Slope safety assessment based on dynamic anchor force

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ABSTRACT: Anchor cable is widely used in rock slope reinforcement. In the design, the force of the anchor cable is often simplified as a constant load, which cannot reflect the deformation. To accurately evaluate the stability of the slope reinforced with anchor cables under earthquake load, the nonlinear mechanical model is introduced. Based on the Newmark method, the displacement formula is derived. The differences between the two models are compared under the framework of vulnerability. The results show that: 1) Deformation of anchor cables due to slope sliding. The anchor force is showing an increasing trend. 2) The stability of the slope is related to the ground motions. Vulnerability analysis can be used for quantitative analysis of slope safety. 3) The slope considering the change of anchor cable force has a greater probability of instability. Simplifying the anchor cable to constant loads may lead to an underestimation of the danger.

Keywords: Anchor cable, Slope, displacement, Newmark, Earthquake.

1.1 General Layout

Disasters caused by earthquakes endanger lives and economic development (Lin et al. 2017). As an important part of hydropower engineering and traffic engineering, slopes need to be stable under seismic loads. Affected by the environment and excavation, some slopes need to be reinforced. Anchor cable is the main reinforcement measure of rock slope (Zhang et al. 2019). With the increase of such projects, its security has become a hotspot. It is of great significance to carry out research on anchor cable slopes.

Pseudo-static method and Newmark method are the main methods for seismic stability analysis. The Pseudo-static method has the advantage of simple application, so it is widely used by practitioners. The safety factor in the specification is also based on the quasi-static method. The quasi-static method's disadvantage is that it cannot reflect the influence of seismic wave duration and frequency. Shaking table tests and seismic investigation show that the influence of seismic wave parameters can not be ignored in some cases (Zhang et al. 2020; Yuan et al. 2015). To overcome the above shortcomings, Newmark proposed using residual displacement to evaluate the safety of the slope. The sliding soil mass is assumed to be a rigid block on an inclined base. When the limit state is exceeded, the slope slides. The strength of the soil is not affected by sliding. The displacement can be obtained by integrating the acceleration. If the displacement does not exceed the allowable value, the slope is considered stable. Many scholars have carried out research based on this method. Ambraseys & Sarma (1967) believed that the frictional resistance of the sliding surface was affected by pore water pressure. In the process of vibration, the frictional properties may be attenuated. It is not appropriate to simplify the frictional resistance to a constant value. The Newmark method assumes that the sliding surface is a plane. Makdisi & Seed (1978) introduced the curve slip surface into the calculation of residual displacement, which extended the application range of the Newmark method. The limit analysis is of strict physical significance, and the range of true solutions can be determined by upper and lower limits. Ling (1997) applied the limit analysis method to solve the upper limit of displacement. The above studies believe that horizontal earthquake is the main cause of damage, but not enough attention has been paid to the vertical earthquake. Pradatta (2018) derived the displacement formula for horizontal and vertical earthquakes and compared the influence of loading direction. Besides, the Newmark method is also used in reinforced slopes. Li (2010) took the slope reinforced by stabilizing pile and anchor cable as an example to analyze the optimal position of the reinforced structure. However, in this study, both anchor cable and stabilizing pile are equivalent to a constant load. The change in yield acceleration is not taken into account.

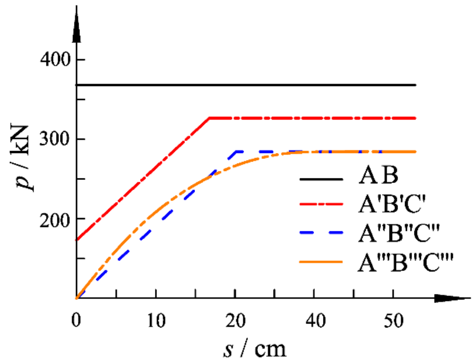
In this paper, the force-displacement models of anchor cables are analyzed. The nonlinear model was introduced into the design of the slope. Combined with the Newmark method, the real-time update of the anchor cable force is realized. The different models were compared using the vulnerability analysis method.

