Landslide mechanism and strengthening analysis of cutting slopes in expansive soil areas in China

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Abstract: Being a special type of soil, expansive soil can be found in almost all countries. It is very easy to induce slips in superficial layers if cutting slopes have not been supported. The backscarp of the landslides, the scale of which is small, usually occur in the middle of the slopes, and seldom happen at the top of the slopes. The toe is usually arcuate in shape. To research the forming mechanisms of superficial slides in expansive soil, regional, numerical calculations are used to simulate the effects of cracks and fissures in superficial layers on the deformation of the slope. Meanwhile, a creep model of expansive soil slopes is analyzed. Based on a case study monitoring results, remediation methods are explained and compared. The results, together with the numerical analysis, indicate that superficial characteristics of the slides are caused by many cracks and fissures formed in the slope surface, and that frame beams can restrain expanding of cracks and fissures and effectively strengthen the cutting slopes in expansive soil.

Résumé: Étant un type spécial de sol, le sol expansible peut être trouvé dans presque tous les pays. Il est très facile d'induire des glissades dans des couches superficielles si coupant le démuni de pentes soutenu. Le backscarp des éboulements, dont l'échelle est petite, se produisent habituellement au milieu des pentes, et se produisent rarement au dessus des pentes. L'orteil est habituellement arqué dans la forme. Pour rechercher les mécanismes de formation des glissières superficielles dans le sol expansible, des calculs régionaux et numériques sont employés pour simuler les effets des fissures et des fissures dans des couches superficielles sur la déformation de la pente. En attendant, un modèle de fluage des pentes expansibles de sol est analysé. Basé sur une étude de cas surveillant des résultats, des méthodes de remédiation sont expliquées et comparées. Les résultats, ainsi que l'analyse numérique, indiquent que des caractéristiques superficielles des glissières sont provoquées par beaucoup de fissures et fissures formées dans la surface de pente, et que les faisceaux d'armature peuvent retenir l'extension des fissures et des fissures et efficacement renforcer les pentes de découpage dans le sol expansible.

Keywords: expansive soil, cut slope, landslide, forming mechanism, numerical simulation, FLAC 3D

INTRODUCTION

There are some particular kinds of soils formed due to complex geological processes. Being a special kind of clay, expansive soil can be found on almost all countries. It possesses such characteristics as swelling and shrinkage potential, cracking and over-consolidation, which endanger slope stability (Linchang Miao *et al.* 2002). Due to several drying-wetting cycles many cracks and fissures occur in the surface of the slope, which accelerates the failure of the slope. Its characteristic is small scale and shallow layer and with backscarp's occurring in the middle of the slope. According to the reports, the annual loss due to the damage caused by expansive soils is up to ¥100 million (10 million) in China. There is an urgent demand to improve our understanding of the fundamental behaviour of expansive soil and design methodology for civil engineering structure constructed on these soils (Ng *et al.*, 2003). It is not ideal to explain engineering properties of expansive soil with saturated soil theory. Progress is achieved by introducing unsaturated soil theory into expansive soil (Fredlund & Raharjo 1993). However, slides usually happen under the conditions that the slopes are saturated. Although many tests and researches have been carried out, failure mechanisms of the expansive soil slope needs further research. It is easy to induce landslides in shallow layer if the cut slope is not strengthened in time, especially after prolonged rainfall (Ng *et al.* 2003, Fredlund & Raharjo 1993).

Three properties of the soil, which include swelling and shrinkage potential, cracking and over-consolidation, show different risks in different engineering situations. Among the three properties, cracking can have a key effect on failure of cut slopes in expansive soil areas. The literature (Junping Yuan & ZongZe Yin 2004) explained distributing rules of cracks and fissures with fractal theory. Shiguo Xiao (2001) divided the slope of expansive soil into superficial, middle and deep layers and considered that the superficial layer was strongly affected by the weather conditions, which caused loss of the strength. According to this analysis, the superficial destabilization of the slope can be explained. Cracking is also an important factor resulting in the slope failure in shallow layers. Chenggang Bao (2004) used unsaturated soil theory to research the slope in expansive soil areas. Matrix suction in unsaturated soil mechanics makes it clear that the strength of expansive soil varies with volume water content.

