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STUDY ON THE SUPPORT - ANCHOR COMBINED TECHNIQUE TO CONTROL PERILOUS ROCK AT THE SOURCE OF AVALANCHE BY FRACTURE MECHANICS

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Abstract. As a kind of existing and potential geological disaster at source of avalanche on cliffs or steep slopes, perilous rock has developed in the western area of China widely and it poses a serious threat to highways, railways, pipelines, cities, and mining for a long time. More than ten years of engineering experience have shown the necessity and importance to pay our attention to the avalanche sources in active collapse mitigation. The support - anchor combined technique is devoted to the active hazard mitigation measures of perilous rock. This paper introduces fracture mechanics to investigate the design procedure of the support - anchor combined technique. To obtain reasonable design parameters of the technique, both stability assessment criterion and three safety classes of protection engineering for perilous rock is proposed, further, stable analysis methods for various types of perilous rock are established by using fracture mechanics. Abiding by the idea that to improve stability coefficient to a higher level, the support force of structure and the anchorage force of anchorbolt from the support - anchor combined technique are introduced into stability analysis methods established above, which can estimate the section dimension of support subunit and the amount of anchorbolt of the technique. Engineering applications of the technique in thousands of protection engineering have identified the remarkable effectiveness.

Key words: perilous rock at source of avalanche, loads and loading combinations, fracture stress intensity factor, stability coefficient of perilous rock, the support – anchor combined technique, fracture mechanics.

1. Introduction.

Rockfall is defined as the falling of single rock or stone with volumes smaller than 5 m^3, while rock avalanche belongs to packet collapse (Chen, et al., 2001). In the past ten years, hundreds million dollars in economic losses are produced and about 6000 persons are killed by rockfall and avalanches in China. A large amount of rock avalanche with $\sim 2\times 10^9$ m^3 in volumes and deposits up to 200-300 m thick at Karivhoh, travelling more than 7 km and covering about 18km^2, all rock-avalanche bodies is composed of intensively crushed debris and overlain by a blocky carapace (Strom, 2004). Rockfalls and rock avalanches belong to a major erosion process shaping ridge crests and alpine summits (Cox and Allen, 2009). Strong seismic shaking caused or triggered most of gigantic large-scale rock-slope failures through reconnaissance 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 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 and Agliardi(2004). Based on variations in kinetic and potential energies and frictional losses, Zambrano (2008) proposed one formula to estimate movement velocities of 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 avalanche dissipated not only through friction but also during impacts and block breakage (Tommasi, et al., 2008). Manzella and Labiouse (2008) presented an experimental study of rock avalanches runout and propagation carried out with a small-scale physical model.

However, studies before-mentioned are focused on the subsequent processes after occurrence of paroxysmal avalanches. To achieve hazard mitigation effectively before the occurrence of paroxysmal avalanches, putting our attention on the avalanche sources has a significant realistic meaning. With regards to this, Chen and Tang (2004) defined potential unstable rock block at avalanche source on cliffs or steep slopes as perilous rock. Further, attention is focused on the dominant fissure behind perilous rock, failure mechanism for all kinds of perilous rock was investigated in detail by Chen et al. (2006, 2007, 2008) and Tang et al. (2010). Stability analysis method for perilous rock is classified as sliding perilous rock, toppling perilous rock and falling perilous rock, which is comprehensively established by Chen et al. (2004, 2009). Due to existing extensively for toppling perilous rock, the support - anchor combined technique, granted the patent of invention by the State Intellectual Property Office of China (ZL200610054335.7), is applied widely in practice. To promote application of the technique in engineering design procedure, this paper will make a comprehensive description by using fracture mechanics.

2. Stability assessment criterion.

Stability of perilous rock at source of avalanche can be characterized by stability coefficient under action of loads. Unstable, primary stable and stable statuses are classified in stability analysis of perilous rock. Chen et al. (2004, 2009) proposed the stability assessment criterion of perilous rock (Table 1). For example, to anyone of sliding perilous rock, it is designated in unstable status, primary stable status and stable status if its stability coefficient is less than 1,0, in 1,0 ~ 1,3, and bigger than 1,3, respectively.

It is persuasive to consider safety classes of protection engineering of perilous rock. Hundreds of protection engineering, built in the area of the Three Gorges Reservoir of China, have displayed the safety criterion of protection engineering of perilous rock showed in table 2. Safety class **A** represents the objective of protection, such as important city, industrial and mining establishments, or transportation junction and public utilities, safety class **B** represents the objective of protection, such as less important town, buildings, industrial and mining establishments, or important artery traffic, and safety class **C** represents anyone of objectives except safety class **A** and **B**. For example, to any one of toppling perilous rock, whose stability coefficient after implementation of protection engineering must be more than 1,5 to safety class **A**, 1,4 to safety class **B**, and 1,3 to safety class **C**.

