Analysis of slope instability induced by heavy rainfall on a highway

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Abstract. Recent heavy rainfall has resulted in a risk of instability on the side slopes of a highway. Using simulation software to construct a finite element analysis model of the slope, the calculated slope stability coefficient does not meet the specification requirements, indicating that the slope is in an unstable state; based on the site investigation data and expert opinion, to determine the "slope reduction + anchor + intercepted drainage" reinforcing program. After analyzing the stress field and displacement field of the slope after reinforcement, the stability coefficient of the slope is 1.41, which is 28.18% higher than that before reinforcement; the study shows that: (1) after reinforcement, the stress on the slope is predominantly concentrated around the reinforcement measures, which clearly demonstrates the effectiveness of the measures in generating substantial stress within the reinforced area; (2) after reinforcement, the maximum displacement of the slope decreased by over 90% in comparison to its pre-reinforcement state, clearly demonstrating the effectiveness of the reinforcement measures in preventing sliding failure of the slope; (3)the stability coefficient of the slope is significantly improved after reinforcement, indicating that the reinforcement program is feasible.

Keywords: Finite elements; Stability; Anchors; Reinforcement.

1. Introduction

Slope instability reinforcement has always been one of the hot issues in the field of geotechnical engineering. How to quickly, economically and effectively carry out slope management and reinforcement is an important challenge, domestic experts and scholars have carried out a lot of research in this regard[1-4]. Zhang Bangxin et al [5] compared and analyzed the effect of different reinforcement schemes based on the sensitivity of geotechnical body parameters; Liu Zhongshuai et al [6] devised a slope reinforcement plan grounded on real-time monitoring data, subsequently identifying the optimal plan that balanced both effectiveness and economic considerations; Tao Lianjin et al. [7], utilizing the limit analysis method, derived the displacement formula for anti-slide piles and, within the framework of vulnerability analysis, conducted a comparative study on the differential impacts of far-field and near-field seismic waves on slope stability; Pei Zhenwei et al [8] realized the design calculation of miniature anti-slip pile group and the rapid modeling of real slopes on BIM platform; Dong Gaoyi et al [9] analyzed the stability of mixed granite slopes containing spherical weathered bodies and developed different reinforcement schemes; Wang Yankun et al [10] conducted sensitivity analyses based on the finite element model for the slopes with unreinforced, anchored, and geogrid, and with anchored and geogrid respectively.In summary, the level of rapidity, economy and effectiveness of existing research in slope stabilization and management is low, and there is still much room for exploration.

Based on this, this paper takes an unstable slope as the research object, combines the relevant information, quickly constructs the slope finite element model before and after reinforcement based on finite element software, numerically analyzes the slope stress field, displacement field and stability coefficient changes, determines the most suitable slope reinforcement scheme based on the economy and effectiveness of the comparison, and constructs the analysis-simulation-comparison of the rapid analysis technology system, realizes the slope reinforcement management, and improves the rapidity, economy and effectiveness of the research results for similar slope projects. The rapid analysis technology system of analysis-simulation-selection is constructed, which realizes the improvement of slope stabilization and management in terms of rapidity, economy and effectiveness, and the results of the study have important reference value for similar slope projects.

2. Project Overview

This section of slope is located on the right side of a highway eastbound, an excavated rocky slope; slope length of 180m, height of about 35m, slope direction of 169.5 °, the top of the slope for the natural slow slope, slope planting of economic forests, the surface layer covered with a shallow layer of sandy clayey phyllosilicate soil layer, the lower part of the outcrop of the strong weathering of granite, the thickness of the rock layer reaches more than 5m; the project area is located in the subtropical monsoon climate zone, a long summer without winter, plenty of sunshine, rainfall amplitude of temperature difference is small, the monsoon is obvious. The project area is located in the subtropical monsoon climate zone, with long summer and no winter, sufficient sunshine, abundant rainfall, small amplitude of temperature difference and obvious monsoon, with an average annual precipitation of 1774.1 mm; the vegetation on the hillside is developed, and the geomorphology is a stripped hilly area, and the flood plain strata are distributed sporadically in the low-lying and smooth sections between the mountains. The site investigation determined three sections of the slope, as shown in Fig. 1, of which section 2-2 is the main section.

