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Original Article

Field investigation and numerical simulation on rockfalls in Zhangmu Town, Tibet, China

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Abstract: Zhangmu Town in Tibet of China, which lies in the southern piedmont of the median Himalayas, is a small but strategically important port of trade exchange between China and Nepal. Many rockfall events have occurred in Zhangmu since 1970, resulting in huge economic losses and serious influence on the bilateral trade. We conducted a detailed field investigation on the high and steep slope in Zhangmu Town, and analyzed the distribution features, stability, failure modes and evolution of dangerous rocks of potential rockfalls. Then we numerically simulated the movement path, velocity and accumulation forms of the rockfall with PFC^{3D} program. The results indicated that the dangerous rock belt could be divided into three sections, namely, unstable section, slightly stable section and basically stable section. It was estimated that the rock debris and single dangerous rock would be unstable in the case of earthquakes or rainstorms. Due to the terrain constraints, the fallen rocks would scatter near the mouth of the Zhangmu ditch and in the Buqu River through multiple times of rolling, collision-induced diversion and bouncing. Without reinforcement, the rockfall could cause serious damage to the car parks, gas stations and National Highway 318 along the line from Zhangmu Town to Zhangmu ditch. Based on the field survey and numerical simulation, we recommended rockfall removal and interception as the major prevention measures, and protective sheds as auxiliary measure.

Keywords: Rockfalls; Failure mode; Stability analysis; Numerical simulation; Micro parameters; Prevention measures

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1 Introduction

Rockfall is the free or bounding fall of rock debris down steep slopes due to external disturbance and/or internal stress redistribution, from stable state to unstable state, and finally deposits in the flat region or near the barriers through the process of detaching, bouncing, rolling and slide (Klimes 2011; Singh et al. 2016). As a dynamic process, rockfall is one of the major geological disasters in mountainous or engineering slopes, which may cause catastrophic damage to human and infrastructure due to high velocity and potential, despite limited volume. With the increasing infrastructure such as railway, highway and hydropower stations constructed in mountainous regions, more severe damages resulted from rockfall have been found (Pappalardo et al. 2014; Piacentini et al. 2015; Yu et al. 2019).

The factors responsible for rockfall generally involve the earthquake, rainfall, freeze, thawing, weathering, climate and so on. At present, the methods to analyze the temporal and spatial movement of rockfall basically include the field survey, model test, theoretical analysis and numerical simulation. Based on two examples from the Central Italian Alps, an approach to rockfall modeling has been proposed which is based on a lumped mass algorithm and takes advantage of high-resolution topography and input data, and of operating in close integration with a geographical information system (GIS) environment (Agliardi and Crosta 2003). Dussauge et al. (2003) statistically analyzed the volume distribution of natural rockfall on various geological settings and volume ranges. Abellán et al. (2006) carried out the on-site survey and analysis to the rockfall in Eastern Pyrenees, Spain by means of 3D laser scanning technique. Sturzenegger et al. (2007) proposed a model incorporating fracture intensity and block geometry into a GIS system to assess the rockfall risk. Viero et al. (2012) investigated the source and deposition areas of the Cima Una rockfall, and analyzed the rockfall kinematics. Chen et al. (2013) compared 2D and 3D DDA rockfall analysis in predicting trajectory and dynamic behavior, and found that 3D DDA simulations are more appropriate for rough tree-laden inclined slopes in providing detailed spatial distribution, whereas 2D DDA simulation has better efficiency for slopes dominated by valleys and ravines. Lambert et al. (2013) analyzed the hazard and risk of rockfall with Rockyfor3D software through a real case study. Leine et al. (2013) conducted a 3D simulation on rockfall with nonsmooth contact dynamics, and analyzed the influence of rock geometry on rockfall trajectory and dynamics. Sarro et al. (2014) simulated the Son Poc rockfall by RocPro3D software which uses GIS technology to produce 3D rockfall trajectories lines, and estimated velocity and energy of falling blocks, as well as bounce heights, impacts, and stopping points. The results matched well field observations, with a very good accuracy between real and modeled outcomes. Thoeni et al. (2014) analyzed the block trajectories and velocities with and without drapery on the base of classical discrete element method, considering the interaction between rockfall and drapery. Wei et al. (2014) analyzed the mechanisms and characteristics of motions of rockfall according to the detailed field investigation and empirical-based method, and found that two intersecting joints and bedding plane divided bedrock into blocks and the weathering and rainfall infiltration accelerated the erosion process and precipitated ruptures. Koo et al. (2016) established the 3D finite-element model by a new bilinear force-displacement model, and analyzed the vertical and horizontal performance of flexible steel barriers under different weights and geometries with consideration of impacts by a rigid single spherical boulder and a rigid slab. Tan et al. (2018) constructed a large-scale physical modeling device to investigate the interaction between a flexible barrier and a falling boulder with different diameters，and proposed a simple approach for estimating the impact loading of a boulder on a flexible barrier. Li et al. (2019) automatically identified the discontinuity sets by 3D terrestrial laser scanning and fuzzy K-means algorithm, obtained the spatial distribution features of rock slope, and quantitatively assessed the rockfall failure mechanisms and evolutions of the Hongshiyan post failure rock slope after the 2014 Ludian earthquake. In the above literature, some researchers used different kinds of software to simulate the motion characteristics of rockfall and analyze the evolution mechanism based on GIS, 3D laser scanning and other technologies; the other researchers studied the interaction between impact force and protective structure based on rockfall test. These researchers have put forward prevention measures and schemes for actual rockfall cases based on the field investigation, theoretical analysis, and numerical simulation.

The rockfalls detached from cliff at the northern Zhangmu have occurred many times, which blocked the road, smashed vehicles and houses, and caused casualties. Based on the field investigation and numerical analysis, the distribution characteristics, scale, influencing factors, motion and accumulation characteristics of the dangerous rocks for potential collapse was ascertained, and the damage range of rock falls and the influence on Zhangmu Town are predicted.

2 Study Area

2.1 Location and meteorology

The study area is located in the Zhangmu Town, Nielamu County, Rikaze City, Tibet, China. The Zhangmu Town lies in the southernmost part of Tibet Plateau and on the left bank of Boqu River in the south slope of central Himalaya, with a total area of about 70 km², as shown in Fig. 1. The Zhangmu Town is 80 km far away from Katmandu, Nepal, and 780km away from Lhasa, China. The dangerous rock blocks exist in the northern Zhangmu Town, the left bank of Boqu River and the right bank of Zhangmu ditch which is a branch of Boqu River, mainly on the steep rock slopes along the line from Zhangmu Town to Zhangmu ditch.

The Climate in the study area belongs to the mountainous humid subtropical monsoon climate, with temperature gradually decreasing from south to north. The humid current from Indian Ocean advances from south to north along the Ganges Basin, and then forms the cyclonic precipitation or orographic precipitation when encountering the natural barrier of Himalaya. Hence, the study area is subject to extremely intensive rainfall, and is one of a few rainstorm centers in Tibet. The climate data shows that the study area has an average temperature of 12°C, with maximum temperature of 32°C, minimum temperature of -1°C, annual precipitation of 2400-3100 mm, average annual precipitation of 2820 mm, and evaporation of around 1500 mm. Rockfall is easily triggered in the study area because 80% of annual rainfall occurs in summer.

