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Stability analysis considering the distribution and strength of the fissures for expansive soil slope

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SUMMARY: Fissure is the key factor to affect the stability of the slope. Usually, the expansive soil slope with fissure structure is regarded as homogeneous. The effect of fissures is reflected by decreasing the strength parameters. This cannot be objective to reflect the characteristics of expansive soil fissures. To complement the limitations, a method is found that take the slope as a combination of homogeneous soil, fissures with filling soils and tension fissures. Based on the investigation of a large number of landslides in China, take the spatial information such as height, angle, thickness and length of typical controlling fissure obtained from the site survey into the slope model, mainly including the vertical fissures in the surface soil and the filling fissures of clay minerals in the slope, to establish the geometric model of slope. Then, on the basis of triaxial tests and field large direct shear tests, take the strength parameters of the expansive soil and the fissure surface into account, establish a geological model of expansive soil slope with real fissures. Equilibrium methods in program Slide, which meet compartmentalization between the forces and torque balance and are suitable for line slide surface are chosen as the methods of slope stability analysis. A stability analysis is done to the landslide on the South-to-North Water Transfer Project to find out the influence of fissure to expansive soil slope stability and its law. The results show that, when considering the vertical fissures, groundwater and low angle large fissures at toe of the slope, safety factor falls significantly, slide surface which made of vertical fissure at slope top and slip surface developed from the bottom of the vertical fissures to the slope foot, assume a broken line form, and its failure characteristics is basically the same as that of actual landslide.

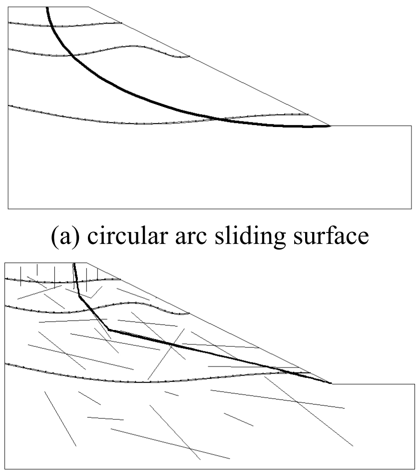
KEYWORDS: expansive soil, slope, fissure, stability analysis, sliding surface.

1 INTRODUCTION

The calculation method of the slope stability of the expansive soil is adopted as the method of the common clay slope(Zheng, et al. 2014; Yao, et al. 2012; Zheng, et al. 2005). However, many engineering practice shows that the stability of expansive soil slope is different from that of conventional clay slope, for many gradual slopes, if calculated through the conventional slope stability analysis method, they should be absolutely stable, but in fact the landslides happened(Cheng, et al. 2011). The expansive soil slopes in Nanyang area still slide under the slope ratio of 1:6 to1:5, and many landslide of soft expansive rock occurs under the extremely smooth slope of 8 degrees to 9 degrees. These engineering examples show that there are still many shortcomings when the conventional clay slope stability analysis method is applied to the stability analysis of expansive soil slope(Hou, et al. 2013; Oh, et al. 2015).

Most of the expansive soil slopes with fissures are regarded as homogeneous in conventional slope stability analysis method. Strength parameters are obtained from the laboratory or in situ tests in calculation, they will be considered for the overall strength parameters of the slope soil, on the basis of this, by reducing the size of the strength parameters to reflect the effect of the fissures(Ito, et al. 2013; Peng, et al. 2014), and using limit equilibrium method for slope stability analysis. The sliding surface of slope gotten by the method is often in the shape of a circular arc (see Figure 1a). However, after investigation of 19 excavated channel landslide in Nanyang section of the South to North Water Transfer Project, we found that landslides are controlled by all kinds of fissures, the trailing edge of the sliding surface is mainly controlled by the vertical fissures in the soil and the lower part of the sliding surface is controlled by the low angle large fissures, and the surface morphology was broken line (see Figure 1b). Therefore, the conventional method in the analysis of the stability of the expansive soil fissure slope often has a discrepancy to the actual conditions.

