Stability evaluation and safe guarding for excavated road slope in mountainous area

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Abstract: The stability of cut slopes in mountainous areas has serious impact on road performance and traffic safety. The need for stability evaluation and safe-guarding cut slopes is described. Evaluation principles, working procedures, evaluation methods and a variety of remedial techniques are suggested. Ideas on stability evaluation and safe-guarding the cut slope in mountainous area are also presented.

Résumé: La stabilité de la pente coupée dans le secteur montagneux a l'impact sérieux sur l'exécution de route et la sécurité routière. La nécessité de l'évaluation et du coffre-fort de stabilité gardant la pente d'excavation est décrite. Le principe d'évaluation, la méthode de travail, la méthode d'évaluation et la variété de coffre-fort gardant des techniques sont suggérés. Quelques idées sur l'évaluation de stabilité et coffre-fort gardant la pente de coupe dans le secteur montagneux sont présentés.

Keywords: highway, mountainous area, cut slope, stability evaluation, safe guarding

INTRODUCTION

Highways can enhance traffic capability and traffic safety dramatically. Therefore, highways in China, especially those in mountainous areas are developing at an unprecedented rate. However, the accident rate for highways is four times higher than that for ordinary roads. The reason is that insufficient consideration is given to environmental factors in respect of traffic safety during construction of highways compared to some other countries (Wang 2002).

There are various environmental factors that influence traffic safety. For instance, the road plan and profile, road type and continuity, evenness of the road surface, capability of preventing skidding, visible distance, entrance and exit junctions, slope design, scenery along the road, traffic safety facilities, etc[1]. For highways in mountainous areas, plan and profile of the path are mostly limited by terrain. In order to ensure the requirements of line parameters for the roads, substantial excavated slopes and filled embankments associated with the roadbed, bridges, tunnels, etc, are usually used in the design. Therefore, the number of excavated slopes can be significant for the construction of highways in mountainous areas. Incidents, including rolling stones, spalling, collapse, slope instability, etc., induced by cut slopes, especially a high cut slope, will have significant impact on traffic safety. The frequency of these incidents being dependent upon the stability of the slope.

For road design in China, except for significant bridges and tunnels, the available ground information is insufficient. This does not satisfy the needs of stability evaluation for cut slopes and protective design especially in areas of complex geology. This can result in inadequate design of slopes and associated protective measures. As a consequence evidence of slope instability, including large-scale landslides, during construction and operation can be observed in mountainous areas. However, if a systematic ground investigation and stability evaluation of the proposed excavations along the line of the roads is undertaken at design stage, it is likely that the incident rate induced by the slope instability would reduce dramatically. This would in turn potentially reduce construction cost, accelerate construction, and contribute to the early recovery of the environment as well.

The author performed the stability evaluation and the study of remedial works for cut slopes in various mountainous areas including Badalin in Beijing, Guiyang-Xinzhai in Guizhou, Hechi (Shuiren)-Nanning in Guoxi, etc. These areas being generally representative of cut slopes in mountainous areas in China and therefore summarise appropriate stability evaluation and safe-guarding techniques

STABILITY EVALUATION PRINCIPLES

According to the characteristic of the cut slope in mountainous areas, the following stability evaluation principles are applied:

- Combination of the regional and local geology: The regional area geological environment and condition contribute to the geological problems of slopes. The current stable status is the result of geological evolution. Further understanding of the regional geological characteristic will contribute to a better understanding of the local geological structure, the present condition and will allow predictions of prospective trends (Zhang 1994).
- Combination of qualitative and quantitative evaluation of geological methods and processes: sufficient acquaintance of the geological phenomena results in the development of a conceptual model. Physical and

numerical modeling are used to determine boundary conditions, strength parameters of the rock mass, influential factors as well as sensitive factors and allows quantitative calculations to be performed to provide necessary parameters or quantitative data for the design of remedial works (Zhang 1994).