Table 1. Stability assessment criterion of perilous rock.

Stable status	Unstable	Primary stable	Stable
Sliding perilous rock	< 1,0	1,0~1,3	> 1,3
Toppling perilous rock	< 1,0	1,0~1,5	> 1,5
Falling perilous rock	< 1,0	1,0~1,5	> 1,5

Table 2. Factor of safety of protection engineering of perilous rock

Safety class	**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

3. Stability coefficient of perilous rock using fracture mechanics.

3.1 Loads and lading combinations acting on perilous rock. Loads and lading combinations acting on perilous rock dominate the stability status of perilous rocks. Three kinds of load acting on perilous rock, i.e., dead weight of perilous rock, water pressure in dominant fissure (including statuses in nature and in rainstorm) and seismic force, are paid attention to the stability analysis. Moreover, two types of seismic force, horizontal seismic force and vertical seismic force, are respectively distinguished. For the three kindes of load, dead weight of perilous rock belongs to permanent load, water pressure in dominant fissure belongs to periodic load varying with statuses in natural and in rainstorm, and seismic force belongs to incidental load with low frequency.

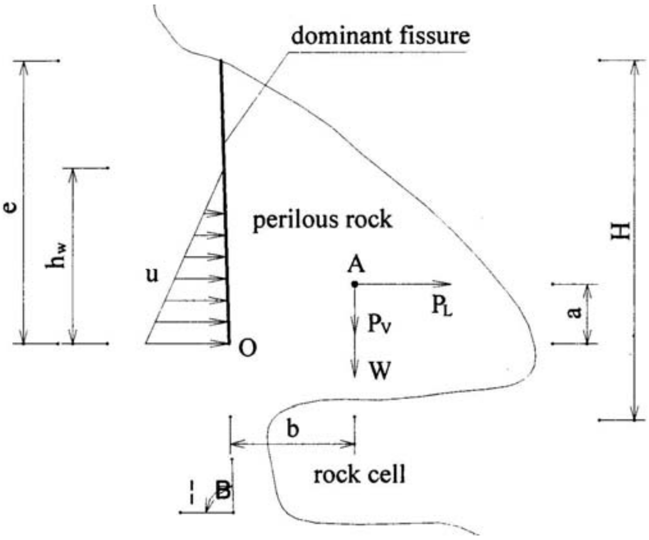


Fig. 1. Loads acting on perilous rock.

Loads acting on perilous rock are showed in Fig. 1. Decomposing W, P_L and P_V along the orientation and in the normal direction of dominant fissure, integrated tangent force and normal force are calculated in formula (1) and (2), respectively.

$$T = P_L \cos\beta + (W + P_V)\sin\beta \; ; \qquad (1)$$

$$N = P_L \sin\beta - (W + P_V)\cos\beta \; ; \qquad (2)$$

$$W = \gamma V \; ; \qquad (3)$$

$$P_L = k_L W \; ; \qquad (4)$$

$$P_V = k_V W \, , \qquad (5)$$

where, T represents the integrated tangent force (kN), N stands for the integrated normal force (kN), P_L and P_V represent the horizon component and the vertical component of earthquake force acting on the center of gravity of perilous rock respectively (kN), β is the dip angle of dominant fissure (Degree), W represents the dead weight of perilous rock (kN), V represents the volume of perilous rock (m^3), k_L is designated as the coefficient of horizontal seismic force, while k_V is represented of vertical seismic force, γ is the specific gravity of perilous rock every cubic meter (kN/m^3).

When the end point **O** of dominant fissure is lower than the center point **A** of gravity in perilous rock, flexural moment along point **O** obtains in formula (6).

$$M = (W + P_V)b + P_L a \, . \qquad (6)$$

However, when point **O** is above point **A**, formula (6) is adjusted as formula (7).

$$M = (W + P_{\mathrm{V}})b - P_{\mathrm{L}}a\ . \tag{7}$$

In formula (6) and (7), parameters a and b denote the vertical distance and the horizon distance between point **A** and point **O**, respectively.

Moreover, assuming the distribution of water pressure in dominant fissure is linear along the fissure, formulas to calculate water pressures in natural status and in rainstorm status are established, showed in formula (8) and (9), respectively.

$$Q = \frac{1}{18}\gamma_{\mathrm{w}} e^2 l\ ; \tag{8}$$

$$Q = \frac{2}{9}\gamma_{\mathrm{w}} e^2 l\ , \tag{9}$$

where Q is the water pressure acting on perilous rock (kN), $\boldsymbol{e}$ is the vertical height of dominant fissure (m), γ_{w} is the water gravity every cubic meter in dominant fissure (kN/m^3), $\boldsymbol{l}$ represents the horizontal length of perilous rock along the orientation of slope (m).

