Research on Duration for Perilous Rock to Form

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Abstract: As one geological disaster in the area of the Three Gorges Reservoir of China, perilous rocks dominate stability of slopes in the area. Most cliffs or steep slopes are alternately composed of inflexible rock such as sandstone and soft rock such as mudstone in the area, and due to different weathering velocities rock cells in soft rock below inflexible rock are usually developed. Any perilous rock belongs to a part of inflexible rock. To appraise the safety of perilous rock, it is essential to approach duration for perilous to form is of interest. In the present paper, authors analyze weathering velocity of rock cell and establish method to calculate length of critical rock cell. Duration for perilous rock to form can be divided into three parts, (1) duration to form critical rock cell, (2) damage duration of control fissure, and (3) fracture duration of control fissure. Further, methods to calculate these durations are established in details based on damage mechanics and fracture mechanics.

Key words: Rock mechanics, Perilous rock, Duration for perilous rock to form, Rock cell, Control fissure, Damage and fracture of perilous rock

1 Introduction

Perilous rock, locating in steep slope or cliff and being surrounded by rock fissures, belongs to a rock block with little stability. As the dominant geological disaster in the area of the Three Gorges Reservoir of China, perilous rock shows some typical features such as distribution widely, little stability and catastrophic status (Chen HK, et al, 2004a). Comparison with sliding of slope such as translational planar slides and compound slides, perilous rock is similar to rock falls, avalanches and collapses of rock slopes. Braathen et al. (2004) focused in more detail on source areas for potential rock avalanches using for stability analysis and knowledge from structural geology. Usually, the source area of the rock avalanches has two topographic constraints: (1) vertical relief contrasts between the breakaway zone and the mountain front must exceed a threshold of 400m, and (2) the slope inclinations must be steeper than 20 degrees (Eeginald L H, et al, 1999; Hu HT, 1989; Chen HK, et al, 2005). In respect of perilous rock, whose stability is dominated by forming and expanding of control fissure behind the perilous rock block (Chen HK, et al, 2006). Chained regularity of perilous rock identifies evolution principle of slope (Chen HK, et al, 2004b), which focuses on formation of perilous rock block (Fig.1). Obviously, Figure 1 expresses that perilous rock belongs to a part of inflexible rock such as sandstone, and is influenced by evolution of rock cell in soft rock such as mudstone below sandstone. To appraise the safety of a perilous rock, it is essential to approach duration for perilous rock to form is of interest in present paper.

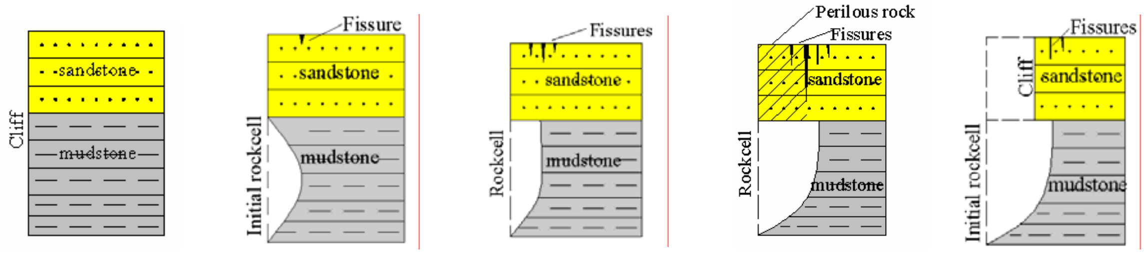

Fig.1 Formation of perilous rock with rock cell evolution

2 Developing of Critical Rock Cell

2.1 General assumption

(1) Weathering velocity both inflexible rocks (e.g. sandstone and carbonatite) and soft rocks (e.g. mudstone) are even respectively.

(2) Simplify scale of rock cell in soft rock below inflexible rock as a rectangle.

(3) Physic features both inflexible rocks and soft rocks are homogenic respectively.

(4) Simplify evolution of rock cell as a plane strain problem.

2.2 Weathering velocity of rock cell

When weathering time t passed, weathering thickness of sandstone and mudstone can be estimated in the following formulas.

$$a = v_1 t \quad (1)$$

$$b = v_2 t \quad (2)$$

Where, v_1 and v_2 are the average weathering velocity of sandstone and mudstone respectively (cm/day).

Then, level length L of rock cell vertical to surface of slope can be calculated in the next formula.

$$L = (v_2 - v_1)t = v't \quad (3)$$

Where, v' is the net different weathering velocity between sandstone and mudstone (cm/day).