Are the landslides of this kind and their characteristics in expansive soil regions determined by reduction of strength caused by many fissures? To answer this, this paper uses the numerical analysis method—FLAC 3D to explore the slide characteristics and its forming mechanism. Through the case study and its monitoring data an effective strengthening method is put forward. FLAC 3D is adopted to simulate strength delimination and cracks in the surface of the slope in expansive soil area. The results show that reduction of the strength in the surface is a contributory factor inducing shallow slides rather than a primary factor. The main inducement is many cracks and fissures caused by drying-wetting cycles. Creep exerts an important influence on occurrence of the landslides. On the other hand, generation of cracks and fissures accelerates creep. Monitoring results tell us that the anchor frame beam is an effective method strengthening the expansive soil cut slope.

FLAC SIMULATION

Delamination simulation

FLAC 3D is a three-dimensional explicit finite-difference program for engineering mechanics computation. It can simulate the behaviours of three-dimensional structures built of soil, rock or other materials that undergo plastic flow when their yield limits are reached (Itasca 1997). It offers a wide range of capabilities to solve complex problems in mechanics and especially in geomechanics.

The cut slopes in expansive soil areas are divided into two layers including weathered and un-weathered layers because the slopes are easily influenced by the weather. Weathering depth in the region varies from 1.5 to 2.5 m. Cohesive forces in weathered layer are reduced and the friction angle is not much affected by the weather. Therefore, the strength parameters in the unweathered layer can be obtained through test data, and cohesive forces of the weathered layer can be got by reduced strength. In simulation of FLAC3D the weathered and unweathered layers are in different groups. The calculated results can be seen in Figure 1. It can be illustrated from Figure 1 that the maximal displacement occurs at the toe of the slope rather than at the middle part of the slope and that backscarp of the slide may emerge in the middle of the slope.

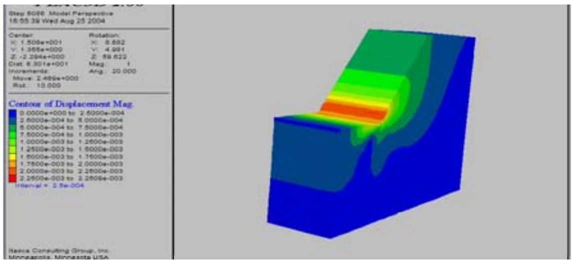


Figure 1. Effect of weathering layer on the slope deformation

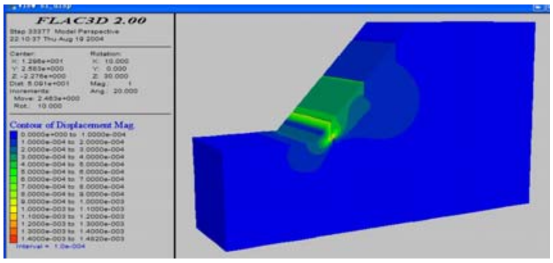


Figure 2. Effect of cracks on the slope failure

Calculation of fissures and cracks

Cracks or weak interlayers in FLAC3D are usually defined by *interface*, whereas cracks and fissures in the surface of the slope are only distributed in superficial layer of the slope and are no perforative cracks. Hence *interface* fails to simulate the cracks and fissures in the surface of the slopes. The paper uses a quite thicker lattice to emulate run time. *Null* is used to define the cracks and fissures. The length or depth of the cracks occurring in the slope surface is about 1 m and the width of the cracks varies from several mm to over ten mm. The width of the cracks is defined as 20 mm in the paper because the cracks with the width of 20 to 50 mm have no obvious effect on deformation of the slope in the simulation of FLAC 3D. Distribution of the slope cracks is disorderly and unsystematic. It can be seen that the cracks and fissures in the middle part of the slope are more than the ones at other parts. Distributing of the slope cracks and fissures has been studied (Junping Yuan & Zongze Yin 2004). To simplify the analysis, linear cracks with even distribution are assumed and with a depth of 1 m and a width of 20 mm, and the distribution density is one per metre. Figure 2, which is the deformation result of expansive soil cut slope with cracks, illustrates that the slope failure happens in superficial layers, and that steep backscarp of the slide is situated near the middle part of the slope. This accords with the characteristics of practical landslides. It is a trend that the slope toe is pushed and extruded by the slide body. Uniform width of the cracks is used in the paper, which fails to reflect the wedge characteristics (the top wider and the bottom narrower) of the actual cracks. This can explain why maximal displacement occurs in the slope body rather than on the surface.

