Static and Dynamic Stability Analysis of the Gravity Anchorage Slope Using the Three Dimensional Finite Element Method

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Abstract: Stability evaluation of the high and steep slope formed by foundation excavation of a gravity anchorage is a key problem in safe construction and operation of the suspension bridge. Taking the gravity anchorage slope of Taoyuan Jinsha River Suspension Bridge of Dayong Expressway in Yunnan Province as a case study, through the field investigation and geological borehole data, a three dimensional finite element model was established to evaluate the stability of the anchorage foundation slope under the excavation and earthquake actions. The reinforcement effect of the support system including the anti-slide piles, bolts, pre-stressed anchor cable and lattice beam was studied. Using the support system, the maximum displacement of the slope decreased by 41%, and development of the plastic zone of the slope was controlled during the earthquake. The research results are used in the construction and design of this project, and also can be used for reference by the similar projects.

1. Introduction

With the rapid development of road traffic construction in China, suspension bridge design and construction technology are becoming more and more mature, and more large-tonnage and long-span suspension bridges are built. Anchorage is the main load-bearing structure of the suspension bridge, which can be divided into gravity anchorage and tunnel anchorage. Compared with the tunnel anchorage, construction of a gravity anchorage is relatively simple and the adaptability is better, so most of the completed suspension bridge projects adopt gravity anchorage [1].

At present, the research on gravity anchorage mainly focuses on the mechanical response of gravity anchorage itself. Taylor [2] put forward the concept and design idea of anchorage based on its own stability in 1982 and applied it to practical engineering. Andersen et al. [3] assessed the structural safety of the gravity anchorage of the suspension bridge across the eastern channel of Great Belt using the limit state formulations based on work principles. Tatsumi et al. [4] believed that the anchorage strength is conservative and large enough than the engineering requirements, and the stress concentration area in the anchorage system should be emphatically considered for strength analysis. Carter [5] introduced an innovative structural concept for the design of gravity anchorage of Izmit Bay Bridge in highly seismic regions. Kim et al. [6] analysed the stability of the gravity anchorage of the Yi Sun-sin Bridge during the
excavation and construction process. Wu et al. [7] studied the nonlinear problems of the anchorage system of the Xinghai Bay Sea-crossing Suspension Bridge using the three dimension finite element model.

The existing research has not combined the gravity anchorage with the stability of excavated slope. During the construction of suspension bridges in southwest China, high and steep slopes are often formed in the foundation excavation of the gravity anchorage, and these gravity anchorages are mostly located in sites with high seismic intensity, so it is very important to evaluate the dynamic stability of the slopes under the earthquake action. Based on the gravity anchorage slope of the Taoyuan Jinsha River Suspension Bridge, Yunnan Province, China, the excavation processes of the anchorage foundation pit are simulated using the three dimensional finite element method, the dynamic stability of the slope under earthquake is analysed, and the reinforcement effect of the support system is studied.

2. Project overview and numerical model
Taoyuan Jinsha River Bridge is located in the southeast of Zhaizi Village, Taoyuan Town, Yongsheng County, Lijiang City, Yunnan Province, China. It is the controlling project for the construction of Dali-Yongsheng Expressway. The main span of the bridge is the single-span simply supported steel box girder ground anchorage suspension bridge. The main span of the bridge is 636m long, and gravity anchorages are used on both sides. In view of the topographic and geological conditions of the gravity anchorage engineering site of Dali bank, combined with the excavation design scheme of the anchorage foundation pit and the geological boreholes data, the three dimensional finite element model of the anchorage foundation pit is established. The three dimensional model of foundation pit after excavation is shown in Fig. 1 (a), the rock and soil layers include the crushed stone, block stone, slightly dense-medium dense silt, dense-semi-diagenetic silt, dense silt and limestone strata, and there are 403460 nodes and 2260007 elements. Fig. 1 (b) shows a typical section along the transverse bridge direction of the foundation pit, where the X direction pointing to the east and the slope is located on the east side.

The model is used to simulate the excavation process of the anchorage foundation pit step by step, then the dynamic response of the slope under earthquake is calculated. Finally, the support system is simulated.