2.2 Geomorphology and geological setting

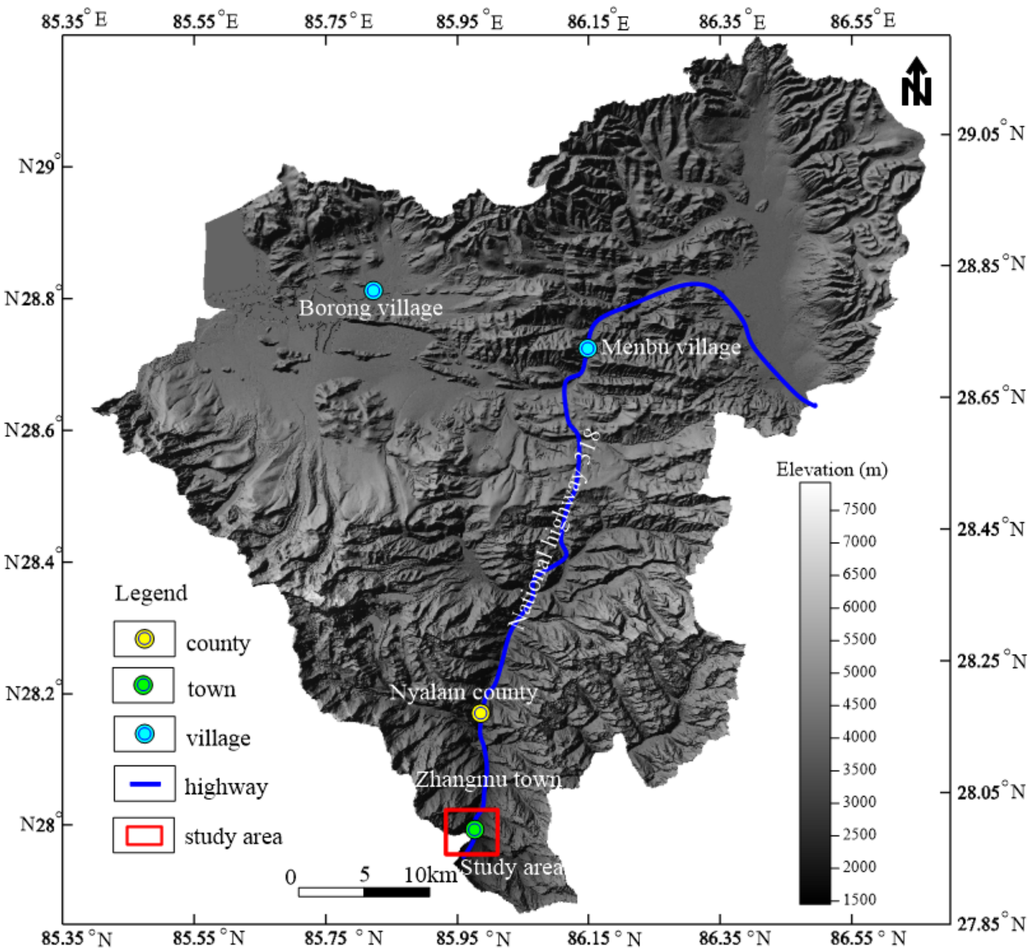


Fig. 1 Schematic location of the study area.

The study area is located in the high and steep left-bank slopes of Boqu River, with highly undulating terrain and deep valley. The ground elevation of study area is 2150 m to 3500 m, with height difference of 1350 m. The dangerous rocks are basically found in the section of 2700-3430 m elevation. There is a NW-SE-strike, about 1km long, hundreds of meters high rock cliff in the 2700-3100 m section, with slope of 70°-90°, locally protruding. The 3100-3200 m section is basically the rockfall accumulation area, with slope of 45°-60°. The 3200-3430 m section is the source of rockfall, with slope of 40°-60°, locally protruding. The section below 2700m elevation is generally made of loose accumulation, with gentle slope of 20°-40°. Three sections of zigzag National Highway 318 cross the slope foot.

The rock outcrop in the rockfall area consists mainly of the strata of Pre-sinian Dalemaqiao Formation, pre-Sinian System (AnZd), which is made of biotite plagio-gneiss with biotite quartz and schist Granite gneiss, with medium to coarse grained lepido granoblastic texture, schistose or gneissose structure. The Quaternary gravel and cobble accumulation is found on the ground surface, as shown in Fig. 2.

There are a great number of discontinuities in the study area, dominated by steep faults and joints of NW-SE strike and SW inclination. There exist four approximately parallel faults with similar feature and attitude of 215°-225°∠60°-70°, three in northern Zhangmu Town, one at the mouth of Zhangmu ditch. The four faults are all normal faults, with NW-SE strike and SW inclination, and the fractured zone is about 2-5m wide. The developed joints are almost parallel to the faults, which generally formed 20-50m wide dense joint belt close to the faults, with density of 2-10 joints per meter.

2.3 Historical rockfall accidents

According to the residential survey and literatures, the rockfall in Zhangmu Town firstly happened since 1972, with small amount each time. In 1986, strong earthquake occurred in the study area, and the rockfall began to become intensive. During the period

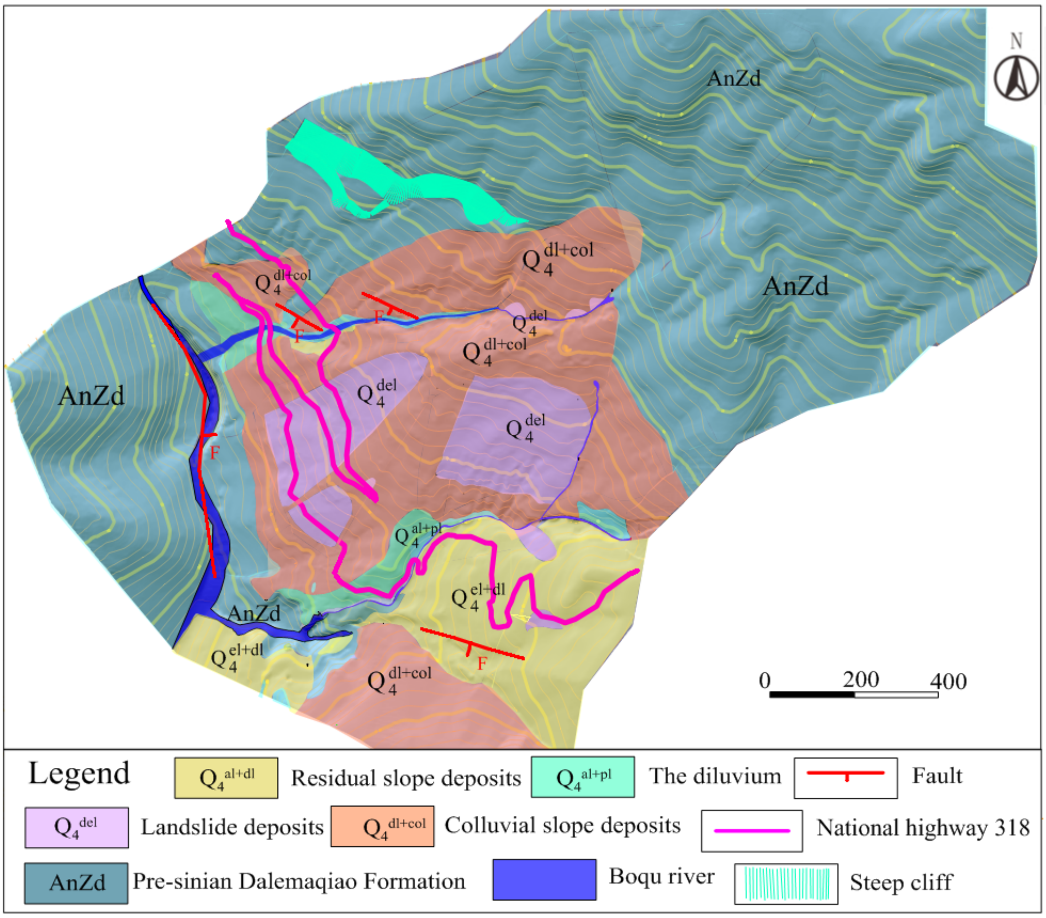


Fig. 2 Regional geology of the study area.

from 1987 to 1989, rockfall of large amount and long duration happened frequently, both in dry season and in rainy season, which damaged the vehicles and caused heavy pedestrian casualties and traffic jam. Preliminary statistical data indicates that, by 2020, the rockfall in Zhangmu Town had resulted in more than 30 casualties and damaged 14 vehicles, 14 residential houses and a foreign trade warehouse. After 1990, the rockfall amount gradually decreased despite the extremely heavy rainfall in 1991 and 1998.

At present, the source of rockfall is reduced due to the reduction of dangerous rock in the upper slope as well as the slope prevention measures such as reinforcement, water drainage and vegetation planting. The study area is temporarily stable especially after the installment of passive and active flexible structures. However, under extreme conditions (heavy rainfall, earthquake), the risk of unstable failure of dangerous rock mass is still great, which poses a great threat to the safety of the roads and peoples.

3 Field Investigation

In 2014, field investigation of Zhangmu rockfall was carried out, and theoretical analysis, engineering geological mapping, topographic mapping and other methods were used to find out the distribution, morphological characteristics, scale, stability and development trend of dangerous rock in the study area.