It should be noted that $\boldsymbol{P}_{\mathrm{L}}$ and $\boldsymbol{P}_{\mathrm{V}}$ can't be considered simultaneously in all formulas above and due to the impossibility to reach the same perilous rock for **P**-wave and **S**-wave triggered by earthquake.

Based on appearance frequency of loads, three types of lading combination are recommended, showed as followings.

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

Case 2: Dead weight of perilous rock and water pressure in rainstorm status in dominant fissure.

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

Specially, **case 1** is ignored in stability analysis of toppling perilous rock, and so does **case 2** in falling perilous rock. To a concrete perilous rock, the lading combination with the minimum stability coefficient is designated as the design load of protection engineering.

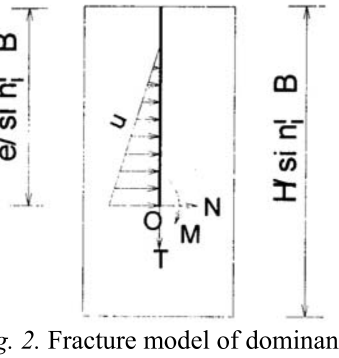


Fig. 2. Fracture model of dominant fissure.

3.2 Fracture stress intensity factor of dominant fissure in perilous rock. In view of fracture mechanics, destabilization process of perilous rock belongs to a fracture problem of dominant fissure under action of loads, representing in $\boldsymbol{T}$, $\boldsymbol{N}$, $\boldsymbol{M}$ and $\boldsymbol{u}$ (Fig. 2). Assuming it is uniform distribution of $\boldsymbol{T}$ and $\boldsymbol{N}$ along dominant fissure, the fracture model showed in Fig. 2 is decomposed into 4 categories dominated by $\boldsymbol{u}$, $\boldsymbol{\tau}$, $\boldsymbol{M}$ and $\boldsymbol{\sigma}$, respectively (Fig. 3), and described in detail as followings.

To situation $\boldsymbol{A}$ in Fig. 3, introducing uniform distribution assumption of water pressure along dominant fissure, the fracture stress intensity factor of the dominant fissure can be determined in formula (10).

$$K_{11} = 5{,}51\bar{u}\sqrt{\pi a_0}\ . \tag{10}$$

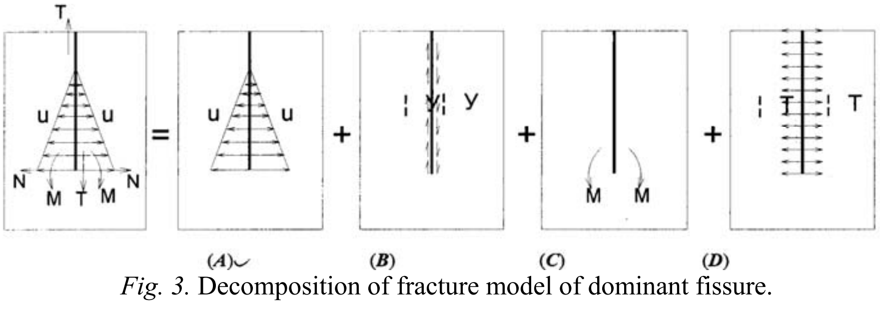


Fig. 3. Decomposition of fracture model of dominant fissure.

To category ***B*** in Fig. 3, the fracture stress intensity factor under action of shear stress$\boldsymbol{\tau}$-can be determined in formula (11).

$$K_2 = 1{,}12\tau\sqrt{\pi a_0}\ . \tag{11}$$

To category ***C*** in Fig. 3, the fracture stress intensity factor under ***M*** action can be determined in formula (12).

$$K_{13} = F(a)\sigma_{\max}\sqrt{\pi a_0}\ . \tag{12}$$

And to category ***D*** in Fig. 3, the fracture stress intensity factor under action of normal stress$\boldsymbol{\sigma}$can be calculated in formula (13).

$$K_{14} = 1{,}12\sigma\sqrt{\pi a_0}\ . \tag{13}$$

Further, some indirect variables in formula (11), (12) and (13) are calculated in following formulas.

$$e = a_0 \sin\beta\ ; \quad \bar{u} = \frac{1}{2}\gamma_{\mathrm{w}} h_{\mathrm{w}}\ ; \quad \tau = \frac{T\sin\beta}{H}\ ;$$

$$F(a) = 1{,}122 - 1{,}40R + 7{,}33R^2 - 13{,}08R^3 + 14{,}00R^4\ ; \quad \sigma_{\max} = \frac{6M}{H^2}\ ; \quad R = \frac{e}{H}\ ; \quad \sigma = \frac{N\sin\beta}{H}\ .$$

