Evaluation method of highway slope stability based on deep displacement curve characteristics

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Abstract：Taking the slope of Yunnan Wuyi Expressway as a case study, the typical geologic generalization models of three kinds of slopes were established by means of statistical analysis. The limit equilibrium method, finite element numerical simulation method, and deep displacement curve type analysis are combined to evaluate the slope stability under various working conditions in a comprehensive way. The relationship between the deep displacement characteristic curve and slope stability, and a slope stability criterion is established based on the characteristics of deep displacement curve. This method is a supplement to the current Chinese standards on slope stability evaluation. According to the analysis to typical slope projects in central Yunnan, this evaluation method is simple and feasible, which is suitable to evaluate the stability of various types of highway slopes in central Yunnan in China.

1. Introduction

More and more cutting or backfilling slopes are constructing in the hilly and mountainous regions in western China due to the ongoing implementation of China's western development strategy. Thus, the slope stability problems must be involved during the construction and operation of such projects. In addition, the slope stability is related with the safety, schedule and cost for project construction, and thus is very important to the engineering design and construction. Yunnan Province, located in western mountainous region in China, has focused on the development of highway network in recent years. Meanwhile, Yunnan region has complex hydrological conditions and changeable climatic conditions, with frequent occurrence of earthquakes and landslides. Various complicated and adverse factors have great threat to many highway slopes. Therefore, it is important to provide feasible and effective slope stability evaluation methods by studying the geological conditions, and deformation & failure characteristics.

Slope stability is often evaluated by engineering geological analysis method, limit equilibrium method, limit analysis method, numerical simulation method and reliability method. Currently, the widely used quantitative analysis for slope stability is generally conducted by the safety coefficient from limit equilibrium method, displacement & stress from numerical simulation method, or failure probability from reliability method. However, these methods are only used under certain conditions, and the evaluation index is single, which is difficult for establishing control value or allowance value. For example, *Specifications for Design of Highway Subgrades JTG D30-2004* stipulates that the cutting highway slope need no support if its safety factor is 1.20 to 1.30[1]; however, *Specification of Design and Construction for Landslide Stabilization DZ/T0219-2006* stipulates that the designed slide

safety factor for Level I landslide slope is 1.30 to 1.40 under deadweight conditions[2]; the calculated or measured displacement can also be used for slope stability evaluation, but with greater difficulty, and many scholars analyze the landslide stability by using displacement – time curves in combination with other mechanical & physical parameters of typical surface points[3]. In addition, deep displacement is a direct index for analyzing inner deformation of slope. He Manchao pointed out that the slope slide surface can be effectively judged by measured inner displacement, which can predict and evaluate the slope stability[4]. Zhou Wu monitored the deep displacement of rock slopes near Three Gorge Dam by measured deep displacement, and ensured the safety of slopes at the important sites[5]. Chen He et al. combined the deep displacement with new SAA measuring technique to divide landslide evolution into various stages in terms of kinetic energy and its change rate, and then carried out the early warning and prediction for landslide[6]. Tang Luosheng et al. quantitatively analyze the shear strength by means of measured deep displacements, which can determine the relative parameters in a more accurate way[7]. However, there is a little research in China in deep displacement characteristics of landslide. Jin Xiaoguang et al. divided the deep displacement curves into V-shaped, D-shaped, B-shaped, r-shaped, pendulum shaped, and composite shaped ones in terms of shape, and then carried out preliminary evaluation for various shapes of displacement curves of landslides[8].

The comprehensive evolution of slope stability is generally conducted by a combination of various methods against a given slope in an independent or cooperative way. Zhang Weizhong analyzed a slope with FEM, limit equilibrium method, and AHP-extenics model, which improved the judgment of slope stability[9]. Xiao Shu compared the analytical results with measured data in slope instability by a combination of limit equilibrium method and joint based reliability analysis, testifying the application of reliability analysis in joint slope of open-pit mine[10]. Zhao Zhifeng et al. analyzed the slope stability during excavation by combining the surface measurement, deep measurement and numerical simulation, which is a good guideline to construction and dynamic monitoring on slope safety[11].

However, there is little research in combining deep displacement curve and slope stability evaluation. Most of deep displacement curves are used to optimize existing slope stability evaluation methods or directly to conduct continuous measurement on slope stability. Based on previous research data, this paper took Yunnan Wuyi highway slope for example, established the generalized geological model, and analyzed the slope stability under various conditions by combining the limit equilibrium method, FEM numerical simulation and deep displacement curves. Thus, the direct relationship between deep displacement curves and slope stability was established, and a simple on-site slope stability evaluation method was built to ensure the construction safety.