3.1 Distribution characteristic of rockfall belt

The rockfall belt is located in the steep slope in the northern Zhangmu Town, and the lithology consists mainly of the biotite plagiogneiss, biotite quartz schist and granite gneiss, with attitude of 26° ∠30°. The rockfall belt is approximately shaped like a triangle along 114° strike, with large NW elevation difference and small SE elevation difference. It is about 944m long, with average height of 625m and total area of around 1.54 km^2. The elevation of the top of rockfall belt is 3430-3450 m, and that of the bottom of rockfall belt is 2700-2950 m, with height difference of 500-750 m. The source of rockfall is approximately 1000 m above the National Highway 318, with high potential and steep slope. According to the feature, stability and risk level, the rockfall belt is divided into three sections (Fig. 3), namely, unstable section, slightly stable section and stable section.

Unstable section. Located in the 3210-3428 m elevation, it is in the shape of an ellipse, with area of around 0.22km^2. Most dangerous rock blocks in the study area are in this section where a source of rockfall is. The unstable section has a slope of 40°-60°, partially with depression terrain. There are four single dangerous blocks which consist mainly of mica gneiss and schist. The collapsed blocks deposited here in a disorderly way, generally with large size up to 6.6 m × 4 m × 1.7 m, and the loose collapsed block is about 1.76×10^6 m^3 in volume.

Slightly stable section. Located in the 3131-3210 m elevation, it has irregular shape, with area of about 0.24 km^2. This section is mainly the rockfall accumulation area, with slope of 45°-60° and block volume of about 6×10^6 m^3. Some blocks scattered on the slope, and some embedded in the slope. Some blocks have poor stability, and may slide or roll downward the slope under strong rainfall or earthquake.

Stable section. Located in the 3131-3210 m elevation, it is shaped like an irregular trapezium, with area of approximately 1.07 km^2. It is generally an about 1.0 km long, hundreds of meters high nearly vertical rock slope, and consists mainly of granite gneiss. The rock in this section is hard, with good weathering resistance and rock mass integrity. This section is generally stable, with low probability of rockfall.

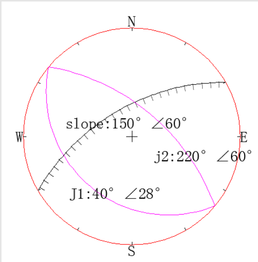
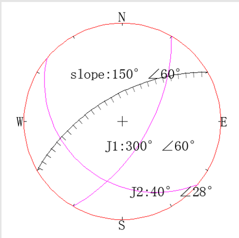
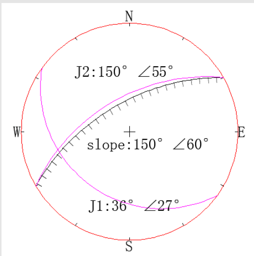
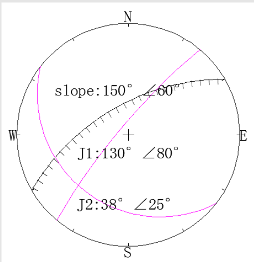
3.2 Feature of single dangerous block

The field investigation results indicated four single dangerous blocks, as listed in Table 1. According to the lithology, existing rockfall, unfavorable structural plane combination, rock mass loosing and rock failure, the failure mode of dangerous blocks can be divided into three categories, namely, toppling mode, slide mode and fall mode.

3.3 Stability of single dangerous block

The stability of single dangerous block is controlled by various factors, which needs the consideration of many parameters and complex boundary conditions. However, it is very difficult to determine the accurate parameters and boundary conditions. Therefore, some uncertain factors must be

Table 1 Characteristics of single dangerous block in Zhangmu Town

No.	Photo	Stereographic projection	Characteristics of single dangerous block
1			Cuboid-shaped, 6 m long, 3 m wide, 5.5 m high, controlled by two structural sets with attitudes of 220°∠60° and 40°∠28°, respectively. The first set belongs to tension plane, almost vertical, and most discontinuities are through. The second set is about 2 m long flat and coarse gneissosity plane, with good extension, filled with about 20 cm thick highly weathered argillaceous debris. Most part of this block is protruded, with a curved hollow on the bottom, which is subject to fall-mode rockfall.
2			Irregular shape, 12 m long, 4.5 m wide, 6 m high, controlled by a structural plane with attitude of 40°∠28 and a 6 m long steep structural plane with attitude of 300°∠60°. There is a hollow on the side due to the fall of some rock. This block is generally stable, and local fall-mode rockfall from this block has happened.
3			Cuboid-shaped, 8m long, 5.5 m wide, 4.5 m high, controlled by two structural sets with attitudes of 150°∠55° and 36°∠27°, respectively. The first set belongs to tension crack, 3.5 m long, 2-8 m wide, 3-5 cm spacing, filled with argillaceous debris. The second set is relatively flat, with good extension and 5-8 cm span, which is subject to toppling-mode rockfall.
4			Long column shaped, 30 m long, 27.9 m wide, 6 m high, controlled by two structural sets with attitudes of 130°∠80° and 38°∠25°, respectively. The first set consists of almost vertical tail tension cracks with undulating surface, and the cracks are about 20m deep and 1-4m wide, and are all through. The second set has flat surface, with gneissosity. There are secondary tension cracks in this block, which may result in slide-toppling-mode rockfall.

simplified to conduct the quantitative calculation (Collins and Stock 2016; Hu et al. 2018; Singh et al. 2016).

The toppling-mode rockfall generally occurs where the crack fully separates single block from the parent rock, and is basically induced by rainstorm and earthquake. The calculation model is shown in Fig. 4, and the corresponding formula is expressed as

A. the block gravity center is outside the supporting point

$$F_S = \frac{\frac{1}{2} f_{lk} \cdot \frac{(H-h)}{\mathrm{Sin}\,\beta}\left(\frac{2}{3}\frac{H-h}{\sin\beta} + \frac{b}{\cos a}\cos(\beta-\alpha)\right)}{W \cdot a + Q \cdot h_0 + V\left(\frac{H-h}{\mathrm{Sin}\,\beta} + \frac{h_w}{3\mathrm{Sin}\,\beta} + \frac{b}{\cos a}\cos(\beta-\alpha)\right)} \quad (1)$$

B. the block gravity center is inside the supporting point

$$F_s = \frac{\frac{1}{2} f_{lk} \cdot \frac{(H-h)}{\mathrm{Sin}\,\beta}\left(\frac{2}{3}\frac{H-h}{\sin\beta} + \frac{b}{\cos a}\cos(\beta-\alpha)\right) + W \cdot \alpha}{Q \cdot h_0 + V\left(\frac{H-h}{\mathrm{Sin}\,\beta} + \frac{h_w}{3\mathrm{Sin}\,\beta} + \frac{b}{\cos a}\cos(\beta-\alpha)\right)} \quad (2)$$

where F_S is the safety factor, H is the vertical distance in meter from crack top to supporting point, W is the block weight (kN/m), f_{lk} is the characteristic value (kPa) of tensile strength of dangerous block, h is the crack depth (m), h_w is the water height in crack (m), V is the crack water pressure (kN/m), here V=0.5$\gamma_w h_w^2$, Q is the seismic force (kN/m), Q=ηW, here η is the

