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Stability Analysis of Slope Considering the Energy Evolution of Locked Segment

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Abstract: Researches on the energy evolution of the key blocks is helpful to reveal the failure process of locked-segment type slope, whose stability is governed by the locking section along the potential slip surface. In order to study the failure mechanism of the locked segment in the process of slope progressive failure due to strength attenuation, a series of stability analysis on the numerical models of locked-segment type slope were implemented to record the relationship curve between energy and strength reduction coefficient. Then, according to the variation law and characteristic of energy evolution, the failure process of the locked segment was divided into four stages: elastic stage, initial damage stage, extensive damage stage and failure stage. And the reduction coefficient corresponding to the peak of the energy evolution curve was employed to achieve landslide warning. In addition, the method to determine the safety factor of locked-segment type slope was given, and its reliability was verified by comparing with other traditional methods. Finally, the formula for calculating the initial sliding velocity was presented based on the residual strain energy which is defined as the elastic strain energy of the locked segment when the slope is unstable.

Keywords: Locked segment; Stability analysis; Elastic strain energy; Initial sliding velocity; Safety factor

1 Introduction

Locked-segment type slope generally refers to the large rock slope controlled by one or more key blocks and containing huge potential energy. And it is characterized by high-speed sliding after its failure, sometimes accompanied by luminescence and heating. The locked segment is the key block controlling the stability of slope (Chen et al. 2017, Gehle and Kutter 2003), and can be regarded as a geological structure with high strength and stress concentration existing in the potential sliding surface (Chen et al. 2019, Zhang et al. 2020, Zhao et al. 2019). In the process of slope failure, the stress concentration and brittle failure often occur in the locked segment (Pan et al. 2014, Shen et al. 2020). Once the slope fails, a large amount of internal energy will be released from the locked segment, causing landslides and threatening the life and property security of people nearby (Tan 1993, Tang 1991). Therefore, revealing the failure mechanism of the slope locked segment is not only of great significance for slope disaster prevention, but also more reasonable and efficient for slope treatment through the use of the locked segment, which attracts extensive attentions from scholars and engineers (Cao et al. 2018, Chen et al. 2018, Chen et al. 2020, Joshi and Kothiyari 2010, Liu et al. 2020). Qin et al. (2010) proposed two exponential laws for the critical displacement evolution of collapse hazard based on the theory of renormalization group, and found that the critical displacement of slope instability was related to the displacement at the starting point of accelerated creep and the number of locked segment. Chen et al. (2012) established the mechanical model of the compression-shear perilous rock and the constitutive equations between locked segment tangential resistance force and shear displacement. From experiments and numerical simulation, Huang and Gu (2018) believed the failure mode and evolution mechanism of the locked segment were controlled by the angle of rock bridge, namely the angle between the line of the end of the tensile crack to the end of the creep section and the horizontal direction. Chen (2019) claimed that the stability of slope with a locked segment was controlled by factors such as the location, range and quantity of the locked segment. At present, the prediction of instability about the

locked-segment type slope, is mainly based on the mechanical theory to study the failure mode of the locked segment, which needs to consider many factors at the same time and is quite complex. In fact, the failure of rock is an instability phenomenon driven by energy (Lin et al. 2020, Lin et al. 2020, Lin et al. 2020, Wang et al. 2020, Wang et al. 2020, Zhang et al. 2021). Therefore, the stability of the locked-segment type slope can be evaluated more simply and accurately by revealing the energy evolution during the failure process of it.

From the perspective of thermodynamics, there is always existing energy input, conversion and output with external system in the process of slope failure (Chen et al. 2021, Liu et al. 2016, Wang et al. 2016, Yuan et al. 2020, Yuan et al. 2020). Specifically, part of the gravitational potential energy of slope is gradually converted into elastic strain energy and plastic dissipative energy in the locked segment (Wang et al. 2018). Whereafter, the locked segment will fail and the initial kinetic energy for landslides will be released if the energy accumulation and dissipation cannot meet the input of gravitational potential energy. In this paper, the failure mechanism of the locked segment was firstly studied by analyzing the characteristic of energy evolution, and the failure process of the locked segment was divided into different stages. Then, according to the residual strain energy, i.e. the elastic strain energy before the failure of the locked segment, the formula for calculating the initial sliding velocity after the failure of the locked segment was put forward. Meanwhile, the concept of warning safety factor was introduced, and a new method to determine the safety factor of the slope by using the sudden drop in energy in the locked segment was proposed, which was verified by comparing with existing methods. The research results of this paper have good theoretical significance and application value in the early warning of failure, stability evaluation and reinforcement treatment of such slope.

