Stability analysis of high soil slope in a pumping and storage power station

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Abstract. The entrance tunnel of a pumped storage power station is arranged upstream of the entrance and exit water outlet on the right bank of the lower reservoir. The tunnel body is of Chengmendong type. The entrance terrain is relatively gentle, the slope is 25 ~ 30°, and the rock weathering is deep. To study the stability of soil slope in the entrance section during the construction period, GeoStudio software is used to calculate and analyze the stability of natural slope conditions, artificial slope (without reinforcement measures), and artificial slope (with reinforcement measures) using Bishop and Morgenstein ~ Price limit equilibrium method, to provide a theoretical basis for slope support. It also provides a theoretical and practical reference for slope stability analysis in similar projects.

Keywords: soil slope; stability calculation and analysis; Bishop method; Morgenstern ~ Price method

1 Introduction

The inlet tunnel of a pumped storage power station is arranged upstream of the inlet/outlet on the right bank of the lower reservoir. The excavation elevation of the inlet floor is 310.758 m, the excavation elevation of the bottom floor is 210.800 m, the length of the tunnel is 1823 m, the average longitudinal slope is 5.58%, the maximum longitudinal slope is 7.57%, and the section of the tunnel adopts the Chengmendong type. The typical excavation section size is 8 m×8.35 m (width × height). The slope of the cave entrance is 25 ~ 35º, the bedrock lithology is crystalline fused tuff, and two fine-grained granite veins are developed. The rock weathering in this section is deep, the total regolith thickness is large, the strong regolith thickness is uneven, the rock mass is mainly broken to relatively broken, and the engineering geological conditions are poor. The cave opening is located in the overburden layer and the whole weathering layer, the stability condition of the cave formation is poor, and special support treatment should be adopted before entering the cave. The slope excavated by the entrance is an earth slope composed of overburden and full weathering, with poor stability. It is suggested to excavate less, strengthen support, enter the cave early, take good drainage measures, and enter the cave only after the slope and cave face are well supported.

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One of the difficulties in the design of a pumped storage power station is that there are many high soil slopes, especially the long soil sections of the caverns, such as the traffic tunnel into the plant, the ventilation and safety tunnel, and the diversion and drainage tunnel, and the covering layer of the slope and the full-strength weathering layer are thick and unevenly distributed. The geological profile of the slope at the entrance of the traffic tunnel is shown in Figure 1. The suggested values of the physical and mechanical parameters of the main rock and soil layers of the slope are shown in Table 1.

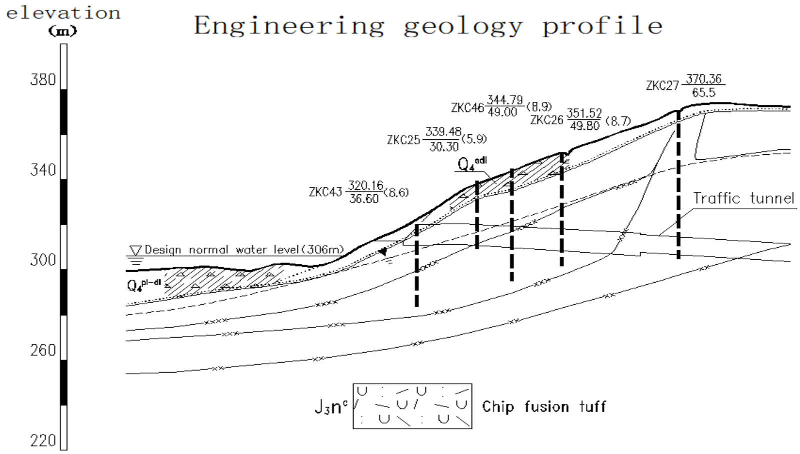

Fig. 1. Engineering geological profile of the slope at the entrance of the traffic tunnel

Table 1. Suggested values of physical and mechanical parameters of main rock and soil layers

Geotechnical designation	Basic physical indicators of the natural state		Saturated consolidation fast shear	
	density	Saturation density	cohesion	The angle of internal friction
	ρ	ρsr	c	φ
	g/cm³	g/cm³	kPa	°
Residual slope deposit silty clay	1.82	1.85	20~22	22~24
Total regolith (upper)	1.87	1.89	18~20	25~27
Total weathering layer (lower part)	1.90	1.95	22~24	28~30
Fragmentary strongly weathered rock mass	2.45	2.52	55	37.5

For soil slope, especially high soil slope, the best and most effective design scheme is often to ease the slope ratio as far as possible in a limited space, and then arrange deep drainage holes in the plum shape to discharge the water seepage inside and on the surface of the soil slope. If necessary, a dewatering well can be added on the top of the working face with soil holes and more water seepage to reduce the underground water level.

