Comprehensive Analysis of the Stability and Design of a High Cutting Rock Slope

SUN Ying\textsuperscript{1,2} and ZHANG Guo-cai\textsuperscript{1,2}

\textsuperscript{1}CCCC Fourth Harbor Engineering Institute Co., Ltd, Guangzhou 510230, China
\textsuperscript{2}CCCC Key Laboratory of Environment Protection & Safety in Foundation Engineering of Transportation, Guangzhou 510230, China.

Abstract. To realize the harmonious unification of safety and economy when designing slopes, we used geological analysis and performed a qualitative evaluation to investigate the controlling factors affecting slope stability. The finite element strength reduction method (SRM) and traditional limit equilibrium method were used to investigate the stability safety factor of a high and steep rock cutting slope in Northern Guangdong. The results showed that the influence of the structure surface on slope stability is determined by the combination of the structure surface, shape of the structure surface, filling between structure surfaces, penetration of the structure surface, and water content and sensitivity of the structure surface; the influence of only one factor on slope stability is limited. We analyzed the slope and design it optimally; the results showed after reinforcement of the second-level slope, the slope revealed an incompletely penetrated shallow slip zone and an evident deep potential slip zone. Compared to the reinforcement that was without an anchor cable, the safety factor increased when the potential slip zone moved down. Based on the SRM and traditional limit equilibrium method, the design scheme of this slope meets the safety requirements of permanent slopes, and the excavated stone can be used for roadbed filling. Thus, the optimized design scheme can coordinate safety and economic indicators. Moreover, the application of strong engineering measures to the joint development of slope in engineering practice is conservative and unreasonable. The design of these slopes can provide a reference for slope design and construction.

1. Introduction
A high cutting slope is usually designed for expressways in hilly terrains, where high and steep rock cutting slopes are abundant, to meet technical requirements\textsuperscript{[1]}. High and steep slopes constitute the environment of engineering construction and line operation, and their stability is an essential prerequisite.

The evaluation of slope stability has always been the basic proposition of geotechnical mechanics\textsuperscript{[2]}, and is considered as the first priority in engineering design and construction. In terms of slope stability research methods, combining actual physical and mechanical properties of rock and soil to conduct qualitative and quantitative (semi quantitative) analyses has always been an important topic in slope engineering research\textsuperscript{[3]}. Qualitative analysis includes engineering geological analogy and graphic methods, whereas quantitative analysis mainly includes limit equilibrium and numerical analysis methods. At present, both methods are primarily preferred for slope stability analysis\textsuperscript{[4,6]}. This article considers the high and steep rock cutting slope on the right side of Guangzhou–Lianzhou expressway as an example. The limit equilibrium method, engineering geological analysis, and finite
element strength reduction method (SRM) were used to evaluate the stability of this slope. From the aspects of safety and economics, the article optimized the original design scheme on the basis of slope stability.

2. General Situation of the Project

2.1 Regional geological structure
The terrain where the high and steep rock slope is located fluctuates greatly. The slope is steep with relatively dense vegetation, and its natural slope angle is 17°. The landform belongs to the weak clastic rock group area (II), alluvial plain, and valley landform. Part of its landform is plain and composed of piedmont alluvial proluvial fan. This site is located in a hilly denudation landform with a simple rather than an adverse geological structure, and its regional geology is stable. According to the seismic parameter zoning map of China (GB 183006-2015), the peak acceleration of earthquakes in the site area is 0.05 g, and its characteristic period of seismic response spectrum is 0.35 s, corresponding to grade VI geological basic intensity. No adverse geology, special rock, and soil are observed in the site. Therefore, this article did not consider the influence of an earthquake in the evaluation of the stability of this slope.

2.2 Engineering geological conditions
With 200.0 m length and 36.14 m maximum excavation height, this slope, which is located 0.5 km south of Shiying Village, Xingzi Town, Lianzhou City, and Qingyuan City (Fig. 1), passes through a precipitous terrain. Its natural slope angle is deep, and a simple rural road exists near the bottom of the hillside, resulting in inconvenient traffic. Fig. 2 shows the engineering geological plane of this slope.