2. Case and geology
The Wuyi Highway, part of central Yunnan urban economic zone, begins from Wuding County with eastern connection to Xundian County, and ends at eastern Yimen County with planned connection to the Chuxiong to Eshan Highway.

The 104km long Wuyi Highway is located in the central Yuannan across various terrains with complex engineering geological conditions, almost covering all the common geological conditions in Yunnan Province. The investigation on 109 slopes along Wuyi Highway indicates that 26 slopes are loose deposit, 54 slopes are stratified, and 29 slopes are rock. Among these slopes, 7 slopes contain weak mudstone. Therefore, it is impractical to evaluate every slope due to the enormous figure. In this paper, the slopes are typically divided into three geological catalogs as follows:

2.1. Loose deposit slope
This type of slope is generally the cutting slope or infilling slope in gentle terrain with thick Quaternary deposit overburden and deep bedrock. The slope is basically low, almost with two steps of 1:1 excavated slope. The generalized geological model for Quaternary deposit slope is established in terms of slope type, slope height, slope ratio and strata properties, as shown in Figure. 1.

For highway slopes, the slope rate and height are always determined by design requirements. Thus, the deposit type and compaction of the Quaternary deposit slope are generally the major factors

affecting the slope stability. Intrinsically, the deposit type and compaction are the properties of rock and soil, which can be represented by unit weight, cohesion, angle of internal friction, deformation modulus, and Poisson's ratio, etc. According to the geological investigation and tested data of Wuyi Highway project, the parameters of Quaternary deposit are divided into large, medium and small groups, as listed in Table 1, to simulate the deep displacements under construction.
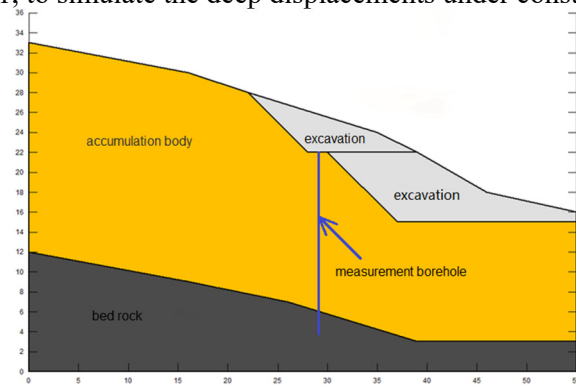

Figure 1. Generalized geological model of Quaternary deposit slope.

Table 1. Calculation parameters of Quaternary deposit slope.

Condition	Unit weight (kN/m^3)	Cohesion (kPa)	Angle of internal friction (°)	Deformation modulus (MPa)	Poisson's ratio
A	17.5	17	17	8	0.40
B	18.0	20	22	10	0.35
C	19.0	30	30	12	0.30

2.2. Stratified slope

This type of slope, generally formed by excavation, is almost located in hilly region or low mountains. It consists of Quaternary deposit overburden (clay and silty clay, etc.) and deep stratified rock (mudstone, sandstone and slate, etc.), generally with rock strata dip angle of 10 to 30°, large height and deep groundwater. The excavated slopes are almost three-step 1:1 form. The generalized geological model for this type of slope is shown in Figure. 2.
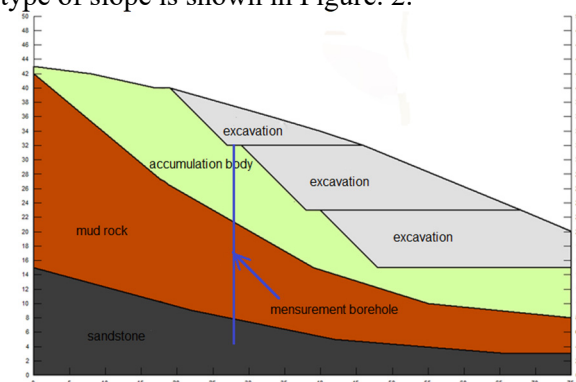

Figure 2. Generalized geological model of stratified slope.

Most unstable slopes in central Yunnan resulted from the slide of upper deposit along the interface between deposit and deep rock strata. The dip angle of rock strata is critical to such instability. According to geological investigation, the dip angle of rock strata is generally less than 40°. Thus, the dip angle is determined to be 15°, 25°, and 35°, separately, to simulate the various conditions.