The reason causing the distortion of the method is that, through strength attenuation to reflect the effect of fissures on the slope stability, using a single, homogeneous soil for calculation, cannot objectively reflect the fissures characteristics, especially not take the fissure spatial distribution information and fissure surface intensity into the computational considerations, cannot reflect that the fissures would constitute the potential sliding surface. Even if the strength parameters used in the calculation is the lowest strength on the fracture surface, for the actual slope, it is correct only when the slip surface is located on the fracture surface, but the reality often cannot meet these conditions, resulted in the selection of parameters is too small. And if without considering these fissures, cannot reflect the fissure effect on the stability of the slope, resulting in the calculation parameter and safety factor are too large. In addition, because of the effect of the fissures, the strengths of the samples obtained from the same spot often have significantly discreteness, and there is no single soil strength index. Therefore, it is necessary to put forward a method that can reflect the influence of the fissures, and the calculation condition is close to the real state of the expansive soil slope.



(a) circular arc sliding surface

(b) broken line sliding surface

Figure 1. Conventional generalized sliding model and actual sliding model of expansive soil slope

2 A GENERALIZED MODEL AND ANALYSIS METHOD FOR FISSURE SPATIAL INFORMATION AND INTENSITY

2.1 Fissures of expansive soil slope

The fissure is one of the most typical engineering geological characteristics of expansive soil(Yuan, et al. 2004; Abdullah, et al. 2010; Okasha, et al. 1992; Du, et al. 1999). Expansive soil contains lots of hydrophilic clay minerals, its swelling and shrinkage effect is obvious. In repeated cycles of wetting and drying conditions, a lot of cross fissure formed in soil, coupled with the tectonic fissures and unloading fissures caused by structural factors and stress unloading, ultimately resulting in the expansive soil slope macro morphology of fissure covered. These fissures can be divided into two categories according to their morphology, distribution characteristics and formation, one is the shallow expansion fissure within the scope of weathering effect, the other one is the deep lager fissure.

Fissure is the key factor to affect the stability of expansive soil slope(Li, et al. 2012; Estabragh, et al. 2013). Fissure gives the special structural to expansive soil, destroys the integrity of the soil, lead to difficulties in the soil strength test and evaluation. In addition, due to uneven and random of the fissure, the expansion soil strength is anisotropic, and fissure and filling interlayer has an important impact on expansive soil slope stability. The deep sliding failure which is most serious and in expansive soil slope stability is mainly caused by the open, development, linking of large fissures in the internal slope, and also the soil swelling deformation caused by the moisture migration and infiltration. Because this kind of landslide is controlled by fracture surface, it usually has an obvious sliding surface.

2.2 Vertical fracture in surface soil

Due to the long-term, periodic wetting and drying cycles, there are vertical fissure layers on the top of the expansive soil slope surface (see Figure 2).

Figure 2. Vertical fissures of surface soil

Usually the soil fissures in this layer are closed, after the excavation of the slope, they open due to the loss of lateral support. On the macro level, the soil layer is a collection of vertical soil columns that lose the integrity, when the slope is very steep, or the middle and the lower part of the slope soak in water to soften, due to the underlying support strength is reduced, the layer of vertical fissures development is more significant. When the underground water level is high, or after a long time rain, these fissures will be filled with water, and generate hydrostatic pressure. Therefore, in the slope stability analysis, slope top has the granular clods with a certain thickness, this layer is only provide the slide force on the slope, but cannot provide the anti-sliding force. It can be found in the actual slope failure that the vertical fissures in this layer often constitute the trailing edge of the sliding surface, and the slope in this layer has a large vertical deformation. Therefore, in order to reflect the actual conditions, this layer should be taken into consideration.

In this paper, the soil layer is considered as a vertical cross layer of soil columns and thin layer fissure from a certain depth h below the surface. Under anhydrous conditions, it can be taken into account the soil weight loading on the slope. When there is ground water or rain, it is necessary to consider the hydrostatic pressure.

