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Full Length Research Paper

Stability analysis method of perilous rock in source of avalanche

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Perilous rocks are a potential geological disaster on cliffs and/or steep slopes and can initiate avalanches. They are classified into three types: sliding perilous rocks, toppling perilous rocks and falling perilous rocks. Moreover, two subtypes of toppling perilous rocks are distinguished, one in which the upsetting point is outside of the center of gravity of the perilous rock, and one in which the upsetting point is inside. Hitherto, stability analysis of perilous rocks is the original aspect in avalanche mitigations. The authors establish the stability analysis method of perilous rocks systematically in this paper. The method includes four aspects: (1) Lading combinations acting on perilous rocks; (2) shear strength parameters of the dominant fissure; (3) assessment criterion for perilous rocks, and (4) calculation formulas of the stability coefficient of perilous rocks, which has been applied effectively in control engineering of about 30000 perilous rocks in Western China.

Key words: Perilous rock in source of avalanche, types, loading combinations, shear strength parameters of dominant fissure, stability analysis method.

INTRODUCTION

A rockfall is defined as the fall of single rocks and stones with a volume smaller than 5 m^3, while a rock avalanche is a more massive collapse (Chen et al., 2009a). Both rockfalls and rock avalanches belong to one type of global geological disasters. In the past ten years, these disasters caused hundreds of millions of dollars in economic losses and killed about 6000 persons in China. All rock-avalanche bodies from avalanche at Karivhoh are composed of intensively crushed debris overlain by a blocky carapace (Strom, 2004). At Deali Fault, Alaska, thousands of landslides, primarily rock falls and rock slides were triggered by the M 7.9 earthquake of 3 November 2002. The materials of these avalanches, despite being composed of coarse, blocky rock fragments, flowed as a viscous fluid (Jibson et al., 2006). Rock falls and rock avalanches belong to a major erosion process shaping ridge crests and alpine summits (Cox et al., 2009).

It was determined through reconnaissance that strong seismic shaking caused or triggered most of the gigantic large-scale rock-slope failures in the Tien Shan (Strom and Korup, 2006). The effective friction coefficient of rock avalanches diminishes gradually as a function of the avalanche volume (Blasio, 2009). By considering the maximum obstacle height at the slope surface and the radius of the falling rock, one formula to estimate the tangential coefficient of restitution was proposed by Dorren et al. (2006). The sensitivity of lateral dispersion of rockfall trajectories on slope had been systematically evaluated as a function of macro-topographic, micro-topographic and model special features by Crosta et al. (2004). Based on variations in kinetic and potential energies and frictional losses, Zambrano (2008) proposed one formula to estimate movement velocities of a large rock body. To determine factors for rockfall source area, rockfall tracks, and rockfall runout zones on a forested slope in mountainous terrain, a combined approach using field and modeling techniques was put forward by Dorren et al. (2004). The energy of an

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Figure 1. Hundreds of perilous rocks exist on a cliff at Wanzhou city, the area of Three Gorges Reservoir, China.

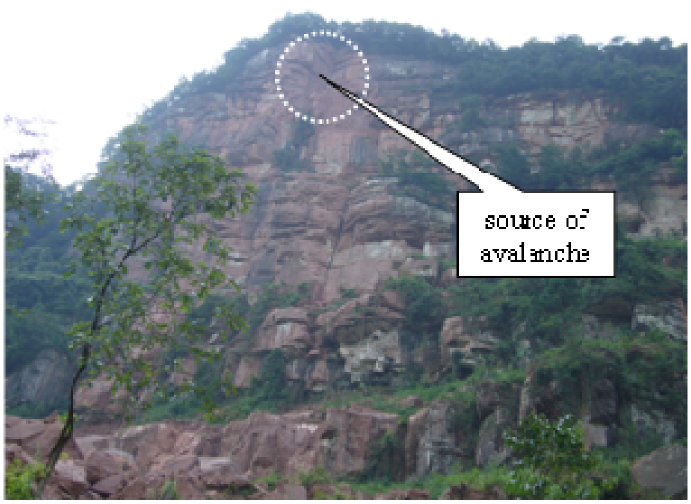

Figure 2. Geomorphologic vestige of an avalanche occurrence on 25 Nov., 2004, at the nation-level scenic area of Simianshan, Chongqing city, China.

avalanche is dissipated not only through friction but also during impacts and block breakage (Tommasi et al., 2008). Woltjer et al. (2008) pointed at the urgent need to improve realistic simulations of rockfall base on the interaction of understory and rockfall activity. Manzella et al. (2008) present an experimental study of rock avalanches' run-out and propagation carried out with a small-scale physical model. Rockfall activity by the disturbance of tress growth is investigated by Stoffel et al. (2005).