2.3. Rock slope with weak belt

This type of slope is basically the excavated deep high slope with thin overburden and rock outcrop. The rock strata have generally large dip angle and consist mainly of sandstone, slate and mudstone, etc. The excavated slope is generally four-step 1:0.75 slope with little groundwater. Generally speaking, the rock slope has little chance to suffer from overall instability but always suffers from local instability such as rock fall and collapse. However, the rock masses in central Yunnan are basically the stratified structure with interlayer of sandstone, slate and mudstone. In addition, the mudstone will soften and disintegrate under water and then a soft fractured zone may occur at some stratum, which is the controllable factor for overall slope stability. The typical generalized geological model of rock slope with soft fractured zone was established, as shown in Figure. 3. In this model, the Quaternary deposit overburden was neglected, and the slope consists mainly of sandstone with soft mudstone.

The slope with soft belt or fractured zone is more instable than common slope, and thus the measurements always focus on the slope with soft belt or fractured zone. The characteristics of measured curves and slope stability are related with the distribution and strength of soft fractured zone. In this paper, the dip angle of rock slope is discussed, and the generalized geological models of rock slope with dip angle of 5-10°, 10-20°, and 20-30° are separately established to simulate the deep displacement under three different conditions.

The deep displacement curves measured in Yunnan may vary greatly due to the complex geological conditions. Thus, the study on the deep displacement curves of slopes in Yunnan will be of great benefit to understanding the curve types and engineering importance. In addition, the geological generalization of enormous slopes in central Yunnan into three typical slopes will be beneficial to the overall evaluation of slope stability and deep displacement rule under various geological conditions.
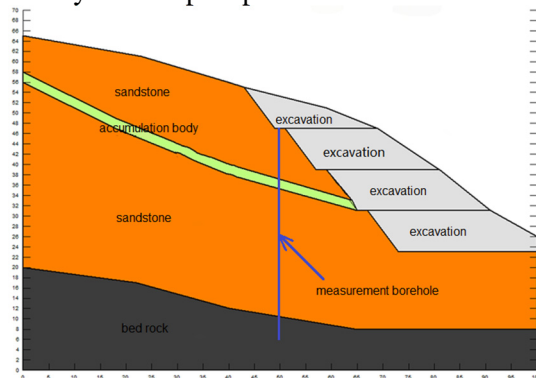

Figure 3. Generalized geological model of rock slope with weak belt.

3. Deep deformation characteristics

The Geo-studio software, one of popular geotechnical softwares in the world, was developed by GEO-SLOPE Company in Canada in the 1970s. This software is good at the numerical simulation in geotechnical, geological, environmental fields, and it consists of several modules such as SLOPE/W, SIGMA/W, SEEP/W, QUAKE/W, TEMP/W and AIR/W. In this paper, the SIGMA/W module was used to simulate various conditions of three typical slopes of Wuyi Highway. For convenient comparison purpose, the measurement boreholes of three typical slopes are all located in the first step, and the simulated results are shown in Figure. 4.

Figure. 4(a) indicates that, as the mechanical properties of deposit decrease, the maximum horizontal displacement of slope increases from less than 1mm to about 10mm and finally up to around 35mm. Therefore, the displacement increase rate is far beyond the mechanical decrease rate of deposit. According to the measured deep displacement curves of common slopes and curve classification (see Table 2) by Jin Xiaoguang[8], the simulated curves under conditions A and B are summarized as r-shaped curves, and those under condition C are summarized as v-shaped curves. Therefore, the simulated curves vary from v-shaped to r-shaped to r-shaped as the mechanical properties of deposit decrease.