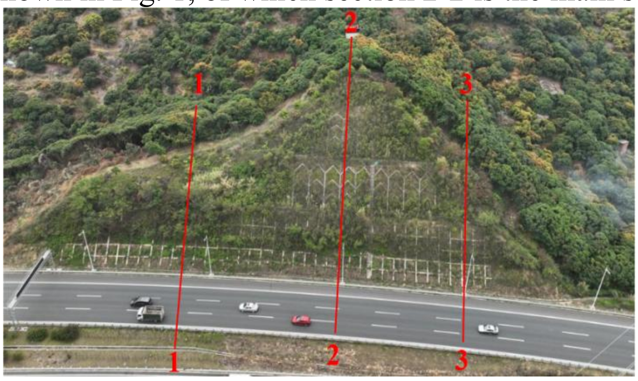

Fig. 1 Section Layout

3. Model construction

The geological survey has determined the geological structure of the main section of the slope, as illustrated in Fig. 2, and the physical and mechanical parameters of the rock and soil mass within this section have been ascertained through both indoor and outdoor experiments, as detailed in Table 1.

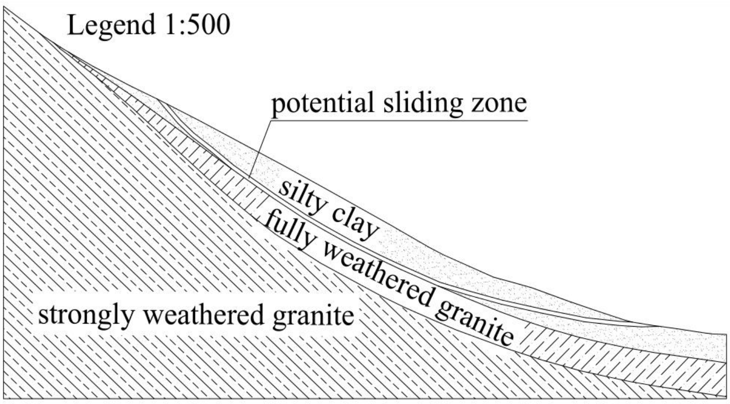

Fig. 2 Geological Tectonics

Table 1. Physical and mechanical parameters

Category	Severe/(kN.m^{-3})	Cohesion/kPa	Friction angle/(°)	Modulus of elasticity/MPa	Poisson's ratio
subsoil	18	32	16	6	0.3
silty clay	19.2	40	17	5.5	0.35
fully weathered granite	19.4	29	30	90	0.3
strongly weathered granite	20	45	32	150	0.32
anchor	-	-	-	200000	0.35

In order to determine the stability of the main section of the slope, abaqus simulation software is used to construct a finite element analysis model as shown in Fig. 3, in which the geotechnical body is meshed with triangular planar strain cell type (CPE3), and the mesh is analyzed by the mesh checking module, and the mesh is in accordance with the requirements of numerical calculation

