A new design approach for highway rock slope cuts based on ecological environment protection

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ABSTRACT: With China's fast development, especially that of highways in mountainous areas, there are many unavoidable high cut rock slopes. Specifications for the design of highways in China prescribe that the design of any slope with a height of more than 30m should be compared with bridge and tunnel design schemes, economically. Despite existing guidelines, many high slopes are designed as equally high cuts based on traditional design methods, due to the engineering geological conditions and highway alignment. Actually, these excessively high cuts relative to the natural slope height seriously damages the original ecological environment and groundwater systems, in some cases irreversibly. With the aim of reducing ecological damage, we propose a new design approach which minimizes the ecological and environmental disturbance by decreasing the amount of cut slope through a steep excavation scheme. This approach requires that: (1) the geological conditions are good and the rockmass is self stable; (2) damage to the rock is minimized through use of controlled blasting (buffers, pre-splits); (3) a 20-m high bench be introduced if the local geological conditions are not very good; (4) reinforcement is added where needed to ensure stability during construction; and (5) deformation of the slope and working condition of the reinforcement be monitored to ensure stability. This new design is demonstrated through its application to a cut slope along the provincial trunk highway S223 in Guangdong province. Results from numerical modeling using UDEC reveal that compared with a traditional design scheme for which the cut would be 90 m high, a steeper cut limiting the height to 23.5 m, with the remaining height following its natural profile, would generate a comparable stability state. With cable reinforcement, the stability of slope excavated steeply can be further assured.

1 INTRODUCTION

With China's fast growing economy, numerous road construction projects have obtained great achievements. However, with highway construction, especially in mountainous areas, there are many unavoidable high cut slopes. Specifications for the design of highway subgrades prescribe that the design scheme of slopes with heights greater than 30m should be compared with bridge and tunnel schemes, economically (JTGD-30 2004). Despite existing guidelines, it is still quite common to see many high slopes being designed as high cuts due to the engineering geological conditions, highway alignment, costs and issues related to traditional design ideas. In some cases, the traditional design method of “high backfill, high cut” for mountainous highways seriously damages the original ecological environment and groundwater systems, especially to those areas that are ecologically sensitive where damage is often irreversible. It is quite common practice to add vegetation to greenify a cut slope, however this still has problems such as low survival ratios, high maintenance costs and lack of species diversity. With increased awareness of the importance of the ecological environment, it becomes more urgent to decrease the damage to the ecological environment while ensuring stability during the engineering of high cut slopes.

With the aim of reducing ecological damage, we propose a new design approach which helps reduce ecological and environmental damage by reducing the height of a cut for a high rock slope by steepening the angle of the cut, while ensuring that the slope is both safe and economically feasible.

2 ANALYSIS OF STEEP SCHEME

2.1 *Conditions required for steep scheme*

Although the proposed design scheme results in a reduction in the height of the cut slope, it calls for steepening of the cut, which requires that the geological conditions are favorable, the rock strength high, and the rock mass massive (few joints) and no more than slightly weathered. The rock at the toe of the slope must be stable and self supporting.

2.2 *Construction considerations*

Before construction of slope, it is necessary to construct a surface drainage system (e.g. drainage ditch, intercepting ditch, etc.), as well as incorporate other drainage measures (drain holes, underground drainage tunnel, etc.) as the local groundwater conditions require. During construction, excavation, reinforcement and monitoring should be integrated together, and monitoring should be started even during construction. If the local geological conditions and rock mass quality are not very good, the excavation should incorporate benching, with the advised spacing of 20 m. The steep scheme is based on the rock mass strength being high. If the rock mass is damaged because of uncontrolled blasting, it will be more difficult to ensure stability even if reinforcement measures are taken. Thus, the excavation process should be controlled using buffer blasting, smooth blasting and pre-split blasting. Because rainfall usually postpones construction and causes high water pressures to build up along potential sliding surfaces, decreasing the material strength, it is advised that construction be avoided during rainy seasons when implementing the steep scheme.

2.3 *Stability evaluation*

The stress distribution within the slope can be easily determined using numerical methods like distinct element modeling, with results showing the maximum principal stress being parallel to the slope, with a stress concentration developing at the toe. The iso-line of the maximum shear stress is near circular at the slope toe and the rest almost parallel to the slope surface (Zhang et al. 1994). If the rock strength is low, this shear stress concentration may result in the generation of a plastic zone at the toe and tensile cracks behind the slope crest. The deformation in the horizontal direction caused by the excavation is a key index of slope stability. Given the steeper cut in the steep scheme, upon excavation the redistribution of stresses at the slope's toe will be more significant than that implementing slope angles following traditional design schemes. If reinforcement is not strong enough and in time, these have high stress concentrations may result in excessive yielding and the slope may become unstable.