The studies before-mentioned are focused on the subsequent processes or dynamics after the occurrence of paroxysmal avalanches. However, to achieve hazard mitigation effectively before the occurrence of paroxysmal avalanches, putting our focus on the sources of avalanches has a very realistic value. With regards to this, Chen and Tang (2005) define a potential unstable rock block in avalanche source on cliffs or steep slopes as a perilous rock, and pay attentions to the dominant fissure behind the perilous rock. Studies show the rupture mechanism of various types of perilous rocks (Chen et al., 2006; 2007; 2008a). Stability analyses for various types of perilous rocks are the key aspect to determine whether engineering is essential or not, and if necessary, how to choose techniques such as support, anchorage, elimination and support-anchorage union etc. This paper will make a comprehensive description of the stability analysis method in many ways such as types of perilous rocks, assessment criterion, loads and lading combinations acting on perilous rock masses, shearing strength parameters of the dominant fissure, and the stability coefficient of perilous rock.

TYPES OF PERILOUS ROCK IN AVALANCHE SOURCE

Perilous rocks on cliffs and/or steep slopes usually exist singly or en masse before collapse. They are a potential hidden trouble to the safety to buildings, roads, municipal facilities, and inhabitants below the cliffs and/or steep slopes (Figure 1). When perilous rocks become unstable and collapse, rockfalls or avalanches occur, destroying all forest or crops along their route. A geomorphologic vestige of the rockfall or avalanche emerges (Figure 2). However, in studying the stability of perilous rocks, it is valuable to identify the type of affiliation of every perilous rock in the avalanche source area. Based on possible instability patterns, three types of perilous rocks are proposed by Chen et al. (2005). Figure 3 represents the sliding perilous rock, rupturing along its dominant fissure under loads. Two subtypes of toppling perilous rocks are shown in Figures 4 and 5, triggered by rock cell and by the rheology of a weak rock under the perilous rock, respectively. Rock cell is an inward sunken cavity at the bottom of perilous rock. If there is enough free space under the perilous rock, a falling perilous rock could possibly emerge (Figure 6). Particularly, a mass of perilous rocks is composed of many single perilous rocks.

STABILITY ASSESSMENT CRITERION OF PERILOUS ROCKS

The stability of perilous rocks in avalanche source areas can be characterized by the coefficient of stability under

Figure 3. Sliding perilous rock.

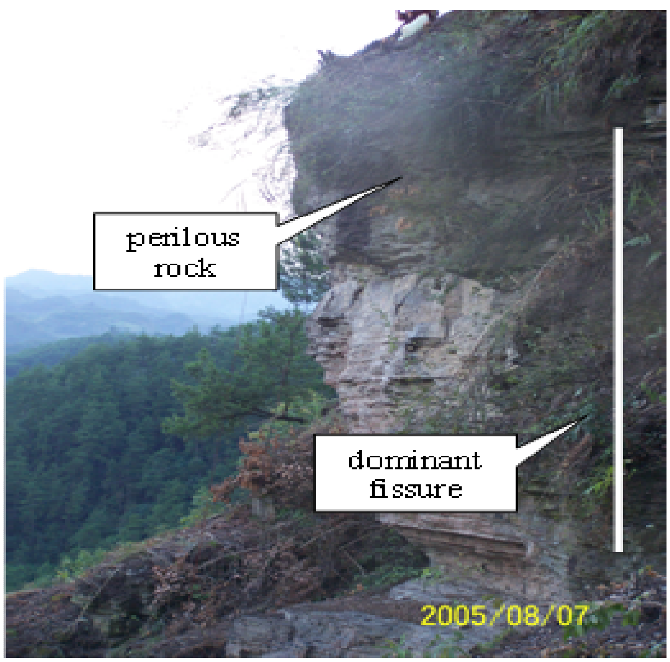

Figure 4. Toppling perilous rock triggering by rock cell.

action of loads. Unstable, primary stable, and stable statuses are classified in stability analyses of perilous rocks. Chen et al. (2004; 2008b) propose one stability assessment criterion of perilous rocks (Table 1). For example, a sliding perilous rock is designated as unstable,

