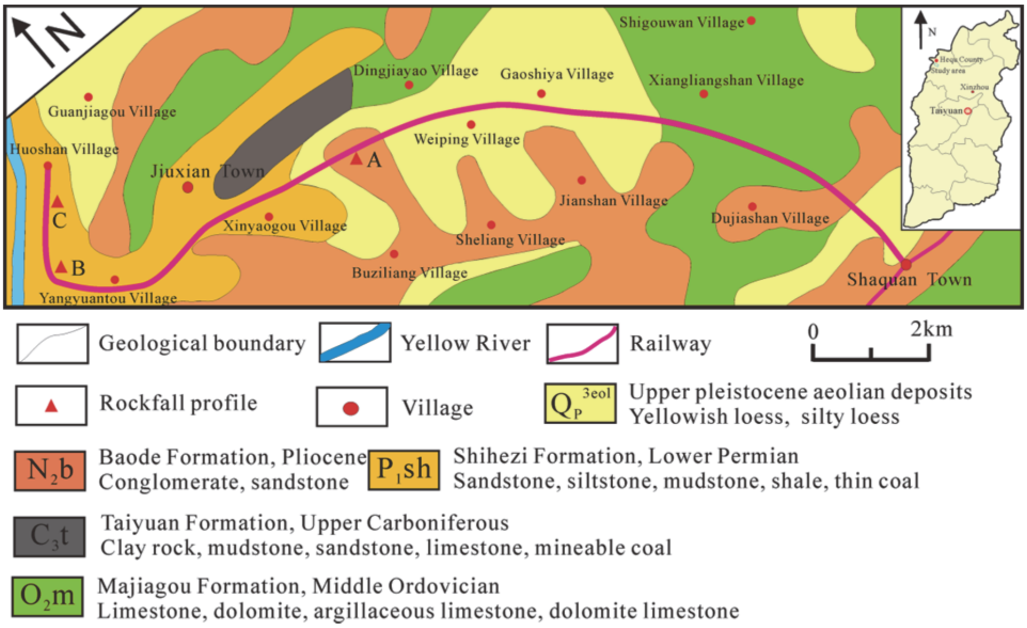

Fig. 1 Location and Geological map of the study area.

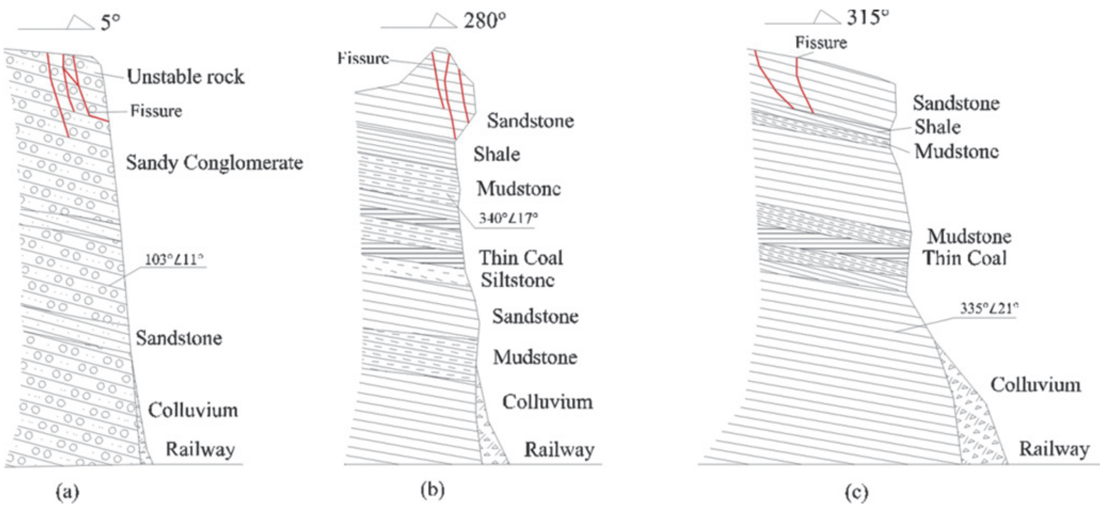

Fig. 2 Two-dimensional model profile of three typical rockfalls; (a) profile A, (b) profile B, (c) profile C.