Abiding by the superimposition assumption of the fracture stress intensity factor, formula (14) is devoted to type I fracture stress intensity factor of dominant fissure in perilous rock.

$$K_{\mathrm{I}} = K_{11} + K_{13} + K_{14} \tag{14}$$

3.3 Fracture stability coefficient of perilous rock. To pay our attention to the dominant fissure of perilous rock, both formula (15) and (16) are effective to estimate fracture angle θ_0 and union fracture stress intensity factor K_{e} of rock near the end of dominant fissure, respectively.

$$\theta_0 = \arccos\left[\frac{3 + \sqrt{k_0^2 + 8k_0}}{k_0 + 9}\right]; \tag{15}$$

$$K_e = \frac{1}{2}[k_1 K_1 + k_2 K_2 + \sqrt{k_3 K_1^2 + k_4 K_2^2 + k_5 K_1 K_2}\,], \tag{16}$$

where $k_0 = (K_1/K_2)^2$, K_1 represents the tension fracture stress intensity factor of dominant fissure (kPa•m$^{1/2}$), K_2 represents the shear fracture stress intensity factor of dominant fissure (kPa•m$^{1/2}$), and some indirect variables such as $k_1 \sim k_8$ are calculated in the following formulas

$$k_1 = \cos\frac{\theta_0}{2};\ k_2 = \frac{1}{2}\left[(3\cos\theta_0 - 1)\sin\frac{\theta_0}{2} - 3\sin\theta_0\cos\frac{\theta_0}{2}\right];\ \ k_3 = k_1^2 + k_7^2;$$

$$k_4 = k_6^2 + k_8^2;\ k_5 = 2(k_1 k_6 + k_7 k_8);\ \ k_6 = \frac{1}{2}\left[3\sin\theta_0\cos\frac{\theta_0}{2} + (3\cos\theta_0 - 1)\sin\frac{\theta_0}{2}\right];$$

$$k_7 = \sin\theta_0\cos\frac{\theta_0}{2};\ \ k_8 = (3\cos\theta_0 - 1)\cos\frac{\theta_0}{2}.$$

Further, one formula to estimate fracture stability coefficient of perilous rock is proposed in accordance with the ratio of the fracture toughness to the union fracture stress intensity factor near the end of dominant fissure, showing as formula (17).

$$F_{\mathrm{s}} = \frac{K_{\mathrm{IC}}}{K_{\mathrm{e}}}\ . \tag{17}$$

In formula (17), K_{IC} is the rock fracture toughness near the end of dominant fissure (kPa·m$^{1/2}$), determined by fracture mechanical testing in laboratory.

Comparing F_s identified by using formula (17) with the criterion of stability showing in Table 1, the safety status of perilous rock is reasonably discriminated.

4. Calculation of the support force and the anchor force in the support-anchor combined technique.

Mechanical model of the support-anchor combined technique is expressed in Fig. 4. If the factor of safety of the protection engineering of perilous rock is represented in F_s^0 designating in Table 2, it is necessary to choose suitable techniques such as the support-anchor combined technique when $F_s < F_s^0$. Further, a proportion between support force and anchorage force is introduced, then

$$N_s = r_0 N_m , \tag{18}$$

were, N_s represents the support force (kN), N_m is the anchorage force (kN), and $\boldsymbol{r}_0$ is the proportionality factor of support force to anchorage force, usually sampled between 2 and 2,5.

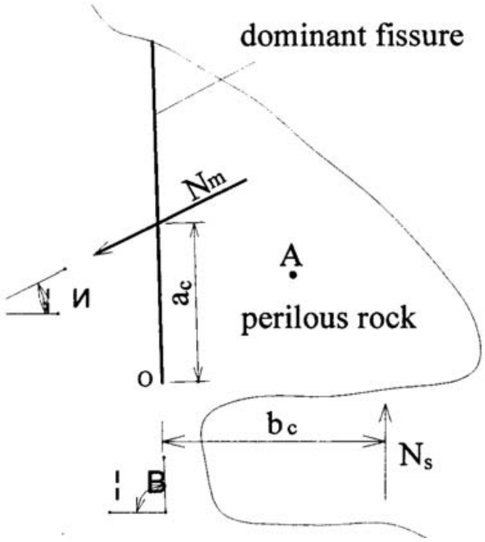


Fig. 4. Mechanical model of the support - anchor combined technique.