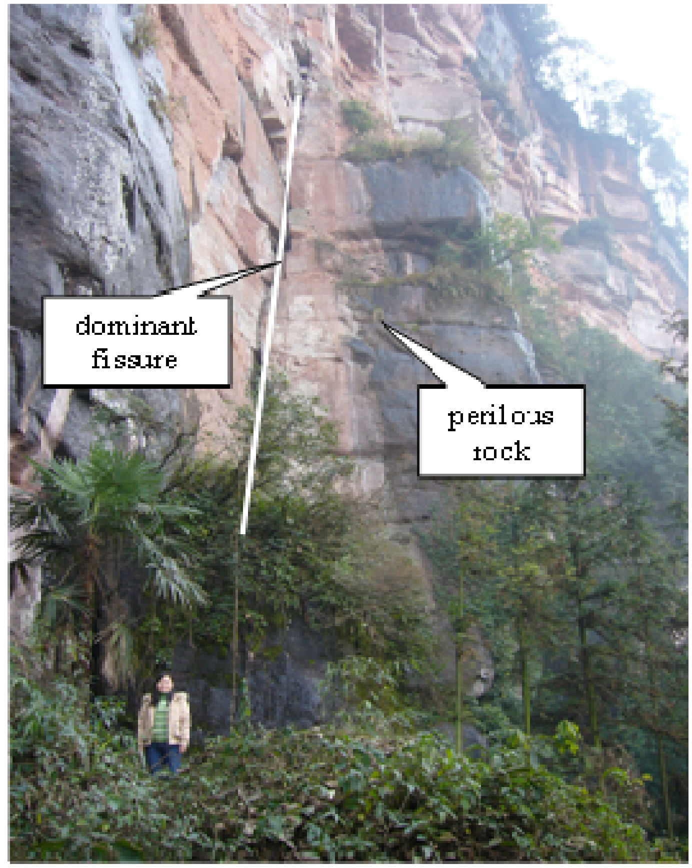

Figure 5. Toppling perilous rock triggering by rheology of weak rock under the perilous rock.

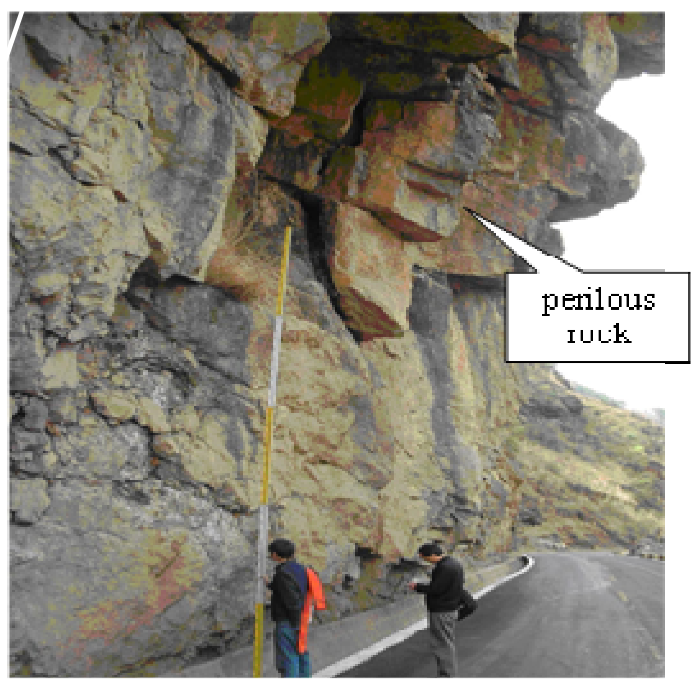

Figure 6. A falling perilous rock.

Table 1. Stability assessment criterion of perilous rock.

Status types	Unstable	Primary stable	Stable
Sliding perilous rock	<1.0	1.0~1.3	>1.3
Toppling perilous rock	<.0	1.0~1.5	>1.5
Falling perilous rock	<.0	1.0~1.5	>1.5

Table 2. Safety criterion of control engineering of perilous rock.

Safety grade types	A	B	C
Sliding perilous rock	1.40	1.30	1.20
Toppling perilous rock	1.50	1.40	1.30
Falling perilous rock	1.60	1.50	1.40

primary stable or stable when its coefficient of stability is less than 1.0, between 1.0 and 1.3, and bigger than 1.3, respectively.