2.3 Filling fissures of clay minerals in the lower part of the slope

Tectonic fissures or preexisting fissures mainly are inner surface of the soil and shrinkage fissures in the diagenesis, including bedding, level, unconformity surface and preexisting fissures surface. In expansive soil site survey, we see very smooth with waxy luster fissures, filling with gray green clay mineral or black iron manganese (see Figure 3). These fissures is results of soil repeated creep to the cell shrinkage center or the opposite direction under expansion in the deposition process, due to the creep has the effects of sorting and rounding of soil granules, the fissure surfaces often are smooth and with waxy luster, and is the natural weak plane in the soil. Moreover, this kind of fissures is often the active region of water movement because of the special force and deformation features, the soils are gray and gray green under eluviation. These weak planes have extensive range, it has significant impact on the stability of the slope when such filling fissures develop in slope foot and central slope and the trend is the same with the slope. A large number of landslide survey data show that the leading edge of expansive soil landslide cut out in such fissures, constitute the inferior edge of the sliding surface. Take these fissures into the analysis process of slope stability has very important significance to predict the sliding surface shape and reflect the actual stress state of the slope.

Figure 3. Fissures filling with clay minerals

In this paper, based on the slope fissure geological survey, by means of excavating geological profiles and trenches, record the fissures extended long or contained fillings, get the trend, dip angle, height and filling information. The distribution characteristics of the fissures and the trend and the direction of the channel are combined deal with the rose graph and the extreme projection. Select all fissures having the same trend with the slope as dangerous fissures, using analytic geometry method, combined with the actual survey results to make appropriate treatment to the extending length and thickness of the fissures, and convert the spatial information to model coordinates, according to the real space distribution, put fissures into slope geometry model.

2.4 Slope geometry model

According to the actual channel, the 2D geometry model of the slope is established. In principle, the range of the model is determined according to the significant influence of soil stress redistribution caused by excavation. Calculation range in vertical direction is from the surface to the depth below the channel bottom 0.5 to 1.0 times of excavation depth, and in horizontal direction, it is from the excavation boundary to the distance of the maximum excavation depth, calculating boundary are out of the influence range of excavation.

Through converting the vertical fissures and low angle large fissures into the thin layer elements in the model and considering the strength and the mechanical parameters of those thin layer elements, to reflect the influence of fissures on the slope stability. The thicknesses of the thin layers are selected as the average thickness of the measured fissures, which are generally 3~8cm. Therefore, the generalization of the fissures space information is in the following way.

Firstly, the slope surface equation is established in the plane coordinate system.

$$y = ax + b, x \in (m, n) \qquad (1)$$

For the fissure distributing in elevation *h*, the dip angle is θ, the length is *l*, and the thickness is *t*, the coordinate of the end point in the slope surface is $[(h-b)/a, h]$. In the model, the fissure is simplified to a linear form, and the equation can be expressed as a linear equation.

$$y = \tan\theta(x - \frac{h-b}{a}) + h,\ x \in (\frac{l}{\sqrt{1+\tan^2\theta}} + \frac{h-b}{a}, \frac{h-b}{a}) \qquad (2)$$

Translate the fissure equation upward fissure thickness *t*, and intersection with the slope equation, get the four vertex coordinates of the parallelogram fissure, put the coordinates into the slope model, and deal with the vertical fissures within a certain range below the surface, so as to establish the geometry model.

2.5 Slope geological model

Based on the geometry model of the slope, the geometric elements in the model are related to the geological features, and the strength values are given, constructing the geological model of the generalized fissured slope.

The selection of soil parameters directly affects the rationality of stability analysis and the results. The strength parameters are divided into soil strength parameters and fissure surface strength parameters, which are gotten mainly through indoor direct shear and triaxial test. At the same time, in order to consider the size effect and disturbance, the in-situ shear tests are carried out. The parameters of soil and fissures are determined by the comprehensive analysis of the results of laboratory and field tests.

3 GEOLOGICAL FEATURES OF TYPICAL LANDSLIDE

3.1 Engineering geological survey of the landslide

The landslide in Nanyang section of the middle route of the South to North Water Transfer Project is selected as an example to analyze the slope stability.