2.4 *Advantages of steep scheme*

Compared with common cut slope designs, the steep scheme is ecological environmentally more friendly because it decreases the cut slope height, the excavated quantity of rock and soil, the amount of slope surface disturbed and engineering cost. Most importantly, the steep scheme results in less natural vegetation being removed. Figure 1 shows the difference in cut slope profile between the common and steep schemes. Because the slope height is remarkably decreased, difficulties associated with construction and maintenance of the slope is reduced greatly.

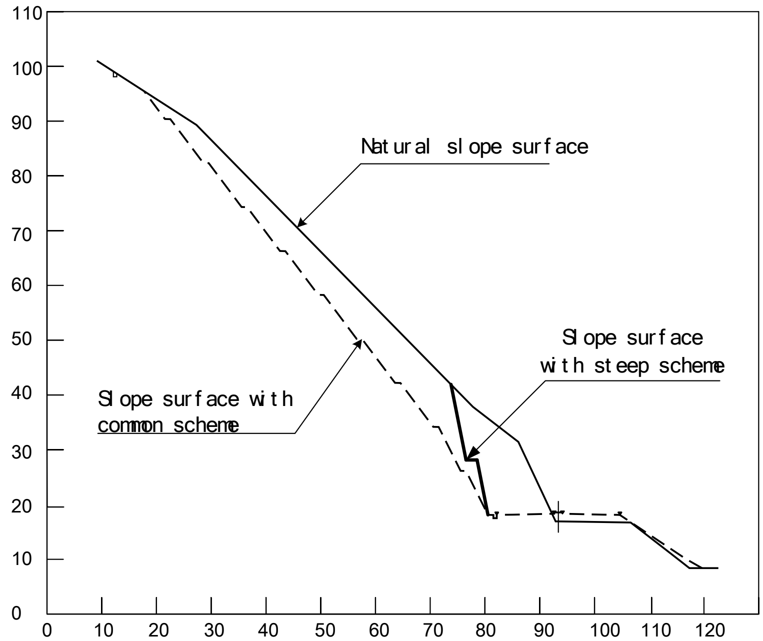


Figure 1. Illustration comparing the cut slope profiles for the common and steep design schemes.

3 CASE STUDY

To illustrate the application of the new design approach, a case study is provided including a detailed analysis using the steep scheme design method. The slope is a typical roadside cut slope along the provincial trunk highway S223 in Guangdong province. The road is on the right side of Meijiang River, the width of subgrade is 22.5m and the natural slope is relatively steep.

3.1 *Engineering geological conditions*

Four test exploration holes extending under the base of the slope were drilled to obtain information on the strata. At the top of the slope is a fully weathered sandstone and mudstone 1.5-3 m thick. Below this, in the middle of slope, is a strongly weathered sandstone with a thickness of 3-6 m. At the bottom of slope is a slightly weathering sandstone with a thickness of 6-12 m. The uniaxial compressive strength of the bottom unit varies ranges from 24.9-49.6 MPa, so the rock falls in the category of hard rock with a RQD equal to 50-90% (Zuyin 2006).

Based on the intensive site investigation undertaken before excavation and construction, a detailed engineering geological map was constructed incorporating discontinuity and other geological structure statistics. The rock mass is bedded and locally fissile. The RQD index is mainly 65, so the rock mass is relatively intact. The strata reversely dips into slope, with layer thicknesses of the strata varying between 0.3-0.9 m. There is a group of conjugated shear joints with spacing 0.2-0.7 m and a small fault which dips steeply out of the slope with little influence on the slope stability. The nature of rock deformation may be controlled by the joint orientation, joint spacing and persistence. A summary of the main discontinuity data is shown in Figure 2.

The nature of the discontinuity surfaces, such as infill, roughness and weathering are important factors. The infill materials in the discontinuities are characterized as sandy clay and remolded clay, containing fragments of sandstone, which is very significant for stability.

The Slope Mass Rating (SMR) classification system is a potentially very useful tool in the preliminary assessment of slope stability, providing information about instability modes and required support measures (Banks 2005). For the case study, the rock is intact and sound, and there is no disadvantageous intersecting structures. The RMR for this slope rates in category III, and the steep slope ratio is considered in the classification.