CREEP MODELLING

The estimate of the stability usually uses the limiting equilibrium method. Although it analyses the slope stability in terms of static and moment balances, the method cannot evaluate deformation of the slope and it ignores the effects of the slope deformation on the stability. The paper uses FLAC 3D to simulate the effect of creep on the slope deformation.

Elasticity, plasticity and viscosity are three basic properties of continuous medium. The combined models are usually used in all the models calculating creep. Its merit is that ideal basic elements properly simulate practical visco-elastic-plasticity media of practical rock mass, and that the whole process of deformation is simulated and the deformation of the complicated rock and soil bodies can be disassembled into deformation in each element with explicit physical meaning, which is available to further know physical and mechanical properties of rock and soil bodies (Itasca, 1997). To model deformation rules of viscoelastic material it is supposed that the material is made up of heterogeneous point units. Some point units are purely elastic the others are purely viscous. Various combinations of the point units constitute all types of models with different viscous elastic characteristics. The creep in Maxwell and Bugers models increases with time until infinite. Therefore, they are liquid models that cannot accord with practical situations. A simple visco-plastic model—PWIPP is used in the paper. Creep parameters can be seen in Table 1 modified in terms of the data by Xiumei Ding (2005). The physical and mechanical parameters can be seen in interrelated literature (Xiumei Ding, 2005). The effect of water is also considered and the calculated results can be seen in Figure 3. It can be seen from Figure 3 that there is a great level displacement at the slope toe and that the most obvious deformation is concentrated between the middle part and the slope toe where the failure will occur. Accumulating totals of creep time effect are considered, as accords with actual conditions. It is well known that landslides of the expansive soil slope usually happen after prolonged rainfall with progressive characteristics. Large numbers of models fail to describe deformation development of the slope with time and the strength after drying-wetting cycles is disposed, instead, by simple strength reduction. Research of slope creep can be seldom seen, especially for expansive soil slope with many cracks and fissures. Creep types and corresponding parameters require in-depth research. Creep parameters should vary for different parts of the slope.

Table 1. Creep parameters of expansive soil (after Xiumei Ding 2005)

A	B	D ($10^{-36}Pa^{-n}s^{-1}$)	Critical steady-state creep rate (10^{-9}/s)	WIPP model exponent, n
108.7	7.2	332	5.39	5.1

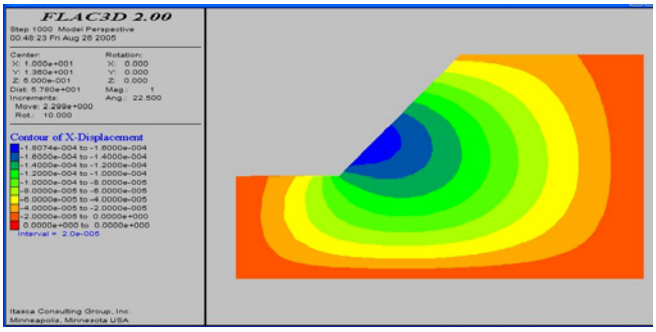
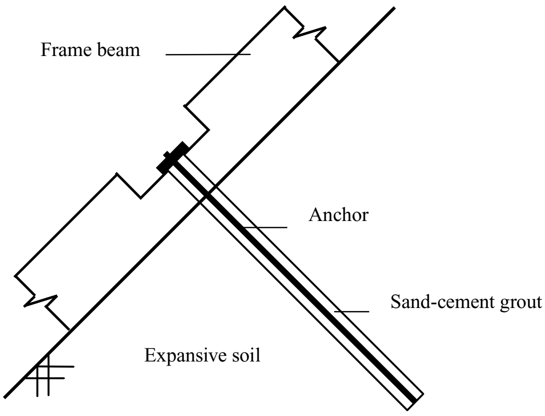


