Research Article

Investigation on the Stability of Fissured Slopes Reinforced with Anchor Cables under Seismic Action

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Based on the upper bound theorem of limit analysis (UBLA) combined with the pseudostatic methods, this paper elaborates on a calculated procedure for evaluating fissured slope stability under seismic conditions reinforced with prestressed anchor cables. An existing simple slope case is presented as a case study in this work. The comparison is given to verify that the solution derived from this study is correct and feasible. By means of a numerical optimization procedure, the critical location of the crack is determined from the best upper bound solutions. The results demonstrate a significant influence of the depth of crack and seismic acceleration coefficient on the critical location distribution of the cracks. Meanwhile, the axial force of anchor cables is investigated via parametric studies. It is shown that the variation of the crack depth has little effect on the axial force of anchor cables. Moreover, this paper also illustrates the variation in the axial force of anchor cables under the impact of five marked factors (crack depth, anchor arrangement, anchor inclination angle, slope angle, and seismic conditions). Finally, the required critical length of the free section of anchor cables is determined to ensure the stability of fissured slopes subjected to seismic action.

1. Introduction

Slope instability is a significant problem in engineering practice and will cause heavy casualties and huge economic losses worldwide [1–3]. In the past decades, stability analysis of slopes is one of the most fundamental and written-about topics in geotechnical research, which is classic but continues to be active in the literature [4–7]. Due to the development of soil tension, cracks are often found at the crest of cohesive soil slopes; Taylor [8] said that “...the action within the tension zone is a subject that is worthy of much study,” whereas the analyses of slopes with crack are relatively scarce. Baker [9] indicated that the tension cracks at the posterior position of the slide surface are induced by the self-weight of soil and other external loads. Moreover, the literature on seismic-induced slope instability has shown that fissured slopes experience seismic activity [10–12]. Thus,

determining the stability of the fissured slopes under seismic action is a particularly important engineering issue in the seismic zone. To stabilize dangerous slopes, anchor cables can be considered as an efficient reinforcement measure in slope engineering [13, 14]. Compared with traditional retaining structures, reinforcement systems involving permanent grouted anchors may provide better technical and economic advantages [15]. Furthermore, under prestressed anchor cables, the strength and bearing capacity of the slope would be fully utilized to effectively improve slope stability, which have been widely used to reinforce high and steep slopes [16].

The existing methods for stability analysis of fissured slopes can be categorized as follows: (i) Limit equilibrium (LE) methods. Terzaghi and Peck [17] derived the estimated formula of tension cracks at the crest of slopes when the forces between soil mass slices applied. Spencer [18], Law

and Lumb [19], and Zhu et al. [20] also used the framework of slices method to investigate the slopes tension stability problems. (ii) Variational LE method. Baker [9] employed variational extremization for the assessment of the impact of the tensile crack of the cohesive soil slope. Since then, Leshchinsky [21] and Li et al. [22] also extended this variational LE method to obtain the factor of safety for fissured slopes. Zhou et al. [23] presented an extension of the variational analysis of slope stability with a tension crack considering seismicity. (iii) Numerical methods. Antão et al. [24] attempted the finite-element upper bound limit analysis, where the presence of a crack of specified location and depth was included in the stability analysis of a slope reinforced with sheet pile. Liu and Zhao [25] conducted a numerical limit analysis on a wet slope with a tension crack in the upper slope surface using the rigid finite-element method (RFEM). Another powerful approach for stability analysis of fissured slopes is the upper bound theorem of limit analysis (UBLA). In many situations, upper bound theorems have proven to be more robust and efficient than the conventional LE method [25]. Based on the UBLA method, Utili [26] investigated the effect of location and depth of vertical cracks on slope stability. Michalowski [5] considered the effect of the crack-opening process on the stability of homogeneous slopes. Recently, the UBLA and the pseudostatic method were used to examine the stability of fissured slopes subjected to seismic loading [11, 12, 27]. As to slope reinforced with anchor cables, Li et al. [15] and Zhao et al. [28] proposed the UBLA method to consider the reinforcing of one row of anchors on slope stabilization under conditions of a rotational failure mechanism. In addition, Yan et al. [29] and Su et al. [30] also applied the UBLA method for evaluating slope stability considering the effect of anchor cables and seismic loading.