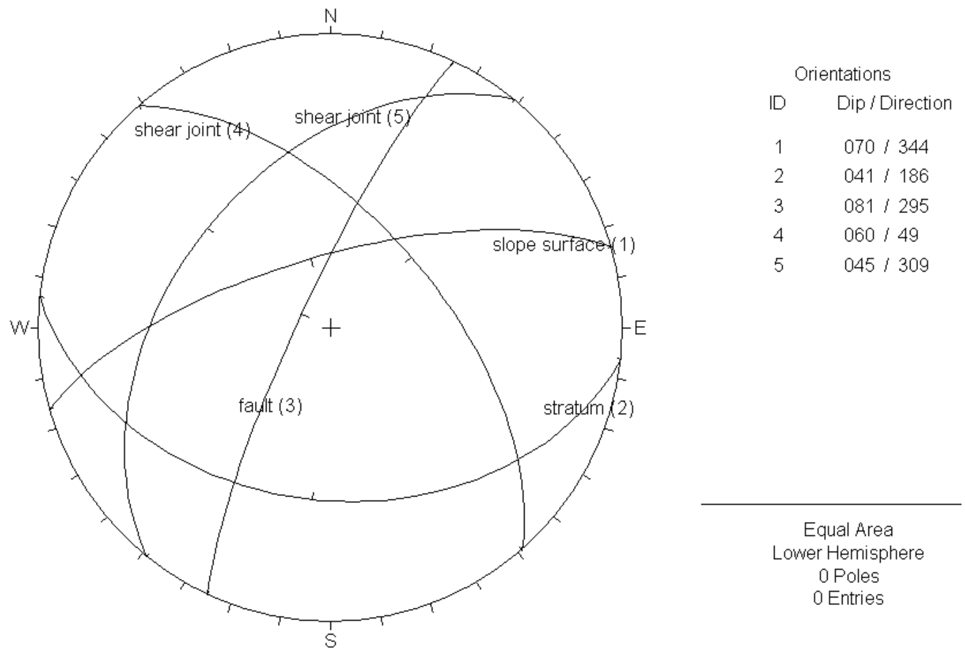


Figure 2. Main joints relative to slope surface for the case study.

3.2 *Original common scheme*

The original design followed that using typical design approaches, and is referred here as the common scheme. The common scheme design would call for a cut slope height of 90 m with 12 benches. The height of each bench is 8m, with bench widths of only 1 m. The slope ratio of the three benches at the bottom of the slope is 1:0.5. These are reinforced with 20m long cable anchors designed with a working tension of 500 kN. The remaining benches follow a slope ratio of 1:0.75 and are only protected with spray-on grass seeding (Li 2007). A typical slope section is shown in Figure 1.

The design is that typically applied to such slopes, with a gentle excavated slope ratio and light reinforcement. Obviously more soil and rock has to be removed as well as the natural vegetation on top, which is environmentally unfriendly. Because the natural mountain slope is quite steep and stable, if adopted, the cut slope would be less steep than the natural slope resulting in a cut height of more than 90m. This means that the cut slope would require most of the natural slope to excavated, disturbing and removing most of the natural vegetation that grows on it.

3.3 *New method: The steep scheme*

The structural stability of slope was evaluated using the stereonet projection based on rock mass mapping and discontinuity analysis from the boreholes. It is concluded that the geological condition is rather good and satisfies the requirements of the steep scheme. Thus, the steep scheme is put forward as shown in Figure 1:

(1) The total height of the slope is 23.5 m, and the ratio of the steep scheme is 1:0.2. There is one bench with a height of 10 m and width of 2 m. The cut slope height above the bench is 13.5 m.

(2) The bench at the bottom is reinforced with anchor bolts with 8 m length and 60 kN design load. Their spacing in the vertical direction is 3.5 m and in the horizontal direction 3 m. The upper cut slope above the bench is reinforced with cable anchors, with 18 m lengths and a designed load of 500 kN. The spacing is the same as the anchor bolts.