It is important to consider the safety grade of control engineering of perilous rocks. Hundreds of control engineering existing in the area of the Three Gorges Reservoir of China display the safety criterion of showing in Table 2 is reasonable. Safety A means that the coefficient of stability of perilous rocks must be 1.40 at least after introducing corresponding engineering measures to important city, industrial and mining establishments, transportation junction and public utilities, Safety B does to less important town, buildings, industrial and mining establishments, and important artery traffic, and safety grade C does to any cases except safety grade A and B. For example, any toppling perilous rock whose coefficient of stability after the government project implementation is more than 1.5 is assigned to safety grade A, 1.4 to safety grade B, and 1.3 to safety grade C. Methods to calculate the coefficient of stability of every type of perilous rock under action of loads will be discussed in this paper.

LOADS AND LADING COMBINATIONS ACTING ON PERILOUS ROCK MASS

Loads and lading combinations acting on perilous rocks control their stability status. Loads acting on perilous rocks are classified into three categories which are dead weight of perilous rock, water pressure in dominant fissure (including statuses in natural and during a rainstorm) and seismic force. Moreover, two types of seismic force, horizontal seismic force and vertical seismic force are distinguished. For the three types of load, the dead weight of a perilous rock is considered a permanent load, water pressure in the dominant fissure is considered a periodic load varying with statuses in natural and during a rainstorm, and the seismic force is considered an incidental load with low frequency.

The dead weight of a perilous rock is calculated using the following formula.

$$W = \gamma V \quad (1)$$

Where:

W is the dead weight of a perilous rock (kN);
V is the volume of a perilous rock (m^3);
γ is the specific gravity per cubic meter (kN/m^3).

Water pressure in the dominant fissure in natural and during a rainstorm is calculated in formula (2) and (3), respectively.

$$Q = \frac{1}{18}\gamma_w e^2 l \quad (2)$$

$$Q = \frac{2}{9}\gamma_w e^2 l \quad (3)$$

The seismic force acting on a perilous rock is calculated in equation (4) considering pseudo-static assumption.

$$P = kW \quad (4)$$

Where:

Q is the water pressure in the dominant fissure (kN);
γ_w is the water weight per cubic meter (9.81 kN/m^3);
e is the vertical length of the conjunction part of the dominant fissure (m);
l is the level length of a perilous rock parallel to the strike of cliff or steep slope (m);
P is the seismic force (kN), and
k is the coefficient of seismic force including k_h and k_v, where k_h is designated as the coefficient of horizontal seismic force, k_v is that of vertical seismic force.

Based on the frequency of loads acting on a perilous rock three types of lading combinations are recommended:

Case 1: Dead weight of perilous rock and water pressure in dominant fissure in natural status.

Case 2: Dead weight of perilous rock and water pressure in dominant fissure during a rainstorm status.
Case 3: Dead weight of perilous rock, water pressure in dominant fissure in natural status and experiencing a seismic force.

Specially, case 1 is ignored for toppling perilous rocks and case 2 is ignored for falling perilous rocks. In the 3 cases, case 2 usually is designated as the design load in the design of control engineering. However, for control engineering of safety grade A in strong earthquake areas and within large-scale reservoir areas, a revised case 3, in which the water pressure in natural status is replaced by water pressure during a rainstorm status is adopted as the design load.

SHEARING STRENGTH CALCULATION OF DOMINANT FISSURE IN PERILOUS ROCK MASS

Stability analysis of perilous rocks has been beset with unreasonable shearing strength parameters of the dominant fissure for years. For example, although there is the connecting section and the disconnected section of the dominant fissure, the design specification of Geological Disasters Control Engineering (DB50/5029-2004) payed attentions to the equivalent cohesive force and equivalent angle of internal friction of the dominant fissure in a perilous rock and proposed the following two formulas.

$$c = \frac{(H_0 - e_0)c_1 + e_0 c_0}{H_0} \quad (5)$$

$$\varphi = \frac{(H_0 - e_0)\varphi_1 + e_0 \varphi_0}{H_0} \quad (6)$$

Where:
c is the equivalent cohesive force of the dominant fissure (kPa);
φ is the equivalent angle of internal friction of the dominant fissure (Degree);
c_0 is the cohesive force of the connecting section of the dominant fissure (kPa);
φ_0 is the angle of internal friction of the connecting section of the dominant fissure (Degree);
c_1 is the cohesive force of the the disconnected section of the dominant fissure (kPa);
φ_1 is the angle of internal friction of the disconnecting section of the dominant fissure (Degree);
H_0 and e_0 are the average height of a perilous rock and the length of the connecting section of the dominant fissure, respectively.