2 MECHANICAL MODEL OF THE STRUCTURE

Mechanical models of anchor cable include fixed value models (AB) and elastic-plastic models (A'B'C'). The curve without pre-tension can be expressed as can be represented by A"B"C". In previous studies, the anchor cable was simplified as the ultimate load, and the yield acceleration was a constant value. When the seismic load exceeds the yield acceleration, the slope slips. The displacement value can be obtained by integrating the acceleration. This paper adopts the nonlinear model. Combined with the Newmark method, the real-time update of the anchor cable force can be achieved. As the slope slides, the anchor cable force and yield acceleration increase. The research shows that the nonlinearity can be simulated by the exponential function. The formula is as follows:

$$F_t = F_{tmax}(1 - e^{-at\Delta L_f}) \tag{1}$$

Where F_{tmax} is the ultimate load of the anchor cable. at is the anchor cable coefficient. $\triangle L_f$ is the deformation. at can describe the relationship between force and deformation, which is related to the length, cross-sectional area, and material.



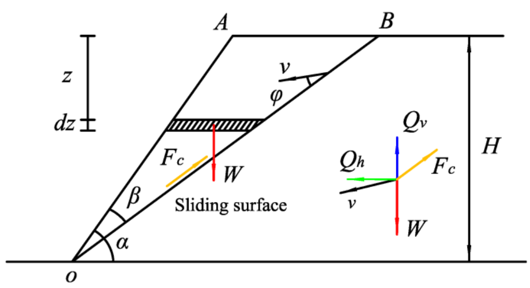


Figure 1. Mechanical model of the anchor cable. Figure 2. Slope reinforced with anchor cables.

3 CALCULATION METHOD

In this paper, a rock slope with a soft interlayer is used as an example. Fig. 2 shows the simplified model. The limit analysis method points out that the external load power is equal to the internal energy dissipation power in the critical state. External loads include gravity, seismic loads, and anchor cable force. The internal load is the cohesion of the failure face. The following assumptions are made in this paper: 1) The slider is rigid and destruction obeys the Mohr-Coulomb criterion. 2) The soil strength is constant and does not decay with sliding. 3) The tensile deformation of the anchor cable only occurs in the free section. 4) The weak interlayer is the sliding surface.

(1) The power of gravity
Gravity is the basic load of the slope. According to the geometric relationship, the mass and power of the sliding soil can be obtained.

$$P_w = \frac{\rho g \sin\beta}{2\sin(\alpha-\beta)\sin\alpha} H^2 v \sin(\alpha-\beta-\varphi) \tag{2}$$

Where M is the mass of the slipping soil, Pw is the power of gravitation, and g is the gravitational acceleration.

(2) The power of seismic load
Divide the soil into microprions in the horizontal direction. Calculate the seismic force of each microprion, and the superposition is the power of the earthquake. The formula for seismic power is as follows:

$$Q_{h,v}(t) = \int_0^H f_a m(z) a(t)_{h,v} \tag{3}$$

$$P_e = Q_h v \cos(\alpha-\beta-\varphi) - Q_v v \sin(\alpha-\beta-\varphi) \tag{4}$$

P_e is the power of the earthquake. fa is the amplification factor, the range is 1~3. Q_h and Q_v are horizontal and vertical seismic loads respectively.

(3) The energy dissipated power at the failure surface
According to the upper limit theorem, the failure surface of the slope is the velocity discontinuity surface. In this paper, the failure surface is a straight line. The angle between the speed direction and failure surface is φ. Energy dissipation is produced by cohesion.

$$P_c = \frac{cH}{\sin(\alpha-\beta)} v \cos\varphi \tag{5}$$

(4) The power of anchor cable
Slope sliding changes the position of the anchor head. The free section is stretched. The angle and length of the anchor cable after sliding can be calculated through geometry knowledge.

$$P_t = \sum_{i=1}^{m} T_m v[\cos(\beta+\varphi-\alpha)\cos\theta' + \sin(\alpha-\beta-\varphi)\sin\theta'] \tag{6}$$

Where Tm is the total tension of the anchor cable ($T_m = m \times T$), m is the number of anchor cables.