The landslide is located in the medium expansive soil area, the original canal slope ratio is 1:2, the crest elevation of left bank of the canal slope is 142.695m, and the slope bottom elevation is 135.384m. The low-lying area is conducive to rainfall collection, so the landslides scales are larger, damage are serious, especially on the left bank.

Nanyang TS109+200 left bank landslide formation is the Middle Pleistocene alluvial (Q_2^{al+pl}), the upper part soil of the landslide is reddish brown silty clay, the thickness is about three meters, and the lower part is brown silty clay, the content of calcium nodules and black iron manganese nodules are low.

The slip direction is 130 degrees, the total landslide length is about 138.48m. The trailing edge of the left bank landslide is substantially vertical, and the length is about 88.4m, near the left boundary, there is a large deformation, broken violently, scarp is high, the largest is up to 1.8m, near the right boundary ,the scattered height is 0.2 to 0.8m. Landslide cuts out along the inclined bedding in slope foot. The landslide profile is shown in Figure 4.

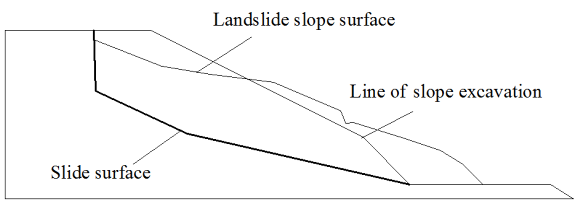


Figure 4. The landslide profile

3.2 Distribution of the landslide fissures

Geology windows are arranged on both sides of the slope and fissures are recorded. It is concluded that there are 105 fissures in the length of L>1.0m in the slope body. The development of the fissures in the slope has the following rules.

Fissures develop mainly in two groups: (1) trend of 120° to 140°, dip angle of 5° to 50°, along the slope, (2) trend of 310° to 325 °, dip angle of 3° to 60°, against the slope.

Fissures distribution has the following rules: steep dip angle fissures along the slope develop in the height of 135m of the slope, dip angle is 75° to 84°, and the fissure surfaces is flat and smooth, filling with gray-gray green clay. At the foot of the slope, low dip angle fissures along or against the slope develop, dip angle is 11° to 28°, and the fissure surfaces is flat and smooth, filling with gray green clay.

To measure the fissures length is greater than 2.0m, in a total of 26, their occurrences characteristics are shown in Table 1.

4 SLOPE GENERALIZATION AND ITS STABILITY ANALYSIS

4.1 The calculation model

The stability analysis of slope is carried out by using the platform Slide from Rocscience. Slide is the two-dimensional limit equilibrium process developed by Rocscience company for the evaluation of the rock and soil slope safety coefficient or failure probability, slide surface can be circular or non-circular form. Calculation method is the limit equilibrium analysis based on the vertical slice method (such as Bishop, Janbu, Spencer). In the calculation, three limit equilibrium methods such as Janbu correction, Spencer and Morgenstern, which can meet inter slice force and moment equilibrium and are suitable for broken line slide surface, are chosen for slope stability calculation.

Take the landslide in Nanyang section TS109 of the middle route of the South to North Water Transfer Project as an example, the slope is

Table 1. Statistical table of typical landslide fissure information

Number	Trend (°)	Dip angle (°)	Length (m)	Elevation (m)	Number	Trend (°)	Dip angle (°)	Length (m)	Elevation (m)
L1	84	17	2.0	134.4	L26	164	81	2.2	136.9
L3	332	11	2.2	134.3	L27	250	80	2.0	136.9
L6	238	23	2.1	134.6	L28	210	36	2.0	138.3
L10	297	20	2.2	134.8	L29	245	23	2.0	138.3
L11	121	15	2.0	135.4	L30	150	16	2.0	137.9
L14	203	46	2.3	135.8	L31	128	44	2.0	137.7
L15	67	27	2.1	135.5	L32	52	28	2.0	138.3
L16	35	34	2.2	134.4	L33	42	16	2.1	138.8
L17	185	25	2.1	135.7	L34	196	75	2.3	138.8
L19	168	42	2.3	136.3	L35	142	50	2.0	138.3
L20	225	44	2.5	136.3	L36	75	10	2.0	138.8
L22	220	36	2.3	136.5	L37	195	42	2.0	138.9
L23	163	81	2.1	136.9	L38	125	17	2.0	140.8