Similarly, Figure. 4(b) shows that, as the dip angle of rock strata increases, the maximum horizontal displacement of stratified slope increases greatly, and the simulated curves vary from V-shaped to D-shaped to D-shaped. In addition, Figure. 4(c) indicates that the simulated curves vary from V-shaped to D-shaped to D-shaped as the dip angle of soft belt increases. The D-shaped curves indicate the various overall movements of slope along slide surface and some common features. For example, all the maximum horizontal displacements from D-shaped curves occur in the interior (different from that of r-shaped curves), and the simulated D-shaped cures change abruptly in the interface between overburden and rock strata or in the soft belt. Furthermore, the larger the dip angle, the greater deformation ratio is.
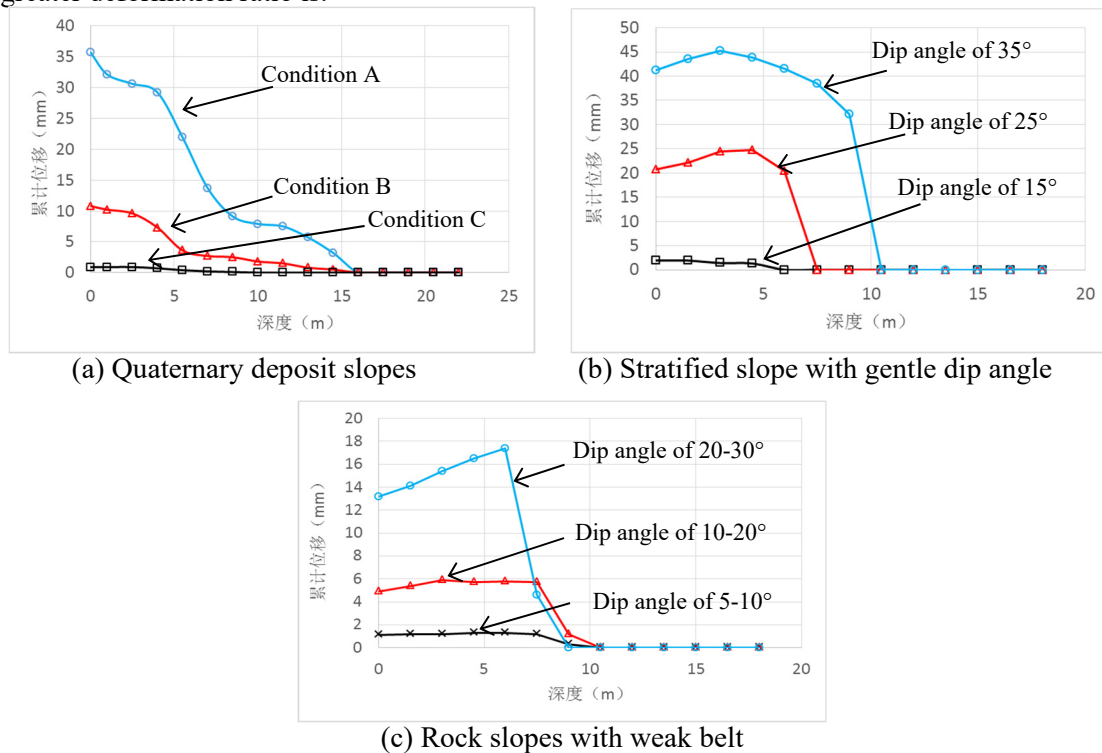
(a) Quaternary deposit slopes   (b) Stratified slope with gentle dip angle

(c) Rock slopes with weak belt

Figure 4. Deep displacement curves of highway slope.

Table 2. Characteristics and types of deep displacement curves.

Curve shape	Description	Deformation and failure of slope
Pendulum	Cumulative displacement varies around initially measured value within the whole depth, with fluctuation of generally less than 10mm.	The slope has small deep displacement and is stable.
V	Large upper displacement and small lower displacement, generally linear.	No obvious slide surface in the interior; under cramp deformation stage.
r	Cumulative displacement changes abruptly at shallow position, and the lower displacement is small.	Obvious slide surface in shallow position.
D	Cumulative displacement changes abruptly at deep position; approximate overall movement occurs in the upper slope.	Obvious slide surface in deep position.
B	Cumulative displacement changes abruptly and obviously at various positions, with step shape or wave shape.	Various slide surfaces occur in the interior.

4. Stability evaluation

Firstly, the slope stability should be evaluated qualitatively or quantitatively to establish the relation between curve shapes and slope stability. Whether the safety factor is good at the slope stability evaluation remains contentious, but it is the popular application in current engineering projects. In this paper, the Morgenstern –Price method in SLOPE/W module was used to simulate the stability of three typical slopes in terms of limit equilibrium, and the safety factor is assumed to be the average value along the slide surface. In addition, the FEM method in SIGMA/W module was used to simulate the same conditions above, and the stress and strain results were input into the SLOPE/W module to obtain the safety factor in another way. The FEM method can consider the stress – train relationship among various interfaces in a more practical manner.

The simulated results are listed in Tables 3 to 5, and the plastic zones are also described, which is a good reference to stability evaluation of various types of slopes in Wuyi Highway.

Table 3. Simulated stability results of Quaternary deposit slope.

| Condition | Safety factor | | Deep displacement | | Plastic zone |
	Limit equilibrium	FEM	Max. displacement （mm）	Curve shape	
A	1.04	1.24	35.7	r	Almost through
B	1.23	1.58	10.8	r	No through
C	1.67	2.37	0.90	V	No through

Table 4. Simulated stability results of stratified slope.

| Dip angle | Safety factor | | Deep displacement | | Plastic zone |
	Limit equilibrium	FEM	Max. displacement （mm）	Curve shape	
15°	1.50	2.16	1.90	V	No through
25°	1.29	1.43	24.8	D	Almost through
35°	1.11	1.25	45.2	D	Almost through

Table 5. Simulated stability results of rock slope with weak belt.