Obviously, the next relational expression needs to follow in design of protection work.

$$\frac{K_{\mathrm{IC}}}{K_{\mathrm{e}}^{\mathrm{f}}} \geq F_s^0 , \tag{19}$$

where, parameter $K_{\mathrm{e}}^{\mathrm{f}}$ represents the union fracture toughness of rock near the end of dominant fissure after the implementation of protection engineering (kPa·m$^{1/2}$).

According to formula (19), the next expression exists.

$$K_{\mathrm{e}}^{\mathrm{f}} \leq \frac{K_{\mathrm{IC}}}{F_s^0} . \tag{20}$$

Letting fracture angle $\boldsymbol{\theta}_0$ of rock near the end of dominant fissure in perilous rock is the same as all about in the constructing of protection engineering, so indirect variables $k_1 \sim k_5$ are constant, and parameter $K_{\mathrm{e}}^{\mathrm{f}}$ depends on K_1 and K_2 unavoidably, expressed as K_1^{f} and K_2^{f} respectively. Hereby, formula (16) is rewritten as followings.

$$K_{\mathrm{e}}^{\mathrm{f}} = \frac{1}{2}[k_1 K_1^{\mathrm{f}} + k_2 K_2^{\mathrm{f}} + \sqrt{k_3 K_1^{\mathrm{f}\,2} + k_4 K_2^{\mathrm{f}\,2} + k_5 K_1^{\mathrm{f}} K_2^{\mathrm{f}}}\,] . \tag{21}$$

To a concrete perilous rock, when the support-anchor combined technique is implemented, support force N_{s} and anchorage force $\boldsymbol{N}_{\mathrm{m}}$ are introduced, which produces the tangent force T^{f}, the flexural moment M^{f} and the normal force $\boldsymbol{N}_{\mathrm{f}}$ acting on the dominant fissureare calculated in formula (22), (23) and (24), respectively.

$$T^{\mathrm{f}} = T + N_{\mathrm{m}} \cos(\theta + \beta) - N_{\mathrm{s}} \sin\beta ; \tag{22}$$

$$M^{\mathrm{f}} = M - N_{\mathrm{s}} b_{\mathrm{c}} - N_{\mathrm{m}} a_{\mathrm{c}} \sin(\theta + \beta) ; \tag{23}$$

$$N^{\mathrm{f}} = N + N_{\mathrm{m}}\sin(\theta+\beta) - N_{\mathrm{s}}\cos\beta\,, \tag{24}$$

where $\boldsymbol{\theta}$ is the dip angle of anchorbolt (degree), $\boldsymbol{a}_{\mathrm{c}}$ designates the vertical distance between the end of dominant fissure and the intersection point between anchorbolt and dominant fissure (m), $\boldsymbol{b}_{\mathrm{c}}$ expresses the horizontal distance between the end of dominant fissure and the support point (m), and the others are the same before.

Based on the formula (22), (23) and (24), we obtain $\boldsymbol{\sigma}_{\max}$, $\boldsymbol{\sigma}$ and $\boldsymbol{\tau}$ easily by considering implement of the technique. Further, methods to solve corresponding fracture stress intensity factor are established.

$$K_{13}^{\mathrm{f}} = K_{13} - F(a)\sqrt{\pi a_0}\,\frac{6}{H^2}[r_0 b_{\mathrm{c}} - a_{\mathrm{c}}\sin(\theta+\beta)]N_{\mathrm{m}}\,; \tag{25}$$

$$K_{14}^{\mathrm{f}} = K_{14} - 1{,}12\sqrt{\pi a_0}\,\frac{6}{H^2}[\sin(\theta+\beta) - r_0\cos\beta)]N_{\mathrm{m}}\,. \tag{26}$$

Then

$$K_1^{\mathrm{f}} = K_1 + \sqrt{\pi a_0}\left[1{,}12\sin(\theta+\beta) - 1{,}12 r_0\cos\beta - \frac{6 r_0 b_{\mathrm{c}} F(a)}{H^2} + \frac{6 a_{\mathrm{c}} F(a)}{H^2}\sin(\theta+\beta)\right]N_{\mathrm{m}}\,; \tag{27}$$

$$K_2^{\mathrm{f}} = K_2 + \frac{1{,}12\sqrt{\pi a_0}}{H}[\cos(\theta+\beta) - r_0\sin\beta]N_m\,. \tag{28}$$

To simplify the operation, letting

$$t_1 = \sqrt{\pi a_0}[1{,}12\sin(\theta+\beta) - 1{,}12 r_0\cos\beta - \frac{6 r_0 b_{\mathrm{c}} F(a)}{H^2} + \frac{6 a_{\mathrm{c}} F(a)}{H^2}\sin(\theta+\beta)]\,;$$

$$t_2 = \frac{1{,}12\sqrt{\pi a_0}}{H}[\cos(\theta+\beta) - r_0\sin\beta]\,,$$

so formula (27) and (28) express as $K_1^{\mathrm{f}} = K_1 + t_1 N_{\mathrm{m}}$ and $K_2^{\mathrm{f}} = K_2 + t_2 N_{\mathrm{m}}$ respectively, and substituting them into formula (21), the next formula is derived.