2 Failure mechanism of locked segment and early warning effect of peak point

2.1 Slope model with a locked segment

As described in Fig. 1, the height of the slope model (H) is 30 m, the angle of slope is 72° , and the angle of sliding surface is 60° . The width and length of the locked segment are 0.5 m and 4.5 m respectively, and the bottom of it is located at the midpoint of the sliding surface. The distance from the left boundary to the foot of the model is 1.5 times the height (i.e., $1.5H$), the distance from the right boundary to the top of the model is 2.5 times the height (i.e., $2.5H$), and the thickness of the foundation is 1.0 times the height (i.e., $1.0H$). Totally, there are 21,200 zones and 13,557 nodes in the model. The left and right boundaries are constrained in the horizontal direction, and the bottom boundary is fixed in all directions. Furthermore, this study adopts the constitutive model of the Mohr-Coulomb elastoplastic model (Bejarbaneh et al. 2015, Meng et al. 2018, Xie et al. 2020, Zhao et al. 2020), i.e. Mohr-Coulomb yield criterion is used. Additionally, convergence emerges when the ratio of the maximum unbalanced force to the average node force is less than 10^{-5} . Table 1 shows the physical parameters of rock adopted in this study, and it should be noted that the same parameters were applied to the locked segment and the slope.

2.2 Elastic strain energy of the locked segment

As previously described, under the influence of temperature, water, force, wind and other factors in the external system, the slope gradually deforms, and even loses its stability. And that, the essence of this process is the input and output of energy. With the attenuation of strength parameters of rock mass, deformation and stress concentration will occur in the locked segment. In accordance with the knowledge of thermodynamics, the gravitational potential energy of slope is gradually transformed into elastic strain energy, plastic dissipative energy and kinetic energy, namely:

$$\Delta U_g + \Delta U_e + \Delta U_d + \Delta U_k = 0 \quad (1)$$

where, ΔU_g is the increment of gravitational potential energy, ΔU_e is the increment of elastic strain energy, ΔU_d is the increment of plastic dissipative energy, and ΔU_k is the increment of kinetic energy of the slope body.

In the progressive failure process of slope, the locked segment, as the key block to control the stability of slope, accumulates a lot of energy which is accompanied by complex energy conversion, and therefore, studying and revealing its evolution is helpful to understand its failure mechanism. Before slope failure, the increment of gravitational potential energy and kinetic energy in the locked segment is relatively small, so the evolution of elastic strain energy is mainly considered. In term of the theory of elastic mechanics, the total elastic strain energy contained in the locked segment can be obtained by integrating the energy density of its element, namely the following formula:

$$U_{lock} = \int_v \frac{1}{2E} [\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\nu(\sigma_1\sigma_2 + \sigma_1\sigma_3 + \sigma_2\sigma_3)] dV \quad (2)$$

where, U_{lock} is the sum of elastic strain energy in the locked segment, E is the elastic modulus of the locked segment, $\sigma_1, \sigma_2, \sigma_3$ is the first, second and third principal stresses of any element in the locked segment, ν is the Poisson ratio in the locked segment.

2.3 Energy evolution and failure mechanism

Numerical simulation method is widely applied in geotechnical engineering (Lin et al. 2020, Yin et al. 2020). The self-customized fish program, which reduces the strength parameters of the slope in turn according to a specific ratio in FLAC^{3D}, was used to simulate the progressive failure of slope caused by the attenuation of strength. The reduction coefficient can be determined by the ratio of the initial strength to the critical strength. In the process of reduction, all the elements in the locked segment will be walked through, to record the changing law of elastic strain energy in it.

In this paper, the variation range of the reduction coefficient was determined by trial calculation, from 1.0 to 3.1. During the failure process, deformation and stress concentration gradually occur in the locked segment during the reduction of slope strength parameters. The evolution of elastic strain energy in the locked segment can be seen in Fig. 2. And that, from its evolutionary characteristics, the failure process can be divided into the following four stages, and the variation range of reduction

coefficient in different stages is shown in Table 2.

(1) Elastic stage: In this stage, there is no plastic zone in the locked segment, and the elastic strain energy in the locked segment increases linearly. At this time, it can be considered that the locked segment in the initial stage is in the elastic stage.

(2) Initial damage stage: With the further decrease of rock parameters, due to the concentration of shear stress, a small amount of plastic zone appears at the bottom of the locked segment in a relatively slow development rate. The curve of elastic strain energy in the locked segment gradually slows down until peak, showing strong nonlinear changes. At this time, it can be considered that most of the elements in the locked segment are still in the elastic working stage, and only a small part of the lower part of the elements enter the damage stage.