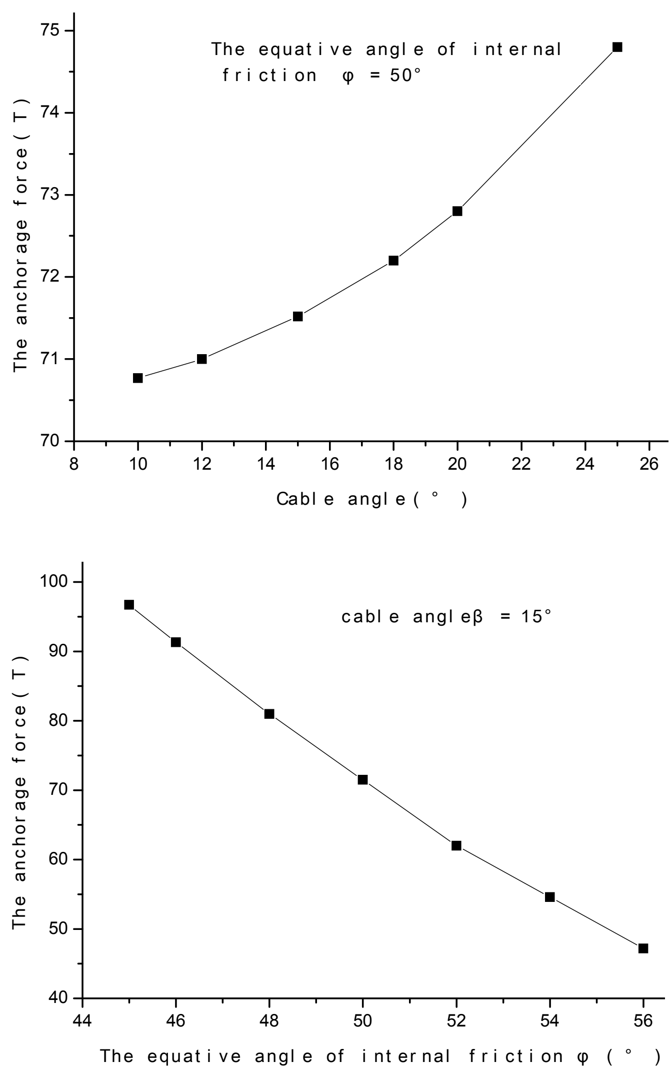
3.4 *Parameter analysis*

The limit equilibrium method was used to understand the principal factors involved for estimating the factor of safety. The potential failure surface is assumed to be a compound slide based on the site investigation, so we chose the Bishop method in accordance with the site conditions.

Because the rock classification index RMR for this slope is III, the equivalent angle of internal friction may be estimated as 45-55° based on the Technical Code for Building Slope Engineering (GB-50330 2002). A sensitivity analysis was performed for key input parameters such as the angle of internal friction and orientation of cable installation. The analysis results are summarized in Figure 3.

We can infer from Figure 3a that if the equivalent angle of internal friction is set to 50°, the anchor force almost decreases with the cable angle linearly. In contrast, Figure 3b shows that if the cable angle is set at 15°, the greater the friction angle, the snaller the anchor force provided from the cable anchors. The cable angle and angle of internal friction both influence the anchor force considerably, especially the latter.

The angle of internal friction of 50^{o} and cable angle of 20^{o} based on the geological conditions and numerical results, produces a safety factor of 1.3, which satisfies the requirement of the design code.



(a)

(b)

Figure 3. Relationships between: a) anchor force and cable angle; and b) anchor force and friction angle.

3.5 *Monitoring of the steeply cut slope*

Deformations at depth and those on surface were monitored by borehole inclinometer and a high-precision total station. The results from the latter are summarized in Figure 4. The working condition of the reinforcement was monitored by cable force gauges, with the results summarized in Figure 5.

Note that because of the influence of excavation sequencing, the data plotted in the two figures are not identically corresponding. The monitored force on the cable did not satisfy the demands of the design load at the beginning, so the cable was re-tensioned.

The deformation of the slope decreases gradually and the final deformation is very small based on the monitoring data. The change in cable tensions were likewise small after the cables were re-tensioned. No open tension crack behind the cut crest was observed during excavation and after construction had finished.

Monitoring is still ongoing and the data shows that the steep slope should be stable during its operational life.