Based on the above analysis, the purpose of this paper is to extend the UBLA method of slope stability with tension crack by Michalowski [5] and Utili and Abd [11] into slopes reinforced with prestressed anchor cables and seismic condition. A rotational failure mechanism (log-spiral surface) was considered to find the critical results [4, 31–34]. By comparison and analysis of existing slope examples, the correctness and feasibility of the proposed UBLA method have been verified. The calculation can be used to work out the critical location of the crack. A typical case is presented to determine the effect of crack depth, anchor arrangement, anchor inclination angle, slope angle, and seismic conditions on the axial force of anchor cables. Furthermore, analysis and discussion are conducted regarding the required critical length of the free section of anchor cables.

2. Methodology of Analysis

2.1. Basic Assumptions. To formulate the problem, the analyses presented in this work were developed under the following basic assumptions:

- (1) The fissured slope can be considered as isotropic, homogeneous, and dry soil.

- (2) The soil-anchor-reinforced system can be studied in plane-strain conditions.
- (3) The tensile crack always appears at the top of the slope and the crack depth is distributed vertically along the height of the slope.
- (4) The failure surface passes through the toe of the fissured slope and the sliding soil mass moves as a rigid body.
- (5) The seismic action of the fissured slope sliding soil mass is simplified to pseudostatic load.

2.2. Failure Mechanism of Fissured Slopes. As previously assumed, an isotropic and homogeneous fissured slope reinforced with a row of anchors is considered in the present study. The failure mechanism with the log-spiral line beneath the toe of the fissured slope is shown in Figure 1, where log-spiral line AD is the failure surface of the fissured slope, and H and H_1 are fissured slope height and crack depth, respectively. L_1 and L_2 are a horizontal distance from point B to point C' and a horizontal distance from the crack to point C' , respectively. The parameters X_E and α are the horizontal distance from the anchor head to the toe of the slope and the inclination angle of anchors, respectively. The parameters β and θ_d are the slope angle and the angle related to the cracks, respectively. The parameters θ_0 and θ_h are angles of the failure mechanism. The parameters r_0 and r_h are polar diameters of the log-spiral line. The fissured slope is represented as a rigid body that slides along the log-spiral surface with center O and angular velocity ω .

From Figure 1, the geometric relationship of the failure mode can be expressed as

$$H_r = \frac{H}{r_0} = \sin \theta_h \exp[(\theta_h - \theta_0)\psi] - \sin \theta_0, \quad (1)$$

$$\begin{cases} L_{1r} = \frac{L_1}{r_0} = \frac{\sin(\theta_0 + \beta)}{\sin \beta} - \frac{\sin(\theta_{jh} + \beta)}{\sin \beta} \exp[(\theta_h - \theta_0)\psi], \\ L_{2r} = \frac{L_2}{r_0} = \cos(\theta_0 - \theta_d) \exp[(\theta_d - \theta_0)\psi], \end{cases} \quad (2)$$

where $\psi = \tan \varphi_m / F_s$. The strength reduction technique is widely used in the stability analysis of safety factor F_s , based on the linear Mohr-Coulomb (M-C) failure criterion [35, 36]. Similarly, $c_m = c / F_s$. The parameters c_m and φ_m are the mobilized cohesion and internal friction angle for the fissured slope to attain the limit state of stability, respectively.

Due to the assumption of the failure mechanisms through the bottom of the crack, knowledge on the known depth of the existing crack, H_1 , brings in an additional equation about θ_d , which can be determined by the unknown θ_0 and θ_h and the geometric relationship in Figure 1.

FIGURE 1: Basic definitions for a fissured slope reinforced with anchor cables subjected to seismic action.

$$\begin{aligned} \sin \theta_d \exp(\theta_d \psi) &= \sin \theta_0 (\theta_0 \psi) \left(1 - \frac{H_1}{H}\right) \\ &+ \sin \theta_h \exp(\theta_h \psi) \left(\frac{H_1}{H}\right). \end{aligned} \quad (3)$$

2.3. Upper Bound Theoretical Framework of Fissured Slopes Reinforced with Anchors. The upper bound approach of limit

analysis is used herein to analyze the stability of fissured slopes reinforced with one row of anchors, which provides a powerful mechanical tool for the stability analysis under the limit state. To solve slope stability problems, the use of limit analysis has almost exclusively concentrated on the kinematic theorem [4]; this is generally simpler to use than the static approach under certain assumptions [15].