$$K_{\mathrm{e}}^{\mathrm{f}} = \frac{1}{2}\left[l_1 + l_2 N_{\mathrm{m}} + \sqrt{l_3 N_{\mathrm{m}}{}^2 + l_4 N_{\mathrm{m}} + l_5}\,\right], \tag{29}$$

where indirect variables are expressed as

$$l_1 = k_1 K_1 + k_2 K_2\,;\quad l_2 = k_1 t_1 + k_2 t_2\,;\quad l_3 = k_3 t_1{}^2 + k_4 t_2{}^2 + t_1 t_2\,;$$

$$l_4 = 2k_3 K_1 t_1 + 2k_4 K_2 t_2 + k_5(K_1 t_2 + K_2 t_1)\,;\quad l_5 = k_3 K_1{}^2 + k_4 K_2{}^2 + k_5 K_1 K_2\,.$$

Combining formula (29) with formula (20), we obtain the formula to estimate the anchorage force N_{m}

$$N_m = \frac{1}{2(l_3 - l_2{}^2)}\left[-l_4 - 2Al_2 + \sqrt{(l_4 + 2Al_2)^2 - 4(l_3 - l_2{}^2)(l_5 - A^2)}\,\right], \tag{30}$$

where, $A = 2K_{\mathrm{IC}} / F_{\mathrm{s}}^0 - l_1$.

Substituting N_{m} into formula (18), then the support force N_{s} is determined.

To support subunit of the technique, when admissible compressive strength of support subunit is represented in $[R_{\mathrm{c}}]$ the section dimensions of support subunit is effective to estimate in formula (31)

$$b_1 \times b_2 \geq \frac{N_{\mathrm{s}}}{[R_{\mathrm{c}}]}\,, \tag{31}$$

where, b_1 and b_2 are the length and the width of the support (m), respectively.

Meanwhile, to anchorage subunit of the technique, when admissible tension strength every anchorbolt is expressed in $[T]$, anchorbolts n required in protection works can be estimated in formula (32)

$$n \geq \frac{LN_{\mathrm{m}}}{[T]}, \tag{32}$$

where, L represents the length of perilous rock along the orientation of cliff or slope (m). All these anchorbolts must be arranged to abide by the corresponding standard such as the standard DB50/5029-2004. However, anchorbolts, located at the lowest position on the perilous rock, must be higher than $(\boldsymbol{a}_{\mathrm{c}} + \boldsymbol{B}\tan\boldsymbol{\theta})$, and $\boldsymbol{B}$ is the average width of perilous rock (m).

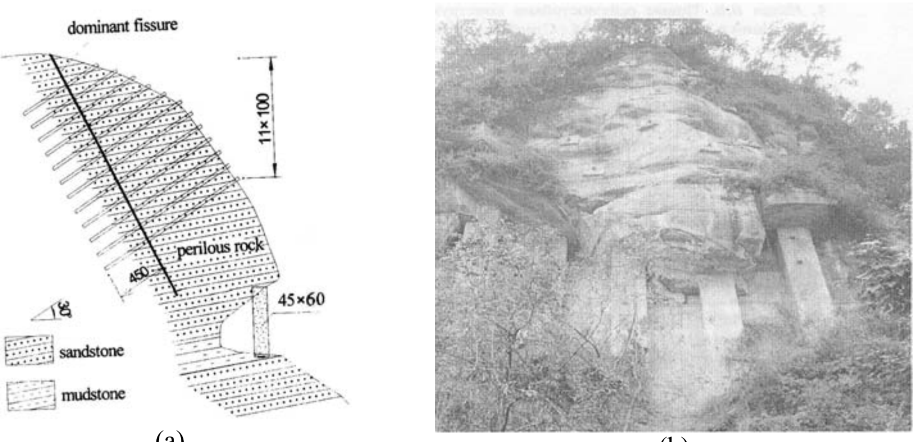
5. Engineering application.