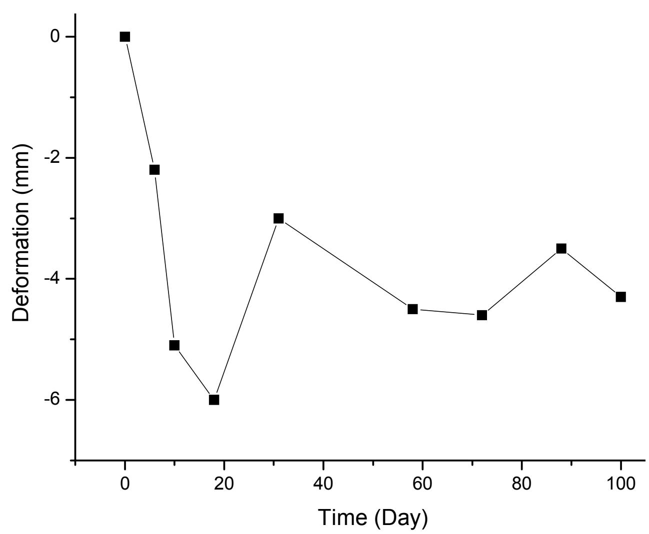


Figure 4. Horizontal deformation response of cut slope.

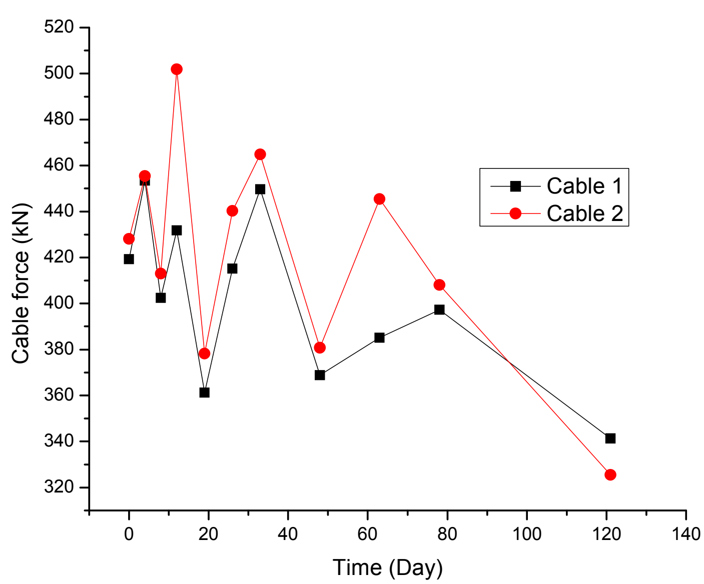


Figure 5. Histories of cable force response.

3.6 *Economic comparison between the two schemes*

Compared with the common scheme, the steep scheme saves 540,000 RMB (US$80,000) in cost. The detailed breakdown in the excavation amount and cost is summarized in Table 1.

Compared with the common scheme, the steep scheme is both economical and ecological environmentally friendly. In general, the steep excavation approach decreases slope height, the excavated volume, disturbance of the natural slope surface and engineering cost. In addition, due to the decreasing slope height, construction difficulties and future maintenance is greatly reduced.

Table 1. Comparison of the two excavation methods.

	Slope height (m)	Excavated volume (m^3)	Surface area of excavated slope (m^2)	Engineering cost (RMB*)
Common scheme	90.2	7.57E+05	8.11E+05	1,780,000
Steep scheme	23.5	1.64E+05	9.50E+04	1,240,000

* RMB = China Yuan.

4 CONCLUSIONS

By introducing the steep excavation scheme to the case study, the following conclusions may be drawn:

(1) The steep excavation scheme requires that the engineering geological conditions are good, the rockmass self-stable; if the local geological conditions are not very sound, the excavation should be benched.

(2) The steep scheme also requires that the excavation process should not badly damage the rock. To do so controlled blasting measures may be required and/or the cut slope should be reinforced more strongly than usual.

(3) The deformation of the slope and the working conditions of the reinforcement should be monitored to see how the slope responds.

(4) The steep excavation is better than the traditional scheme in terms of ecological environmental effect, slope height, the excavated amount of rock and soil, the amount of disturbed area on the slope surface, and engineering cost.

(5) If the geological conditions permit, the steep cut scheme, which can ensure that slopes are both safe and economically sustainable, should be used preferentially.

With cable reinforcement, the stability of the steeply excavated slope can be guaranteed. Deformation of the slope and the cable force are monitored in detail during the construction period. The deformation data showed that slope movements decreased gradually with the final deformation being very small. The cable tensions indicated the need to re-tension the anchors, with subsequent tensions being small. It is optimistically estimated that the steep slope should be stable during operation. Comparison between the steep and common schemes affirms that the steep excavation is better than the traditional scheme in terms of ecological environmental impact, cut slope height, the excavated volume, the disturbed slope surface area, and engineering cost. It is concluded that if geological conditions permit, the steep cut scheme should be used given its benefits

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