3. Slope stability under excavation and earthquake

3.1. Stability analysis for stepwise excavation
Figure 2 shows the displacement contour and vector of the typical section during stepwise excavation. The displacement contours show that the displacement is mainly perpendicular to the excavation surface, as reflected in the uplift of the pit bottom and the horizontal extrusion of the side wall into the pit. After the first excavation step, the maximum displacement is located at the bottom of the pit, about 2cm. After the second excavation step, the maximum displacement occurs in the crushed stone area on the east side of the pit bottom, which is about 5 cm. After the third excavation step, the maximum displacement
occurs in the silty sand layer of the bottom and west side of the pit, which is about 5 cm. After the fourth excavation step, the maximum displacement occurs in the crushed stone area of the pit bottom and the foot of the pit slope at the eastern side, which is about 9 cm. When the excavations are completed, the maximum displacement on the slope is about 8.5 cm, which means that the slope during the excavation process maybe unsafe.

3.2. Seismic dynamic stability analysis
Seismic dynamic stability analysis of the anchorage foundation pit slope is carried out after the stepwise excavation. The input seismic acceleration time history is shown in Figure 3, where the duration is 42s and the peak acceleration is 3.545m/s$^2$. Figure 4 is the maximum shear strain increment distributions of the typical section at different times. It shows that the maximum shear strain increment mainly concentrates on the pit slope surface at the initial time. At 5s, the maximum shear strain increment develops along the boundary of limestone layer and crushed stone layer. At 20s, the increment value of maximum shear strain exceeds 0.07, which means that the slope of anchorage foundation pit is instability.
4. Analysis of the supporting effect

4.1. Support scheme

According to the design scheme of the anchorage foundation pit, the slope is divided into five levels from the foot to the top. Based on the three-dimensional finite element model, the model of the supporting system is established (Figure 5a). As shown in Figure 5b, 20 anti-slide piles with length of 30m are arranged on the platform of the second level slope, 135 bolts are arranged on the second level slope, and 213 pre-stressed anchor cables are arranged on the third, fourth and fifth level slope. The bolts and the pre-stressed anchor cables are connected with the frame girder on the pit slope surface.
4.2. Slope stability analysis under the supported condition

Figure 6 shows the displacement contour of the anchorage foundation pit after the excavation under supported condition. It shows that after the excavation, the pit slope has a maximum displacement of 5cm. Compared to the unsupported condition, the support structure restrains the development of pit slope displacement, which reduces the maximum displacement by 41%, and significantly improves the stability of the anchorage foundation pit slope during excavation.

As shown in Figure 7, under the earthquake action, comparing the plastic zone distribution at 45s under the supported condition with that under the unsupported condition, the plastic zone on the pit slope with the support system is obviously reduced, which indicates that the designed support system has a good anti-seismic effect.

Figure 6. Displacement contour of anchorage foundation pit after excavation under supported condition

Figure 7. Comparison of plastic zone distribution of typical section under unsupported and supported condition
5. Conclusion

Aimed at the stability of gravity anchorage foundation pit slope of Dali Bank of Taoyuan Jinsha River suspension bridge on Dayong Expressway in Yunnan Province, a three dimensional numerical model is established. The static and dynamic stability of anchorage foundation pit slope under excavation and earthquake action is analyzed. The supporting effect of anti-slide pile, bolts, pre-stressed anchor cable and frame grillage beam is studied. The main conclusions are as follows:

- The displacement is mainly perpendicular to the excavation surface, as reflected in the uplift of the pit bottom and the horizontal extrusion of the side wall into the pit. After the stepwise excavation, the maximum displacement of the eastern pit slope is about 8.5cm. Under the supported condition, the displacement of the eastern pit slope is 5cm. Compared to the unsupported condition, the support system constrains the development of the pit slope displacement, reduces the maximum displacement of the pit slope by 41%, and significantly improves the stability of pit slope during excavation.

- Under the earthquake action, the plastic zone of the pit slope of anchorage foundation pit runs through the boundary of limestone layer and gravel soil layer, resulting in instability failure; compression-shear failure occurs mainly on the sliding surface, and tension-shear failure occurs mainly on the top of the pit slope. Under the support condition, the plastic zone on the pit slope with the support system is obviously reduced, and the pit slope is in a stable state during the earthquake, which means that the support system has a good anti-seismic effect.

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