Take sandstone and mudstone, sitting in area of the Three Gorges Reservoir, Northern Tianshan of the Xinjiang Uygur Autonomous Region and Xiaojiang basin of Yunnan province of China, as typical examples, approach the weathering velocity of rocks. It is identified that weathering velocity both sandstones and mudstones are decreased gradually from surface of slope backward through observations and investigations in real time field since 1993 (Tab.1 and Fig.2). Figure 2 shows the variations of weathering velocity of mudstones in rock cells below sandstones, and reveals shield clearly to weathering of mudstone in rock cell by sandstone over rock cell. Further, equations to indicate weathering velocity of mudstones in rock cells are provided in Table 2. Perhaps most importantly, due to the ratio of weathering velocity of sandstones to mudstones is in 3~6%, it is permissible to neglect weathering of sandstones in researches on evolution of rock cell.

Table 1 Weathering velocity both sandstones and mudstones in three areas

	The Three Gorges Reservoir	Northern Tianshan of Xinjiang	Xiaojiang basin of Yunnan
Weathering velocity of Sandstone, cm/day	7.7×10^{-5}	8.9×10^{-4}	3.6×10^{-4}
Weathering velocity of Mudstone, cm/day	1.5×10^{-3}	1.4×10^{-2}	8.7×10^{-3}

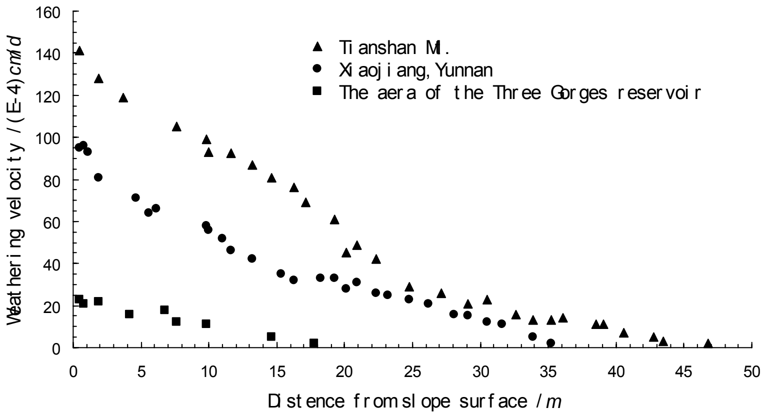

Fig.2 Curves of weathering velocity of mudstones in rock cell below sandstones

Table 2 Weathering velocity equations of mudstones in rock cells

	The Three Gorges Reservoir	Northern Tianshan of Xinjiang	Xiaojiang basin of Yunnan
Fitting equation	$v_2 = 23.00 - 1.2L$	$v_2 = 123.81 - 3.06L$	$v_2 = 83.56 - 2.49L$
Fitting coefficient	0.9766	0.9698	0.9705

Notes: L indicates distance of rock cell from surface backward (*m*), v_2 is the weathering velocity of mudstone ($\times 10^{-4}$cm/day).

2.3 Length of critical rock cell

When control fissure emerges at top of inflexible rock, the rock cell is defined as critical rock cell, whose critical length L_{cr} is the distance between the surface of slope and the point with tension stress larger than permissible tension strength of the inflexible rock. Whereas, rock block over critical rock cell is defined as initial perilous rock, and initial perilous rock is simplified as cantilever beam (Fig.3).

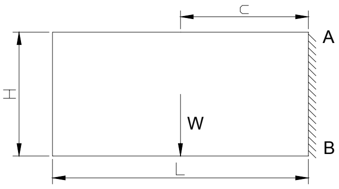

Fig.3 Initial perilous rock over critical rock cell

Weight of initial perilous rock is calculated in the following formula.

$$W = LH\gamma \quad (7)$$

Where, H is the height of initial perilous rock (m), γ is the density of rock (kN/m^3), and W stands for the weight of initial perilous rock (kN). Then moment acting on section AB is calculated in formula (8).

$$M = \frac{1}{2} H\gamma L^2 \quad (8)$$

Further, obtain the maximum tension stress at point A.

$$\sigma_{\max} = \frac{3\gamma L^2}{H} \quad (9)$$

Where, the unit of $\sigma_{\max}$ is kPa.

Let permissible tension stress of the inflexible rock be expressed in $[\sigma_t]$, when $\sigma_{\max} = [\sigma_t]$, which means rock at point A to begin damage, the damage develops possibly along section AB and becomes control fissure. At the same time, L must be the length L_{cr} of critical rock cell and can be obtained in the following formula.

$$L_{cr} = \sqrt{\frac{H[\sigma_t]}{3\gamma}} \quad (10)$$

2.4 Duration of critical rock cell

The general pattern of weathering equation of mudstone in Table 2 indicates as follows.

$$v = A + kL \quad (11)$$

Where, both A and k belongs to weathering coefficients of mudstone, whose values are different in various region.

