Case study of cutting slope with progressive failure due to continuous excavation

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ABSTRACT

This paper reports a case study of progressive failure on a high cut slope due to continuous excavation. The characteristics of each stage failure induced by excavation are analyzed through geological investigation and field monitoring. The slope safety situation was monitored and analyzed. The monitoring results provide the important guidance for slope dynamic design and construction. It is important that the reinforcement of pre-stressed anchoring cables for the slope should be carried out after the slope excavation accomplished as soon as possible. Slope construction monitoring plays an important role in ensuring high slope safety. The results revealed that the slope instability was triggered by the continuous excavation of the slope, and the failure mode of slope is progressive sliding.

Keywords: instability, continuous excavation, high cut slope, failure mode

1 INTRODUCTION

In recent years, with the extension of expressway to mountainous areas, a large number of high cutting slopes have appeared in China. High slopes are often affected by terrain conditions and human activities, and are often prone to landslide disasters (Wang et al. 2013, Xu et al. 2012, Zhang et al. 2012, Zhang et al. 2014). The high cutting slope of highway usually has a long construction period for excavation and reinforcement, but in this long period, it often faces the interference of continuous rainfall, snow weather and other environmental factors. If there is no good organization and construction scheduling, the excavation slope does not have timely reinforcement measures, which is likely to cause the slope stability to gradually reduce and makes the deformation of rock and soil mass accumulates, and finally sliding failure occurs.

Through the study on the geomechanical model test of soft rock slope, under the condition of layered excavation without retaining structure, unloading stress will cause large deformation of the slope and eventually lead to slope instability (Xiao et al. 2007). Guo et al. (2013) based on the strength reduction method and limit equilibrium method calculation, the safety factor of slope gradually reduces with excavation, and adopting the construction form of excavation with supporting meantime is very necessary. During the excavation process of soft rock, the horizontal displacement and the vertical displacement showed gradually increasing trend, the vertical displacement of different feature points was generally bigger than the horizontal displacement (He et al.

2013). Therefore, it is necessary to adopt reasonable construction methods and optimize the design of the strengthening and enhancing engineering (Nie and Zhou 2011).

This paper presents a siltstone high slope which is instability during excavation and construction of K443+260~K443+585 in Renbo Expressway, Guangdong Province, China. The field monitoring of surface displacement, deep displacement and anchor stress was carried out. The process of deformation non convergence development and gradual traction failure under repeated disorder excavation is analyzed. The monitoring and analysis results can provide the basis for dynamic design and information construction of slope. To ensure the safety and stability during slope excavation construction, and provide reference for similar projects.

2 PROJECT OVERVIEW

2.1 Engineering geological properties

According to the geological survey report, the main rock and soil layers of the studied slope are residual silty clay (Table. 1), fully weathered to strongly weathered siltstone (soil; D_3^m), strongly weathered siltstone (fragmented; D_3^m), moderately weathered siltstone (fragmented; D_3^m), and slightly weathered siltstone (thick layer; D_3^m). The main inclination of the strata is $110^\circ \sim 120^\circ$. The slope excavation surface inclines to 122° , and the relationship between the rock strata and the slope surface is a small-angle bedding slope.

Table 1. Property and distribution of main soil layers of the slope.

Name of stratum	Number	Characteristics	Physical and mechanical parameters			Distribution
			Unit weight (kN/m ³)	Cohesion (kPa)	Internal friction angle (°)	
Silty clay	Q ^{dl}	Hard plastic, including weathered gravel	18~19	26~29	23~26	Sporadic distribution with a thickness of 5.40 m
Fully weathered siltstone	D ₃ ^m	Semi-rock and semi-soil, very soft	21~22	26~33	28~30	Full site distribution, thickness 10.00~28.20 m
Strongly weathered siltstone	D ₃ ^m	The fracture is well developed and the rock is relatively soft.	21~22	30~33	30~32	Local distribution, thickness 1.50~6.50 m
Moderately weathered siltstone	D ₃ ^m	The rock is relatively broken and hard.	22~23	35~40	32~35	Local distribution, thickness 5.90~11.50 m
Slightly weathered siltstone	D ₃ ^m	Layered structure, hard rock	22~23	35~40	32~35	Full site distribution, with the maximum thickness of 11.50 m

2.2 Initial reinforcement design scheme for the slope

The original design of the slope is a 6-grade excavated slope (Fig. 1) with the maximum height up to 62 m. The slope ratios of both the 1st and the 2nd grade slopes are 1:0.75, the slope ratios of the 3rd to 5th grade slopes are 1:1, and the slope ratio of the 6th grade slope is 1:1.25. The heights of the 1st to 5th grade slopes are all 10 m, and the height of the 6th grade slope is 12 m. Benches with a width of 2 m are set between any two adjacent grade slopes. The 1st grade slope is strengthened with four rows of anchor lattice beams, and the length of the anchorage segment is 8 m. The 2nd to 4th grade slopes are strengthened with three rows of anchor cable frame beams, and the length of the anchor cable is 20 m, 22 m and 24 m, the length of the anchorage segment is 10 m, and the design pre-stress is 400 kN.

Fig. 1. The reinforced profile of initial design scheme (cross section of k443+420).

3 EXCAVATION AND DEFORMATION PROCESS

The slope is excavated from top to bottom, and the construction process can be roughly divided into four stages. The main construction contents and slope stability conditions of each stage are summarized in Table 2.

The excavation of the slope began in September 2016.

To speed up the progress of the construction, the upper 3 grade slopes were excavated continuously without any reinforcement measures. Affected by the excavation, the bare rock and soil mass on the slope underwent unloading and relaxation deformation, which resulted in shallow collapse on the fourth and fifth grade slopes on November 24, 2016.