Referring to Figure 1, the region ABCDA is represented as a rigid body rotating around the undefined center of rotation O with the soils below the log-spiral failure surface AD remaining at rest. Based on the UBLA, a slope will collapse if the rate of work done by external loads and body force exceeds the internal energy dissipation rate by soil cohesion. In this study, the work rate of the external force includes the work rate of gravity W_r , the work rate of the horizontal seismic force W_{Eh} , the vertical seismic force W_{Ev} , and the work rate of the axial force provided by anchor W_{anchor} . Note here that the work rate by the anchor is negative. The internal energy dissipation rate by soil cohesion D only takes place along the sliding surface in the present consideration.

According to the work of Chen [4] and Figure 1, the rate of external work for sliding region ABCDA, W_r , can be calculated as the work of region ABC' minus the work of region CDC'. Hence, the external work rate due to soil weight takes the form

$$W_r = \gamma r_0^3 \omega (f_1 - f_2 - f_3 - f_4 + f_5 + f_6), \quad (4)$$

where γ is the unit weight of soil mass and f_1 – f_6 are dimensionless expressions depending on the parameters θ_0 , θ_h , θ_d , and β .

$$\left\{ \begin{aligned} f_1 &= \frac{\exp[3\psi(\theta_h - \theta_0)](3\psi \cos \theta_h + \sin \theta_h) - 3\psi \cos \theta_0 - \sin \theta_0}{3(1 + 9\psi^2)}, \\ f_2 &= \frac{\sin \theta_0 (2 \cos \theta_0 - L_{1r})}{6} L_{1r}, \\ f_3 &= \frac{\{\cos \theta_0 + \exp[(\theta_h - \theta_0)\psi] \cos \theta_h - L_{1r}\} [\sin(\theta_h - \theta_0) - L_{1r} \sin \theta_h] \exp[(\theta_h - \theta_0)\psi]}{6}, \\ f_4 &= \frac{\exp[(\theta_d - \theta_0)\psi] (3\psi \cos \theta_h + \sin \theta_d) - 3\psi \cos \theta_0 - \sin \theta_0}{3(1 + 9\psi^2)}, \\ f_5 &= \frac{\sin \theta_0 (2 \cos \theta_0 - L_{2r})}{6} L_{2r}, \\ f_6 &= \frac{\exp[2(\theta_h - \theta_0)\psi] \{\exp[(\theta_d - \theta_0)\psi] \sin \theta_d - \sin \theta_0\}}{3} \cos^2 \theta_d. \end{aligned} \right. \quad (5)$$

The horizontal and vertical pseudostatic forces are under consideration when calculating the rate of the seismic action, which is similar to that for determining the work rate of the external force due to the soil weight. A horizontal seismic acceleration coefficient, K_h , and a vertical one, K_v ($K_v = \lambda K_h$), are presented here. The directions of earthquake accelerations are not constant in most real situations [12]. The value of λ positive indicates vertical downward acceleration, whereas a negative value indicates vertical upward

acceleration. The rate of external work attributing to vertical and horizontal pseudostatic forces can be expressed as

$$\begin{cases} W_{ev} = \lambda K_h \gamma r_0^3 \omega (f_1 - f_2 - f_3 - f_4 + f_5 + f_6), \\ W_{eh} = K_h \gamma r_0^3 \omega (f_7 - f_8 - f_9 - f_{10} + f_{11} + f_{12}), \end{cases} \quad (6)$$