Effective verifications to formula (5) and formula (6) have been used by hundreds of control engineering since 2000, however, the error are over percent 61 comparing with practical situations of perilous rocks due to unreasonable the equivalent cohesive force and equivalent angle of internal friction of the dominant fissure from the two formulas, Which may be the main reason to revise design scheme over 85% in construction of control engineering against perilous rock disaster.

To improve the ability to prevent perilous rocks disasters, a connection between the dominant fissure and the safety grade of control engineering must be established. Chen et al. (2008b) established the following formulas.

$$c = k_c[R](-0.0160r^2 + 0.9388r + 52.815) \times 10^{-4} \quad (7)$$

$$\varphi = k_\varphi[\varphi](-0.0011r^2 + 0.0729r + 8.996) \times 10^{-1} \quad (8)$$

Where
[R] is the uniaxial compressive strength of the intact rock composed of perilous rocks (MPa), [φ] is the angle of internal friction of the intact rock composed of perilous rocks (Degree), obtained by conventional laborotary tests; r is the connectivity of the dominant fissure (%), defined as the ratio of the length of the connecting section of the dominant fissure to the total length of the dominant fissure;
Both k_c and k_φ are the revised coefficients of shearing strength of the diminant fissure, with the followings values for each safety grade of control engineering.

Safety grade A: k_c= 0.80, k_φ= 0.75
Safety grade B: k_c= 0.85, k_φ= 0.80
Safety grade C: k_c= 0.90, k_φ= 0.85

METHODS TO CALCULATE THE STABILITY COEFFICIENT OF PERILOUS ROCKS

A rigid body is presumed for a perilous rock block in stability analysis. Hereby, methods to calculate the stability coefficient of a perilous rock are established using the limit equilibrium theory (Chen et al., 2009b).

Method to calculate the stability coefficient of s sliding perilous rock

Mechanical model of a sliding perilous rock is shown in Figure 7. The normal force and the tangential force on the dominant fissure of a perilous rock are assembled in formula (9) and formula (10), respectively.

$$N = W\cos\beta - P\sin\beta \quad (9)$$

$$T = W\sin\beta + P\cos\beta \quad (10)$$

Where: β is the dip angle of the dominant fissure of a perilous rock (Degree).

Introducing the homogeneity assumption of the normal force and the tangential force acting on the dominant fissure, two formulas to determine the normal stress and the shear stress acting on the

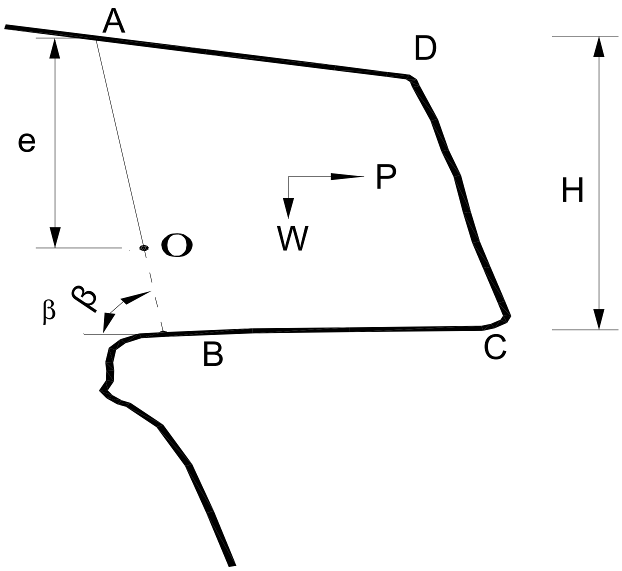

Figure 7. Mechanical model of a sliding perilous rock.