Table 1 The physical parameters of rock blocks and parameters of slope at each profile

Profile	Unstable Rock	Bulk Density (g/cm^3)	UCS (MPa)	Diameter (m)	Slope Gradient (º)	Slope Height (m)
A	Sandy conglomerate	2.47	42	0.2~0.8	65~85	15
B	sandstone	2.62	55	0.3~1.0	60~90	22
C	sandstone	2.62	63	0.4~1.5	50~90	30

UCS: uniaxial compressive strength

The rockfalls have been experiencing in steep and vertical slopes of this railway corridor during recent year, and frequently represent the main threat to the embankment, track, subgrade, train equipment, etc. Rockfalls occur in the strata of Pliocene and Permian age at this railway. We selected three different rockfall profiles and divided into toppling, falling, and sliding model at profile A, B, and C, respectively (Fig. 1 and Fig. 2). The profile A, B, and C are located at 39°09′33″N and 111°14′23″E, 39°09′30″N and 111°10′01″E, and 39°11′01″N and 111°11′04″E, respectively (Fig. 1). The petrography characters of each profile are also illustrated in Fig. 2. The strike measured on the bedrock at A, B, and C profiles are 103°, 340°, 335°, respectively, and the dips are 11°, 17°, 21°, respectively (Fig. 2a, b, c).

3. Rockfall modeling methodology

Rockfall hazard depends not only on the discontinuities but also on the lithology of the rock, the topography, inclination of the slope, size/shape of the boulder and the slope surface properties (Schweigl et al., 2003). During the last decade, various two or three-dimensional programs have been developed and tested to simulate fall of a boulder down from profile and to compute rockfall trajectories (e.g., Guzzetti et al., 2002; Frattini et al., 2008; Bourrier et al., 2009; Tunusluoglu and Zorlu, 2009; Leine et al., 2014). In this study, two-dimensional rockfall simulation was carried out using the Rocscience's analysis package RocFall V. 4.0 program from Rocscience Inc. RocFall is a program designed specifically to statistically assess the risk caused due to toppling, falling, and sliding rocks. The program determines energy, velocity, number of blocks, and bounce height for the entire slope as well as for location of rock end points. In this program, the rock block is considered to be a simple point with rockmass concentrated at the center of gravity. The rock block collides with the slope surface should consider the coefficient of normal restitution (Rn) and coefficient of tangential restitution (Rt). Theses coefficients of restitution are important parameters for obtaining the loss of energy in rockfall simulation at every impact along the slope. The values are dependent on the rock type of each profile and can be measured according to different methods including in situ tests, back analysis and laboratory studies (Azzoni et al., 1995; Giacomini et al., 2009; Asteriou et al., 2012). And also, the RocFall program should consider the angular velocity of the rock block and the roughness of slope surface. The slope forming material mainly is bedrock outcrop (sandstone, shale, mudstone, thin coal, etc.) and colluvium at the slope toe in this study area (Fig. 2). The coefficient of normal restitution (Rn) for bedrock and colluvium (Talus without vegetation) is 0.35 and 0.32 respectively, and the coefficient of tangential restitution (Rt) for bedrock and colluvium is 0.85 and 0.82 respectively taken from the RocFall program. The RocFall program takes into account the angle of each slope for the modeling of slope roughness, therefore, the natural friction angle (U) was considered as 30º. The outlines of the three profiles were determined according to the field investigation. A concave position occurred under the unstable rock in profile B (Fig. 2b) and some soft rock has the scarp in profile C (Fig. 2c). In the current study, for all seeder points, an initial velocity of 0.0 m/s in profile A and B, but 0.1m/s in profile C was assumed to simulate rockfall motion. The physical properties and other parameters of historical rockfalls at each profile are shown in Table 1.

4. Results and discussion

The rockfalls occurred at profile A, B and C along the railway was analyzed. We calculated the masses of falling rock as cube, and different rock masses ranging between 100 kg and 5000 kg based on the field investigation of three profiles and the rockfall historical records of the study area. Most incompetent rocks tend to break during the first impact of the falling rocks on the slope surface and about 75 ~ 85% of energy is lost during that impact (e.g., Evans and Hungr, 1993). The trajectories of falling blocks from RocFall program are shown in Fig. 3. The trajectories indicate that all the blocks will reach or cross the subgrade of railway and will impact on the railway line.