| Dip angle | Safety factor | | Deep displacement | | Plastic zone |
	Limit equilibrium	FEM	Max. displacement （mm）	Curve shape	
5-10°	2.23	2.64	1.30	V	No through
10-20°	1.38	1.58	5.90	D	Almost through
20-30°	1.02	1.26	17.4	D	Through

Tables 3 to 5 indicate that the safety factor by limit equilibrium method is larger than that by FEM for slopes under stable conditions, but the former is approximately equal to the latter for slopes under critical conditions. In addition, the results by FEM are conservative because the constraint force on slices as deformable body is larger than that on slices as rigid body. Furthermore, the plastic zone by FEM deviates greatly from the assumed slide surface, which indicates that the plastic zone has no relations with the assumed slide surface, representing different mechanical mechanism.

In Chinese codes, the safety factor of slopes under natural conditions should be 1.20-1.30. According to the results in Tables 3 to 5, the stability judgement criteria for various slopes in central Yunnan are initially determined by: (1) obvious r-shaped or D-shaped deep displacement curves with more than 10mm deformation along slide surface, and (2) accelerated trend of displacement at maximum position or along slide surface. The latter judgement criteria are just the method in most Chinese codes for forecasting the slope instability[1], which can be conducted by the measured displacement – time plot. The former criteria, based on the spatial distribution of displacements, are provided by this paper as a complementary way, which is beneficial to comprehensive slope stability evaluation. Therefore, the slope stability based on deep displacement characteristics can be judged by: 1) if two conditions are satisfied, the slope will fail; 2) if one condition is satisfied, the slope will be relatively stable; and 3) if no condition is satisfied, the slope will be stable. If the judgements conflict with each other, more analysis should be conducted on the base of geological condition, measured data and simulated results.

5. Conclusions

1 The typical generalized geological models of Wuyi Highway slopes in Yunnan were established to simulate the slope stability under various conditions by combination of limit equilibrium method, FEM and measured deep displacement curves. The relation between deep displacement characteristics and slope stability was obtained, and the preliminary slope stability criteria based on the characteristics of deep displacement curves were developed.

2 The slope stability criteria based on the characteristics of deep displacement curves are complementary to Chinese codes. This method is suitable for the stability evaluation of various slopes in central Yunnan.

However, the cognition on relation between deep displacement curves and slope stability is still shallow. Especially, the deep displacements vary greatly from several millimeters to hundreds of millimeters due to the influence of various factors, which is hard to obtain practical slope stability criteria in a quantitative way. Further research should be carried out in data collection, rule conclusion and mechanism analysis to improve the current slope stability evaluation.

Acknowledgments

References:

[1]   Code for design of highway subgrades (JTG D30-2004)

[2]   Specification of design and construction for landslide stabilization (DZ／T0219-2006)

[3]   Zhang Lei, Shen Mingrong, Shi Zhenming. Displacement supervision method for rock slope engineering and analysis [J]. Rock and Soil Mechanics, 2003, (S1):202-205.

[4]   He Manchao. Real-time monitoring and forecasting of landslides and its engineering application[J]. Chinese Journal of Rock Mechanics and Engineering, 2009, (06):1081-1090.

[5]   Zhou Wu, Li Qiang, Qi Wei. Application of inclinometer into rock slope monitoring in left hydroelectric plant of TGP [J]. Chinese Journal of Rock Mechanics and Engineering, 2001, (S1):1870-187.

[6]   Chen He, Li Yajun, Fang Rui, Li Guo. A novel technique for monitoring deep displacement and early-warning of landslide [J]. Chinese Journal of Rock Mechanics and Engineering, 2015, (S2): 4063-4070.

[7]   Tang Luosheng, Yin Kunlong. Selecting shear strength parameters of landslides based on quantitative analysis to deep displacement data [J]. Journal of Central South University (Science and Technology), 2013, (07): 2965- 2970.

[8]   Jin Xiaoguang, Li Xiaohong, Wang Lansheng, Wang Xiaoqun. Characteristics of landslide deep displacement curve and stability displacement[J]. Journal of Mountain Science, 2000, (05):440-444.

[9]   Zhang Weizhong. Stability analysis and dynamic comprehensive treating about xiangjiapo landslide[D]. Chongqing University, 2007.

[10]   Xiao Shu. Study on joint rock slope stability of open-pit mine based on reliability theory [D]. University of Science and Technology Beijing, 2016.

[11]   Zhao Zhifeng, Xu Weiya. Rock slope stability analysis based on deformation monitoring and numerical simulation [J]. Journal of Hohai University (Natural Science), 2007, (04):398-403.