- Combination of engineering geological condition and construction condition: determine the engineering geological condition and geological model for the slopes. However consideration also needs to be given to slope design criteria, method of excavation, groundwater / rainfall, slope reinforcement and protective measure, etc. as all are important factors.
- Combination of the stability in constructional stage and that in operational period: the stability of the excavated slopes in the construction stage can't necessarily ensure the safety in the operational period. Rainfall, groundwater, weathering agents, seismic loading, etc., may occur within the operational life for the road. Therefore, durability evaluation should be undertaken for the rock mass structure and any reinforcement / protective measures installed when undertaking stability evaluation.
- Combination of the rationality of the evaluation and the operability: the stability evaluation should reflect the geological model and the appearance mechanism, and should be applied to excavation, design and construction of any remedial works.
- Combination of the ordinary evaluation and the detailed study: the number of excavated slopes is large and usually distributed along the road. Due to the urgent time limit for projects, it is necessary to perform preliminary evaluation of the slopes along the whole road to determine the important slopes to be studied in detail to implement remedial works associated with the construction of the roads.

WORKING PROCEDURE FOR STABILITY EVALUATION

Given the length of highway projects in mountainous area, number of slopes to be excavated, labour intensive requirement, time constraints on design etc, it is difficult to perform a detailed geological survey as is undertaken for hydroelectric and mining projects. In order to reduce the time and the cost of the survey, the geological condition during the excavation of the slopes can be used to perform a stability evaluation. Therefore, detailed design is often undertaken in the early stage of the construction of a slope. By doing so, the geological model for the slopes can be visibly and fully determined to perform a rapid analysis and evaluation. At the same time, revisions to excavations and remedial works can be undertaken during the construction stage.

The stability evaluation of a cut slope in a mountainous area is therefore critical, the practical assessment can adhere to the following working procedures; (1) collection and analysis of information, (2) geological survey of the proposed cut slopes along the line of the road, (3) the preliminary evaluation of the stability of the excavated slopes along the whole road, (4) detailed stability evaluation of the more important excavated slopes, (5) propose remedial works for the important cut slopes.

Collection and analysis of the information

Study the available geological information along the line of the road, regional geological structure, physical characteristics of the rock mass, landform and physiognomy, hydraulic geological environment to generate the overall geological model. Study the distribution of the engineering works to generate the inter-relation of the engineering and geological conditions and dominant factors influencing the stability of the slope. Study the physical and mechanical characteristics of the rock and soil materials along the line of the road. Undertake a survey of the area along the line of the road.

Geological survey of excavated slopes along the whole road

Organise specialist technical staff in engineering geology, slope repair, road engineering, etc., to perform the survey to determine the engineering geological condition of the cut slopes through geological sketches, photography, survey, etc., and generate the geological model, appearance and classification. Determine the existing or the potential failure planes in the excavated slopes.

The preliminary evaluation of the stability of the excavated slopes along the whole road

Based on the established geological model for the excavated slope and acquired physical and mechanical characteristics of the rock mass along the line of the road at the design stage, evaluate the stability and propose the method of excavation and remedial works where necessary. Detailed research is expected and will need to be undertaken at a later stage for those slopes, including landslides, which have complicated problems or where it is difficult to determine the stability at the present stage. Assessment of the scheme, including the relocation of the roads, bridge, tunnel or cut-and-cover tunnel etc., should be considered for those cut slopes which require substantial earthworks, have poor stability or likely serious consequences of failure, likely high maintenance costs.

At this stage, a preliminary evaluation report should be submitted to allow application of the recommendations.

The detailed stability evaluation of the important excavating slopes

Correct qualitative evaluation of the geological model and process of the important cut slopes is made by experts in engineering geology, etc., based on which quantitative evaluation of the stability is performed by means of digital measurement and drawing the geology, geological survey including drilling and exploration wells, geophysical prospecting, mechanical testing of the rock and soil materials, numerical methods, or even physical model test, etc. to provide the theoretical evidence and the data for the appropriate the slope type and design of remedial works.

Propose the repair scheme for the important cut slopes

According to the evaluation of the important slopes to be excavated and on the principles of safety, durability, economy and aesthetics, repair schemes including retaining walls, shear piles, anchors, shotcrete, slope protection, grouting, drainage and bio-engineering, etc., will be appropriate for the repair of the cut slope. Given consideration with respect to the environmental design of the highway, it is good practice to propose several remedial schemes followed by the selection of the optimum choice.