Four different parameters were observed in the current study including bounce heights, total kinetic energies, translational kinetic energies, and translational velocities during free fall of rocks along each profile and at middle line of railway were determined (Table 2 and Fig.4) and the results of the simulation are summarized below. Bouncing behavior is not only governed by the geometry and the mechanical characteristics of the slope and the falling block but also depends on the kinematics at impact

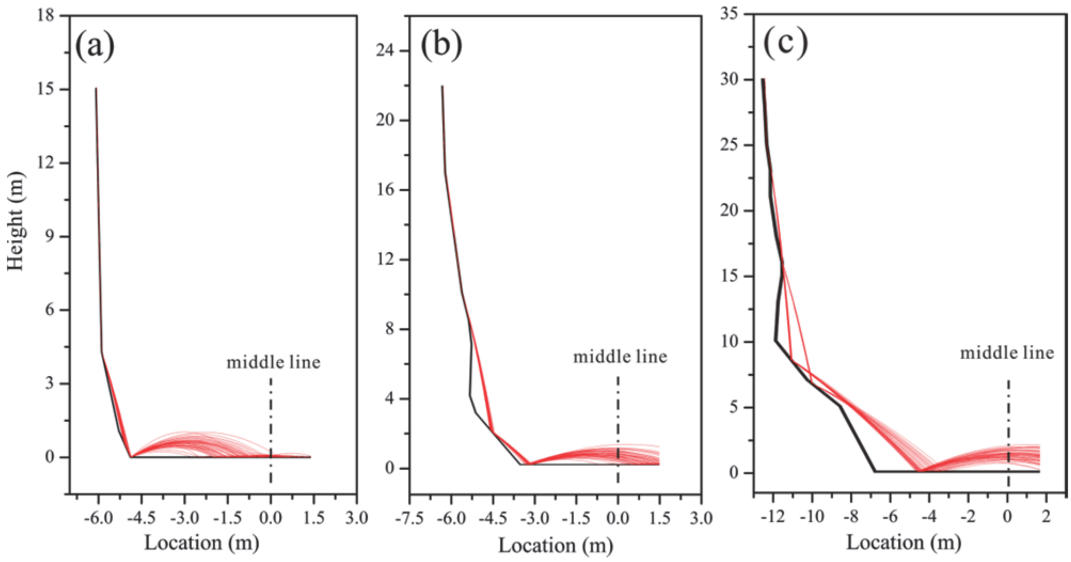

Fig. 3 Rockfall trajectories for the falling blocks in each profile; (a) 500kg blocks of profile A, (b) 1000kg blocks of profile B, (c) 2000kg blocks of profile C.

Table 2 The simulation results extracted from RocFall simulation program in different masses for each profile.

Profile	Mass (kg)	BH (m)	TV (m/s)	TKE (kJ)	TrKE (kJ)
A	100	0~1.12 (0.16)	0~13.71 (7.10)	0~11.78 (3.26)	0~9.40 (2.52)
	500	0~0.96 (0.27)	0~13.66 (6.95)	0~57.66 (15.56)	0~46.66 (12.07)
	1000	0~0.93 (0.37)	0~13.45 (7.00)	0~112.68 (32.08)	0~90.44 (24.49)
B	100	0~4.27 (1.00)	0~16.39 (7.87)	0~15.64 (4.34)	0~13.43 (3.10)
	500	0~4.23 (1.15)	0~15.66 (7.22)	0~71.84 (18.23)	0~61.28 (13.05)
	1000	0~4.18 (1.12)	0~15.49 (7.45)	0~119.00 (38.80)	0~90.69 (27.74)
	2000	0~4.22 (1.00)	0~15.87 (7.35)	0~297.55 (75.83)	0~179.05 (54.17)
C	100	0~6.26 (2.22)	0~20.65 (10.22)	0~26.12 (7.22)	0~21.33 (5.22)
	500	0~6.27 (2.43)	0~20.64 (10.34)	0~105.37 (36.83)	0~130.49 (26.71)
	2000	0~6.24 (2.00)	0~20.66 (10.06)	0~522.39 (140.19)	0~426.80 (101.11)
	5000	0~6.30 (2.37)	0~20.76 (10.27)	0~1316.00 (363.55)	0~1077.52 (264.08)

The values of parentheses are at 0 m location of the middle line of railway in each profile. BH = Bounce height (m); TV = Translational velocity (m/s); TKE = Total kinetic energy (kJ); TrKE = Translational kinetic energy (kJ).

angle. The bounce height values for different blocks were determined in Table 2 and Fig. 4. In profile A, the bounce height reached 0.16 ~ 0.37 m at mass of 100 ~ 1000 kg in middle line of railway (location of 0 m) (Fig. 4a). And also, the bounce heights were range of 1.00 ~ 1.15 m and 2.00 ~ 2.43 m at middle line of railway in profile B and C, respectively (Fig. 4d, g).

