Numerical Simulation Study on Mechanical Properties of Coarse-Grain Mixed Soil High and Steep Slope at Different Water Contents

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Abstract. In order to study the stability mechanism of coarse-grained mixed soil with high steep slope in different areas of water content in southeast Tibet, this paper takes a high-steep slope of Sejila Mountain in Nyingchi City as the research object, and the undisturbed soil configuration for on-site retrieval includes natural water content. Three kinds of soil samples with a rate of 6%, a water content of 3% and a water content of 9% were obtained by using the ABAQUS numerical analysis using the mechanical parameters obtained by the large-scale triaxial test to obtain the development of the plastic zone of the model. The high-steep slope is used to form the penetrating plastic zone and the calculation non-convergence is used as the safety factor for determining the slope instability. The characteristic point displacement is abruptly changed to the safety factor of the slope instability criterion, and the characteristics of high-steep slope failure are observed. And the sliding surface map and displacement change after numerical calculation to lose stability, analyze the safety factor that forms the through-plastic region as a standard, and the safety factor that does not converge to the force and displacement calculation. The high-steep slope can be known by numerical analysis. The numerical calculation of the natural moisture content gives the highest safety factor, indicating that the high steep slope is the most stable under natural moisture content.

1. Preface

The stability analysis of high and steep slopes has always been a research hotspot of experts and scholars at home and abroad. At present, the analysis methods for the stability of high and steep slopes are mainly divided into two types, namely the limit equilibrium method and the finite element analysis method. The finite element method compares indirectly the slope stability. In the 1970s, Zienkiewicz [1] first proposed the concept of shear strength reduction factor. The advantage of strength reduction method is that it retains the ability to solve difficult problems in the original finite element numerical simulation. Based on this, the calculation concept and result the output has been optimized. This method has been widely spread in the geotechnical field. In this paper, the finite element theory analysis of strength reduction method is used to calculate and analyze the high-steep slope of coarse-grain mixed soil in southeast Tibet by ABAQUS finite element software.
2. Basic principle of numerical calculation
In the limit state, the actual shear stress generated by the external load and the minimum shear strength exerted against the external load are equal to the shear strength determined in the actual strength index after the actual strength index is reduced, assuming a high steep slope. The inner soil maintains the same shear strength. This shear strength reduction factor is the overall safety factor $F_s$ of our high-steep slope. This is also called the strength reserve safety factor, which is stable in the limit equilibrium method. The safety factor, these two concepts are the same [2]. Careful in-depth observation of the strength reduction method, found that its essence is the cohesion and internal friction angle becomes smaller, so that a unit of stress can not support its strength, but also beyond the yield surface, can not bear the transfer of stress, next to the soil. The body unit receives, and the soil sample is unstable after the continuous sliding surface or the yield point is connected to the through surface. The strength reduction method should follow the inequality $\phi - \nu$ [3]. The numerical simulation of the stability of this high-steep slope uses the field variable $FV1$ in the material properties of ABAQUS to achieve the reduction of the coarse-particle mixing strength parameters. Using the strength reduction method to select the yield criterion has a great influence on the calculation of the safety factor of the slope. The difference of the selection will result in the difference of the results. This paper uses the Mohr-Coulomb failure criterion, especially for the high steep slope under the monotonic load. The shear failure of the granular mixed soil is very suitable for selecting the failure criterion.

3. Judging basis for stability of high and steep slope
In the simulation calculation, the different strength reduction factors $F_r$ are assumed, and then the finite element numerical analysis is performed according to the reduced strength parameters to see the convergence. When the simulation calculation is carried out, the setting is increased to increase the value of $F_r$. When the critical damage occurs, the strength reduction factor $F_r$ is the safety factor $F_s$ of the high steep slope we are looking for, which is used as the safety of the high steep slope. The measure of the degree. The current criterion for determining critical damage in high-steep slopes is [4]:

1) Numerical simulation calculation to convergence is an important judgment condition, which is related to the selected finite element algorithm.

2) The displacement inflection point generated by the characteristic part is also an important sign of the critical damage of the slope.

3) When a continuous plastic penetration region is generated, it can also indicate that the high-steep slope model has a critical failure.

4. Parameter selection
Using the strength reduction finite element method to analyze the slope stability, the safety factor of slope stability mainly depends on the soil shear strength parameters, and has little relationship with the soil Poisson's ratio and the elastic modulus $E$ [5]. Therefore, in the current ABAQUS numerical simulation of high-steep slope coarse-grain mixed soil, the cohesion $c$, internal friction angle and dilatancy angle are mainly reduced. The value of the shear strength parameter is obtained by the triaxial test of large coarse-grain mixed soil; the bulk density of the soil sample is consistent with the bulk density of the soil set by the test scheme of the triaxial test by the compaction test, regardless of the water content and the bulk density of the soil influences.