THE CONTENT OF THE GEOLOGIC SURVEY OF THE CUT SLOPES

Detailed geological survey of the site is the basis of the stability evaluation of the cut slopes in mountainous areas. The following factors should be considered when undertaking the geological survey:

- The stratum of the slope and the rock characteristics
  The stratum reflects the geological era. The characteristics of the rock mass rock will include quality, bedding, thickness, occurrence and its variation, level of integrity, substances and the weathering level, etc.
- Geological structure (contact, fault, bedding etc.)
  The contact between the strata, may influence the characteristics of the discontinuities and the stability of the slopes. The fault influences the rock characteristic, occurrence, fall, the width of the fracture zones, the scrapes, breccia along the faults, groundwater, impact on the slopes. The bedding influences rock characteristic, the relation with the slopes, the level of the integrity of the rock mass, catchment and divide (Zhang 1994).
- Dominant structural plane (discontinuity or weak interlayer)
  This comprises the distribution, open or closure, filling, roughness of the side wall of the rock mass, saturation, connection, orientation, the relation with the slope surface and the cause of formation.
- Groundwater and rainfall
  The groundwater crop, discharge and spring. The rainfall encompasses duration of the rainfall, the intensity, impact on the slopes, the supply and drainage between the rainfall and the groundwater.
- Construction condition
  This comprises the design height of the slope, the present height of the excavation, the distance between the design elevation and current elevation, current and proposed slope angle, the height and the width of any benches, method of excavation, reinforcement and protective methods.
- Slope deformation and failure evidence
  This encompasses deformation evidence, crack description including distribution, width, length, depth, direction and development trends, the relationship with the excavation works, deformation and/or failure of any slope protection, characteristic of any objects on the slope surface including trees, vegetation, buildings, change of the groundwater system, slope ratio of natural slope.
- Measurement and description of the factors of the landslide
  This comprises the boundary of the landslide, lateral boundary, scarp of slide, crack distribution, general characteristics including tension, shear, compression, geometry, occurrence, location, volume assessment of the slip wedges, formation, substances, the analysis of the cause of the formation, groundwater appearance etc.

THE CLASSIFICATION OF GEOLOGICAL MODES OF THE EXCAVATING SLOPES

Due to the fact that the geological condition of the mountainous terrain in different areas within China varies greatly any classification would need to be performed according to a general method. However, this would be difficult to make an appropriate stability evaluation of the cut slopes for different areas. Therefore, it is necessary to propose a classification according to the individual characteristics of the different areas. The typical highway in karst limestone areas, (Shuiren in Guangxi to Nanning Highway) is taken as an example to allow the classification of the geological model for the cut slopes according to soil, rock and weak base.

Soil slope

- Eluvium (fully weathering shale and mudstone): the stability is dependent on the soil strength, the substances, the orientation of the structural plane, etc.
- Slumpmas (fractured wedges induced by the old slip slope): the stability is dependent on the plane of the old slip slope, groundwater, substances of the slope, etc.
- Tertiary swelling clay: the slope is comprises high liquid limit swelling clay within which there is montmorillonite (with corresponding high water absorption and swelling characteristics) and therefore the stability is dependent on the presence of the swelling clay and the groundwater.

Rock slope

- Dip slope: The incline of the rock layer is the same as that of excavated slope. According to the relation between the rock layer and the angle of the slope, it can be divided into groups which are over dip (the inclination of the rock layer is less than the angle of the slope), ortho-dip (the former is equal to the latter), and under dip (the former is greater than the latter).

- Reverse slope: The incline of the rock layer is contrary to that of excavated slope.
- Transversal slope: The incline of the rock layer crosses that of excavated slope to a significant degree (more than 30°).
- Slopes with a weak base. There is an indicative rock mass structure with interbedded strong layers and weak layers with only a small dip, i.e. the upper is hard rock, the lower is soft rock, weathering rock layer. The failure mechanism is the plastic flow-tension.