10m high, the slope ratio is 1:2, horizontal and vertical boundary are respectively extended of 1.0 times the slope height of 10m. The surface is the stress boundary, the lower boundary is the full constraint boundary, due to the weight of soil, the left and right boundaries are taken as the constraint boundary in the direction perpendicular to the boundary plane, do not consider the influence of initial stress. Put the fissures in Table 1 into the model, and consider vertical fissures within 5m below the surface, fissures are generalized thin layers with thickness of 5cm, extending from the slope surface to slope body. The groundwater depth is 1m at the top of the slope, and 2m at the foot of the slope. Fissure morphology, distribution, quantity, and the distribution of groundwater are almost the same as the actual condition, to ensure the reliability of the calculation results, the calculation model is shown in Figure 5.

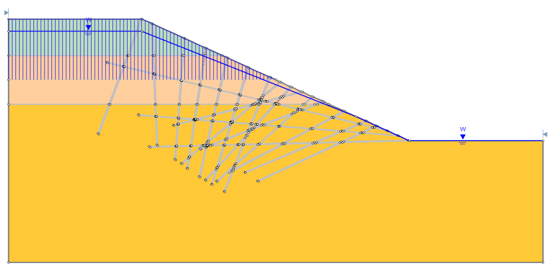


Figure 5. The calculation model of the slope

4.2 Calculation parameters of slope soil

The required slope strength parameters in calculation including soil strength parameters and fissure surface strength parameters. Soil parameters are obtained from the field and laboratory experiments, fissure strength parameters are obtained from triaxial test by putting some certain angle and thickness grey-grey green clay interlayers into the expansive soils. Strength parameters are confirmed in a comprehensive consideration of the tests data of the undisturbed soil and the soil with filling clays (see Table 2).

Table 2. Calculation parameters of slope soil

Location	c (kPa)	ϕ (°)
0 to 3 m	16	14
3 to 7 m	23	16
Below 7 m	23	17
Fissure surface	14	4

4.3 Analysis of slope stability

The stability analysis of the slope considers the following four conditions, H-homogeneous soil, T-vertical fissures in the top of the slope, W-groundwater, F-fissures with fillings. Thus, the slope can be divided into H (homogeneous soil), H+T (homogeneous soil + vertical fissures), H+T+W (homogeneous soil + vertical fissures + groundwater) and H+T+W+F (homogeneous soil + vertical fissures + groundwater + fissure fillings), from the ideal homogeneous slope gradually approximate to the actual working conditions of the slope, stability analysis is taken respectively on the different levels of generalization slope models, calculated safety factors of the slopes are shown in Table 3.

Table 3. Safety factors of the slopes

Working conditions	Safety factors			
	C1	C2	C3	C4
H	1.59	1.72	1.75	1.75
H+T	1.46	1.57	1.67	1.67
H+T+W	1.03	1.11	1.24	1.23
H+T+W+F	0.90	0.90	0.93	0.91

(C1- Janbu simplified; C2- Janbu corrected; C3- Spencer; C4-Gle/Morgenstern-price.)

It can be seen from the calculation results of the slope stability:

When only take the slope layer distribution characteristics into account, the safety factor of slope is more than 1, and floating within the scope of 1.59 to 1.75 because of the different analysis method, slope is safe and stability exist a greater safety margin.

Considering the slope soil layer distribution characteristics and the vertical fissures in the surface, the safety factor of the slope is greater than 1.0, and floating in the range of 1.46 to 1.67, compared to the situation only considering the layer distribution, there is a certain degree of decline, decline of about 4%, indicating that vertical fissures below the slope surface has certain influence on the slope stability, there are still a certain safety margin for the slope.