![Fig. 1 Project location map](image-url)
In accordance with existing data, the strata from top to bottom were divided into the following: a quaternary silty clay (Q$_{el}^{4}+d$) and moderately weathered sandstone within the Upper Cretaceous Nanxiong Formation; rock cores of moderately weathered sandstone with sandy texture, layered structure, and slightly developed joint fissures that were relatively complete and mostly columnar (section length: 7–30 cm, maximum section length: 40 cm, block diameter: 20–60 mm, and core rate: 90%). Fig. 3 shows the geological section.

The surface water in the site area is mainly composed of atmospheric precipitation and gully water. The water discharge varies with seasons and is easily released to the catchment area of the gully bottom. In general, the surface water has minimal effect on the construction of high slopes. However, in rainstorm weather, the amount of water converging into the gully is large, which affects the stability of the high slope. The groundwater types are mainly quaternary pore phreatic water and bedrock fissure water. The depth of the stable water level of the borehole approximates 15.0 m. The quaternary pore phreatic water mainly occurs in the slope residual soil layer. The aquifer thickness is small, and its water yield and permeability are weak. Replenished by atmospheric precipitation, the pore phreatic water has evident seasonal characteristics and discharges in the form of evaporation, horizontal runoff, or vertical infiltration into bedrock fissures. The bedrock fissure water, which is buried in the fissure on the weathering zone of the bedrock, is mainly supplied by atmospheric precipitation and vertical infiltration of overburden.

2.3 Original design scheme
(1) the slope was divided into four grades; the slope ratio of the first-, second-, and third-grade slope was 1:1.0, whereas that of the 4th one was 1:1.25; (2) the anti-slide piles with the cross-sectional area 2.0 m × 3.0 m, gap 5 m, and length 16 m were used in the second-grade slope; (3) the length of the first stage was 5 m, whereas that of the other stages was 2 m; (4) the anchor lattice-beam net and spraying of foreign soil were used in the second- and third-grade slopes; (5) the spraying of foreign
soil and planting were used in the second-grade slope; (6) the intercepting ditch was set at the top of the mountain and prefabricated blocks were used to set the intercepting ditch at all levels of platforms. Several deep drainage pipes were set on the slope. According to the construction experience in this area, the construction unit assumed the inclusion of an optimal space in the optimal design and put forward the demand for an optimal design.

For the purpose of ensuring the safety of the project and reducing unnecessary cost, this article combined traditional slope design methods, including engineering geological analysis and numerical calculation, to calculate and analyze the stability of cutting slope in question to optimize the design scheme.

3. Analysis of Slope Stability and Optimization of the Original Design Scheme

3.1 Engineering geological analysis

In general, joint occurrence and rainfall are the main factors affecting the stability of slope. There was only one group of joint fissures developed in this slope with the occurrence of 31:295°∠24°. After excavation, the inclination of joints was the same as that of the artificial slope, and the dip angle was smaller than that of the slope toe, which is not conducive to slope stability. As a type of structure plane, the influence of joints on the stability of the slope is decided by several factors, such as its combination state, shape, filling material, connectivity, moisture content, and water sensitivity of the structural plane. However, the influence of joints on slope stability is limited because they are closed generally. The influence of moderately weathered siltstone on slope stability is great due to its layered structure. No filling material was observed between the structural planes of sandstone, which means that the structural plane had a slight influence on slope stability. According to geological drilling data, the rock core was comparatively complete and mostly columnar with closed joints and no filling. Thus, the structural plane had poor connectivity and slight influence on the stability of the slope. The water content of the structural plane below water level was higher than that of the sandstone above water level. However, the sandstone was mostly removed by excavation. Although the lower rock mass was relatively complete, it had low water content, thus indicating its negligible influence on the slope stability. In conclusion, joints influence the slope stability, but the influence was little when we considered various factors.

The influence of rainfall on slope stability was to weaken the shear parameters of rock and soil through the erosion of seepage channels. After the excavation of the slope, its silty clay and surface-rock mass were removed. Thus, the phreatic water in the silty clay did not affect the stability of the slope, whereas the bedrock fissure water that was buried in the fissures of the bedrock weathering zone did. The fissures in the upper weathering zone were more developed than the ones in the lower weathering zone. With the upper rock mass being partially removed and the fissures of lower rock mass being relatively undeveloped, the bedrock fissure water was mainly supplied by atmospheric precipitation and vertical infiltration. When the overburden was removed and the vertical infiltration supply disappeared, precipitation was discharged quickly along the rock slope to the outside of the slope toe, and its recharge to bedrock fissure water was limited. In general, rainfall showed a moderate effect on the rock slope stability. In considering rainfall, the slope design should focus on the interception and drainage rather than adopting strong support to save cost on the basis of ensuring safety.