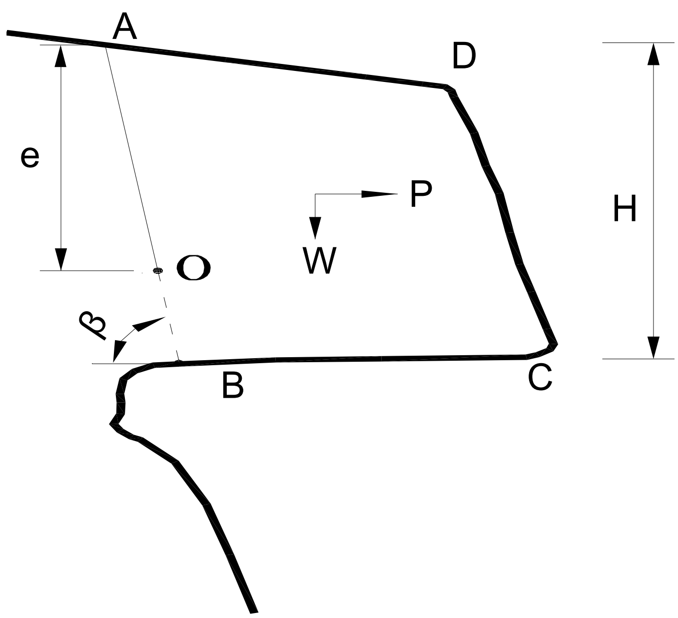

Figure 8. Mechanical model of a toppling perilous rock, where overturning point **C** is in outside of the center of gravity of the perilous rock (first subtype), and point **O** is the tip of the connecting section of the dominant fissure.

dominant fissure respectively are obtained as following.

$$\sigma = \frac{N \sin\beta}{H} \tag{11}$$

$$\tau = \frac{T \sin\beta}{H} \tag{12}$$

And based on the Mohr-coulomb shear strength, the shear strength of dominant fissure in perilous rock is obtained in the following formula.

$$\tau_{\mathrm{f}} = c + \sigma \tan\varphi \tag{13}$$

So, the stability coefficient of a perilous rock can be calculated in formula (14).

$$F_{\mathrm{s}} = \frac{\tau_{\mathrm{f}}}{\tau} = \frac{(W\cos\beta - P\sin\beta - Q)\tan\varphi + c\dfrac{H}{\sin\beta}}{W\sin\beta + P\cos\beta} \tag{14}$$

Further, formula (14) must be discussed in view of lading combinations. Using the water pressure in the dominant fissure obtained from formula (2) (corresponding to case 1), and that obtained in formula (3) (corresponding to case 2), formula (14) is simplified as formula (15).

$$F_{\mathrm{s}} = \frac{(W\cos\beta - Q)\tan\varphi + c\dfrac{H}{\sin\beta}}{W\sin\beta} \tag{15}$$

For case 3, the water pressure in the dominant fissure is calculated in formula (2) while the seismic force is obtained from formula (4), and the stability coefficient of a perilous rock is obtained from formula (14).

Method to calculate the stability coefficient of a toppling perilous rock

Mechanical model of a sliding perilous rock includes two subtypes, one in which the overturning point is in outside of the center of gravity of the perilous rock (shown in Figure 8), and one in which the overturning point is in inside of the center of gravity of the perilous rock (shown in Figure 9).

Formulas to calculate the possible overturning moment M_{t} and antidumping moment M_{a} of the first subtype of sliding perilous rock are established as formula (16) and (17) (corresponding to case 1), respectively.

$$M_{\mathrm{t}} = Ph_0 + Q\left(\frac{e_1}{3\sin\beta} + \frac{H-e}{\sin\beta}\right) \tag{16}$$

$$M_{\mathrm{a}} = Wa + f_{\mathrm{lk}}\frac{H-e}{\sin\beta} + l_{\mathrm{b}} f_{0\mathrm{k}} \tag{17}$$

Then, the formula to calculate the stability coefficient of a perilous rock is put forward.

$$F_{\mathrm{s}} = \frac{M_{\mathrm{t}}}{M_{\mathrm{a}}} = \frac{Wa + f_{\mathrm{lk}}\dfrac{H-e}{\sin\beta} + l_{\mathrm{b}} f_{0\mathrm{k}}}{Ph_0 + Q\left(\dfrac{e_1}{3\sin\beta} + \dfrac{H-e}{\sin\beta}\right)} \tag{18}$$

When water pressure is calculated in formula (2) and the seismic force is omitted in formula (18), a simplified formula (19) is stemmed from formula (18) (corresponding to case 2).