(3) Extensive damage stage: The plastic zone at the bottom of the locked segment develops further, and the plastic zone began to appear at the upper end. With the further decrease of the rock parameters, the development of the plastic zone will accelerate until the plastic zone is completely connected. The elastic strain energy in the locked segment gradually decreases from the peak value, and the rate of decrease gradually increases, until it reaches the energy drop point. At this moment, it can be considered that the locked segment in the later stage is in the severe damage stage.

(4) Failure stage: The plastic zone has completely penetrated the locked segment, the displacement of the sliding mass at the leading edge increases sharply, and the elastic strain energy in the locked segment also drops sharply. When the strength reduction factor is further increased to 3.10, the calculation of the numerical model has been unable to converge. In actual engineering, the macroscopic performance is that the locked segment suddenly breaks and makes a loud noise(Hu et al. 1992), the sliding body changes from a static state to a high-speed sliding state, and the slope is declared to be failure.

The results show that the capacity to energy storage of the locked segment is limited, which is related to the damage evolution. As shown in Fig. 3, when its stored energy is about to reach its peak, part of the input gravitational potential energy will be converted into dissipated energy, which will slow down the rise of elastic strain

energy and cause damage evolution at the same time. Subsequently, the accumulation and dissipation of elastic strain energy reach a balance, its change curve reaches its peak. Then, with the further reduction of the rock parameters, the damage in the locked segment further evolves, the dissipation of elastic strain energy exceeds the input, and the curve begins to decline. Eventually the accumulation and dissipation of energy cannot withstand the further input of the potential energy of the gravity force of the slope, the energy curve will drop sharply, and the locked segment will break, which leads to failure of the slope.

2.4 Early warning effect of peak point

The failure of the locked-segment type slope often occurs suddenly, which has strong unpredictability (Runqiu 2008, Runqiu et al. 2017). In order to avoid the loss of life and property caused by the failure of the locked-segment type slope, a more accurate prediction should be made.

In term of the energy evolution and failure mechanism mentioned above, after the failure of the locked segment, the elastic strain energy drops sharply, and the slope is in a state of failure. However, when a sudden drop in energy is detected in the locked segment, the failure of the slope has already occurred, which leads that the monitoring results at this time are of little significance for slope disaster prevention.

From the mechanical point of view, the further reduction of the strength of the rock mass leads to the damage evolution of the locked segment, that is, crack propagation. As shown in Fig. 3, this process is essentially driven by energy conversion, i.e. the transformation of elastic strain energy into dissipation energy. After the input and output of energy in the locked segment reach a balance, the output of energy will be greater than the input, which makes that the system will tend to be unstable. Therefore, the peak of energy has a better warning effect, and the corresponding reduction factor can be regarded as the warning safety factor of the slope, which has certain geometric and physical meanings. In practical engineering, engineers can judge the stability of the locked segment according to whether the energy change of the key parts of the slope reaches its peak. In this way, early

warning information is issued for the overall instability of the slope, or the slope in an under-stable state is supported and reinforced in time.

3 Safety factor and initial sliding velocity

3.1 Safety factor of the locked-segment type slope

Common methods for judging the stability of slopes include the convergence of numerical computations, the abruptness of the displacement or deformation at a certain characteristic location and connectivity of plastic zone, and the limit equilibrium method (Chen and Jin 2012, Chen et al. 2001, Feng et al. 1999, Liu et al. 2005, Zhang et al. 2016). Generally, it is believed that the plastic zone penetration criterion is a necessary condition for slope failure, but it is not a sufficient condition (Zhao et al. 2005). Pei et al. (2010) believed that the displacement mutation criterion was subjective, but the three types of stability criteria were theoretically unified and consistent. Besides, the limit equilibrium method based on the finite element stress field (ie, Finite Element Stress Method) does not need to assume the force between the blocks and consider the stress conditions (Gordan et al. 2016, Jian et al. 2014, Zeng and Tian 2005), which is often compared to other results. In light of the above analysis, the slope failure will occur when the energy in the locked segment drops suddenly, and the reduction factor corresponding to the sudden drop point can be used as the safety factor. In this section, the above four methods for the stability of the slope were respectively used for calculation and judgment, and comparative analysis was carried out. The horizontal displacement of the characteristic points is shown in Fig. 4, and the results are shown in Table 3.

As described in Fig. 4 and Table 3, the safety factor obtained by the sudden drop in energy is very close to that obtained by other methods. In fact, the process of failure of the locked-segment type slope due to strength attenuation is essentially driven by energy. With the deformation of the slope, part of its gravitational potential energy is transferred to the locked segment, resulting in the accumulation of elastic strain energy in the locked segment. At the same time, the gradual development of the plastic zone leads to the internal accumulation of elastic strain energy decreases and

the plastic dissipation energy increases in the locked segment. Finally, the energy accumulation and dissipation cannot satisfy the input conversion and output of gravitational potential energy. Meantime, the damage in the locked segment is fully developed, which leads that the locked segment breaks and the residual elastic strain energy is converted into the initial kinetic energy of landslides.