Then, in the third stage, from January to April 2017. Affected by the seasonal rainfall in the region, the actual construction time is limited, and the anchor cable is completed grouting and tensioning in such a tight construction period, lead to insufficient anchoring force of most cables. The slope showed accelerated sliding and deterioration of stability, producing local uplift on the leading edge, and the original collapse area was triggered and moved.

Finally, in the fourth stage, from May to August 2017. Some areas have been excavated to the slope toe, and the disturbed areas have not been reinforced in time. Cracks appeared on the natural slope near the electric tower at the top of the slope.

4 MONITORING INSTRUMENTATION

4.1 Monitoring scheme and layout

The instruments in the monitoring system include four deep boreholes, four anchor cable dynamometer and eight surface displacement monitoring points. Fig. 2 shows the detailed arrangement of the monitoring instruments in the study area.

Fig. 2. Layout of the site monitoring points on the slope

Table 2. Slope construction process at section K443+260~K443+585

Construction stage	Time interval	Construction content	Deformation and instability process of the slope
I	2016-09—2016-10	The 6th grade slope was excavated without reinforcement	Stable state
II	2016-11—2016-12	The excavation of the 4th to 5th grade slopes were completed, without any reinforcement measures	Shallow collapse on the fourth and fifth grade slopes on November 24, 2016. The collapse area was approximately 20 m in length and 8 m in height, and it was a whole block of loose collapse
III	2017-01—2017-04	The 4th to 5th grade slopes were reinforced with anchor cable and then excavated the 3rd grade slope	Local uplift on the slope leading edge, and the original collapse area was triggered and moved
IV	2017-05—2017-08	The 3rd grade slope was reinforced with anchor cable, and then the mountain partially excavated to the 1st grade slope.	Cracks appeared on the natural slope near the electric tower at the top of the slope. The maximum width and depth of the cracks were 7 cm and 70 cm, respectively

4.2 Results and analysis

Stage II of slope construction (2016-11—2016-12): In the second stage, only the surface displacement is arranged. Due to continuous excavation and no reinforcement measures taken in time, the surface displacement rate of the slope shows an accelerated upward trend (stage II in Fig. 3). Under the influence of continuous excavation disturbance, the maximum surface displacement at the end of this stage is 29 mm.

Stage III of slope construction (2017-01—2017-04): In this stage, the surface displacement, depth displacement and the anchor force are monitored regularly. For the surface displacement data (Fig.3), the change of displacement shows an increasing form of non-convergence. The maximum displacement point is located at the 5th bench, and the maximum displacement is 118mm. Similarly, the tensile force of the anchor cable increases abnormally (Fig. 4), which is contrary to the conclusion that the stress of the anchor cable should be lost after tensioning, this indicates that the anchor cable is subjected to a large sliding force generated by the sliding body at this stage, and anchor cable plays a positive role in anti-sliding. The deep displacement monitoring results can be clearly seen (Fig. 5 and Fig. 6), during this period, the slope entered the stage of accelerated deformation. When CX1 and CX2 were monitored on March 20 and April 2, 2017, it was found that only part of the monitoring instruments could be inserted, so it was judged that the displacement of the slope was too large and both boreholes were cut. The intersected point of CX1 was at 11 m and that of CX2 was at 19 m. The maximum cumulative displacements of CX1 and CX2 before shearing were 36.64 mm and 70.38 mm, respectively. From February 28, 2017, to March 28, 2017, the average displacement rate of the CX1 borehole at a depth of 11 m was 1.72 mm/d and that of the CX2 borehole at a depth of 19 m was 2.1 mm/d. Both sets of data showed that the slope had a deep landslide with an obvious sliding surface.

Slope construction stage IV (2017-05—2017-08): After both boreholes of CX1 and CX2 were broken,

two new boreholes of CX3 and CX4 were added to the 4th bench of the original section. According to three groups of data, the overall displacement of the slope is not controlled, and each group of data increases significantly, with the maximum anchor force of 581 kN and the maximum surface displacement of 141 mm.

Based on the above monitoring data and field investigation, the deformation and failure of the slope mainly experienced four stages: local collapse of the slope surface, formation of cracks at the foot of the slope, leading edge extrusion and trailing edge tension cracks. The failure mode of slope is progressive sliding.

Fig. 3. Change of slope surface displacement with time.

Fig. 4. Change of anchor force with time at the section of K443+400.

Fig. 5. Cumulative deep displacement curves at the section of K443+420: a displacement at CX1 and b displacement at CX3.

Fig. 6. Cumulative deep displacement curves at the section of K443+400: a displacement at CX2 and b displacement at CX4.

5 CONCLUSIONS

The progressive failure on a high cut slope are analyzed based on the field investigations and monitoring after each stage. The following conclusions can be drawn:

(1) Continuous excavation is one of the main causes of slope deformation and instability, so it is necessary to reinforce the slope in time after excavation, and then carry out the next stage of excavation. At the same time, in the whole construction process, time should be reasonably organized to avoid construction in rainy season as much as possible.

(2) Slope monitoring can accurately reflect the

deformation trend and stress state of the slope, which is a very necessary means to ensure the construction safety of the slope, and provides reliable guidance for the dynamic design and construction of the expressway slope.

(3) In the construction process of high cutting slope, the corresponding dynamic flexible design shall be carried out in time according to the stratum lithology, monitoring data and artificial patrol information revealed after excavation. The original design scheme shall be adjusted in time and effectively, the design scheme shall be optimized, the slope diseases in the construction process shall be effectively controlled, and the orderly and reasonable information construction shall be realized.

(4) Carry out scientific planning of slope construction process, avoid adverse construction seasons such as rainy season, selecting professional teams with strong technical level to carry out construction, strictly control the construction quality of the project, and provide quality assurance for the long-term safety of the slope project.

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