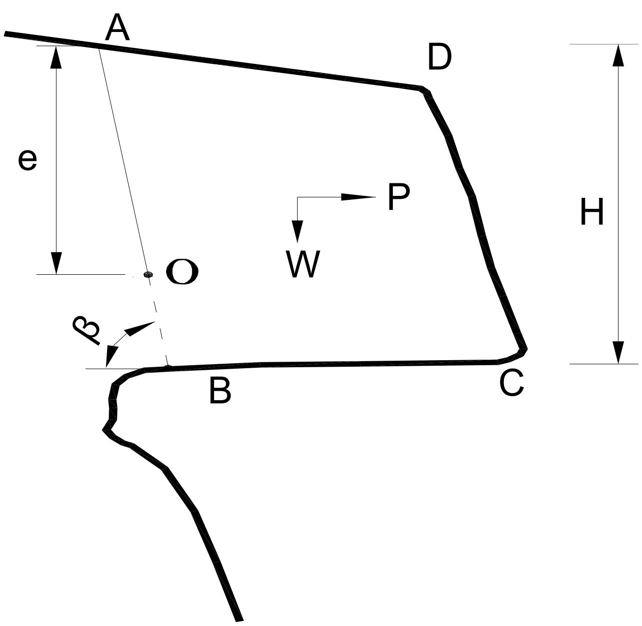

Figure 9. Mechanical model of a toppling perilous rock, where overturning point **C** is in inside of the center of gravity of the perilous rock (second subtype), and point **O** is the tip of the connecting section of the dominant fissure.

$$F_{\mathrm{s}} = \frac{81[(Wa + f_{0\mathrm{k}} l_{\mathrm{b}})\sin\beta + f_{\mathrm{lk}}(H - e)]}{2(9H - 7e)\gamma_{\mathrm{w}} e^2 l} \tag{19}$$

However, if both the water pressure in the dominant fissure and the seismic force are considered, and are calculated in formula (2) and (4) respectively, then formula (18) is simplified as formula (20) (corresponding to case 3).

$$F_{\mathrm{s}} = \frac{162[(Wa + f_{0k} l_{\mathrm{b}})\sin\beta + f_{\mathrm{lk}}(H - e)]}{162Ph_0 \sin\beta + (9H - 8e)\gamma_{\mathrm{w}} e^2 l} \tag{20}$$

Where:

f_{lk} is the tensile strength of the intact rock composed of perilous rocks (kPa);

$f_{0\mathrm{k}}$ is the tensile strength between perilous rocks and the substrate of the perilous rock (kPa),. Specially, $f_{0\mathrm{k}}$ is substituted by f_{lk} when the substrate rock is the same as that of the perilous rock, however, $f_{0\mathrm{k}}$ is substituted by the tensile strength of substrate rock if the substrate rock is weak rocks such as mudstone, clay, and Quaternary sediment;

a is the level distance between the overturning point and the gravity center of the perilous rock (m);

l_{b} is the level distance between the overturning point and the end point of the dominant fissure (m), and the other variables are the same as above.

For the second subtype of sliding perilous rocks, formulas to calculate the possible overturning moment M_{t} and antidumping moment M_{a} are established as formula (21) and (22), respectively.

$$M_{\mathrm{t}} = Wa + Ph_0 + Q\left(\frac{e_1}{3\sin\beta} + \frac{H - e}{\sin\beta}\right) \tag{21}$$

$$M_{\mathrm{a}} = f_{lk}\frac{H - e}{\sin\beta} + l_b f_{0k} \tag{22}$$

Then, the formula to calculate the stability coefficient of a perilous rock is established.

$$F_{\mathrm{s}} = \frac{M_{\mathrm{t}}}{M_{\mathrm{a}}} = \frac{f_{\mathrm{lk}}\dfrac{H - e}{\sin\beta} + l_{\mathrm{b}} f_{0\mathrm{k}}}{Wa + Ph_0 + Q\left(\dfrac{e_1}{3\sin\beta} + \dfrac{H - e}{\sin\beta}\right)} \tag{23}$$

When water pressure is calculated in formula (2) and the seismic force is omitted in formula (23), a simplified formula (24) is stemmed from formula (18) (corresponding to case 2)

$$F_{\mathrm{s}} = \frac{81[f_{0k} l_{\mathrm{b}} \sin\beta + f_{\mathrm{lk}}(H - e)]}{81Wa\sin\beta + 2(9H - 7e)\gamma_{\mathrm{w}} e^2 l} \tag{24}$$

In case 3 of lading combination, by calculating the water pressure in the dominant fissure using formula (2), while omitting the seismic force, then formula (23) is simplified as formula (25).

$$F_{\mathrm{s}} = \frac{162[f_{0k} l_{\mathrm{b}} \sin\beta + f_{\mathrm{lk}}(H - e)]}{162\sin\beta(Wa + Ph_0) + (9H - 8e)\gamma_{\mathrm{w}} e^2 l} \tag{25}$$

Where, all variables are expressed above.