According to this classification, the geological model distribution of the highway of Shuinan in Guangxi is summarized in Figure 1.

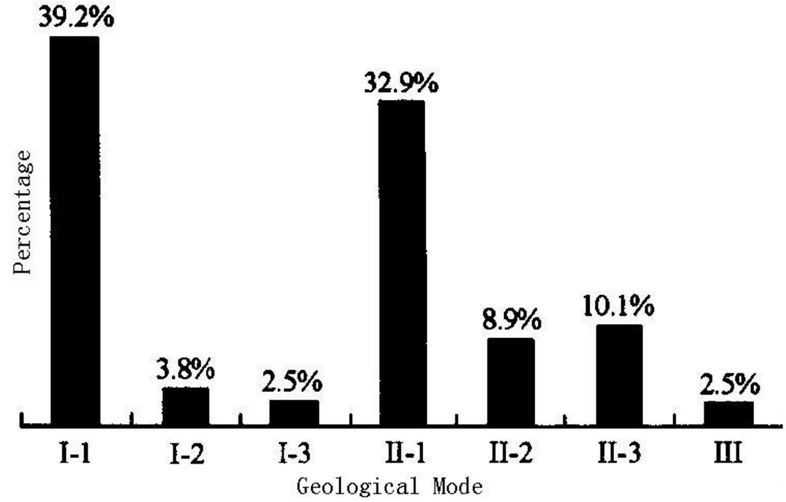

Figure 1. The classification of the geological model for the Shuinan Highway, in Guangxi

THE STABILITY EVALUATION OF THE EXCAVATING SLOPES

Collection and analysis of the information

The following factors should be taken into consideration when determining the results of the stability evaluation for the cut slopes along the line of the road; the characteristic of the rock mass, the type of slope including the height of the slope, ratio, benches, etc., the relation of the primary structural plane of the rock mass and the slope surface, the integrity of the rock mass, the hydro-geological condition, construction condition including the excavation scheme, excavation method, explosive method, etc., remedial works, presence of sliding surface or not, etc.

The methods of the stability evaluation of the slopes

The slope stability problem has always been an important research topic in the rock mechanics. With the development of mathematical methods and the progress of computer techniques, slope stability analysis has developed, e.g. improvement of limit equilibrium theory, wide application of the numerical methods, application of computer modelling, rapid development of random methods and the rise of fuzzy analysis, etc. All these methods have been widely applied to cut slopes in hydroelectric projects, mining, railway engineering, etc. However, the height of the excavated slope is usually relatively small, few cases being more than a hundred meters, the impact of the operational condition on the stability of the slope is usually not significant and the number of the slopes tends to be significant with longer roads. Therefore, the geological model derived from the qualitative evaluation should be emphasised for the stability evaluation method for cut slopes. At the same time, some mature, reliable and rapid quantitative evaluation method, such as the flawless limit equilibrium theory and numerical method, etc., should be adopted (Liu 2000).

Limit equilibrium theory

Limit equilibrium theory is the most typical quantitative method in which the rock mass of the slope within the range of the slip is divided into several little blocks on a particular principle and the equilibrium equation of the slope is generated from the equilibrium condition of the blocks based on which slope is analysed. Due to the advantages of a simple and flexible model (easy to take into account all types of complex shape and loading conditions), brief equations, it is widely used. However, it has shortcomings such as the difficult determination of the potential sliding surface and oversimplified models. In recent years, the method has improved. For instance, the sliding surface along the length is not varied in the traditional limit equilibrium method, but generation of a 3D limit equilibrium method allows the most dangerous slip plan and its corresponding minimum factor of the safety to be determined and improvements of the reinforcement design to be assessed.

Therefore, the limit equilibrium method has been improved with respect to the availability of the models and determination of the sliding surface.