Therefore, the safety factor corresponding to the energy drop point proposed in this paper has a clearer physical meaning, and it has a high degree of unity and consistency in theory with the traditional judgment method, which makes that it can be used as the safety factor of the locked-segment type slope.

3.2 Initial sliding velocity

The failure of locked-segment type slope is the rapid landslide, which is often accompanied by light and heat at night (Pan and Li 2011). Since FLAC^{3D} is the software that analyzes the continuum, it cannot simulate the real effect of a landslides. For this purpose, this paper proposes the residual strain energy, which is defined as the elastic strain energy before a sudden drop in energy occurs, and the initial sliding velocity can be calculated by the following formula:

$$v_{ini} = \sqrt{\frac{2 \times U_r \times k_r}{m_s}} \quad (3)$$

where: v_{ini} is the initial sliding velocity, U_r is the residual strain energy, m_s is the mass of the sliding body, and k_r is the reduction coefficient of residual strain energy considering the instantaneous dissipation of energy.

In order to further study the influence of various parameters of the slope on the initial sliding velocity, this paper selects the height and the elastic modulus as the control variables to study the changes of initial sliding velocity under different conditions. The results are shown in Fig. 5 and Fig. 6.

In Fig. 5 and Fig. 6, the fitting equation of the initial sliding velocity and the slope height is: $v_{ini}=0.00404H-0.00843$, the fitting equation of the initial sliding

velocity and the elastic modulus is: $v_{ini} = 2.5273 \times \sqrt{\frac{1}{E}}$. The results show that under other conditions unchanged, the initial sliding velocity is proportional to the slope height and inversely proportional to the square root of the elastic modulus. From the mechanical point of view, an increase in elastic modulus means a decrease in deformation in the locked segment. Therefore, the accumulated energy used for sliding of the landslides is also reduced, resulting in a decrease in the initial sliding velocity. Noteworthily, this variation is highly consistent with the results given by Cheng(Cheng and Hu 1999) based on the perspective of fracture mechanics, which further proves the reliability of calculation method about the initial sliding velocity proposed in this paper. And it can be predicted that when the height of the slope reaches hundreds of meters, the initial sliding velocity will reach about several meters per second, which is similar to the conclusions of some scholars(Luo et al. 2013, Xie et al. 2008, Xing et al. 2004).

4 Conclusion

The process of damage evolution in the locked segment is driven by energy conversion, and the failure process of the locked segment can be divided into four stages according to its evolutionary characteristics. The following conclusions can be drawn in this paper:

(1) After the peak point of the energy evolution curve of the locked segment, the energy input will be mainly converted into dissipated energy rather than accumulated into strain energy, the development of plastic zone accelerates, and the locked segment tends to become unstable. Therefore, the peak point has an important role in disaster prevention and early warning.

(2) Based on the residual strain energy, which is defined as the elastic strain energy in the locked segment before the failure occurs, a formula for calculating the initial sliding velocity was proposed. Besides, the initial sliding velocity is proportional to the slope height and inversely proportional to the square root of the elastic modulus.

(3) This paper compared and analyzed the reduction coefficient when the drops suddenly in energy with the results of the traditional method. The safety factors obtained under different methods are basically the same, indicating that the energy drop point of the locked segment can be used to determine the safety factor of the locked-segment type slope.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

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Table 1 Physical parameters of rock

Rock	Density $\rho/\text{g}\cdot\text{cm}^{-3}$	Young modulus E/MPa	Poisson Ratio ν	Cohesion c/kPa	Friction $\phi/(^{\circ})$
Slope	2.8	500	0.22	1.5	35
Weak belt	1.5	100	0.35	0.01	5

Table 2 Variation range of the reduction coefficient at different stages

Method	Range	Method	Range
Elastic stage	1.00-1.80	Minor damage stage	2.32-3.01
Minor damage stage	1.80-2.32	Failure stage	3.01-3.10

Table 3 Safety factor under different methods

Method	Result	Method	Result
the abruptness of the displacement or deformation	3.04	A sudden drop in energy	3.01
the connectivity of plastic zone	3.01	Finite element stress method	3.03
the non-convergence of solution	3.09		

Figures

Figure 1

Numerical model of slope with the locked segment

Figure 2

Variation law of elastic strain energy in the locked segment

Figure 3

Schematic diagram of energy evolution in the locked segment

Figure 4

Variations of the displacement at the monitoring points and the energy in the locked segment

Figure 5

Relationship between the initial sliding velocity and the height of the slope

Figure 6

Relationship between the initial sliding velocity and the Elastic Modulus of the slope