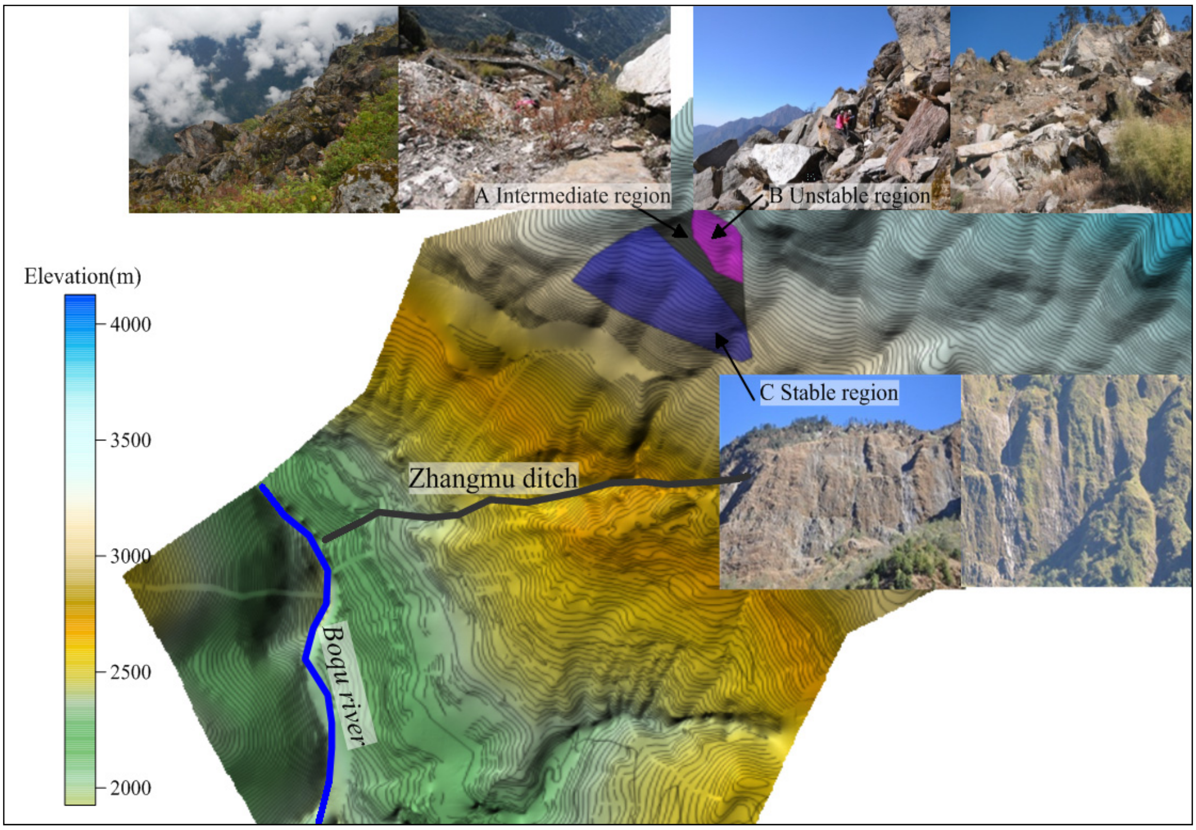
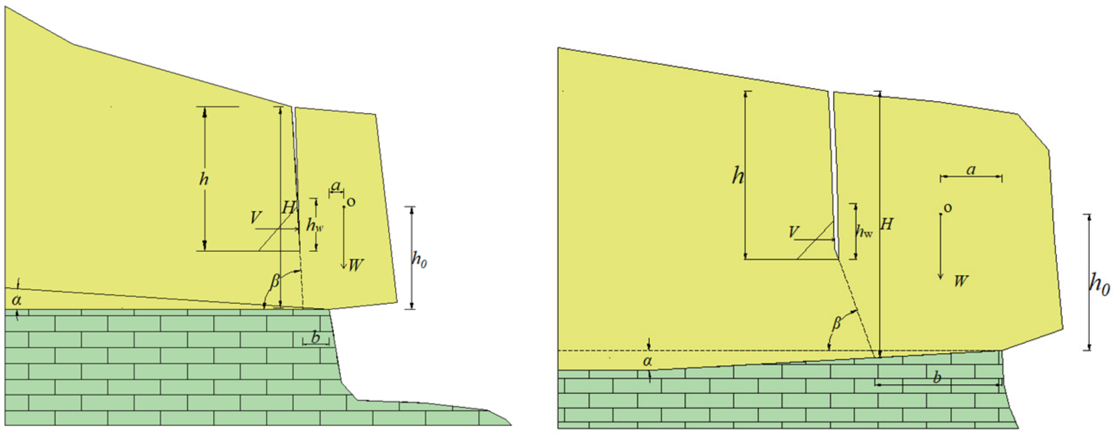


Fig. 3 Distribution of rockfall belt in Zhangmu Town in 2017.



(A) Gravity center outside the supporting point (B) Gravity center inside the supporting point

Fig. 4 Schematic model for analyzing the stability of toppling-mode rockfall.

horizontal seismic coefficient of 0.05, β is the dip angle (°) of crack, a is the horizontal distance from block gravity center to supporting point, and h_0 is the vertical distance from block gravity center to supporting point.

All the toppling-mode rockfall is triggered by steep crack, as shown in Fig. 5, and the safety factor is determined by the minimum of the following two equations:

$$F_S = \frac{c(H-h) - Qtg\phi}{W} \tag{3}$$

$$F_S = \frac{\zeta . f_{lk} . (H-h)^2}{Wa_0 + Qb_0} \tag{4}$$

where ζ denotes the coefficient of bending moment, a_0 denotes the horizontal distance (m) from block gravity center to potential failure plane, b_0 denotes the vertical distance (m) from block gravity center to

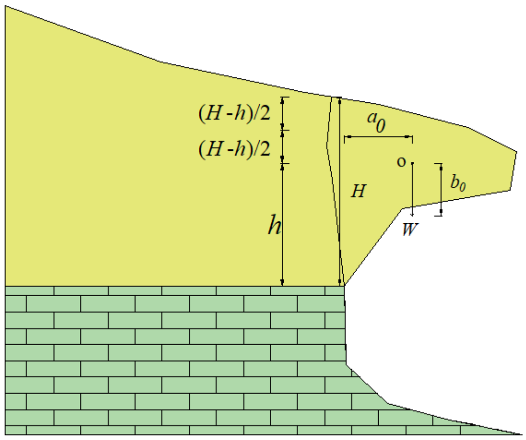


Fig. 5 Schematic model for analyzing the stability of fall-mode rockfall.

centroid of potential failure plane, and f_{lk} denotes the characteristic value (kPa) of tensile strength of dangerous block.

The slide-mode rockfall slides along weak structural plane, as shown in Fig. 6.

For rockfall without steep tail crack, the safety factor is obtained by:

$$F = \frac{(W\cos\alpha - Q\cdot\mathrm{Sin}\,\alpha - V)\cdot tg\varphi + CL}{W\,\mathrm{Sin}\,\alpha + Q\cos\alpha} \tag{5}$$

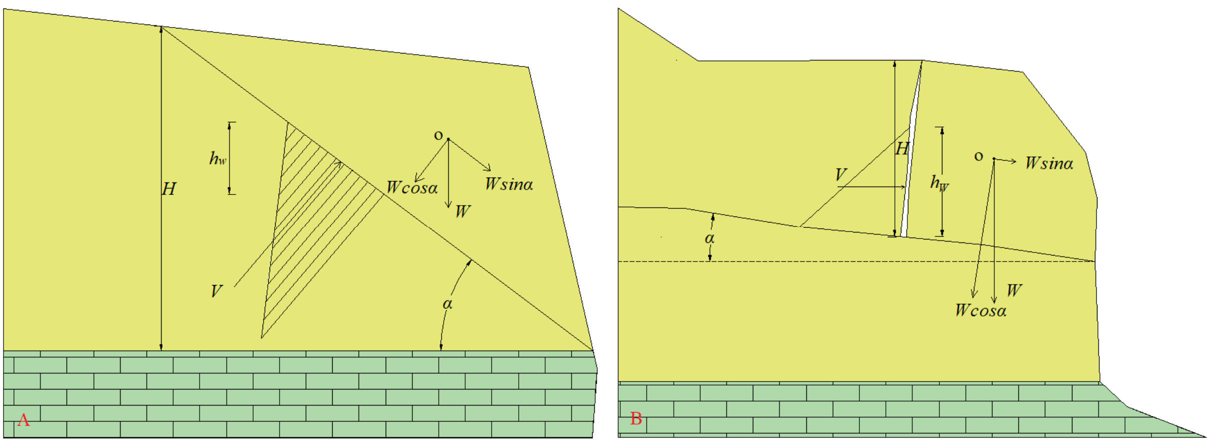
For rockfall with steep tail crack, the safety factor is obtained by:

$$F = \frac{(W\cos\alpha - Q\cdot\mathrm{Sin}\,\alpha - V\,\mathrm{Sin}\,\alpha - U)\cdot tg\varphi + CL}{W\,\mathrm{Sin}\,\alpha + Q\cos\alpha + V\cos\alpha} \tag{6}$$

where C is the cohesion (kPa) between block and underlying strata, φ is the angle (°) of internal friction between block and underlying strata, L is the contact length (m) between block and underlying strata, U is the water pressure in the slide plane, here U=0.5γLh_w, and other symbols are the same to those above.