Numerical method

It is usually a progressive process for the slope evolving from the stability to the instability. From the accumulation of the quantity to the mutation of the quality, it is not simply a 3D problem. It is a 4D problem containing time. In this process, the rock mass deformation is crucial. Small deformations evolve to big deformations, fracturing of the rock mass, connection to a sliding surface, and the development of a landslide. Therefore, for quantitative stability analysis of the important cut slopes, besides the conventional analysis based on the limit equilibrium method, analysis of the evolving process of the deformation and the subsequent failure of the slope should also be performed to fully understand the whole process of the deformation development of the slope. The real understanding of the slope should not be confined to its present status, but should consider the previous status and therefore allow predictions of the slope development and the evolution.

Due to the complexity of the problems, numerical methods should be adopted when studying the deformation evolution of the slopes. The commonly used methods are finite element method, finite difference method and discrete method in which the former two are applied to the continuous medium, whereas the latter to the discontinuous medium like jointed rock mass which can also tackle the problem of the nonlinear large deformation of the continuous medium. Most of the deformation development of the slopes is large deformation problem with the existence of a sliding surface which is considered as a discontinuous problem. Therefore, the discrete element method is a better way to study the evolution and the deformation development of the slopes.

Take the discrete element method as an example. The discrete element method is proposed by Cundall in 1971 which is applied to analyse the stress field of the jointed rock mass. The method focuses on the blocks divided by the joints, these blocks in turn divide the study domain. In the block motion, the gridpoints of the blocks can be separated which means the blocks can contact the surrounding gridpoints but are separate from them. The interaction between the blocks can be acquired from the force-displacement relation. The individual element motion can be obtained from Newton's second law with the input of the unbalanced force and the unbalanced moment of the element.

The results of the stability evaluation of the slopes

According to the stability evaluation principle mentioned above, the stability evaluation results can be classified into three groups.

- General stability
  The slope is generally stable. There is no disadvantageous connection structure. The slope surface is intact or there are few dangerous stones, floatstones. Clean-up should be performed in the slope top.
- Poor stability
  The slope is generally stable. However, there are some disadvantageous unstable wedges. Too steep soil slope will result the local collapse of the slope surface.
- Instability
  The slop is generally unstable. There exists large-scale connected sliding surfaces that will directly induce the overall slope instability.

Still Shuinan highway in Guangxi is taken as an example. The stability evaluation is performed to 68 excavating slopes along the whole road and the results are summarized in Figure 2.

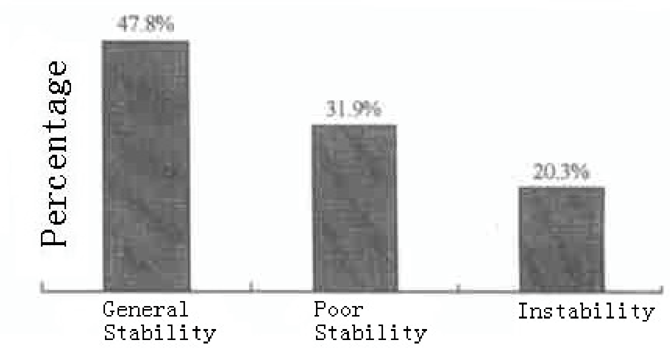

Figure 2. Preliminary stability evaluation result of cut slopes for the Shuinan Highway (Sun 2002)

SAFE GUARDING TECHNIQUES FOR CUT SLOPES

According to the slope stability level, the safe guarding techniques for cut slopes in mountainous areas should comprise the following two aspects, which are the reinforcement of the slope body and protective measures for the slope surface. For those unstable slopes to be excavated, slope reinforcement is the prerequisite for slope safety. For most cut slopes, especially high slopes, suitable protective measures for the slope surface is necessary to ensure the operational safety of the highway.

The reinforcement technique of the slope body for cut slopes

The author summarises reinforcement techniques for the slope body for cut slopes appropriate for highways in mountainous areas such as supporting techniques, e.g. anchor and grouting with drainage, etc., based on experience of the design of reinforcement of the slope body for many excavated slopes in mountainous areas in China, combined with new techniques from both China and elsewhere.

Supporting technique of slope body

For relatively fractured rock and soil material, soil slopes, where low strength results in slope instability or where there is existing evidence of slope movement, the traditional supporting techniques for highway engineering are largely effective. The commonly used supporting techniques are as follows.