At L_i departing from surface of slope in rock cell, when micro length ΔL occurred, weathering time Δt relative to the ΔL can be calculated in the following formula.

$$\Delta t = \frac{\Delta L \times 10^6}{A + k(L_i + \Delta L)} \quad (12)$$

In formula (12), when $\Delta L \to dL$, the formula becomes.

$$dt = \frac{10^6}{A + kL} dL \quad (13)$$

Then, duration t_0 to trigger critical rock cell is obtained in the following formula.

$$t_0 = \int_0^{L_{cr}} \frac{10^6}{A + kL} dL = \frac{10^6}{k} \ln \frac{A + kL}{A} \quad (14)$$

In formula (14), the unit of t_0 is day, the other parameters is expressed foregoing.

3 Duration of Critical Control Fissure

3.1 Critical length of control fissure

When linking length of control fissure of perilous rock is e, while unlinking part is (H-e), the plane square A_j against shear to restraint rupture of the perilous rock is

$$A_j = H - e \quad (15)$$

Further, shear stress τ in the plane is as follows.

$$\tau = \frac{L_{cr} H\gamma}{H - e} \quad (16)$$

Let permissible anti-shear strength of inflexible rock be expressed in $[\tau]$, when $\tau = [\tau]$, linking length of control fissure in perilous rock is defined as critical length e_{cr} and calculated in formula (17).

$$e_{cr} = H(1 - \frac{L_{cr}\gamma}{[\tau]}) \quad (17)$$

3.2 Damage duration t_1 of control fissure

When stress in top area of inflexible rock is in tension status, rock will be in creep damage stage, whose mechanic model is shown in Figure 4.

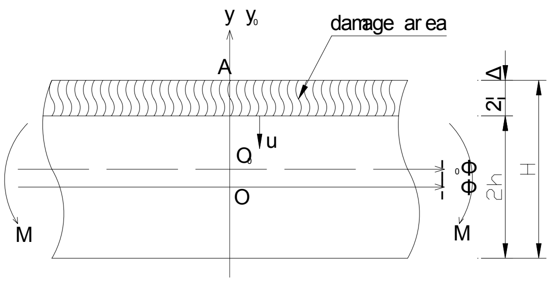

Fig.4 Damage model of perilous rock

In respect that point A in initial perilous rock is in tension stress status firstly, surface zone near point A is the front area of critical damage. To any material, damage equation is expressed as follows.

$$\omega = \omega(t, u) \quad (18)$$

Where, ω is the damage variable, t is the damage duration, u is the distance from damage front zone to expanding part along the direction of expanding. Take total differential to formula (18), i.e.

$$\frac{d\omega}{dt} = \frac{\partial \omega}{\partial t} + \frac{\partial \omega}{\partial u}\frac{du}{dt} = 0 \quad (19)$$

According to classic damage equation of material expressed in the following equation,

$$\frac{d\omega}{dt} = C(\frac{\sigma}{1-\omega})^{\nu} \quad (20)$$

Where, both C and ν are damage coefficient of material determined by creep testing.

With respect to any point P in the front damage zone, whose stress is $\sigma(t)$, then formula (20) becomes

$$(1-\omega)^{\nu} d\omega = C[\sigma(t)]^{\nu} dt \quad (21)$$

Integral equation (21), and based on initial condition: when $t=0$, $\omega=0$, then

$$\omega = 1-[1-C(\nu+1)\int_0^t [\sigma(\tau)]^{\nu} d\tau]^{\frac{1}{\nu+1}} \quad (22)$$

Let $\omega=1$, so damage equation of damage front zone at duration t is as follows.

$$C(\nu+1)\int_0^t [\sigma(\tau)]^{\nu} d\tau = 1 \quad (23)$$

When $\sigma(t)=\sigma_{\max}$, method to calculate duration t_1 for point A to become critical damage is established.

$$t_1 = \frac{H^{\nu}}{3^{\nu} C(\nu+1)\gamma^{\nu} L_{cr}^{2\nu}} \quad (24)$$

For example, on the basis of creep testing to sandstone at Mt. Shoulishan in Wanzhou, in the area of the Three Gorges Reservoir, damage coefficients are obtained, $C=0.0025$, $\nu=-0.6$, put them into formula (24), then

$$t_1 = 1930 L_{cr}^{1.2} (\frac{\gamma}{H})^{0.6} \quad (25)$$

Where, the unit of t_1 is day, the other parameters are expressed foregoing.

3.3 Fracture duration t_2 of control fissure

When point A at top of initial perilous rock gets into fracture stage from damage status, developing process of critical scale of control fissure belongs to fracture problem as □-shaped fissure under the action of moment M, the mechanic model is shown in Figure 5.