The safety factor of single dangerous block is calculated under the natural case (case 1), rainstorm case (case 2), and earthquake case (case 3), respectively. For cases 1 and 2, all modes should consider the gravity. For slide-mode and toppling-mode rockfall under cases 1 and 2, the existing crack water pressure and rainstorm crack water pressure should be considered together. For case 3, all modes should consider the gravity and seismic force. For slide-mode and toppling-mode rockfall under case3, the rainstorm crack water pressure should be considered.

The calculated safety factors under various cases are listed in Table 2, indicating that the stability of dangerous blocks is greatly affected by earthquake. Thus, the probability of rockfall is large under earthquake.



(A) Without steep tail crack (B) With steep tail crack

Fig. 6 Schematic model for analyzing the stability of slide-mode rockfall.

Table 2 Stability analysis of four single dangerous blocks in Zhangmu Town

Case	No.1 block		No.2 block		No.3 block		No.4 block	
	Safety factor	Condition	Safety factor	Condition	Safety factor	Condition	Safety factor	Condition
1	1.19	Slightly stable	2.48	Stable	1.19	Slightly stable	1.07	Slightly stable
2	1.18	Slightly stable	2.24	Stable	1.17	Slightly stable	0.88	Slightly stable
3	1.14	Slightly stable	1.94	Stable	1.07	Slightly stable	0.62	Slightly stable

3.4 Stability of rockfall source area

There is no formula in existing standards for calculating the safety factor of rockfall source area. In this paper, the infinite slope method was used to evaluate the stability of rockfall source (Johari and Javadi 2012; Lu and Godt 2008).

According the infinite slope theory (Fig.7), the safety factors under various cases are determined by the following equations:

Natural case: $$F_S = \frac{tg\psi}{tg\alpha} \tag{7}$$

Earthquake case: $$F_S = \frac{tg\psi}{tg\alpha + K_C} \tag{8}$$

Rainstorm case: $$F_S = \frac{tg\psi}{tg\alpha\left(1 + S\frac{\rho_W}{\rho}\right)} \tag{9}$$

where ψ denotes the angle of internal friction of rockfall source, α denotes the slope angle of rockfall source, ρ denotes the density of rockfall source, ρ_w denotes the density of water, K_c denotes the horizontal seismic acceleration coefficient, namely, the ratio of horizontal seismic acceleration to gravity acceleration, and $s = h_W / H$.

According to the field survey, the average slope angle of rockfall source is about 40°, with ρ_w of 1.0 g/cm^3 tested ρ of 2.7g/cm^3. Based on similar engineering experience, the angle of internal friction of rockfall source is determined to be 45°. The calculation results show that the safety factor of rockfall source under natural case is 1.19, which is slightly stable. The rockfall source will fail when K_c =0.16, approximately under moderate earthquake. Under rainstorm case, the rockfall source will fail when s=0.43.

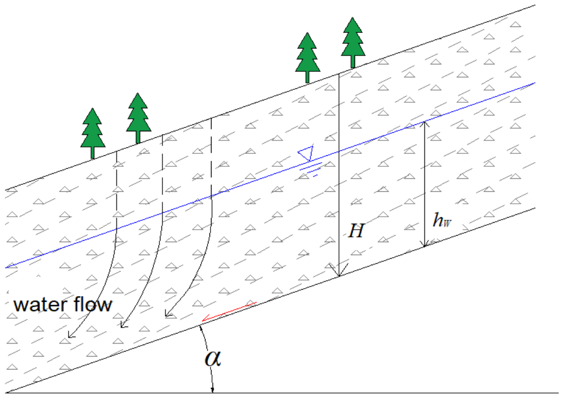


Fig. 7 Schematic model for calculating the safety factor of infinite slope.

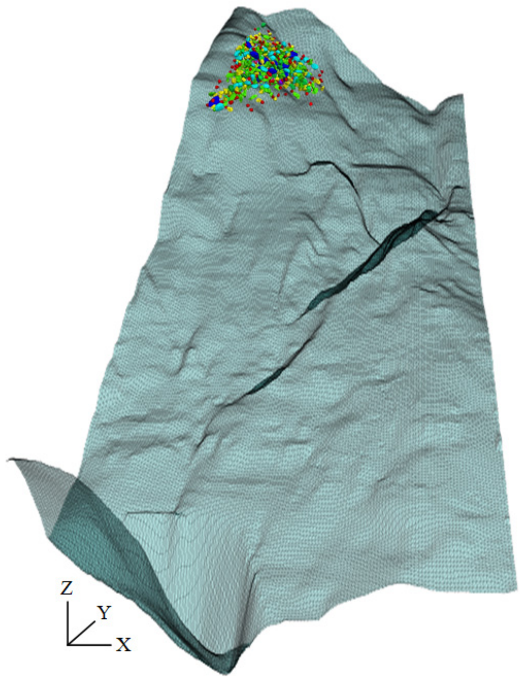


Fig. 8 PFC^{3D} Numerical model.

4 Numerical Simulation of Rockfalls

The rockfall in Zhangmu Town happened frequently and extensively in a large scale, especially since 1980s. To further ascertain the possible kinematic characteristics and hazard range of rockfall in a quantitative way, the PFC^{3D} program was used to simulate the 3D kinematic process of rockfall in Zhangmu Town on the base of field survey. The detailed calculation method, program mechanism and numerical modeling were not provided in this paper, and more information can be obtained from relative references listed in the bracket (Chen et al. 2013; Corona et al. 2017; Gischig et al. 2015; Rammer et al. 2010; Shen et al. 2019; Thoeni et al. 2014).

4.1 Numerical model

The 3D numerical model has the size of 1300m×2900m, with approximate NS direction as Y axis, approximate WE direction as X axis, and vertical direction as Z axis, as shown in Fig. 8. According to the features of terrain and landform, the model is on the south of the 2500-elevation region of opposite bank of Boqu River where the rockfall arrives farthest, on the north of the 3600-elevation region, on the west of a ridge, and on the east of a landslide.

The sphere elements traditionally used for rockfall blocks cannot simulate the effect of real block shape on the kinematic characteristics of rockfall. Therefore, the clump elements with irregular shape were applied in this paper to simulate the rockfall. The rockfall was divided into 14530 clump elements, with volume of about $1.27\times10^6 m^3$. The terrain model was divided into 39270 wall elements. Nine monitoring points were set to observe the variation in velocity and displacement during rockfall movement.

4.2 Parameters

The correlation between macroscopic and microscopic parameters is the key to the successful numerical simulation of rockfall with PFC^{3D} program. Some scholars have analyzed the effect of microscopic contact parameters on the kinematic feature of rock avalanche (Chongbin 2014; Li kun-meng 2016). Based on many trial computations and relative reference data, the microscopic parameters of rockfall were determined, as listed in Table 3.

The energy dissipation of rockfall in PFC^{3D} is basically controlled by mechanical damping which consists of viscous damping and local non-viscous damping. The local non-viscous damping α can be directly added into the kinematic equations, and α=0.5 here. The viscous damping can express the energy loss during contact progress, and γ_n =0.2 and γ_s =0.2 here.

5 Results and Discussion

5.1 Kinematic characteristics of rockfall

The rock at the top of steep slope in the Zhangmu Town has been developed into dangerous blocks due to the long-term weathering and tension, which is subject to rockfall in the case of rainstorm, earthquake or human engineering activities. Some blocks at the top of steep slope had formed rockfall, and deposited in the upper part of steep slope, Zhangmu ditch and right-bank slope. The kinematic trajectory of rockfall from the upper part of steep slope simulated by PFC^{3D} program is shown in Fig. 9 indicating that the fallen rocks move downward along 190°-220° direction due to the gravity and greatly undulating terrain, and then scattered onto the Zhangmu ditch and Zhameila ditch through many times of rolling and bouncing. Some fallen rocks continue to move along 130°-250° direction due to the terrain constraint, and finally deposit along the 300m long National Highway 318 section from Zhangmu Town to Zhangmu ditch in a scattered way, partly in the Boqu River.

The rockfall velocity contour at various times is shown in Fig.10, which indicates that the velocities increase after the rockfall onset and differ with each other even in the same elevation due to mutual collision and friction between rock blocks, with large velocity in the front and small velocity in the tail. At the 24s time, the fallen blocks reach the region nearby Dazhamei River, with maximum velocity of about 70m/s, and then collide the right bank of Zhangmu ditch, resulting in the change in movement direction and the decrease in magnitude.