The supporting method of reducing slope load and adding a surface frame beam supporting system has the characteristics of a simple structure and convenient construction. But this scheme has a large excavation range, occupies a large space, and long construction period, and under the action of a sudden rainstorm or the increase of load above, the slope weight increases, prone to collapse deformation or circular arc sliding deformation, resulting in slope instability.

In the case of limited site space, slope concrete retaining wall can also be used to reinforce the soil slope. The advantage of this form is that it not only shortens the construction period but also improves the overall stability of the slope and the anti-scouring and anti-scouring ability. However, the slope retaining wall itself contributes little to the slope stability, and the overall instability of the slope is caused by the slope itself, and the slope retaining wall is easy to slip together with the slope [1]. In addition, due to hydraulic scouring and penetration, the backfill of the slope-type retaining wall is gradually taken away, which is easy to form a cavity, resulting in the backside collapse and overturn of the panel [2].

Another is to add strong support measures (frame beam system + anchor cable) to the soil slope under the premise of not changing the original slope ratio. The advantage of this scheme is convenient construction, but the disadvantage is that the project investment is large, and the construction is more time-consuming, delaying the overall construction progress. Therefore, the supporting forms of soil slope in different parts should be considered separately.

2 Natural slope stability analysis

Before excavation, the natural slope has good stability in the present situation, and no sliding or cracking phenomenon is found, so the minimum safety factor of the natural slope under each working condition should be slightly larger than 1. The software calculation shows that the stability of the slope is controlled by the rainstorm working condition. According to the principle that the safety factor of natural slope should be slightly more than 1 under the rainstorm condition, the elevation of underground water level under the rainstorm condition is determined through inversion and trial calculation [3]. According to the inversion calculation of the entrance of the traffic tunnel, when the underground water level rises to 10 m below the slope surface line under the rainstorm condition, the analysis results of natural slope stability are shown in Table 2, and the position of sliding arc is shown in Figure 2. Therefore, the actual situation can be better reflected when the underground water level is raised to 10 m below the slope line under the rainstorm condition [4].

Table 2. Calculation results of slope stability

Slope characteristic	condition	Bishop method	Morgenstern ~ Price method	Allowable safety factor
Natural slope	normal	1.178	1.126	1.15
	Heavy rain	1.074	1.035	1.05
	Earthquake	1.094	1.044	1.05

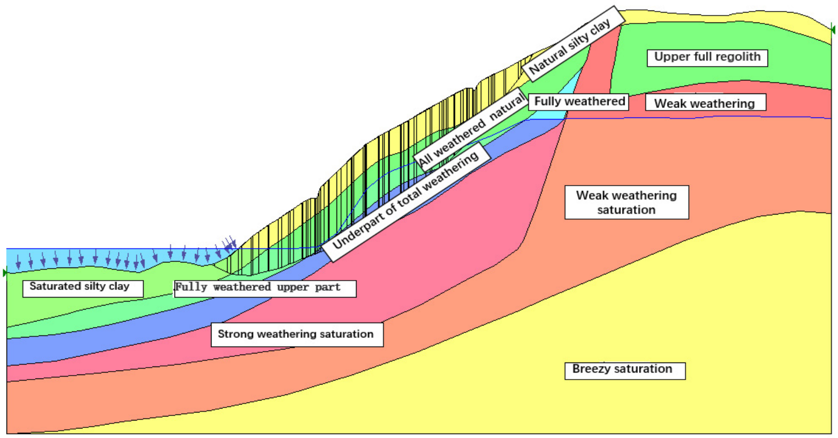

Fig. 2. Schematic diagram of slope sliding surface at the entrance of traffic tunnel (rainstorm condition)

3 Stability analysis of artificial slope

Based on the geological conditions of the plant, on the premise of meeting the requirements of transportation and according to the geological suggestions and planning opinions, the scheme of small excavation and the early entrance of the traffic entrance to the plant is adopted [5]. The slope of the entrance is excavated in accordance with a 1: 0.75 slope ratio and the thickness of the sloping concrete is 1.5 m. The calculation inversion shows that it is reasonable for the water level to rise to 10 m below the slope surface under the rainstorm condition, which is for safety considerations. The groundwater level should be considered as 6 m below the slope line under the rainstorm condition in slope excavation calculation [6].