There are three cliffs with 150~180m in height on the southern slope of Mt. Taibaiyan at Wanzhou city in area of the Three Gorges Reservoir of China. 61 perilous rocks with $2{,}5\times10^5$ m^3 in volumes exists on the cliffs explored in recent years. Perilous rocks are composing of quartzose arkose is about 25kN/m^3 in bulk density in natural status, about 600kPa in admissible tension strength, and 2700kPa in admissible shear strength. The fracture toughness of the rock is about 2007 kPa·m$^{1/2}$. Horizontal seismic coefficient is 0,05, while vertical seismic coefficient is 0,08 in the engineering region. Taking the perilous rock, marked W12#, as an example, whose physical dimension is 32,7 m in length, 6,7 m in width perpendicular to surface of the cliff, and 21,6 m in height, expression for the support-anchor combined technique is presented in details. Continue section of dominant fissure in the perilous rock is 20,4 m in length, 62,5°in dip angle. Anchorbolt required in the protection engineering is designed with 32 cm in diameter and 30°in dip angle, bearing capacity every anchorbolt is about 180 kN. Support structure in the integrated technique is casted in-situ by using C20 concrete. Admissible compressive strength of concrete isn't less than 20MPa. Factor of safety of the protection engineering is 1,5. Some parameters are proposed in the design of the protection engineering considering geometric shape of the perilous rock, b_{c}=5,1 m, a_{c}=7,5 m, and r_0=2,4.

Calculation of the perilous rock is showed expressly in table 3. Further, engineering design is made based on the calculated results. Two aspects are pressed in the design showed in Fig. 5(a), rectangle supports with section 0,45m×0,60m and constructed every 1m along the direction of length of perilous rock, meanwhile, anchorbolts are installed by taking the pattern of 1,0m×1,0m on the perilous rock. The protection engineering showing in Fig. 5(b) is brought to success on May, 2005. Hitherto, the hazard mitigation effect is remarkable.

Table 3 Calculation results to the W12# perilous rock

θ_0 /°	K_1 / kPa$\sqrt{\mathrm{m}}$	K_2 / kPa$\sqrt{\mathrm{m}}$	K_{e}/ kPa$\sqrt{\mathrm{m}}$	K_{IC} / kPa$\sqrt{\mathrm{m}}$	F_{s}	N_{m} /kN	N_{s} /kN	$b_1\times b_2$ /m^2	Number of anchorbolt
46,08	1809,11	1206,52	2132,86	2007	0,9410	2117,57	5082,17	≥0,254	≥ 385



(a) (b)

Fig. 5. Design and construction for the W12# perilous rock, (a) shows the design section to control the perilous rock, and (b) shows the concrete engineering in the design.

6. Conclusions. More than ten years of engineering experience have showed the necessity and importancet to pay our attention to the avalanche source in active collapse mitigation. The support - anchor combined technique is devoted to the active hazard mitigation measures of perilous rock, four conclusions are concluded as followings.

The first, stability assessment criterion of perilous rock is proposed for all kinds of perilous rock at avalanche source, and three safety classes of protection works for perilous rock disaster are identified. Further, loads acting on perilous rock are classified as dead weight of perilous rock, water pressure in dominant fissure and seismic force. In accordance with the frequency of all kinds of load, three lading combinations are clearly designated.

The second, methods to determine fracture stress intensity factor of dominant fissure in perilous rock under action of loads are established by using fracture mechanics, and methods to solve the fracture stability coefficient of perilous rock is defined by the ratio of the fracture toughness to the union fracture stress intensity factor of rock near the end of dominant fissure.

The third, in connection with the support - anchor combined technique, the calculation methods in engineering design are based on the stability coefficient of perilous rock by drawing up the support force of support structure and the anchorage force of anchorbolt, which can estimate the section dimension of support subunit and the amount of anchorbolts against the perilous rock disaster.

The fourth, applications of the support - anchor combined technique in thousands of protection works have displayed remarkable effectiveness of the technique in perilous rock disaster mitigation.

Finally, it is worthy noting that rocks with serious weathering on the top of and under the bottom of the support structure must be cleared in the design of technique, and some expanding concrete about 20cm thickness space between the top of support structure and the bottom of perilous rock must be applied and strong suggested.

Acknowledgments.

Ever since a long time ago, perilous rock and avalanche had become the most serious geological disaster in western China. Studies are carried out by the scientific group and led by the authors have been continuously making under grant of tens of fund, such as the National Natural Fund of China “Study on rupture mechanism of perilous rock”(No.50678182) more than ten years(have been making continuously under the grant of tens of fund more than ten years, such as the National Natural Fund of China “Study on rupture mechanism of perilous rock”(No.50678182)). Great assistance and encourage have been given by scientists, such as professor Li Jijun, academician of the Chinese Academy of Science (CAS), professor Xian Xuefu, professor Zheng Yingren, and professor Zhou Fengjun, academicians of the Chinese Academy of Engineering (CAE). Sincere thanks are liberated by the authors to these scientists and fund departments in charge.