5. Establishment of finite element calculation model
This simulation of high-steep slope coarse-grain mixed soil needs to meet the requirements of high-slope design specifications. The embankment slope ratio is 1: $n$ degrees and the slope height is $H$. The unit type of this time value simulation model is selected as a four-node bilinear plane strain quadrilateral unit (CPE4). The division of the model mesh is local to the edge of each model, and the number of seeds on the corresponding side of the model is equal.
5.1. Stability safety factor for high and steep slope calculation

The high-steep slope soil sample is from the foot of the 1.29Km Sejila Mountain in the southeast of Linzhi Town, Nyingchi City, and is close to the high-steep slope of the 318 National Highway at an altitude of 3040m. The geological compass and the total station will be used to sample the actual slope. The slope and the height of the slope are measured. The slope of the high-steep slope at a foot of the second mountain is at 35°, and the slope height is 60m. Next, according to the experimental data obtained from the previous test, on the ABAQUS Three different water content soil samples including high water content including high natural steepness were simulated and modeled and calculated.

5.1.1. High-steep slope coarse-grain mixed soil natural moisture content 6% stability safety factor.

The plastic zone development of the natural moisture content model of coarse-grain mixed soil with high steep slope is shown in Fig. 1. The steep slope model has a slope of 1:1.483 and the steep slope height is set to 60m. The cohesive force of the No.2 soil is 30.437 kPa and the internal friction angle is 36.17°. The plastic zone starts from the slope and then goes to the interior of the slope. Development, the plastic zone further develops to the top of the slope, forming a penetrating plastic zone. After forming the plasticity, the plastic zone will widen until the calculation iteration of displacement and force does not converge, and the numerical calculation ends. The model iteration process does not converge as the criterion for embankment instability. The field variable FV1 at the end of the iterative 111 step is the safety factor, and the safety factor of the high-steep slope coarse-grain mixed soil natural moisture is 1.707. The two graphs (a, b) in Fig. 1 are the initial states in the calculation process respectively; the through-zone is half in the calculation process; the plastic region is just penetrated and the calculation is completed to the last step.

![Figure 1. Plastic zone development of natural moisture content model of coarse-grained mixed soil with high steep slope (a, t=0.1, FV1=0.65; b, t=0.805, FV1=1.707)](image)

The safety factor under the natural moisture content of the high-steep slope coarse-grain mixed soil is shown in Table 1 to form the penetrating plastic zone and the calculation non-convergence as the criterion for determining the slope instability.

| Natural moisture content 6% | Safety factor (forming through plastic zone) | Safety factor (force and displacement calculation does not converge) |
|-----------------------------|---------------------------------------------|-------------------------------------------------------------|
|                             | 1.608                                       | 1.707                                                       |

The model calculation results under the condition of natural moisture content of high and steep slopes use the change relation obtained by the Combine function, it can be known that FV1 increases from 0.48 and U1 basically does not change when FV1 increases at the beginning. As FV1 increases to a certain
value, \( U_1 \) mutates, and \( U_1 \) continues to grow until the end of calculation. The abrupt change of characteristic point displacement is the criterion for judging the slope instability, and the safety factor of the high and steep slope is 1.595.

The total displacement contour map of the sliding surface of the high-steep slope coarse-grain mixed soil natural moisture model is shown in Fig. 2. At the end of the numerical calculation, the sliding surface formed after the instability of the high-steep slope is the arc-sliding failure form, and the sliding surface extends to the top of the slope through the slope foot, which is the characteristic of high-steep slope failure. It can be seen from Fig. 2 that the high-steep slope is clearly shown in the sliding surface map after the numerical calculation to the loss of stability at a natural moisture content of 6\%, and there will be a displacement change of 47.94 m, and the landslide soil will be produced. The state of transition from rest to motion is accompanied by a large displacement change and a correspondingly large plastic strain change.

![Figure 2. High-steep slope coarse-grain mixed soil natural moisture model sliding surface](image)

**5.1.2. Stability safety factor of 3\% moisture content in coarse-grain mixed soil with high steep slope.** The plastic zone development of the 3\% moisture content model of high-steep slope coarse-grain mixed soil is shown in Fig. 3. The slope and height setting of the high-steep slope model are unchanged. The cohesive force is 16.99 kPa and the internal friction angle is 37.29\(^\circ\) at 3\% moisture content. The plastic zone starts from the slope foot and then develops into the slope. The plastic zone is further developed. At the top of the slope, a plastic zone is formed. After the plasticity is formed, the plastic zone will widen until the calculation of the displacement and force does not converge, and the numerical calculation ends. The model iteration process does not converge as the criterion for embankment instability. The field variable \( FV_1 \) at the end of the iterative 53 steps is the safety factor, and the safety factor of the high-steep slope coarse-grain mixed soil 3\% moisture content is 1.567. The two graphs of Fig. 3 (a, b) are the initial state in the calculation process, the plasticized region in which the through region is half in the calculation process, just passed through, and the calculation is completed to the last step.
Figure 3. Development of plastic zone of 3% model of high-steep slope coarse-grain mixed soil moisture content (a, t=0.1, FV1=0.65; b, t=0.7116, FV1=1.567)