Method to calculate the stability coefficient of a falling perilous rock

Mechanical model of a falling perilous rock is shown in Figure 10. Using the same procedures given above, the formula to calculate the stability coefficient of a falling perilous rock is presented shown as the following.

$$F_s = \frac{(W\cos\beta - P\sin\beta)\tan\varphi + c\dfrac{H}{\sin\beta}}{W\sin\beta + P\cos\beta} \tag{26}$$

For case 1 of lading combinations, formula (26) is simplified.

$$F_s = \frac{0.5W\sin 2\beta\tan\varphi + cH}{W\sin^2\beta} \tag{27}$$

For case 3 of lading combinations, the form of formula (26) is unchanged.

DISCUSSION AND CONCLUSION

The stability analysis method for classifying perilous rocks (which can be sources of avalanches) established in this paper abides by engineering geological investigation procedures strictly following identification, of loads and lading combinations, shear strength of the dominant fissure, assessment criterion of stability, and calculation of the stability coefficient of perilous rocks, and belongs

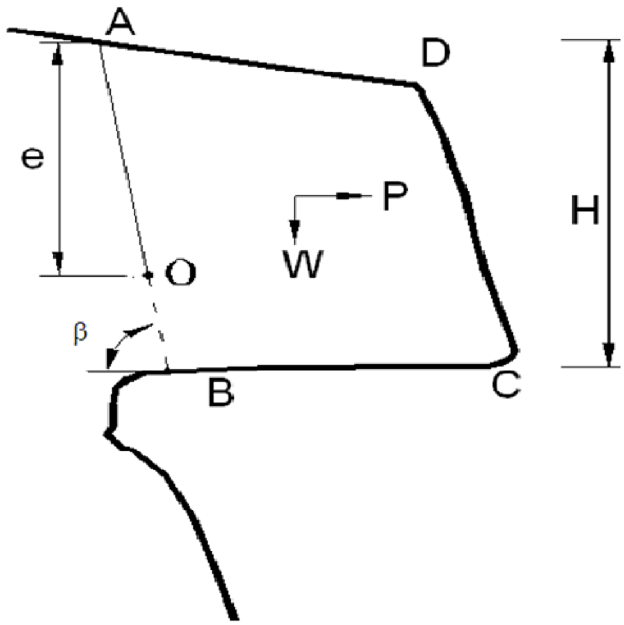

Figure 10. Mechanical model of a falling perilous rock.

to one of three key components of Design Specification of Geological Disasters Control Engineering (DB50/5029-2004). The Specification is the legal technique standard against perilous rocks disasters as a source of avalanches in Chongqing city, one international metropolis and municipality directly under the central government of China. Hitherto, about 500 control engineering more than 30000 perilous rocks have been identified using the methods including Taibaiyan, Tiashengcheng, Mamayan, Futuguan, Moziyan, etc. Meanwhile, the method has been applied in 300 control engineering in maintenance of tens of highways such as the Chengdu – Tibet, the Xichang – Luguhu lake, and the Tian shan for eight years. Observations in-situ to all these control engineering characterizes the practical value of the stability analysis method above-mentioned. Some conclusions are obtained and described as follows.

First, it is important in avalanche mitigation to locate perilous rocks, as they can be the cause of these disasters. Three types of perilous rocks, sliding perilous rocks, toppling perilous rocks, and falling perilous rocks, are demonstrated in this paper. Moreover, two subtypes of toppling perilous rocks, one in which the overturning point is in outside and one in which it is in inside of the center of gravity of the perilous rock, are distinguished.

Second, the stability assessment criterion of perilous rocks is proposed clearly. Two concepts are emphasized, the stability coefficient of perilous rocks and the safety grade of control engineering. Any perilous rock can be discriminated as unstable, or primary stable or stable in accordance with the stability coefficient of the perilous rock. Three types of safety grade*, A, B and* C, are suggested abiding by the importance of objects of protection.

Third, three lading combinations are put forward in accordance with the most frequent combinations of the dead weight of a perilous rock, the water pressure in dominant fissures, and the seismic force acting on a perilous rock. Formulas are proposed to connect the shearing strength parameters of the dominant fissure and the safety grade of control engineering.

Fourth, methods to calculate the stability coefficient for a sliding perilous rock, a toppling perilous rock, and a falling perilous rock are established in detail in terms of the limit equilibrium theory.

Particularly, there are still some problems in the stability analysis of perilous rocks due to the complexity and randomness for perilous rocks to develop, and many aspects need to be studied in depth.

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