where

$$\begin{cases} f_7 = \frac{\exp[3\psi(\theta_h - \theta_0)](3\psi \sin \theta_h + \cos \theta_h) - 3\psi \sin \theta_0 - \cos \theta_0}{3(1 + 9\psi^2)}, \\ f_8 = \frac{\sin^2 \theta_0}{3} L_{1r}, \\ f_9 = \frac{\{\sin \theta_0 + \exp[(\theta_h - \theta_0)\psi] \sin \theta_h\} [\sin(\theta_h - \theta_0) - L_{1r} \sin \theta_h] \exp[(\theta_h - \theta_0)\psi]}{6}, \\ f_{10} = \frac{\exp[3\psi(\theta_d - \theta_0)](3\psi \sin \theta_d + \cos \theta_d) - 3\psi \sin \theta_0 - \cos \theta_0}{3(1 + 9\psi^2)}, \\ f_{11} = \frac{\sin^2 \theta_0}{3} L_{2r}, \\ f_{12} = \frac{(\exp[(\theta_h - \theta_0)\psi] \sin \theta_d - \sin \theta_0) \cos \theta_d}{6} H_r. \end{cases} \quad (7)$$

To account for the reinforced effect of a row of anchors on the fissured slope, an axial force is considered to be applied to the soil sliding mass. According to the existing research by Li et al. [15], the axial force developing in anchor is due to the Earth pressure exerted against the structural facing of the bearing plates or the concrete pad to which the anchors are connected and prestressed, and the reinforcement mechanism consists of transferring the resisting tensile force of anchor to the slope structural facing. Thus, the work

rate of the axial force provided by the anchor can be written as

$$W_{\text{anchor}} = T r_F \omega \cos\left(\frac{\pi}{2} - \theta_T + \alpha\right), \quad (8)$$

where T is the axial force exerted on the per unit width of sliding mass by the anchors and r_F is the distance between the anchor head and the rotation center O . According to the studies of Zhao et al. [28] and Figure 1, the tensile force of anchor acts on the point F ; thus, the value of r_F is

$$r_F = \sqrt{\{r_0 \exp[(\theta_h - \theta_0)\psi] \sin \theta_h - X_E \tan \beta\}^2 + \{r_0 \exp[(\theta_h - \theta_0)\psi] \cos \theta_h - X_E\}^2}. \quad (9)$$

In equation (8), the parameter θ_T is the angle which specifies the relative position of the anchor head and the rotation center, and the parameter α is the angle between the anchor and the horizontal.

Note that the crack prior exists at the top of the slope, which indicates that there is no internal dissipation of energy along the crack. Thus, the energy is just dissipated internally along the failure surface AD , which is found by multiplying the differential area $rd\theta/\cos\varphi$ by c times the discontinuity in

$v \cos \varphi$, and the total internal dissipation rate of energy D can then be calculated as follows:

$$D = \int_{\theta_c}^{\theta_h} c_m (v \cos \varphi) \frac{rd\theta}{\cos \varphi} = c_m r_0^2 \omega f_d, \quad (10)$$

where f_d is a function involving the parameters θ_0 , θ_h , and θ_d .

$$f_d = \frac{\exp[2(\theta_h - \theta_0)\psi] - \exp[2(\theta_d - \theta_0)\psi]}{2\psi}. \quad (11)$$

Based on the failure mechanism and the UBLA mentioned above, the fissured slope stability reinforced with anchors can be addressed by the work-energy balance equation, which is defined as equating the external rate of work to the rate of internal energy dissipation. Expression of the rate of external work due to the soil weight W_r , the horizontal seismic force W_{Eh} , the vertical seismic force W_{Ev} ,

the axial force provided by anchor W_{anchor} , and the rate of internal energy dissipation D can be obtained as follows:

$$W_r + W_{ev} + W_{eh} = D + W_{\text{anchor}} \quad (12)$$

Submitting equations (4)–(11) into equation (12) gives the normalized anchor axial force T_f/rH^2 for the fissured slope under seismic conditions:

$$\frac{T_f}{rH^2} = \frac{(1 + \lambda K_h)(f_1 - f_2 - f_3 - f_4 + f_5 + f_6) + K_h(f_7 - f_8 - f_9 - f_{10} + f_{11} + f_{12})}{H_r^2 \cos((\pi/2) - \theta_T + \alpha) f_p} - \frac{(c/rHF_s)f_p H_r}{H_r^2 \cos((\pi/2) - \theta_T + \alpha) f_p}, \quad (13)$$

where

$$f_p = \sqrt{\exp[2(\theta_h - \theta_0)\psi] \left[1 - 2\left(\frac{X_E}{r_0}\right)(\tan \beta \sin \theta_h - \cos \theta_h) \right] + \sec^2 \beta \left(\frac{X_E}{r_0}\right)}. \quad (14)$$