The safety factor of the high-steep slope coarse-grain mixed soil moisture content 3% is shown in Table 2, in order to form the penetrating plastic zone and the calculation non-convergence as the criterion for determining the slope instability.

Table 2. Safety factor of 3% moisture content of coarse-grain mixed soil in high-steep slope

| water content 3% | Safety factor (forming through plastic zone) | Safety factor (force and displacement calculation does not converge) |
|------------------|---------------------------------------------|---------------------------------------------------------------|
|                  | 1.482                                       | 1.675                                                         |

The model calculation results under the condition of natural moisture content of high and steep slopes use the change relation obtained by the Combine function, it can be known that FV1 increases from 0.48 and U1 basically does not change when FV1 increases at the beginning. As FV1 increases to a certain value, U1 mutates, and U1 continues to grow until the end of calculation. The abrupt change of characteristic point displacement is the criterion for judging the slope instability, and the safety factor of the high and steep slope is 1.493.

Figure 4. High-steep slope coarse-grain mixed soil 3% moisture content model sliding surface

The total displacement contour map of the sliding surface of the 3% water content model of the high-steep slope coarse-grain mixed soil is shown in Fig. 4. After the iterative progress to 53 steps, the numerical calculation ends. The sliding surface formed after the instability is the arc sliding failure form.
The sliding surface extends to the top of the slope through the slope foot, showing the characteristics of high-steep slope failure. It can be seen from Fig. 4 that when the water content is 3%, the high-steep slope is numerically calculated and the sliding surface after the loss of stability is clearly shown in the figure, there will be a displacement change of 10.77m, and the landslide soil will It will change from static to moving, with consequent large displacement changes and correspondingly large plastic strain changes.

5.1.3. Stability safety factor of 9% moisture content in coarse-grain mixed soil with high steep slope. The plastic zone development of the 9% moisture content model of high-steep slope coarse-grain mixed soil is shown in Fig. 5. The slope and height setting of the high-steep slope model are unchanged. The cohesive force is 53.28 kPa and the internal friction angle is 23.8°. The plastic zone starts from the slope and then develops into the slope. The plastic zone further. It develops to the top of the slope and forms a penetrating plastic zone. After forming the plasticity, the plastic zone will widen until the calculation iteration of displacement and force does not converge, and the numerical calculation ends. The model iteration process does not converge as the criterion for embankment instability. The field variable FV1 at the end of the iterative 81 step is the safety factor, and the safety factor of the high-steep slope coarse-grain mixed soil 3% moisture content is 1.38. The following two graphs are the initial state in the calculation process, the cross-section in the calculation process, the penetration zone is half, the penetration is just completed, and the plastic zone is calculated to the final step.

![Figure 5. High-steep slope coarse-grain mixed soil moisture content 9% model plastic zone development (a, t=0.2, FV1=0.8; b, t=0.5868, FV1=1.38)](image)

The safety factor of the high-steep slope coarse-grain mixed soil moisture content of 9% is shown in Table 3, in order to form the penetrating plastic zone and calculate the non-convergence as the criterion for determining the slope instability.

| Safety factor (forming through plastic zone) | Safety factor (force and displacement calculation does not converge) |
|---------------------------------------------|---------------------------------------------------------------|
| water content 9%                            | 1.331                                                         |
|                                             | 1.38                                                          |

The model calculation results under the condition of natural moisture content of high and steep slopes use the change relation obtained by the Combine function, it can be known that FV1 increases from 0.48 and U1 basically does not change when FV1 increases at the beginning. As FV1 increases to a certain value, U1 mutates, and U1 continues to grow until the end of calculation. The abrupt change of characteristic point displacement is the criterion for judging the slope instability, and the safety factor of the high and steep slope is 1.34.
After iteration and 81 steps of numerical calculation, the sliding surface formed after the instability is a form of circular arc sliding failure, which extends to the top of the slope through the foot of the slope. As can be seen from figure 6, when the moisture content of the high and steep slope is 9%, there will be a 155m displacement change after numerical calculation, and the landslide soil mass will also produce a large plastic strain.