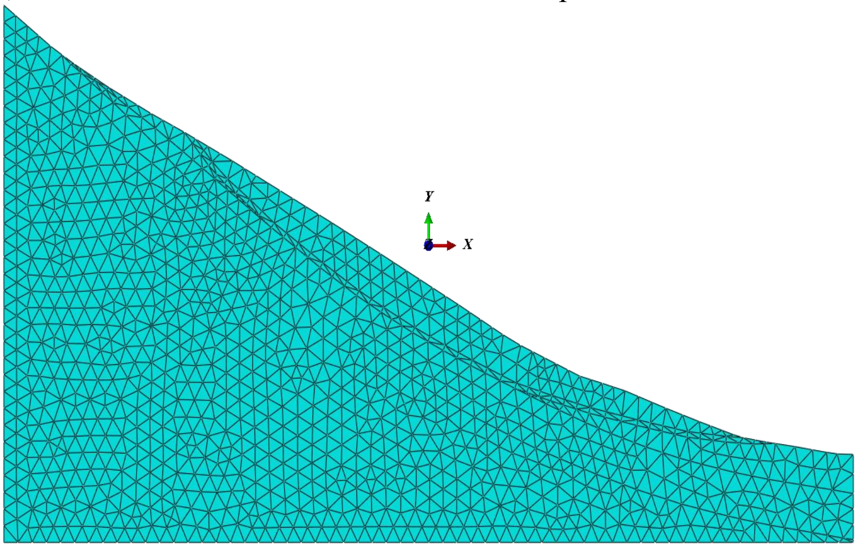

Fig. 3 Finite element model

4. Stability analysis

Based on the finite element model constructed in Fig. 3, the stability calculation of the slope is carried out by using the intensity discount method built in the software to analyze the stress field, displacement field and the change of slope stability coefficient of the slope, and the average stress cloud and displacement cloud of the slope are obtained as shown in Fig. 4 and Fig. 5, respectively.

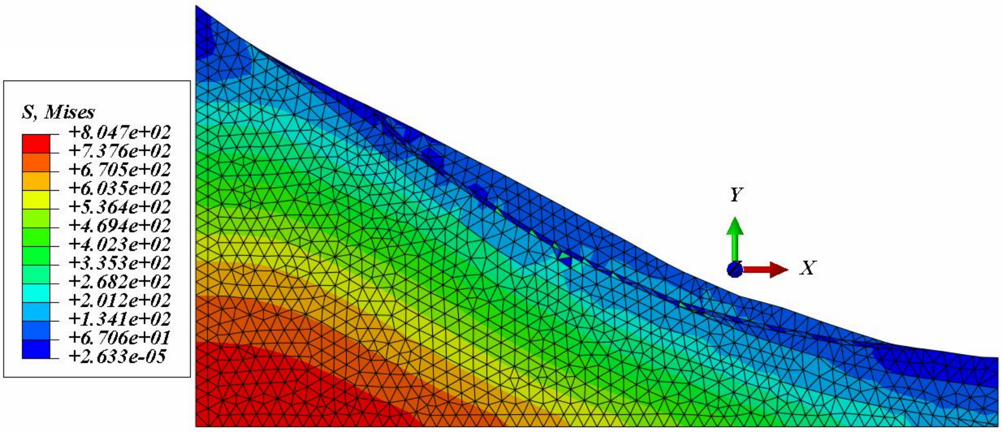

Fig. 4 Stress cloud diagram

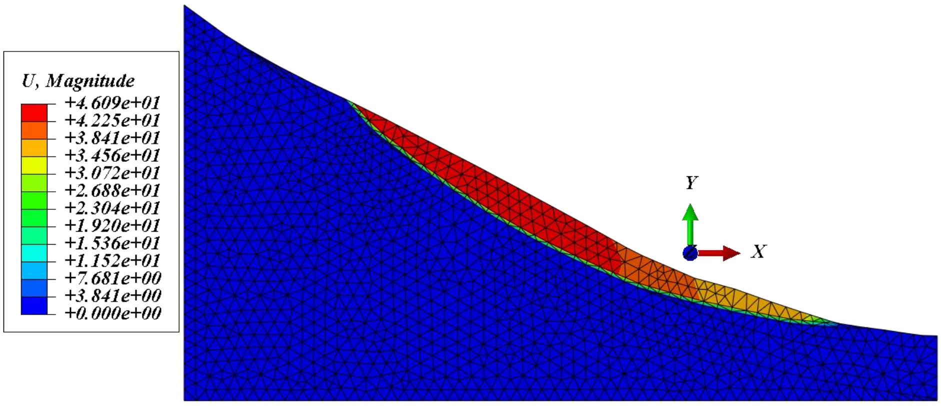

Fig. 5 Displacement cloud map

From Fig. 4 and Fig. 5, it can be seen that: the average stress of the slope decreases gradually from the left slope bottom to the slope surface, and the levels are distinct, the maximum value is 8.05×10^2kPa, and the average stress in the area of the slope's flour clay and sliding zone is the smallest; the displacement of the slope mainly concentrates in the sliding zone and its overlying flour clay area, the maximum value is 46.09mm, and the displacement value of the strongly weathered granite and the whole-weathered granite area is smaller, the overall stability of the slope bottom is better than that of the slope surface area, and the slope surface is more stable than that of the slope bottom. The overall stability of the bottom of the slope is better than that of the slope surface.