On the basis of the analysis of the last step, further, the groundwater distribution of the slope is brought into the model, It can be found, the safety factor of the slope is still larger than 1.0, about 1.03 to 1.24, but decrease significantly relative to the previous conditions, and about 25% lower. It shows that the existence of groundwater has a great influence on the stability of the whole slope. This is because, with the underground water level rise and fall, the soils around the water level line are in reciprocating cycle of wet and dry, because of the water, the soil will produce obvious wet expansion and dry shrinkage deformation, and form a large number of expansion and shrinkage fissures, on the other hand, in moisture conditions, shear strength attenuation effect is significant, both of these have adverse effects on expansive soil slope stability. According to the calculation results, the safety coefficient of slope at this time has been close to 1, which is the state of limit equilibrium.

In these three conditions, the most dangerous sliding surfaces are circular arc in whole or in part (see Figure 6). In consideration of the surface vertical fissures, the trailing edge of the most dangerous sliding surface develops from the arc to the vertical shape along the fissures. Sliding surface develops from the arc to the combined of the vertical fissures and the arc from its bottom extends to the foot of the slope.

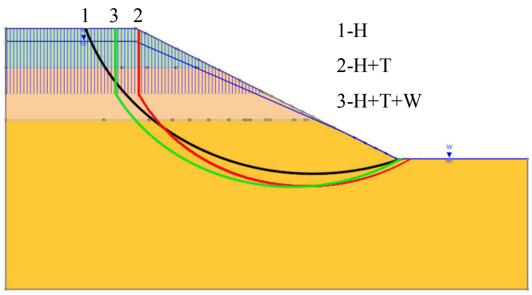


Figure 6. The most dangerous sliding surfaces under different working conditions

Based on the above analysis, finally take the typical fissures in the form of weak interlayer into the model to consider, calculate in a most authentic working condition. It can be found, according to the strength parameters, taking into account the layer distribution characteristics and surface vertical fissures, groundwater and the fissures in the slope, the safety factor of slope is less than 1.0, compared with previous calculations, which has the largest decline, about 26%. It shows the weak interlayers have the most significant influence on the stability of the whole slope. The slope is in unstable state in this situation, the most dangerous sliding surfaces are shown in Figure 7. The sliding surface is comprised of the vertical fissures in the top of the slope, and the straight line shaped sliding surface develop from the bottom of the vertical fissures to the foot of the slope, sliding surface was a broken line form, the shape of sliding surface formed by the influence of the vertical fissures and the low angle large fissures, which basically has the same characteristics with the actual landslides.

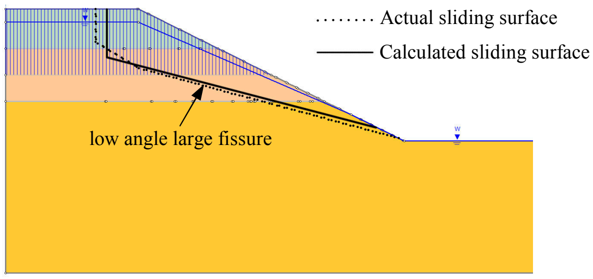


Figure 7. Calculate and actual sliding surface

5 CONCLUSIONS

To complement the limitations of existing expansive soil slope stability analysis method, Based on the investigation of a large number of landslides in the middle route of the South-to-North Water Transfer Project in China, take the spatial information such as height, angle, thickness and length of typical controlling fissure obtained from the site survey into the slope model, mainly including the vertical fissures in the surface soil and the filling fissures of clay minerals in the slope, establish the geometric model of slope.

On this basis, limit equilibrium methods, which can meet inter slice force and moment equilibrium and are suitable for broken line slide surface, are chosen for slope stability calculation. With the model closer to the real slope conditions, the stability of the slope is also getting closer to engineering practice. When considering the vertical fissure surface, groundwater and gentle-dipping fissure at toe of the slope, safety factor falls significantly, the safety factor of slope is less than 1.0, and the slope is in unstable state. Sliding surface which made of vertical fissure at slope top and slip surface developed from the bottom of the vertical fissures to the slope foot, assume a broken line form, and its failure characteristics is basically the same as that of actual landslide.

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