(5) Acceleration and displacement
Displacement is an important indicator for evaluating the safety. It is related to the frequency and duration of ground motions. When the seismic force exceeds the critical condition, the slope has the

tendency to slide. Acceleration is a fluctuating curve that can be derived from the power balance theorem.

$$a(t)=\frac{P_w+P_v(t)+P_h(t)-P_c-P_t(t)}{mv} \tag{7}$$

The soil strength does not change during the sliding process. According to the conservation of power, the displacement of the slope can be obtained by quadratic integration of the acceleration.

$$s(t)=s(t-\Delta t)+v(t-\Delta t)\Delta t+\frac{1}{2}a(t)\Delta t^2 \tag{8}$$

4 CASE STUDY

Typical rock slope are used to analyze the differences between fixed and nonlinear models. The slope parameters are as follows: slope height H = 40 m, slope angle α = 60°, the angle between the failure surface and the slope surface β = 10°, density ρ = 2700 kg/m3, cohesion c = 50 kPa, internal friction angle φ = 30°, gravitational acceleration g = 10 m/s2. There are three anchor cables on the slope. The length of the free section L_f= 15 m, the length of the anchor section L_a = 8 m, and the spacing between the horizontal rows is 5 m. The yield load T_{max} = 260×3 kN, and the prestress of the anchor cable is 65%. Twelve seismic records were selected from the database of the US Pacific Earthquake Engineering Research Center. Through normalization, the acceleration peak is adjusted to 0.1-1.0g. A total of 120 seismic waves were obtained.

Table 1. Classification of slope seismic performance level.

Destruction level	Limit state	Feature description	Displacement (cm)
Basically intact	LS1	The slope does not slide, and there is no risk of instability	0-1
Minor damage	LS2	The slope has local instability, the risk of damage is small, and only local reinforcement is required.	1-5
Moderate damage		The slope has local instability, the risk of damage is small, and only local reinforcement is required.	5-15
Severe damage	LS3	Severe collapse and landslide disaster occurred	>15

The vulnerability refers to the probability that the structure reaches or exceeds different damages state under the seismic load. In this paper, PGA is taken as the intensity index of ground motion. Residual displacement can be used as the failure index. The classification of seismic performance is crucial for vulnerability analysis. In the field of high-rise buildings, the seismic performance is divided into five levels: basically intact, minor damage, moderate damage, severe damage, and collapse. Underground projects such as tunnels and chambers often use four levels: basically intact, minor damage, moderate damage, and severe damage. In this paper, the seismic performance is divided into Table 1. Combining the research of Jibson and Michael, the quantified threshold of performance level is defined by the slope sliding displacement.

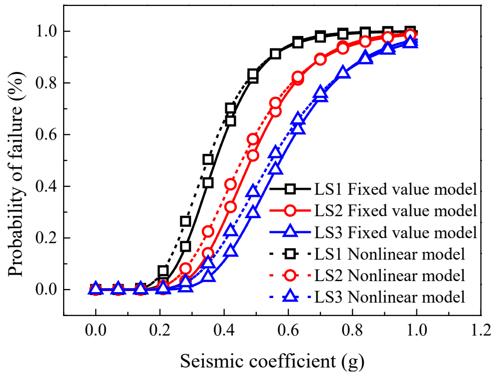


Figure 3. Vulnerability curve.

The damage degree of the slope can be evaluated according to the fragility curve. It can be seen from Figure 3 that the transcendence probability increases with the increase of PGA. When the earthquake intensity is the same, the exceedance probability of the nonlinear model is greater than that of the fixed value model. Taking 0.4g as an example, the transcendence probability of the fixed value model is 59.04%, 26.38%, and 11.15%. The transcendence probability of the nonlinear model is 65.23%, 35.44%, and 18.52%. The difference between the two models is 6.19%, 9.06%, and 7.37%. The influence of the reinforcement structure deformation on the slope cannot be ignored.