A point in the powdery clay area on the slope surface was selected as the tracking research point, and the main slip surface displacement appeared at the inflection point as the judgment criterion of instability, and the stability coefficient of the main cross-section was plotted as shown in Fig. 6 (the minus sign of the displacement in the figure is only for the purpose of turning the curve with the X-axis as the symmetry axis).

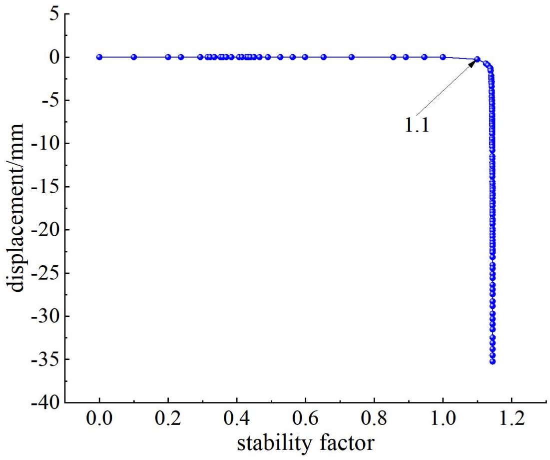

Fig. 6 Stability coefficient variation curve

As depicted in Fig. 6, a sudden change in the displacement of the tracking study point occurs when the predefined field variable reaches 1.1. Upon evaluation using stability criteria, the stability factor of the main section is ascertained to be 1.1, which falls short of the specified range of 1.2 to 1.3 for such slopes under natural conditions, as outlined in relevant regulations. This discrepancy underscores the current slope's non-compliance with regulatory standards and its precarious stability status, necessitating the formulation of reinforcement measures for effective slope management.

5. Reinforcement management

Combined with the site investigation and expert opinion, it is determined to adopt the "anchor + slope reduction + intercepting and draining" reinforcement program for slope management, which is shown in Fig. 7. Among them, the drilling diameter of anchor is 130mm, length is 9m, laying spacing is 2 m, and the plane is 30° angle laying; Slope cutting and load reduction is to excavate the powdery clay area and fully weathered granite area on the slope surface, the excavation area and boundary are shown in Fig. 7; In the back edge of the top of the slope, 2m away from the construction of intercepting ditch, the ditch wall is poured with C20 concrete.

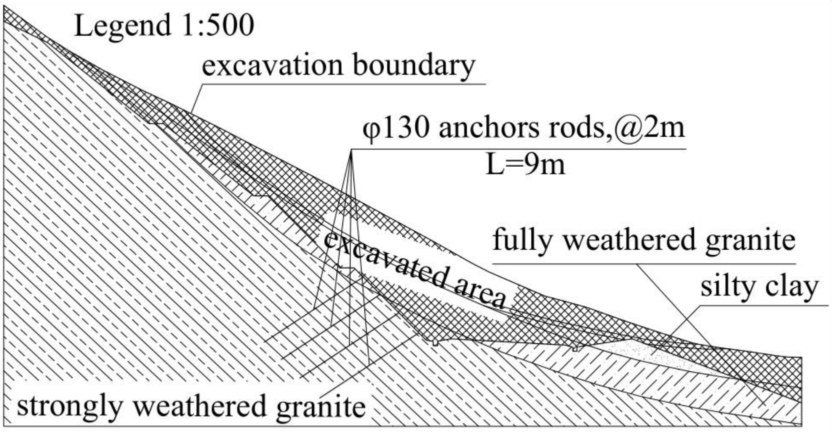

Fig. 7 Layout of reinforcement scheme

The finite element model constructed for the slope after cut slope and load reduction is shown in Fig. 8, horizontal displacement constraints are applied on both sides of the slope, horizontal and vertical displacement constraints are applied on the bottom surface, the slope body is meshed with CPE4 cell type, and the anchors are meshed with T2D2 cell type.