![Figure 6. High-steep slope coarse-grain mixed soil 9% moisture content model sliding surface](image)

5.2. Comparative analysis of stability safety coefficient of high-steep slope coarse-grain mixed soil at different moisture contents

The coarse-grained mixed soil of high-steep slope was numerically calculated at a water content of 3%, a natural moisture content of 6%, and a water content of 9%. The summary safety factors are shown in Table 4 below:

| Water content  | Cohesion (kPa) | Internal friction angle (°) | Displacement (m) | Safety factor (forming through plastic zone) | Safety factor (force and displacement calculation does not converge) |
|----------------|----------------|-----------------------------|------------------|-----------------------------------------------|---------------------------------------------------------------|
| 3%             | 16.99          | 37.29                       | 10.77            | 1.482                                         | 1.567                                                         |
| 6% Natural moisture content                   | 30.437         | 36.17                       | 47.94            | 1.608                                         | 1.707                                                         |
| 9% Water content                             | 53.28          | 23.8                         | 155              | 1.331                                         | 1.38                                                          |

The relationship between the water content and the safety factor calculated by the high-steep slope coarse-grain mixed soil at a water content of 3%, a natural moisture content of 6%, and a water content of 9% is shown in Fig. 7.

![Figure 7. Relationship between water content and safety factor](image)
By observing the numerical calculation results of Table 4, and the relationship between the water content and the safety factor of Fig. 7, it can be seen that with the increase of water content, the coarse-grained soil samples of the high-steep slope at the foot of Sejila Mountain contain some silt, powder. When the soil is combined with water, the cohesive force is gradually increased. When the water content of the slope soil increases, the water acts like a lubricant, and the water forms a lubricant on the surface of the soil, so that the internal friction angle is gradually decreasing; the high-steep slope loses stability, and the displacement also occurs with water. The rate increases and increases. The high-steep slope in southeast Tibet is affected by rainfall. When the water content of the soil increases, it will accelerate the landslide and produce a large displacement. The analysis of the formation of the penetrating plastic zone is the standard safety factor and it is known that the safety factor of the non-convergence of force and displacement is not the same. The numerical calculation of the high-steep slope at the natural moisture content has the highest safety factor, indicating that the high-steep slope is the most stable under the natural moisture content.

6. Summary

Through the study of coarse-grained soil samples of high-steep slopes with high and steep slopes at an altitude of 3040m at the foot of Sejila Mountain in Nyingchi Town, Nyingchi City, southeast Tibet, numerical simulation calculations were carried out for three soil samples with different water content under natural moisture content. The following conclusions:

(1) The plastic zone of the high-steep slope numerical analysis model is generated from the slope foot, then develops into the interior of the slope, and finally penetrates to the top of the slope. The sliding surface of the slope model is arc-shaped, and the sliding surface passes through the slope foot, and the extent to which the sliding surface extends to the inside of the slope is deepened as the cohesive force of the soil increases.

(2) With the increase of water content, the coarse-grained soil samples of the high-steep slope at the foot of Sejila Mountain contain some silt, and the fusion of silt and water leads to an increase in cohesive force. When the water content of the slope soil increases, the water acts like a lubricant, and the water forms a lubricant on the surface of the soil, so that the internal friction angle is gradually decreasing; the high-steep slope loses stability, and the displacement also occurs with water. The rate increases and increases. The high-steep slope in southeast Tibet is affected by rainfall. When the water content of the soil increases, it will accelerate the landslide and produce a large displacement. The analysis of the formation of the penetrating plastic zone is a standard safety factor. As well as the safety factor of the non-convergence of force and displacement calculations, the numerical calculation of the high-steep slope at the natural moisture content has the highest safety factor, indicating that the high-steep slope is the most stable under the natural moisture content.

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References

[1] H.Zheng, D.F.Liu, C.F.Lee, L.G.Tham. Displacement-controlled method and applications to material non-linearity.International Journal for Numerical & Analytical Methods in Geomechanics, 29 (3): 209-226, 2005.

[2] Chen Lihong, Yu Wei, Zhang Hongtao. Several problems of shear strength reduction finite element method [J]. Chinese Journal of Geotechnical Engineering, 2011, 33 (S1): 433-437.
[3] H. Zheng, F. F. Liu, C. G. Li. Slope stability analysis based on elasto-plastic finite element method. International Journal for Numerical Methods in Engineering, 64 (14): 1871-1888, 2005.

[4] Pei Lijian, Qu Benning, Qian Shanguang. Uniformity of slope instability criterion by finite element strength reduction method [J]. Rock and Soil Mechanics, 2010, 31(10): 3337-3341.

[5] Lian Zhenying, Korea City, Kong Xianjing. Study on stability of excavation slope by strength reduction finite element method [J]. Chinese Journal of Geotechnical Engineering, 2001, 23 (4): 407-411.