- Retaining wall: gravity type, thin wall type, anchored back, soil nails, poling boards , etc.
- Anti-slide pile: reinforced concrete structure, most commonly used measure to repair cut slopes.

Anchoring technique of slope body

For poorly stable excavated rock slopes and some soil slopes, anchoring techniques that can enhance the rock strength and integrity and improve the state of stress within the rock mass are highly efficient. The commonly used anchoring techniques are as follows.

- Prestressing anchor
  This is an active anti-sliding technique for the slope body. Pre-stressed, high-strength, low relaxation steel strand is installed to enhance the normal stress of the steel strip and reduce the downslide forces resulting in an improvement the slope stability. Pre-stressed anchors can be combined with reinforced concrete beam, lattice or anti-sliding piles to further reinforce the rock or soil slopes.
- Rock bolt
  Implant the rigid rock bolt into the rock mass with the end grouted locally or along the whole rock bolt to reinforce the slope through enhancing or altering the stress field of the surrounding rock mass to enhance the integrity and stability.

Grouting with drainage technique of slope body

By means of the surface drainage system such as a drainage ditch, intercepting ditch, etc., underground drainage system such as blind slot, underground drainage tunnel, drain bar, etc., can enhance the rock and soil strength and therefore structural plane or sliding plane strength. For the unstable rock slopes, collapsed stack layers, Karst breccia stack layer or loose-packed rock mass, grouting can reinforce the surrounding rock mass or the stack layer to enhance the rock and soil strength and stability of the slope.

Protective measures for the surface of the cut slopes

Reinforcing the unstable excavated slopes alone cannot ensure the operational safety of a highway in a mountainous area. For instance, the local slope can collapses during the operational period, releasing rock debris etc. Therefore, for most excavated slopes, especially high slopes, it is crucial to adopt protective measures for the surface of the cut slope.

Masonry protective technique

Protection of the slope surface can be achieved with masonry, prefabricated concrete members or shotcrete, etc. Shotcrete comprises stones with cement, and can be installed in conjunction with rock bolts.

Ecological protection technique

Single or multiple plants can be grown along the slopes to protect the surface. This technique is based on providing plants suitable to the local climate and geological condition and should blend with indigenous species present on site to provide an aesthetically pleasing finish. The primary protection techniques are direct planting, planting with geocell mattresses / geonet, plant gouge, etc.

Rolling stone compliant protective technique

The rolling stone compliant protective technique is based on Soft Netting System (SNS) mainly made up of a steel bar net to prevent rolling stones / rock falls from happening. The technique is commonly used in the protection of cut slopes. SNS compliant net is mainly made up of steel column, steel bar net, upper (lower) supporting rope, upper tensile anchoring bolt and cable, lateral tensile anchoring bolt, and cable, etc (Oi 2000).

CONCLUSION

Although the stability evaluation and the safe-guarding of cut slopes in mountainous areas are at an early stage, emphasis should be placed on their study. According to the study, design and construction of many cut slopes in mountainous area, the authors are able to summarise their conclusions as follows.

- The stability evaluation of cut slopes along the line of the road in mountainous areas is of great importance in terms of engineering, economy, environment and society.
- The stability evaluation has to be based on a detailed geological survey, rock and soil testing and construction condition survey on site.
- The qualitative evaluation of the geological model and process of the cut slopes is key to the evaluation of their stability. The quantitative evaluation is an important supplementary means by which important supporting evidence for the design of any remedial works can be provided.
- The adoption of the developed digital measurement and drawing system for the engineering geology of slopes allows effective and rapid stability evaluation and design of the remedial works for highway slopes.
- Computer aided numerical simulation can reproduce the failure process and mechanism for cut slopes and allow predictions to be made as to the prospective level of stability or failure mechanism.
- Risk analysis and evaluation based on the reliability theory with necessary monitoring and emergency precautions can be performed for the individual excavated slopes.
- Safe, enduring, economic, beautiful, flexible reinforcement and protection is important to safeguard the operational safety of cut slopes in mountainous areas.

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