Joints and rainfall were the main factors affecting the slope stability. The influence of number and occurrence of joints on the slope stability was not significant, whereas that of rainfall can not be neglected.

3.2 Optimization scheme

Combined with the engineering geological analysis and method used in the original design scheme, this article considered that the anti-slide pile scheme was extremely conservative. Considering the controlling factors of the slope stability, the following optimization scheme was proposed:

(1) The slope was graded every 10 m.
(2) The slope ratio of the first-, second-, and third-grade slope was 1:1.50, and the fourth-grade slope was 1:2.00; the step width was 2 m.
(3) The second-grade slope was reinforced by an anchor cable with the length 28 m and anchorage section length 10 m.
(4) The anchor cable was arranged at the node of the anchor cable lattice beam. The horizontal and vertical spacing of the lattice beam is 3.0 m, and its section size was a square with the length 0.5 m.
(5) The side ditch was set at the foot of the slope.
(6) The slopes were protected by hanging nets, spraying, and planting grass with foreign soil, and deep drainage pipes, drainage holes, and intercepting ditches were set up.
(7) When one grade was excavated, plain concrete was supposed to be sprayed on the slope surface for temporary protection before the implementation of protection and reinforcement measures.

Fig. 4 Geological section of the optimization scheme

3.3 Finite element SRM
The engineering geological analysis can only evaluate the stability of the slope qualitatively and analyze controlling factors affecting its stability. However, this analysis cannot evaluate the stability of design schemes and the effect of support schemes quantitatively. Therefore, quantitative analysis was needed for a scientific and reasonable design.

The shear strength reduction factor was defined as the ratio of the maximum shear strength exerted by the soil in the slope to the actual shear stress generated by external load in the slope at a fixed external load. The shear strength reduction factor defined here is consistent with the slope stability safety factor defined in the limit equilibrium analysis essentially.

In SRM, the parameters (φ and c) of shear strength are reduced by a shear strength reduction factor $F_r$, as defined in accordance with Eqs. (1) and (2). The reduced shear strength parameters $c_r$ and $φ_r$ were used to replace the original ones ($c$ and $φ$) as shown in Eq. (3).

$$c_r = c / F_r $$

$$φ_r = \tan^{-1}\left(\frac{\tan φ}{F_r}\right) $$

$$τ_{rP} = c_r + σ \tan φ_r $$

where $c_r$, $φ_r$, and $τ_{rP}$ are the reduced cohesion, friction angle, and shear strength, respectively [7-8].

The initial value of the reduction factor $F_r$, should be small enough to ensure that the slope deformation is almost elastic at the beginning. According to the principle of dichotomy, the reduction factor $F_r$ increases gradually, and the reduced strength index continues to gradually decrease until the slope becomes unstable.
The reduction coefficient value before the overall instability is the stability safety factor of the slope. This article used the finite elements SRM in Midas-GTS software to analyze the stability of a slope \(^9\). In natural state, the slope was stable. However, when it was excavated, the stress was redistributed and stress concentration was observed in several areas. In case of a rainstorm, the weight and pore water pressure of this slope increased, which were unfavorable to the stability of the slope. The design scheme considered the most unfavorable conditions for calculation and design. We considered the rainstorm to calculate the stability of this slope. We selected the parameters for stability calculation by considering the synthetic parameters of the original design, regional empirical parameters, and recommended parameters (Table 1) \(^10\).

The SRM was used to calculate the stability of the slope in original design scheme, optimization scheme, and optimization comparison scheme.