The rockfall velocity is generally affected by block size, shape, block rotation, overburden and elastic-plastic property. To analyze the change in rockfall velocity, 9 monitoring points were set to observe the variation of rockfall velocity and displacement with time. As shown in Fig. 11, the X-direction velocity of block is up to about 40m/s when the fallen rocks reach the Zhameila ditch. After the blocks cross the Zhameila ditch, the X-direction velocities gradually decrease while the Y- and Z-direction velocities continually increase. The fallen rocks are diverted at the Zhangmu ditch, and finally deposit in the Boqu River.

5.2 Potential evolution of rockfall

The potential evolution of rockfall in Zhangmu Town depends directly on the change in the condition of the upper part of steep slope which was cut by

Table 3 Parameters for rockfall simulation

Microscopic parameter	Value	Microscopic parameter	Value
K_n (Pebble-facet) (KN/L)	1E+05	f (Pebble- facet)	0.6
K_s (Pebble-facet) (KN/L)	6E+04	f (Pebble- pebble)	0.02
K_n (Pebble-pebble) (KN/L)	4.88E+05	cb_tens (Pa)	1E+02
K_s (Pebble- pebble) (KN/L)	6E+04	cb_shears (Pa)	5E+02

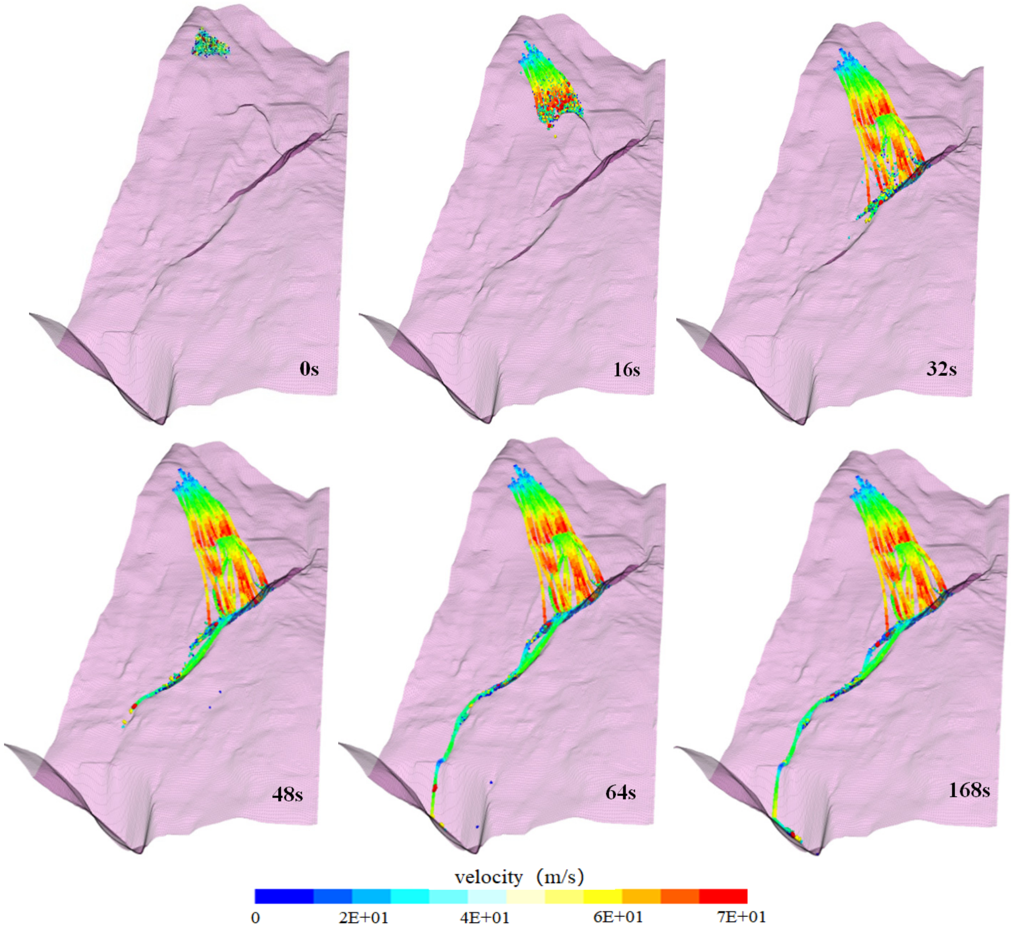


Fig. 9 Kinematic trajectory of rockfall simulated by PFC^{3D} program.

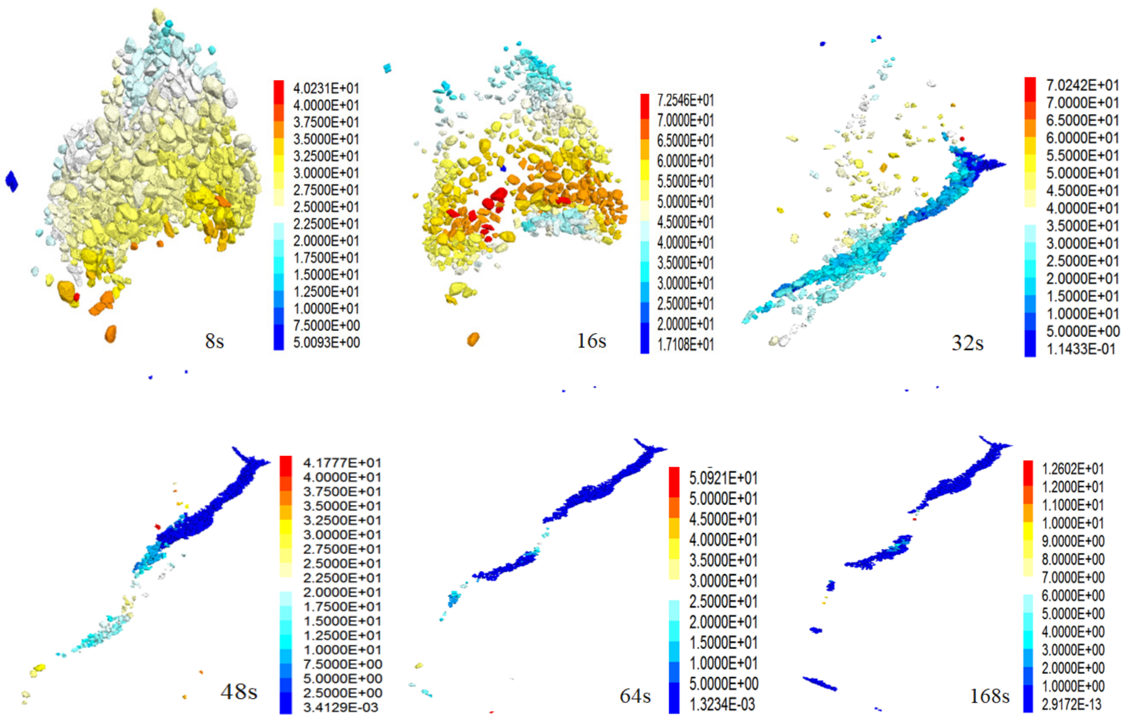


Fig. 10 Rockfall velocity contour (m/s).

adverse joints and gneissosity and is subject to rockfall. However, a potential rockfall source will be generally stable if it does not suffer from adverse external factors. Actually, any potential rockfall source, including that in Zhangmu Town, must experience complex and long-term actions. The upper part of steep slope in Zhangmu Town will be subject to long-term rainfall, water immersion, erosion,