Based on the finite element model of the reinforcement scheme, the stress field, displacement field and stability analysis of the reinforced slope were carried out, and the average stress cloud and displacement cloud of the slope were obtained as shown in Fig. 9 and Fig. 10, respectively.

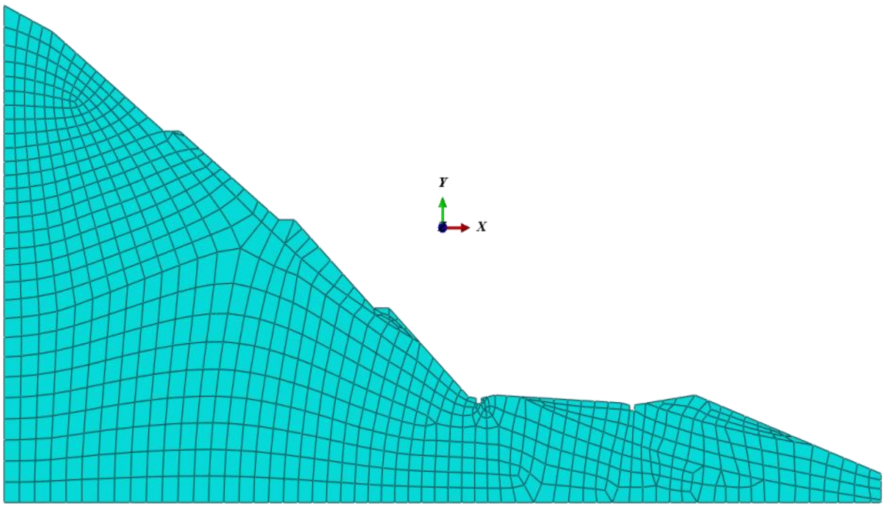

Fig. 8 Finite element model of the reinforcement scheme

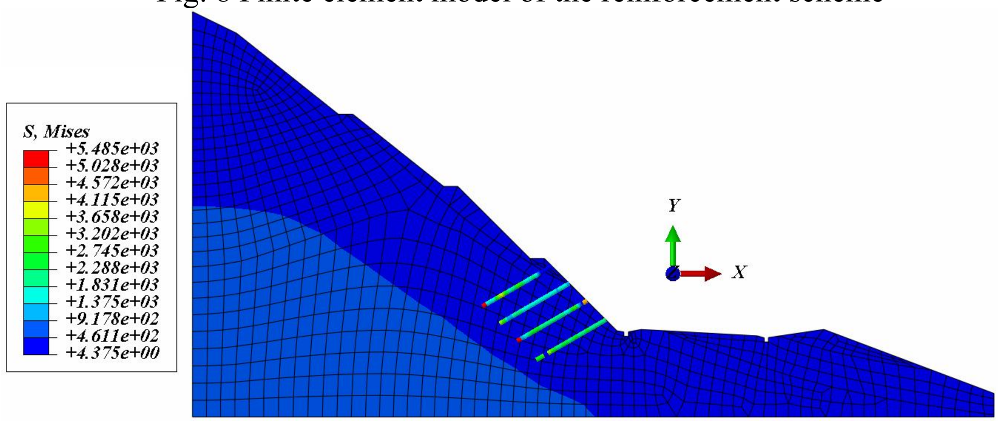

Fig. 9 Average stress

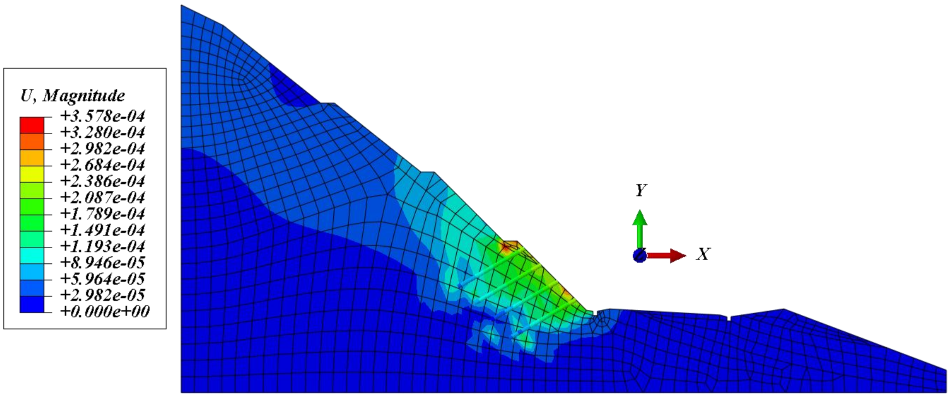

Fig. 10 Displacement cloud map

From Fig. 9 and Fig. 10, it can be seen that: the average stress of the slope is mainly concentrated in the anchor rods, and the maximum stress is 5.49×10^3kPa, while the overall average stress of the slope body is small; all the anchor rods produce effective stress, indicating that it has a slip-resisting effect on the displacement damage of the slope; the displacement of the slope is mainly concentrated in the anchor rods and their surrounding areas, and the maximum displacement is 3.58×10^{-4}mm, which is relatively decreased by More than 90%, indicating that the reinforcement measures effectively prevented the sliding damage of the slope.

To assess the stability of the reinforced slope, the same tracking study points as those used prior to reinforcement were selected, with the criterion for instability determination set as the occurrence of sudden displacement changes. The analysis subsequently yielded the stability factor of the reinforced slope, as illustrated in Fig. 11.

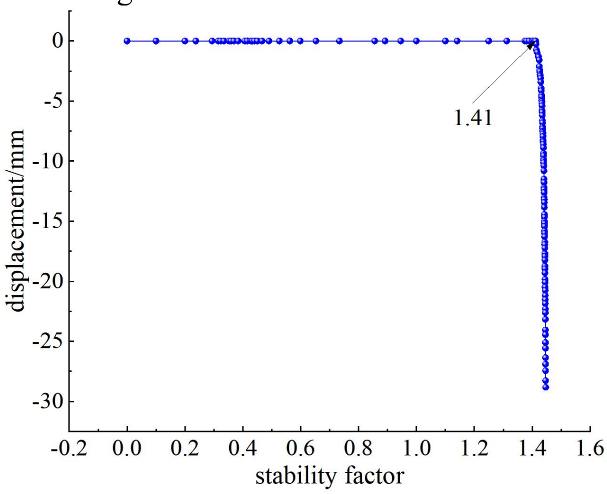

Fig. 11 Stability coefficient variation curve