Referring to equation (13), for fissured slopes reinforced with anchors subjected to seismic action, a dimensionless

parameter $c/\gamma HF_s$ is introduced here to calculate the slope safety factor F_s :

$$\frac{c}{rHF_s} = \frac{(1 + \lambda K_h)(f_1 - f_2 - f_3 - f_4 + f_5 + f_6) + K_h(f_7 - f_8 - f_9 - f_{10} + f_{11} + f_{12})}{f_d H_r} - \frac{(T_{fk}/rH^2)f_p H_r^2 \cos((\pi/2) - \theta_T + \alpha)}{f_d H_r}. \quad (15)$$

In equations (13) and (15), the expressions of both T_f and T_{fk} correspond to the axial force of anchor, but their meanings used are different: the former is unknown and can be defined as the required value, whereas the latter is given to evaluate the stability of the fissured slope. Moreover, considering the parameters f_1 – f_{12} all including F_s , an implicit function method is used to solve equation (15) to obtain the safety factor F_s .

By means of the mathematical optimization method, the minimum of $T_f/rH^2 = f_1(\theta_0, \theta_h, \theta_d, \theta_T, \varphi, \alpha, \beta, \lambda, K_h, X_E)$ and $c/\gamma HF_s = f_2(\theta_0, \theta_h, \theta_d, \theta_T, \varphi, \alpha, \beta, \lambda, K_h, X_E)$ over the two geometrical variables θ_0 and θ_h provides the best upper bound solution.

3. Results and Discussion

In this section, to demonstrate the application of the method used, an idealized dry homogeneous slope example formerly examined by Cai and Ugai [37] is considered: a slope with height $H = 8.0$ m, slope angle $\beta = 45^\circ$, and $\gamma = 20$ kN/m³. The frictional cohesive soil properties $\varphi = 20^\circ$ and $c = 12$ kPa. One row of grouted anchors is arranged and has the initial design parameters $X_E = 4.0$ m, $\alpha = 15^\circ$, and $T_{fk} = 40$ kN/m.

3.1. Verification. To validate the proposed analytical approach, two cases are illustrated to verify the reasonableness of the obtained solutions on slope stabilization. In Case 1, the arrangements X_E of anchor cables range from 2.0 m to 6.0 m with the increments of 1.0 m. In this case, the parameter α is taken as 15° , and $T_{fk} = 40$ kN/m. The calculated solutions of the factor of safety F_s can be compared with results given by Deng et al. [16], as shown in Table 1. When different X_E values are considered in anchor-reinforced slope analysis, it should be noted that the upper bound solutions proposed in this study are consistent with the simplified Bishop method and the LE method results of Deng et al. [16], with the maximum difference being less than 0.5%. In Case 2, the orientation angle α of anchor cables increases from 0 to 45° with an interval of 7.5° . In this case, the parameter X_E is taken as 4.0 m, and $T_f = 40$ kN/m. Li et al. [15] introduced the safety factors calculated by limit analysis and that by SLOPE/W. As can be seen in Figure 2, the trends of the three results are the same. In addition, the dotted blue lines, which represent the results of this study, are in good agreement with the solid lines, representing the results by limit analysis of Li et al. [15].

The two comparisons prove that the results derived from this study are reasonable for evaluating the stability of the

TABLE 1: Comparison of the slope safety factor F_S with different arrangements X_E of anchor cables.

X_E (m)	F_S		
	Simplified Bishop method [16]	LE method [16]	This study
2.0	1.246	1.243	1.249
3.0	1.226	1.225	1.230
4.0	1.206	1.209	1.213
5.0	1.185	1.194	1.195
6.0	1.164	1.179	1.176

FIGURE 2: Comparison of the slope safety factor F_S with different orientation angle α of anchor cables.

fissured slopes reinforced with anchor cables subjected to seismic action.