Figure 3. Visco-plastic deformation of expansive soil slope



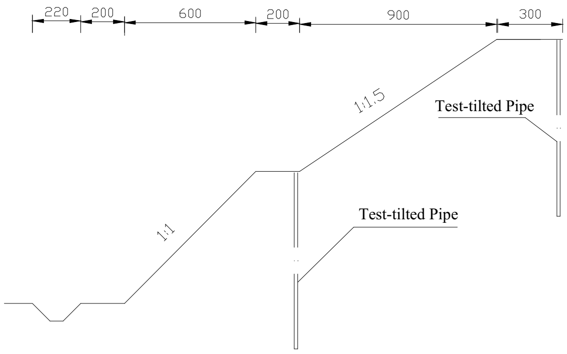


Figure 4. Diagrammatic sketch of anchor frame beam

Figure 5. Arrangement plan of slope monitoring

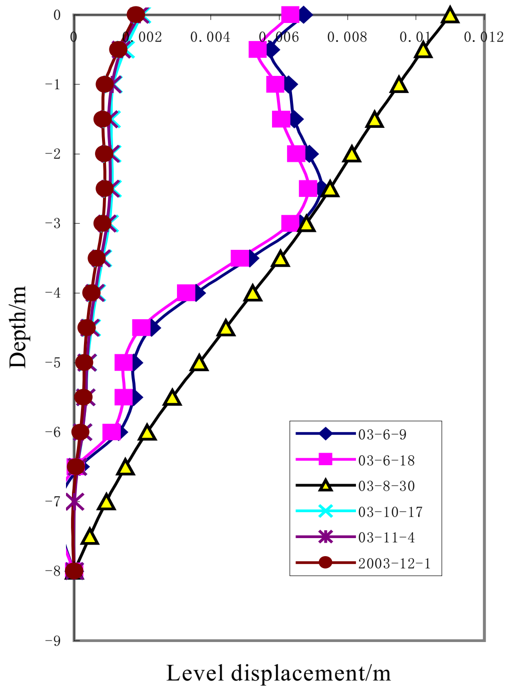


Figure 6. Monitoring data of slope level displacement

CASE STUDY

Anchor frame beam is a method for strengthening the cut slope in expansive soil regions. A concrete frame beam is embedded on an unsaturated expansive soil slope by an anchor, giving the slope high stiffness (Figure 4). At the same time greening can be taken into account. The anchor is inserted into the slope and fixes the frame beam. The frame beam restrains deformation of the expansive soil slope, especially horizontal deformation, and increases the slope stability of the expansive soil. It can avoid expansion of cracks and fissures in superficial layers of expansive soil cut slopes and improve stress distribution of the superficial layer of the slope. The whole strength of the slope is enhanced. Therefore, an anchor frame beam should be a good method for strengthening the cut slope due to convenient usage and considering greening.

A high expansive soil cut slope on a freeway in Hubei was strengthened by an anchor frame beam (Figure 4). The excavation depth was about 12 m, with two-stage excavations. After the excavation, test-tilted pipes of 8 m were installed to know reinforcement effect of the anchor frame beam (Figure 5). The pipes of 8 m can satisfy monitoring requirements because the deformation of expansive soil slope concentrates at the upper 2 to 3 m below the slope surface. On Oct 17th 2003 the protection was finished. The monitoring results indicated that accelerated levels of displacement of the slope towards the outboard occurred before Oct 17th 2003, that is, before being strengthened, and that there was no obvious level displacement of the slope after being strengthened (Figure 6). The results showed that the anchor frame beam could effectively strengthen the expansive soil slope and restrain the deformation of the slope. During the period from October to December, there was little change in the slope displacement, showing marked strengthening effects. The monitoring data made it clear that level displacement of the slope increases with time and that, after the reinforcement, the trend of deformation increase with time is remarkably reduced. The anchor frame beam has a good strengthening effect and deserves wide use for strengthening the slope in expansive soil areas as viewed from this case study and its monitoring data.

CONCLUSIONS

Based on above analysis the following conclusions can be drawn:

Most landslides usually happen after several drying-wetting cycles or prolonged rainfall. Drying-wetting cycles result in many cracks and fissures that endanger the slope stability. At the same time, rainfall makes the strength of the expansive soil slopes decrease rapidly. Therefore, many cracks and fissures, which is an important factor causing shallow landslides and determines the characteristics of the slides, can accelerate the slope creep and deformation.

The monitoring results of slope inclinometers indicated that the anchor frame beam has a good strengthening effect and deserves wide use for strengthening slopes in expansive soil areas. Hence it is a good method strengthening cut slopes.

Creep models and their parameters need in-depth research due to many cracks and complicated conditions of the expansive soil slope.

Acknowledgements: This research is supported by National Natural Science Foundation of China for the Key Project *Western Zoology and Environment* (90102002).

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