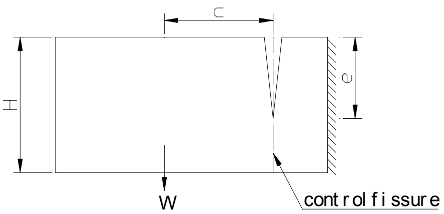

Fig.5 Fracture model of control fissure of perilous rock

Fracture strength factor of fissure is certificated in the following formula (LI QF, et al,1998).

$$K_I = F\sigma_{\max}\sqrt{\pi a} \quad (26)$$

$$F = 1.122 - 1.40(\frac{a}{H}) + 7.33(\frac{a}{H})^2 - 13.08(\frac{a}{H})^3 + 14.00(\frac{a}{H})^4 \quad (27)$$

Due to the next condition exists when the control fissure is in fracture.

$$K_I = K_{Ic} \quad (28)$$

Where, K_{Ic} is the fracture tenacity ($\text{kPa}\sqrt{\text{m}}$), and **a** is the critical damage or initial fracture scale of control fissure (m).

Combine equations (9), (26), (27) and (28), and omit high rank of (a/H), then

$$(1.122 - 1.4\frac{a}{H})\sqrt{a} = \frac{HK_{Ic}}{3\sqrt{\pi}L_{cr}^2} \quad (29)$$

Let $B = \frac{3.14}{H}$ □ $Q_0 = \frac{HK_{Ic}}{3\sqrt{\pi}L_{cr}^2}$

Solution equation (29), then

$$a = \frac{1.26 + \sqrt{1.59 - 4BQ_0^2}}{2B} \quad (30)$$

Obviously, the next condition exists in formula (30).

$$L_{cr} \geq 0.73 K_{Ic}^{0.5} H^{0.25} \quad (31)$$

State clearly above, when e=a, control fissure of perilous rock is in fracture stage. Draw lessons from fracture studies to pure bend beam by Yu SW et al (1997), the next important equation is established.

$$\frac{t_2}{t_1} = 1 + \frac{2}{2n-1}[1-(\frac{h}{h_0})^{2n-1}] \quad (32)$$

To present researches, n=1, h_0=0.5H, then equation (32) can be simplified as

$$t_2 = (1 + \frac{2e_{cr}}{H})t_1 \quad (33)$$

Where, unit of t_2 is day, the other parameters are expressed foregoing.

To sum up, duration T for a perilous rock to form is typified in the following formula.

$$T = t_0 + t_1 + t_2 \quad (34)$$

Take Mt. Shoulishan sitting in eastern region of Wanzhou district in the area of the Three Gorges Reservoir as an example, to approach the duration for perilous rock to form. The Mt. is composed and constituted by sandstone and mudstone alternately. Height of the Mt. from top to foot is about 240m, and exists 25 cliffs in sandstones with slope angle between 60~80Deg. Inclination slope composed of mudstones between cliffs is 15~30Deg. Rock cells are abundant below cliffs, whose height is 2~4m and length from surface of slope backward is 6.7~8.2m. Permissible tension strength is 1.03MPa while permissible shear strength is 2.79MPa. 67 perilous rocks are developed in the Mt., single volume is ~7904.8m^3. As one of these perilous rocks, that locating at back of Xiejia yard in the ninth cliff from foot of the Mt. avalanched at September 2005. Two rudiment parameters of the perilous rock are V=341m^3, H=4m. Based on formulas established foregoing, results are obtained: $L_{cr} = 7.16\,m$, $t_0 = 1068\,years$, $e_{cr} = 3.72m$, $t_1 = 176\,years$, $t_2 = 503\,year$, so the duration **T** for the perilous to form is 1747 years.

4 Conclusion

The first, in cliffs or steep slopes, perilous rock always develop in inflexible rock such as sandstone with evolution of rock cell in soft rock such as mudstone below sandstone. In other words, rock cell is a indicator for perilous rock to develop, which means that perilous rock gradually forms wit h evolution of rock cell.

The second, on the basis of observations and investigations in real time field in three zones of China, i.e., the Three Gorges Reservoir, Northern Tianshan of Xinjiang, and Xiaojiang basin of Yunnan, weathering velocities of mudstones are obtained while weathering velocity equations are established by data fitting.

The third, length of critical rock cell can be calculated when the maximum tension stress is equal to permissible tension stress of inflexible rock. Further, method to identify duration for critical rock cell to form is established.

The forth, divide duration of critical control fissure into two parts, one is the damage duration of control fissure, and another is fracture duration of control fissure, which are obtained respectively by certain methods found in damage mechanics and fracture mechanics. Totally, duration for single perilous rock to form is expressed in the three types durations foregoing.

Researches of the paper is valuable in appraising the safety of perilous rocks, cliffs and steep slopes.

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