The grade and safety factor of the entrance slope are shown in Table 3, and the stability analysis results of the artificial slope of the entrance slope of the traffic tunnel are shown in Table 4. The calculation results show that the stability safety factor of the entrance slope of the traffic tunnel does not meet the requirements of the specification under the condition of no support after the excavation in accordance with the 1: 0.75 slope ratio. Slope reinforcement measures shall be taken: 5 rows of 120 T and 30 m long prestressed anchor cables on the slope, the calculated distance of anchor cables is 4 m×8 m (considering the influence of the entrance), and 2 rows of cast-in piles at the bottom of the slope, the distance is 4 m×4 m. After taking reinforcement measures, the safety factor of slope stability meets the specification requirements. The typical sliding arc position is shown in Figure 3 and Figure 4.

The diameter of a single cast-in-place pile is 2 m, the strength of concrete is C30, and the shear resistance provided by concrete is mainly considered. The shear strength of concrete is generally 0.1 ~ 0.15 times the compressive strength.

$$\tau=0.1\times14.3=1.43 \text{ Mpa} \tag{1}$$

Taking the shear strength into the calculation, the shear strength provided by a single pile can be:

$$Q=1430\times\pi\times1^2=4490\ \text{kN} \tag{2}$$

In calculation, according to conservative consideration, the shear resistance provided by a single pile is calculated as 4000 kN.

Table 3. Grade and safety factor of the entrance slope of the traffic tunnel

Slope	Category and grade of the slope	Condition		
		Persistent condition	Brief condition	Occasional condition
Entrance slope of traffic tunnel	Class a, classII	1.15	1.05	1.05

Table 4. Calculation results of slope stability

Slope characteristic	Conditions	Bishop method	Morgenstern ~ Price method	Allowable safety factor	Remarks
Artificial slope No reinforcement	Normal	0.934	0.933	1.15	No slope reinforcement measures
	Heavy rain	0.934	0.933	1.05	
	Earthquake	0.915	0.907	1.05	
Artificial slope Reinforcement measures	Normal	1.220	1.176	1.15	5 rows of 120 T, 30 m long prestressed anchor cables on the slope, spacing 4 m×8 m. 2 rows of cast-in piles at the bottom of the slope, spacing 4 m×4 m.

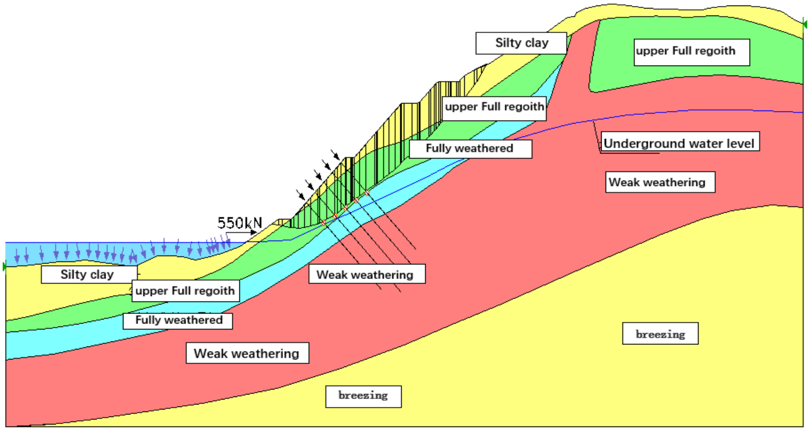

Fig. 3. Schematic diagram of artificial slope sliding surface at the entrance of traffic tunnel (C-C artificial slope has reinforcement measures, under normal conditions.)