3.2. Determination of the Critical Location of Crack. With the same arrangement of anchor (i.e., $X_E/H = 0.5$), through the computations, the critical location of crack can be determined, as shown in Figure 3. The normalized location of the crack L/H is plotted against the normalized depth of crack H_1/H for $\lambda = -0.5, 0.5$ and $K_h = 0.1, 0.3$, and the required safety factor F_S ranges from 1.2 to 1.6 with increments of 0.2. As shown in Figure 3, the critical crack location L/H decreases obviously with the increase in the depth of crack H_1/H . It also can be seen that the higher the required safety factor of the slope F_S is, the greater the value L/H will be, which means the farther the crack location is from the edge of the slope. Comparing Figures 3(a) with 3(b), it can be found that the critical crack location L/H increases with K_h increasing. However, the critical crack location L/H decreases with λ increasing. It implies that, with an increase in the horizontal seismic acceleration and with a decrease in the

vertical seismic acceleration, the critical location of the crack becomes deeper.

3.3. Determination of the Axial Force of Anchor Cables. Considering the effect of the crack depth H_1/H on the designed stabilizing axial force of anchor cables, Figure 4 presents the changes in the normalized anchor axial force T_f/rH^2 for various case parameters. According to Terzaghi Theoretical Soil Mechanics [38], the depth of cracks was no more than half of the height of the slope where the slope angle is 90° , which was also applied to slope whose angle is less than 90° . Cousins [39] also obtained the same finding as above when the slope was under anhydrous conditions. Thus, herein set the depth of crack H_1/H ranges from 0 to 0.5. It can be seen in each chart that the variation of the crack depth has little influence on the axial force of anchor cables. The curve is approximately symmetric in the range of $H_1/H = 0-0.5$, and the maximum axial force of anchor cables is distributed in the range of $H_1/H = 0.2-0.3$, which is illustrated by dotted lines delimiting an area of Figures 4(a) and 4(b). It is quite surprising that the difference between the maximum and minimum axial force of anchor cables is less than 10%. Besides, the charts in Figure 4 are suitable for designing the axial force of anchor cables for a fissured slope with certain safety requirements. Moreover, it is noted that the normalized axial force of anchor cables T_f/rH^2 increases with λ and K_h increasing. This is because the increase in the horizontal seismic force coefficient and the vertical downward seismic force direction will aggravate the fissured slope failure. So more anchor axial force of anchor cables is needed to stabilize the fissured slope.

Figure 5 shows the relation between the designed stabilizing axial force of anchor cables and the arrangement of anchor (i.e., $X_E/H = 0.3-0.8$) for different seismic conditions, and the dashed line indicates the slope with crack (i.e., $H_1/H = 0.2$). From Figure 5, it is noted that the designed stabilizing axial force of anchor cables T_f/rH^2 increases as the normalized arrangement of anchor X_E/H increases. When $X_E/H = 0.3$, the designed stabilizing anchor axial force of the slope with crack is close to that of the slope without crack. But with the increase in the value of X_E/H , the gap between the required anchor axial force of the slope with crack and without crack becomes larger. What is noteworthy is that the solid line of the slope without crack does not exist at $\lambda = -0.5$ and $F_S = 1.1$ in Figures 5(c)-5(d). These are reasonable because when the direction of seismic force is vertical upward, the slope without crack may reach the safety factor $F_S = 1.1$ without the need for anchor cables. However, the slope tends to be unstable when the seismic force is vertically downward, and the anchor cables are required for slope under the same safety factor.

To investigate the impact of the variability of anchor inclination angle on the designed stabilizing axial force of anchor cables, four different cases are also adopted. The results of the designed stabilizing axial force of anchor cables T_f/rH^2 vary with the anchor inclination angle α under seismic action which are shown in Figure 6. It can be concluded that as the anchor inclination angle α increases,

FIGURE 3: Critical location of the cracks for fissured slopes reinforced with anchor cables: (a) $\lambda = 0.5$; (b) $\lambda = -0.5$. FIGURE 4: Effect of crack depth H_1/H on designed stabilizing axial force of anchor cables: (a) $\lambda = 0.5$; (b) $\lambda = -0.5$.