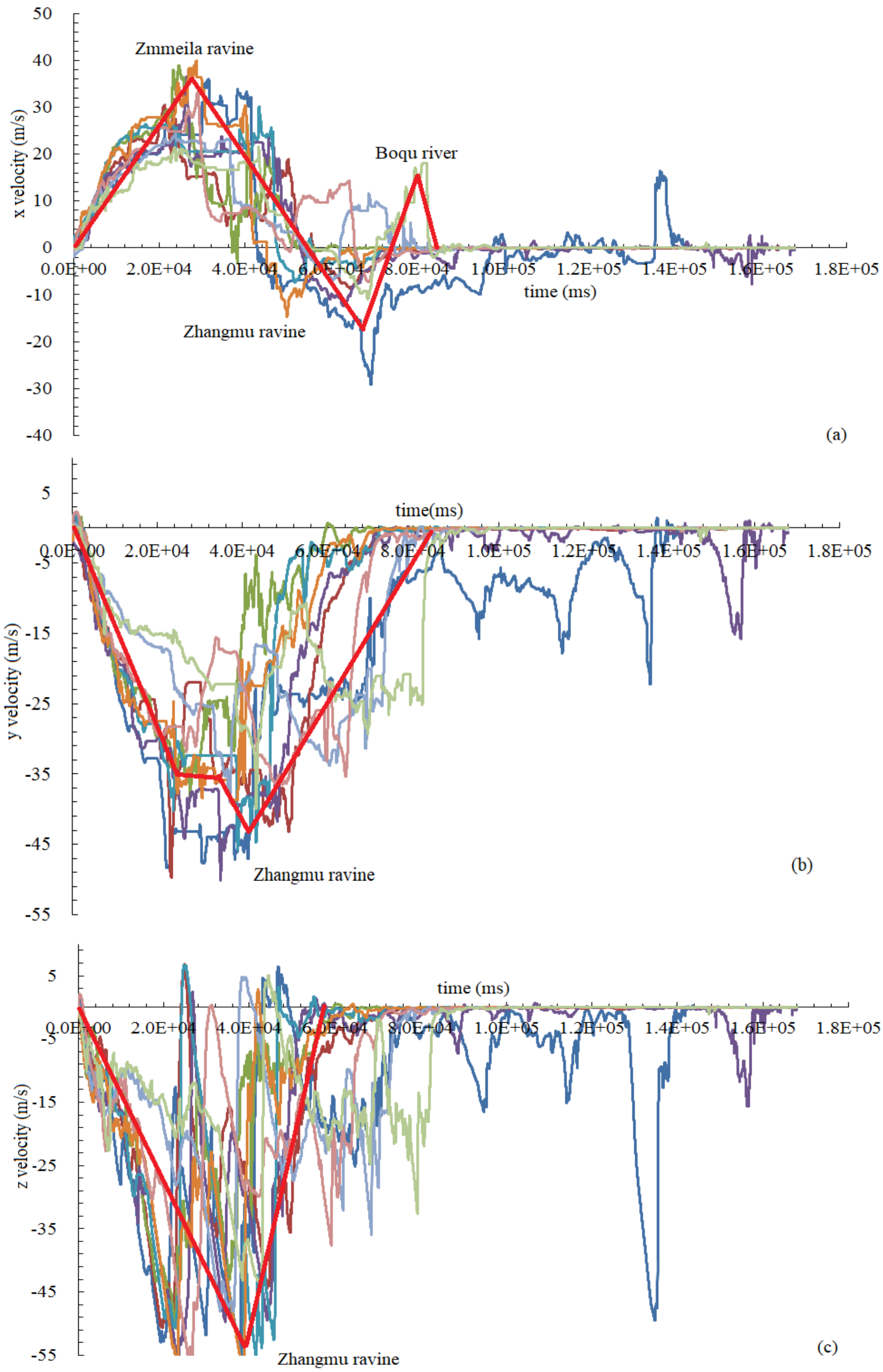


Fig. 11 Velocity curve for x velocity (a), y velocity(b) and z velocity (c) at the monitoring point.

weathering induced by temperature difference and freezing, and possible strong earthquake of VIII intensity. Due to adverse combination of structural planes and steep terrain, rockfall may happen from the upper part of steep slope in Zhangmu Town in the case of highly adverse factors such as strong earthquake, which poses great threat to the infrastructures and residents below in the form of block fall or debris flow.

5.3 Casualty and damage range

According to the field survey, historical rockfall records, and literatures, the rockfall volume was estimated to be about $4\times10^6 m^3$ in total since 1972, with annual rockfall volume of around $0.06\times10^6 m^3$. Due to the terrain constraint, most fallen rocks will be diverted along streams and damaged the structures such as roads, houses and car parks at the right side of Zhangmu ditch. The potential rockfall poses great threat to the car parks, gas station, 300m long section of National Highway 318, 30 to 40 households and about 300 residents along the line from Zhangmu Town to Zhangmu ditch, as shown in Fig. 12.

5.4 Recommended prevention measures

The rockfall is generally prevented by active measures, such as bolting, bracing, grouting, pointing, drainage, active flexible net and block removal, and passive measures, such as retaining wall, interception ditch, fence, passive protective net and protective shed (Binal and Ercanoglu 2010; Dhakal et al. 2011; Mavrouli and Corominas 2010; Plassiard and Donze 2010; Volkwein et al. 2011).

According to the geological conditions, possible evolution and damage range, the active prevention measures and the passive measures are proposed for the unstable section and the slightly stable section. The removal and interception are recommended as the major rockfall prevention measures, with protective shed as auxiliary measure. The prevention

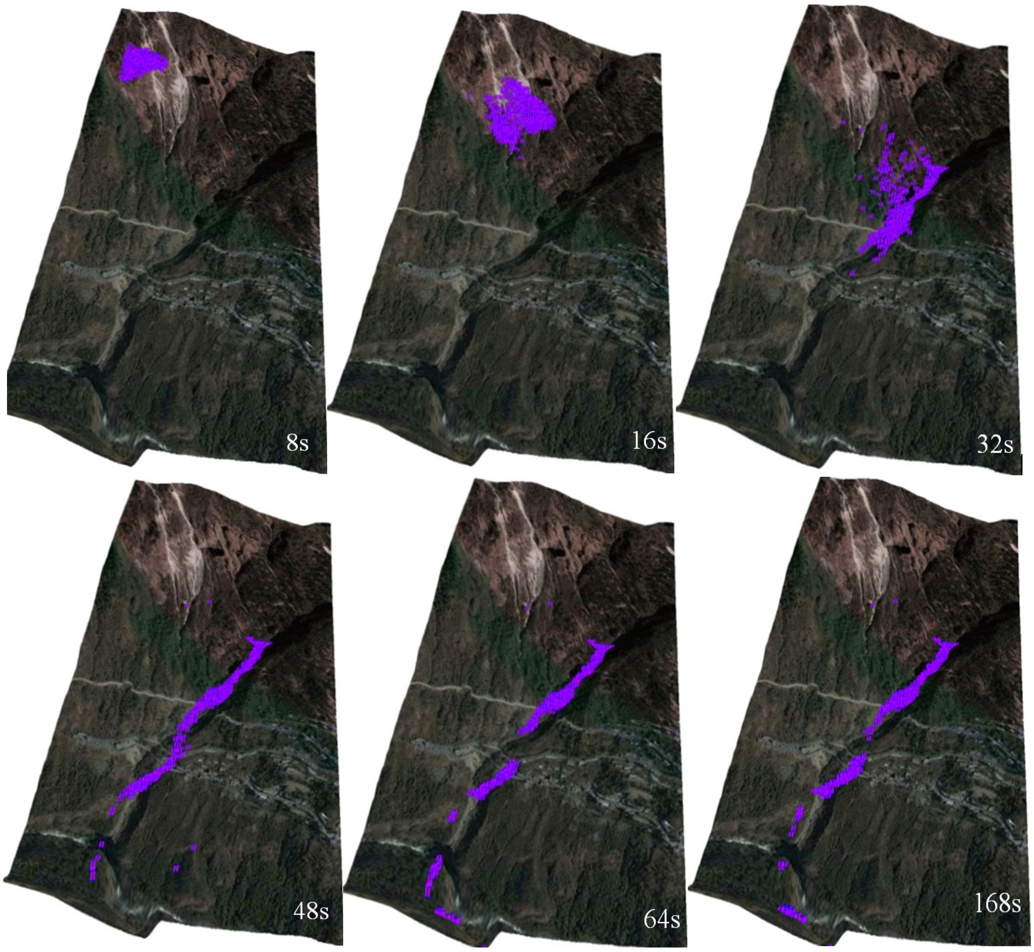


Fig. 12 Characteristics of rockfall accumulation at different time.

measures are schematically shown in Fig. 13 and Fig. 14.

Blast removal project. In the collapse unstable zone with an elevation of 3210-3428m, there are four rockfall bodies with a total release of about 3000m3, among which three rockfall bodies have poor stability. Considering the size, location and construction site limitation of the four rockfall bodies, it is suggested to use controlled blasting technology to remove the four rockfall bodies, so as to eliminate the potential safety hazards of rockfall bodies.