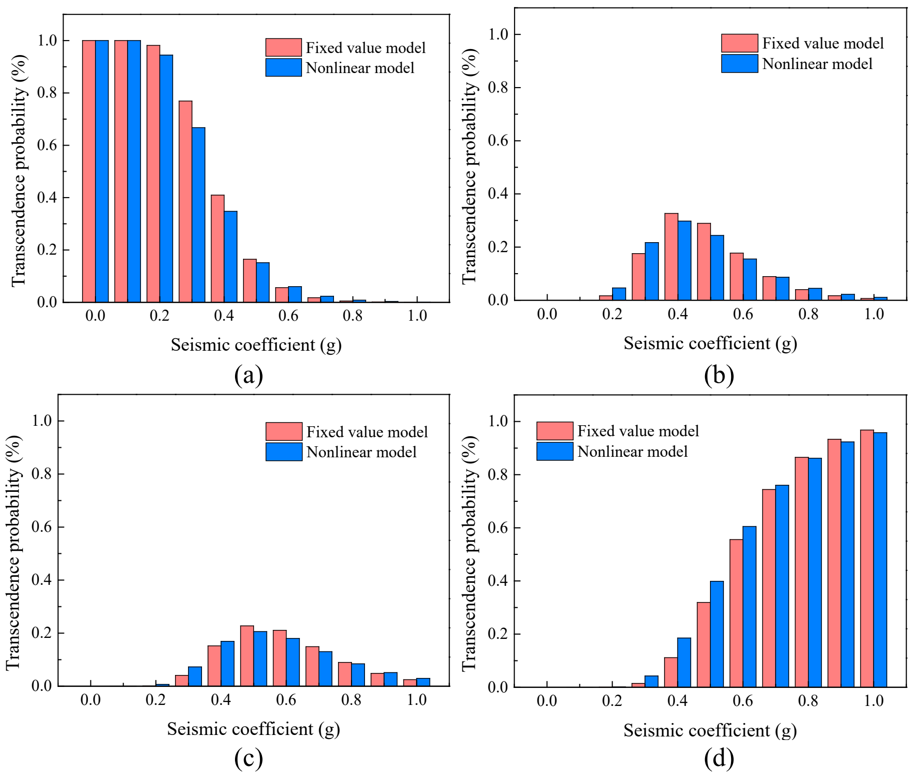


Figure 4. Probability of damaged state (a) basically intact (b) minor damage (c) moderate damage (d) severe damage.

Figure 4 shows the probability that the slope is in different failure states. With the increase of the PGA, the probability that the slope is in a basically intact state decreases monotonically. The probability of a severe damage state is increasing. The probability of minor damage and moderate damage showed a trend of increasing first and then decreasing. When the PGA is 0.1-0.3, the slope is mainly in a basically intact state. When the PGA is 0.3-0.7, it is mainly minor damage and moderate damage. When the PGA >0.7, the slope is more likely to be severely damaged. The trends of the two models are the same. The nonlinear model has a higher failure probability than the fixed-value model.

This phenomenon is the same as in the previous section. Neglecting the deformation of the reinforced structure may lead to an underestimation of the risk. Combined with the seismic intensity of the engineering site, the possible failure state of the slope can be determined.

5 CONCLUSION

In this paper, the nonlinear anchor cable model is introduced into the slope stability assessment. Combined with the Newmark method, the relationship between the anchor cable force and displacement is analyzed. The differences between the fixed value and nonlinear models are compared through the vulnerability analysis method. The main conclusions are as follows:

The anchor cable force has a time effect. At the initial stage of the earthquake, the anchor cable force is pretension. After the earthquake, the anchor cable force increases significantly.

The safety of the slope can be evaluated quantitatively by using the vulnerability analysis method with peak seismic acceleration and residual displacement as indexes.

Vulnerability analysis can quantitatively assess the stability of the slope. The damage status is divided into four grades: basically intact, slightly damaged, moderately damaged and severely damaged.

The model of the anchor cable has a great influence on the results. Slopes with nonlinear models have higher transcendence probability. Neglecting the change of anchor force may lead to an underestimation of the risk.

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