FIGURE 5: Effect of the arrangement of anchor X_E/H on designed stabilizing axial force of anchor cables: (a) $\lambda = 0.5$ and $K_h = 0.1$; (b) $\lambda = 0.5$ and $K_h = 0.3$; (c) $\lambda = -0.5$ and $K_h = 0.1$; (d) $\lambda = -0.5$ and $K_h = 0.3$.

the designed stabilizing axial force of anchor cables T_f/rH^2 increases. When the angle α is less than 20° and the required slope safety factor F_S is less than 1.2, the increase in the amplitude of anchor axial force is small, but when the angle α is more than 20° and the required slope safety factor F_S exceeds 1.2, the designed stabilizing axial force of anchor cables increases rapidly. It also can be seen from Figure 6 that, under the same safety factor, the designed stabilizing

anchor axial force of the fissured slope (i.e., $H_1/H = 0.2$) is significantly greater than that of the slope without cracks, which is consistent with the phenomenon in Figure 5. Meanwhile, the slope which has no crack may reach the safety factor $F_S = 1.1$ without the requirement for anchor cables which is clearly shown in Figures 6(c) and 6(d).

To better illustrate the effect of slope angle on the anchor supporting the fissured slope, the relationship between the

FIGURE 6: Effect of the inclination angle of anchor α on designed stabilizing axial force of anchor cables: (a) $\lambda = 0.5$ and $K_h = 0.1$; (b) $\lambda = 0.5$ and $K_h = 0.3$; (c) $\lambda = -0.5$ and $K_h = 0.1$; (d) $\lambda = -0.5$ and $K_h = 0.3$.

axial force provided by anchor cables under seismic loading and the different slope angle β is plotted in Figure 7. As can be seen, a larger axial force is required when the slope angle β increases; especially when the slope angle exceeds 55° , the designed anchor cable axial force T_f/rH^2 increases rapidly. This means that the slope angle increase will increase the possibility of the slope collapse. Thus, the more axial force of anchor cables can be applied to maintain slope stability. It also can be seen from Figure 7 that anchor cable supporting is not always required for fissured slope at any angle β . Instead, the angle β should reach a certain value. For example, for a fissured slope seismic condition of $\lambda = -0.5$ and $K_h = 0.1$ and the required safety factor $F_s = 1.2$, the anchor cables are required to play their role when the slope angle

$\beta = 40^\circ$. Furthermore, with the increase of angle β , the gap of anchor axial force between the fissured slope and no crack slope is larger, which indicates that the steeper the fissured slope is, the more dangerous it is.

To completely study the impact of seismic conditions on the stability of the fissured slope, Figures 8(a) and 8(b) present the different values of T_f/rH^2 by taking the seismic coefficient (i.e., K_h and λ) as the x -coordinate. Considering slope with different required safety factors F_s ($F_s = 1.2, 1.4$, and 1.6) and slope with and without crack conditions, three pairs of variation lines are obtained in each figure. In Figure 8, the designed anchor cable axial force T_f/rH^2 increases linearly with an increase in the horizontal seismic acceleration coefficient K_h . It also can be seen that

FIGURE 7: Effect of the slope angle β on designed stabilizing axial force of anchor cables: (a) $\lambda = 0.5$ and $K_h = 0.1$; (b) $\lambda = 0.5$ and $K_h = 0.3$; (c) $\lambda = -0.5$ and $K_h = 0.1$; (d) $\lambda = -0.5$ and $K_h = 0.3$.

the value T_f/rH^2 increases linearly as the seismic coefficient λ ($\lambda = K_v/K_h$) increases, which indicates that a fissured slope under vertical downward seismic acceleration is more dangerous than that under vertical upward seismic acceleration. This further confirms the results in Figures 4–7 about the influence of seismic condition on the anchor axial force.