The kinetic energy of fallen blocks has a direct relationship with their masses and the square of the velocity of these blocks. Larger the block size will produce more energy causing more destructive rockfall. The vegetation cover has an effective impact in decreasing falling rocks. The three profiles in this railway all covered with outcrop and talus without vegetation. The total and translational kinetic energies and translational velocities further decrease after continuous impacts along the slope, but these energies and velocities continue to be increased until reaching the maximum limit at each profile (Fig. 4). The maximum total and translational kinetic energies and translational velocities are found as 11.78 ~ 112.68 kJ, 9.40 ~ 90.44 kJ, and 13.45 ~ 13.71 m/s for profile A of 100 ~ 1000 kg blocks respectively; 15.64 ~ 297.55 kJ, 13.43 ~ 179.05 kJ, and 15.49 ~ 16.39 m/s for profile B of 100 ~ 2000 kg blocks; and 26.12 ~ 1316.00 kJ, 21.33 ~ 1077.52 kJ, and 10.06 ~ 10.34 m/s for profile C of 100 ~ 5000 kg blocks. And also, these values are range of 3.26 ~ 32.08 kJ, 2.52 ~ 24.49 kJ, and 6.95 ~ 7.10 m/s of 100 ~ 1000 kg blocks for profile A at middle line of railway respectively (Fig. 4b, c); 4.34 ~ 75.83 kJ, 3.10 ~ 54.17 kJ, and 7. 22 ~ 7.87 m/s of 100 ~ 2000 kg blocks for profile B (Fig. 4e, f); 7.22 ~ 363.55 kJ, 5.22 ~ 264.08 kJ, and 10.06 ~ 10.34 m/s of 100 ~ 5000 kg blocks for profile C at middle line of railway (Fig. 4h, i). Perret et al. (2004) mentioned that kinetic energy could be divided into three intensity zones. First zone has a value more than 300 kJ are of highest intensity and cause major damage to the infrastructure. Medium intensity energies range of 30 ~ 300 kJ, which may leave infrastructures impaired and