### Table 1 Physical and mechanical parameters

| Name                        | unit weight (kN/m\(^3\)) | cohesion (kPa) | friction angle (°) |
|-----------------------------|--------------------------|----------------|-------------------|
| hard plastic silty clay     | 19                       | 18             | 17                |
| Moderately weathered argillaceous siltstone | 23                       | 30             | 26                |

Table 2 shows the safety factor of the calculation results. The safety factor of the original design scheme was 1.92, whereas for the permanent grade-I slope, the safety factor of 1.30 was large enough to meet the requirements. Thus, the original design scheme was conservative. The optimization scheme had the safety factor 1.43 and met the requirements of permanent slopes. On the other hand, the top of the slope can be pushed 23 m outward in this scheme. Thus, several spaces had to be excavated, and the excavated stone can be used for subgrade reinforcement to save cost.

### Table 2 Calculation of the results of SRM

| Scheme                   | scheme               | space can be pushed outward compared with original design scheme / m | factor of safety |
|--------------------------|----------------------|--------------------------------------------------------------------|-----------------|
| original design scheme   | anti-slide piles     | /                                                                  | 1.92            |
| optimization scheme      | The slope ratio of the first-, second-, and third-grade slope was 1:1.50, whereas that of the fourth one was 1:2.00; the width of the slope stage was 2 m, and the second slope was reinforced. | 23               | 1.43            |
| optimization comparison scheme | The slope ratio of the first-, second-, and third-grade slope was 1:1.50, whereas that of the fourth one was 1:2.00; the width of the slope stage was 2 m. | 23               | 1.18            |

In Midas-GTS software, the potential slip surfaces were shown by equivalent strain contours. Figs. 5 and 6 display the plots of the equivalent strain contours of the optimization comparison scheme and optimization scheme. A potential sliding surface was observed in the optimization comparison scheme, whereas an incomplete shallow sliding surface and an evident deep potential sliding surface after the second slope were noted in the reinforced optimization scheme. The safety factor increased with the downward movement of the potential sliding surface.
As shown in Fig. 7, the axial force of the anchor on the free part was the tensile stress. The tensile stress (641.6 kN) was within the bearing capability of the anchor.

3.4 Limit equilibrium method

The limit equilibrium method is based on the principle of static equilibrium and is used to analyze the stress state under various failure modes and evaluate the stability of the slope using the relationship between the anti-sliding force and the sliding force of the slope \([11-12]\). As a traditional design method, the limit equilibrium method is used widely by designers. The traditional slice method, i.e., the bishop method, was used to analyze this slope. The result was 1.88, as shown in Table 3. This finding confirmed the judgment of numerical calculation results. With the safety factor 1.34 (>1.3), the optimized scheme met the requirements of a permanent slope and had its safety factor increase by 1.19% when compared with the optimized
According to the results of the SRM or limit equilibrium method, the optimized design scheme meets the design requirements of a permanent slope with a safety factor of 1.30–1.40. Compared with the original design scheme (safety factor: 1.80–2.00), the optimized design scheme not only meets the safety requirements but also saves the project cost.

4. Conclusions
In engineering practice, imposing strong engineering measures on jointed slopes is conservative and unreasonable. This article evaluated the stability of a slope scientifically and reasonably and optimized the original design scheme at a safe and economic level through engineering geological analysis, finite element SRM, and limit equilibrium method. The multiple conclusions drawn were as follows:

(1) The influence of a structural plane, such as joints, on slope stability is determined by several factors, including the combination state, shape, filling material, connectivity, moisture content, and water sensitivity of the structural plane. The influence of a single factor on slope stability is limited.

(2) Joints and rainfall are the main factors affecting slope stability. The influence of joints on slope stability is not significant, whereas rainfall has a moderate effect.

(3) In consideration of rainfall, the design of this slope should prefer interception and drainage, rather than strong support, to lower cost while guaranteeing safety.

(4) A potential sliding surface occurred in the optimization comparison scheme, whereas an incomplete shallow sliding surface and an evident deep potential sliding surface after the secondary slope had been reinforced in the optimization scheme. The safety factor increased with the downward movement of the potential sliding surface.

(5) In the optimization scheme, the top of the slope should be pushed outward by 23 m. Thus, an excavation space remained for stone excavation, which can be used for subgrade reinforcement to save cost.

(6) According to results, whether the SRM or limit equilibrium method is used, the optimized design scheme meets the design requirements of a permanent slope (safety factor: 1.30–1.40). Compared with the original design scheme (safety factor: 1.80–2.00), the optimized design scheme not only meets safety requirements but also saves project cost.

5. References
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