3.4. Determination of the Required Critical Length of Free Section of Anchor Cables.

In order to ensure the stability of

the fissured slope, the anchoring section of anchor cables needs to fully enter the sliding bed. Thus, it is important to determine the required critical length of the free section of anchor cables. Figure 9 investigates the influence of the arrangement of anchor X_E/H on the required critical length of free section of anchor cables L_{EF}/H for the slope with and without cracks. An interesting phenomenon shows that when the anchor is in front of a specific position, the required critical length of the free section of anchor cables will increase with the increase of the depth of the slope crack. But beyond this position, the opposite phenomenon will occur,

FIGURE 8: Effect of seismic conditions on designed stabilizing axial force of anchor cables: (a) $K_h = 0 \sim 0.3$; (b) $\lambda = -0.5 \sim 0.5$.

FIGURE 9: Continued.

FIGURE 9: Effect of the arrangement of anchor X_E/H on the required critical length of free section of anchor cables L_{EF}/H : (a) $\lambda = 0.5$ and $K_h = 0.1$; (b) $\lambda = 0.5$ and $K_h = 0.3$; (c) $\lambda = -0.5$ and $K_h = 0.1$; (d) $\lambda = -0.5$ and $K_h = 0.3$.

and the increase in the crack depth will lead to a decrease in the required critical length of the free section of anchor cables. For example, in Figure 9(a) where $\lambda = 0.5$, $K_h = 0.1$, and $F_s = 1.2$, the specific position of anchor $X_E/H = 0.47$, and in Figure 9(b) where $\lambda = 0.5$, $K_h = 0.3$, and $F_s = 1.2$, the specific position of anchor $X_E/H = 0.4$. The possible reason for this phenomenon is that, with the increase of crack depth, the location of the crack is close to the edge of the slope, as shown in Figure 3, resulting in changes in the critical slip surface. It is also observed from Figure 9 that, under the same depth of the crack, the greater the safety factor, the larger the required critical length of free section of anchor cables and the smaller the specific position of the anchor cables. In addition, the values of K_h have considerable influence on the required critical length of the free section of anchor cables, but the values of λ have little influence on it.

4. Conclusions

The UBLA combined with the pseudostatic method is applied to investigate the stability of fissured slopes under seismic load reinforced with anchor cables. An existing simple example is that a homogeneous slope reinforced with anchors is presented in this work as a case study. Based on a rotational failure mechanism and a numerical optimization procedure, the proposed method is adopted to obtain the critical location of the crack. Then, to better stabilize the fissured slope, five factors (i.e., crack depth, H_1/H , anchor arrangement, X_E/H , anchor inclination angle, α , slope angle, β , and seismic conditions, K_h and λ) are considered to determine the axial force of anchor cables. Moreover, the

required critical length of the free section of anchor cables is determined to ensure the stability of the fissured slope. Besides, based on the results of parametric studies, the following conclusions can be drawn:

- (1) The critical location of crack L/H increases (i.e., the crack is away from the edge of the slope) as the required safety factor of the slope F_s and the horizontal seismic acceleration coefficient K_h increases, but it decreases with increases in the depth of crack H_1/H and the vertical seismic acceleration K_v ($K_v = \lambda K_h$).
- (2) The variation of the crack depth has little effect on the axial force of anchor cables. It is found from Figures 4–8 that the normalized axial force of anchor cables T_f/rH^2 increases with λ and K_h increasing, which implies that more anchor axial force of anchor cables is needed to stabilize the fissured slope, due to the fact that the increase of the horizontal seismic force coefficient and the vertical downward seismic force direction aggravate the fissured slope failure. It is also undoubted that the higher the required safety factor of the slope F_s is, the greater the axial force of the anchor cables T_f is. Moreover, an increase in the arrangement of anchor X_E , the anchor inclination angle α , and the slope angle β could result in a greater axial force of anchor cables which is more needed to stabilize the fissured slope under seismic conditions.
- (3) When the arrangement of anchor X_E is in front of a specific position, the required critical length of the free section of anchor cables L_{EF} will increase with the increase of the depth of crack H_1 . However, when

the arrangement of the anchor is beyond this position, L_{EF} shows an opposite tendency. In addition, the horizontal seismic acceleration coefficient K_h has considerable influence on the required critical length of free section of anchor cables L_{EF} , but the seismic coefficient λ has little influence on it.

Data Availability

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

Conflicts of Interest

The authors declare that there are no conflicts of interest related to this paper.

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