РЕЗЮМЕ. Більш ніж десять років інженерного досвіду в західній частині Китаю показали необхідність і важливість уваги до джерел лавин з метою активного зменшення катастроф. Для вимірювання активного зменшення ризику від небезпечних грунтів розроблена об‘єднана методика «опора-анкер». У роботі застосована механіка руйнування для дослідження процедури створення розрахункової схеми об‘єднаної методики «опора-анкер». Для отримання коректних параметрів схеми запропоновано критерій оцінки стійкості і три класи безпеки інженерного захисту для небезпечних грунтів. Далі на основі механіки руйнування розвинуті стійкі методи аналізу для різних типів небезпечних грунтів. На основі ідеї про покращення коефіцієнтів стійкості до вищого рівня в методи аналізу стійкості введено силу опори в конструкції та силу анкера для анкерного болта в опорі з об‘єднаної методики «опора-анкер». Це дозволяє оцінити в застосованій методиці розмір секції в опорі і кількість анкерних болтів. Інженерні застосування запропонованої методики показали суттєву ефективність у тисячах випадків інженерного захисту.

1. *Blasio F.V.D.* Rheology of a wet, fragmenting granular flow and the riddle of the anomalous friction of large rock avalanches // Granular Matter, 2009, **11** (3): 179 – 184.
2. *Chen H.K., Tang H.M., Wang R.* Calculation method of stability for unstable rock and application to the Three Gorges Reservoir // Chinese Journal of Rock Mechanics and Engineering, 2004, **23** (4): 614 – 619 (in Chinese).

3. *Chen H.K.,Tang H.M.,Ye S.Q.* Research on damage model of dominant fissure in perilous rock // Appl. Mathem. and Mech., 2006, **27** (7): 967 – 974.
4. *Chen H.K. and Tang H.M.* Method to calculate fatigue fracture life of dominant fissure in perilous rock // Appl. Mathem. and Mech., 2007, **28** (5): 643 – 649.
5. *Chen H.K., Xian X.F., Tang H.M., Feng Q.H.* A massive development mechanism and countermeasures for perilous rocks in the Three Gorges reservoir of P. R. China: the example of the Taibaiyan cliff at Wanzhou // J. of Chongqing University, 2008, **31** (10): 1178 – 1184 (in Chinese).
6. *Chen H.K., Xian X.F., Tang H.M., Wang L.F.* Stability analysis method for perilous rock // Chinese J. of Appl. Mech., 2009, **26** (2): 278 – 282 (in Chinese).
7. *Cox S.C. and Allen S.K.* Vampire rock avalanches of january 2008 and 2003, Southern Alps, New Zealand. Landslides, 2009, **6** (2): 161 – 166.
8. *Crosta G.B. and Agliardi F.* Parametric calculation of 3D dispersion of rockfall trajectories // Natural Hazards and Earth System Sciences, 2004, **4**: 583 – 598.
9. *Dorren L.K.A., Berger F., Putters U.S.* Real-size experiments and 3-D simulation of rockfall on forested and non-forested slopes // Natural Hazards and Earth System Sciences, 2006, **6** (1): 145 – 153.
10. *Dorren L.K.A., Maier B., Putters U.S., Seijmonsbergen A.C.* Combining field and modeling techniques to assess rockfall dynamics on a protection forest hillslope in the European Alps // Geomorphology, 2004, **57** (3 – 4): 151 – 167.
11. *Manzella I. and Labiouse V.* Qualitative analysis of rock avalanches propagation by means of physical modelling of non-constrained gravel flows // Rock Mechanics and Rock Engineering, 2008, **41** (1): 133 – 151.
12. *Strom A.L.* Rock avalanches of the Ardon River valley at the southern foot of the Rocky Range, Northern Caucasus, North Osetia. Landslides, 2004, **1** (1): 237 – 241.
13. *Strom A.L. and Korup O.* Extremely large rockslides and rock avalanches in the Tian Shan mountains, Kyrgyzstan. Landslides, 2006, **3** (2): 125 – 136.
14. *Tang H.M., Wang L.F., Chen H.K., Xian X.F.* Collapse sequence of perilous rock on cliffs with soft foundation // Chinese Journal of Geotechnical Engineering, 2010, **32** (2): 205 – 210 (in Chinese).
15. *Tommasi P., Campedel P., Consorti C., Ribacchi R.* A discontinuous approach to the numerical modeling of rock avalanches // Rock Mechanics and Rock Engineering, 2008, **41** (1): 37 – 58.
16. *Zambrano O.M.* Large rock avalanches: A kinematic model // Geotechnical and Geological Engineering, 2008, **26** (3): 283 – 287.

From the Editorial Board: The article corresponds completely to submitted manuscript.

Поступила 12.10.2010 Утверждена в печать 22.11.2012