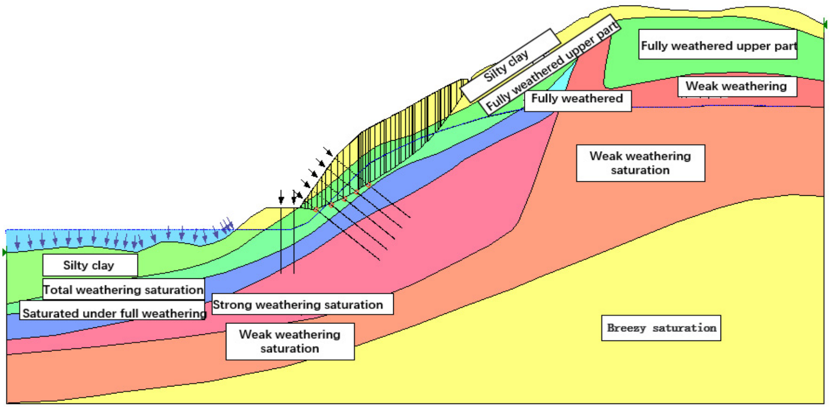

Fig. 4. Schematic diagram of artificial slope sliding surface at the entrance of traffic tunnel (reinforcement measures for artificial slope - rainstorm condition)

4 Support design

The high soil slope at the entrance of the traffic tunnel adopts the support form of unbonded prestressed anchor cable combined with slope-pasting concrete [7]. In order to ensure the safety and stability of the road surface at the entrance of the traffic tunnel and the slope below, concrete anti-slide piles are added [8]. The anti-slide piles are connected by connecting beams, and the combined action of the anti-slide piles and the surrounding soil is used to transfer the sliding force of the soil to the stable stratum. The anchorage action of stable strata is used to generate passive resistance to balance the soil sliding force and increase the anti-sliding force of a high soil slope. The supporting profile is shown in Figure 5 [9].

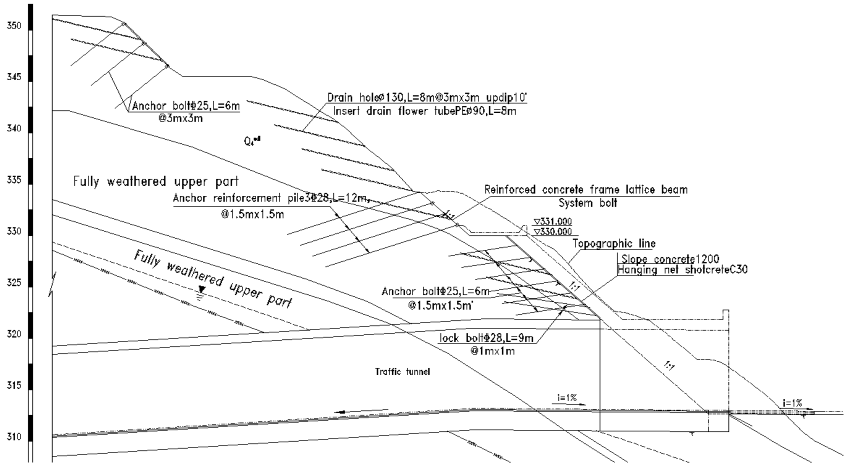

Fig. 5. Supporting profile of traffic tunnel into the factory

5 Conclusion

1. The stability of a high soil slope is of vital importance to safety in practical engineering. If it is not paid attention to, it will have a great impact on the stability of the slope around the reservoir, especially after impounding the slope.
2. GeoStudio software is used to analyze and compare the stability of the natural slope in the early stage of excavation through two limit equilibrium methods, and the accuracy of calculation is increased. Relatively speaking, we have a preliminary understanding of the actual geological condition of the slope and achieve the purpose of slowing down the slope according to the actual terrain and excavation slope ratio. Then the artificial slope (no reinforcement measures) and artificial slope (reinforcement measures) stability calculation and analysis [10] are implemented.
3. For the support of a high soil slope, whether it is to adopt slope wall support, to ease the slope to set an anti-slide pile, or to carry out strong support of frame beam anchor cable system, the expected effect can be achieved in the end. The limitations of each support scheme are worth further optimization and improvement in engineering practice.

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