Interception project. According to the stability analysis results of rockpile in the collapse unstable zone with an elevation of 3210 to 3428m, rockpile will be unstable under extreme operating conditions (seismic conditions, heavy rain conditions), and the large-scale rockpile will fall down along the cliffs to pose a serious threat to the 318 line of National Road, Car park, Zhangmu ditch and Poqu River. Therefore, it is necessary to intercept it in situ, to avoid the start-up of large-scale collapse of the rockfall disaster. In view of the large scale of the rockpile, high impact energy characteristics, combined with the site construction conditions, it is proposed to lay the first high-energy collapse rockfall interception project at an elevation of 3150m, to withstand the impact of large-scale collapse. Along the elevation of 3130m, a second interception project of medium energy rockfall is laid to form the second interception project, which

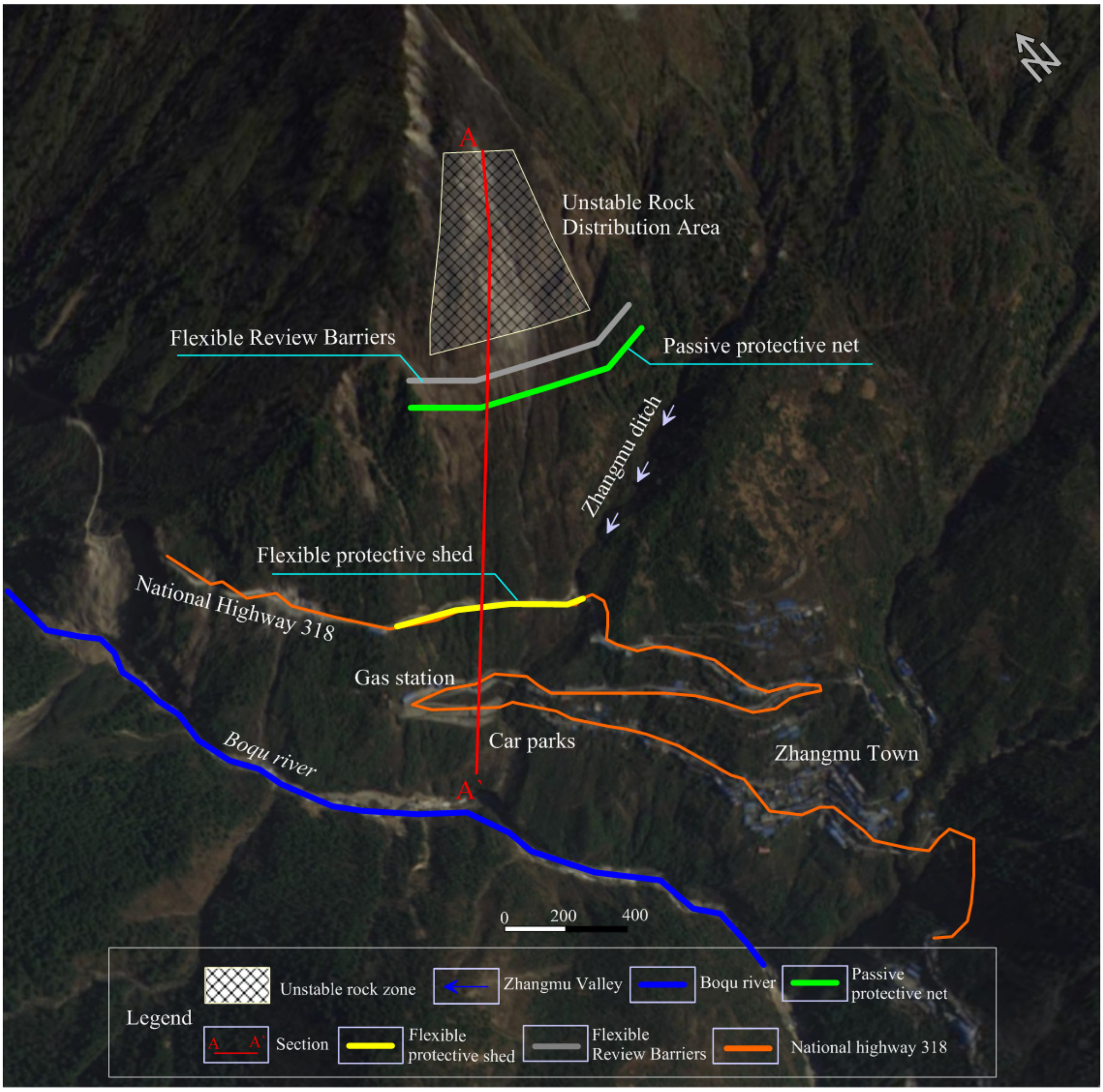


Fig. 13 Schematic layout of rockfall prevention measures.

can effectively intercept part of the "fish that escaped from the net".

Shielding project. Due to the collapse source area from the lower road height difference of about 1000m, after the collapse disaster, the collapse of rockfalls after rolling, bouncing accumulation in zhangmu Ditch, Zamira Ditch, some scattered in the armed police 2 battalion ~ Zhangmu ditch mouth area of the 300m long national Highway 318. After the rockfall is removed and a two-stage interception project is set up in the collapse disaster formation area, a small number of rockfalls may still fall and cause harm. These rockfalls may be small in size, but have high impact velocity and considerable impact energy. Therefore, shielding project is adopted to protect national Highway 318.

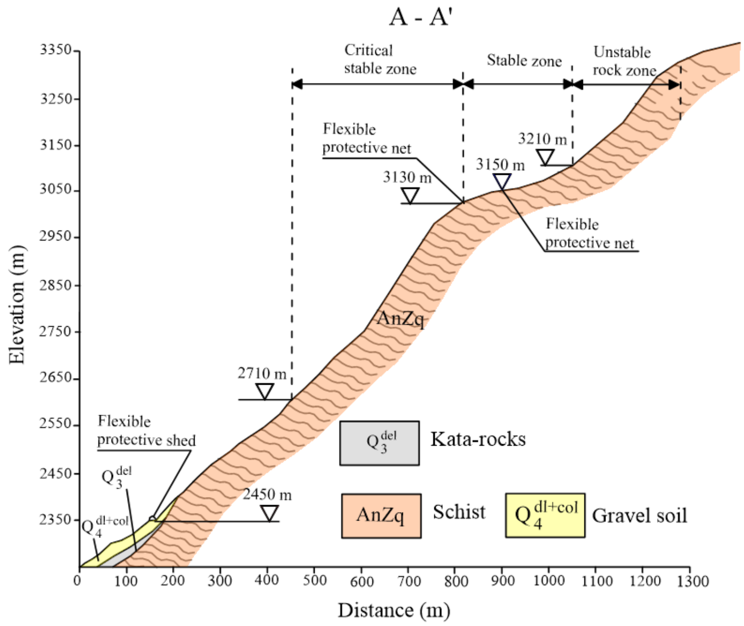


Fig.14 Schematic profile of rockfall prevention measures.

6 Conclusions

According to the field investigation on the rock slope in Zhangmu Town, the 3D numerical model was established to simulate the kinematic progress of rockfall and analyze the possible evolution, damage range and kinematic behavior of rockfall source in both qualitative and quantitative ways. The research results of this paper can provide some technical support for the prevention and control planning of the rockfall in Zhangmu. The following conclusions were obtained.

(1) The dangerous block belt in Zhangmu Town is totally about 944m, with top elevation of 3430-3450m, bottom elevation of 2700-2950m, and total area of about 1.54 km². According to the geological conditions and stability evaluation, the dangerous block belt is divided into unstable section, slightly stable section and stable section.

(2) The historical large-scale rockfalls in Zhangmu Town have caused severe damage. The dangerous blocks are affected by many factors such as steep terrain, adverse combination of structural planes, and long-term rainfall, which will probably result in rockfall again in the case of water immersion, strong rainfall or potential strong earthquake.

(3) After the rockfall happens, the fallen rocks will move downward along 190-220° direction due to terrain constraint, and then scatter onto the Zhangmu ditch through many times of rolling and bouncing. Some fallen rocks continue to move along 130-250° direction, and finally deposit in the Boqu River near the region from Zhangmu Town to Zhangmu ditch. The maximum velocity of rockfall is around 50-70m/s.

(4) Based on the principle of both safety and economy, the prevention measures of blast removal project and Interception project are put forward, supplemented by shielding project.

Because the collapse movement is a complex dynamic process with many influencing factors, numerical analysis and calculation usually simplify the influencing factors. In the analysis of the paper, the influence of the collision broken and obstacles of trees on movement characteristics of rockfall was not taken into account, which will be gradually improved in the future work.

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