It can be seen from Fig. 11: the displacement of the tracking study point of the slope after reinforcement occurs abruptly at 1.41, i.e., the slope stability coefficient is 1.41, which is 28.18% higher than that before reinforcement, meeting the relevant requirements of the specification, indicating that the reinforcement measures are feasible and effective in preventing the destruction of the slope.

6. Conclusion

(1) The stability coefficient of the slope before reinforcement is 1.1, which does not meet the specification requirements, indicating that the slope is in an unstable state and needs to be reinforced.

(2) The stability coefficient of the slope is 1.341, which is 28.18% higher than that before reinforcement, and the stress field of the slope after reinforcement is mainly concentrated in the anchor and its surrounding area, and the maximum value of the displacement decreases more than

90% relative to that before reinforcement, which shows that the reinforcement measures effectively prevent the sliding damage of the slope.

(3) The stress field, displacement field and stability coefficient of the slope before and after reinforcement show that the reinforcement scheme of "Slope reduction + anchor + anti-slip pile" is effective and suitable for this slope reinforcement.

(4) Given that the current analysis overlooks rainfall and other operational conditions, it is suggested that subsequent analyses incorporate comprehensive considerations of various scenarios, including rainfall and earthquakes, in order to further ensure the accuracy of the results and the overall stability of the slope under complex environments.

(5) The rapid analysis technical system established in this paper serves as a crucial reference for informing temporary disposal decisions and recommendations pertaining to other similar slopes, thereby enhancing the overall decision-making process.

Acknowledgments

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