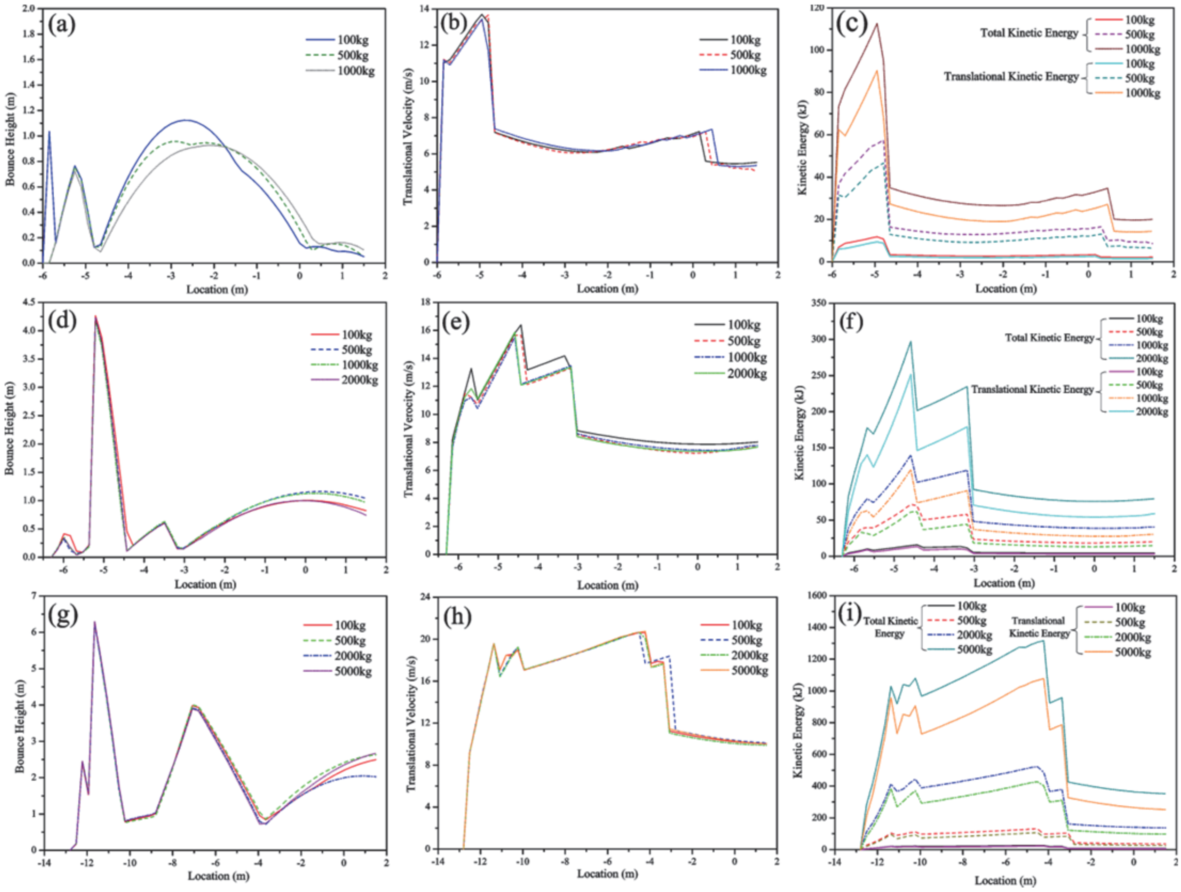

Fig. 4 Graph between bounce height (height above slope), total kinetic energy, translational kinetic energy and translational velocity versus distance for different masses of falling rock in each profile; (a), (b) and (c) profile A; (d), (e) and (f) profile B; (g), (h) and (i) profile C.

disrupt transportation means for considerable period of time. As demonstrated by the maximum parameters values in middle line of railway, most of mass falling blocks along each profile in the current study have fitted in medium intensity range of the kinetic energy. Therefore, most of falling blocks threatened the safety of trains and users, and broken the track and subgrade of railway.

It is essential to take precautionary measures against rockfall hazards. To face the risk posed by rockfall, there are several types of technical measures based on protective structures, such as rockfall constructing barrier fences and restraining nets (Peila et al., 1998). In the current study different techniques were used in different profile, including (i) restraining nets should use in profile A to retain the little unstable block, (ii) most of unstable blocks need to be removed in profile B and then use the nets covered the slope surface, and (iii) most of unstable rock should use rock bolts and anchoring to prevent the cracks or joints in porifle C to slide and fall on the railway.

5. Conclusion

Three typical rockfall profiles in Yinghuo railway corridor, western Shanxi province, have been investigated and analyzed by rockfall simulation. Field investigation indicated that there are many unstable blocks and areas that are belong to sandy conglomerate in age of Pliocene and sandstone in age of Lower Permian. The present study of three profiles in railway provides useful information about rockfall simulation investigations. Two-dimensional rockfall analyses are performed using the data collected from the study area. The conlusions obtained from the present study can be drawn as follows:

(1) To describe the rockfall hazard along the Yinghuo railway, an extensive field survey of rock mass properties, potential critical blocks and slope profile geometry. Three typical rockfall modeling profiles (toppling, falling, and sliding) are observed and the weight of the falling blocks varies between 100 kg and 5000 kg.

(2) The rockfall simulation provides information about the trajectory path and the rockfall bounce height with distance for the rockfall site. For middle line of railway (Location = 0 m), the bounce heights are of 0.16 ~ 0.37 m, 1.00 ~ 1.15 m, and 2.00 ~ 2.43 m for profile A, B, and C, respectively. The rockfall analyses results also revealed that the detached blocks will have

very high velocity and kinetic energy. The total and translational kinetic energies and translational velocities values are of 3.26 ~ 32.0 kJ, 2.52 ~ 24.49 kJ, and 6.95 ~ 7.00 m/s for profile A; 4.34 ~ 75.83 kJ, 3.10 ~ 54.17 kJ, 7.22 ~7.87 m/s for profile B; 7.22 ~ 363.55 kJ, 5.22 ~ 264.08 kJ, and 10.06 ~ 10.34 m/s for profile C in middle line of railway. These values indicate a highly dangerous phenomenon in Yinghuo railway corridor.

(3) To prevent possible loss of Yinghuo railway corridor, considering the remove the little unstable blocks, cover the slope surface by restraining nets, and anchoring the large unstable rocks.

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