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From the new Austrian tunneling method to the geoengineering condition evaluation and dynamic controlling method

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ABSTRACT

The new Austrian tunneling method (NATM) is widely applied in design and construction of underground engineering projects. When the type and distribution of unfavorable geological bodies (UGBs) associated with their influences on geoengineering are complicated or unfortunately are overlooked, we should pay more attentions to internal features of rocks grades IV and V (even in local but mostly controlling zones). With increasing attentions to the characteristics, mechanism and influences of engineering construction-triggered geohazards, it is crucial to fully understand the disturbance of these geohazards on project construction. A reasonable determination method in construction procedure, i.e. the shape of working face, the type of engineering support and the choice of feasible procedure, should be considered in order to mitigate the construction-triggered geohazards. Due to their high sensitivity to groundwater and in-situ stress, various UGBs exhibit hysteretic nature and failure modes. To give a complete understanding on the internal causes, the emphasis on advanced comprehensive geological forecasting and overall reinforcement treatment is therefore of more practical significance. Comprehensive evaluation of influential factors, identification of UGB, and measures of discontinuity dynamic controlling comprises the geoengineering condition evaluation and dynamic controlling method. In a case of a cut slope, the variations of UGBs and the impacts of key environmental factors are presented, where more severe construction-triggered geohazards emerged in construction stage than those predicted in design and field investigation stages. As a result, the weight ratios of different influential factors with respect to field investigation, design and construction are obtained.

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1. Introduction

The main concerns for engineering geologists worldwide include the evaluation of engineering geological conditions, the comparison and suggestion of engineering site selection, the forecast of key geological problems and the dynamic adjustment of design and construction items. In China, many kinds of geological and geomorphological environments are commonly observed, and

the complex engineering geological conditions are the challenging issues and disputations up to now.

In the stages of field investigation and design, some complex engineering geological conditions often have problems confusing engineers or researchers, possibly making them misunderstand or miscalculate. In the stages of project planning or layout setting, the site selection or project spatial alignment can mostly cause unreasonable strategic decisions or problematic designs when unfavorable geological bodies (UGBs) are not well identified. As a result, multiple influential factors associated with unknown weight ratios and thresholds should be considered as the key issues in following analysis process. As deformation or failure modes of rock mass are not adequately understood, there are potential risks in the excavation or reinforcement schedules. Thus, a synthetic method is needed to address above-mentioned problems.

In this regard, the authors propose a geoengineering condition evaluation and dynamic controlling (GEDC) method. The GEDC method includes engineering geological evaluation, comparison of engineering site locations, identification of UGB, and dynamic controlling of removal of rock mass fragments during construction. The GEDC is significantly different from the new Austrian tunneling

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method (NATM) which is based on displacement monitoring and reinforcement of shotcrete and rockbolt with elapsed time, as well as preliminary and secondary support at different steps. The self-stability of rocks grades I–III basically can be guaranteed, while for fractured rock mass of grades IV and V, reinforcement must be employed, depending on variations of structural model and parameters used. In this paper, the GEDC is introduced and a case study of landslide is presented for the purpose of validation.

2. Program and methods

The GEDC can be regarded as an engineering geological program consisting of three key steps:

- (1) Synthetic evaluation of engineering geological conditions by means of interaction matrix of multiple influential factors, analytic hierarchy process (AHP), expert scoring method, etc.
- (2) Identification of UGBs by means of field investigation, analogical analysis, etc.
- (3) Dynamic controlling of rock mass structures with the aid of back analysis using monitoring results or of forecast using index thresholds as deformation rate ratio criterion (DRRC), etc.

2.1. Synthetic evaluation of engineering geological conditions

In the earlier stages of project plan and design, assessment of engineering geological conditions associated with comprehensive analysis methods should be considered. According to the engineering geomechanical meta-synthesis system methods (EGMS) (Yang, 1993) and/or the meta-synthesis in the engineering geology (Wang, 2011), three components, i.e. the associated theories, expert group experience, in situ observation and monitoring, are combined to constitute an approach to solve problems in association with huge open complex system of engineering geomechanics. Some scholars, e.g. Hoek et al. (1995), have already mentioned the importance of theoretical models where above three components for a synthetic evaluation of engineering geological conditions should be combined.

In this approach, the interaction matrix of multiple influential factors, AHP, and expert scoring method is necessary where the input and output can be visibly obtained.

2.1.1. Interaction matrix of multiple influential factors

The interaction matrix analysis method was initially proposed in rock mechanics analyses (Hudson and Harrison, 1992) and was further developed for engineering geology evaluations (Shang et al., 2000). In this method, the main influential factors at different levels are first selected and compared. Then, an asymmetric matrix is constructed with the factors array at main diagonal line, and their interaction degree codes (generally from 0 to 4) are input spatially clockwise, i.e. for one couple of adjacent factors in the diagonal line, the cause (initiative) action codes are arrayed at rows, while the effect (passive) action codes are at columns. Finally, the sum of each row and column is calculated, respectively, and the weight of any influential factor is equal to the ratio of its cause adding effect values to the sum quantity. On the other hand, the function rating code actually depends on the active degree of factors in site, and the rating codes of $N = 0, 1, 2$ indicate non-active, active, and intense active, respectively. The sum of the weight ratio associated with the rating code is equal to the total actual assessment values of factors W_i :

$$W_i = \frac{N\alpha_i}{2} \quad (1)$$

where W_i is the actual weight ratio of factor i , ranging from 0% to 100%; N is the rating code from the actual function of factors in site,

$N = 0, 1, 2$; α_i is the weight ratio of factor i in one region or obtained from the interaction matrix, and $\alpha_i = 0\%–100\%$.

2.1.2. Analytic hierarchy process (AHP)

The AHP is commonly used in engineering for comparison of priority of various factors at different levels. The AHP is regarded as one level-structural mathematical model. First, the level analytical model is set up. Then, a judgment matrix A is organized with codes 1–9. Next, the calculation is carried out step by step to obtain different evaluation results with math checks (Saaty, 2008). The random consistency index CI is used to check the logic trueness of the judgment matrix:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (2)$$

where λ_{\max} is the maximum value of eigenvalue of the matrix A , and n is the number of eigenvalue in the matrix A .

Generally, if $CI \leq 0.1$, it can be noted that the judgment matrix is consistent, and the calculated value of weight ratio W is acceptable.

The random index RI is

$$RI = \frac{\lambda'_{\max} - n}{n - 1} \quad (3)$$

where λ'_{\max} is the average value of the maximum eigenvalue of the matrix A . The RI is an experimental value depending on the number of eigenvalue, n .

Finally, the total level array and consistency are checked. Priority of each parameter C_i to the highest target level A , through level B_i in terms of A/C_i , is represented as $W(A/C_i)$ for overall priority of the consistency ratios of random arrays:

$$CR_2 = CR_1 + \frac{CI_2}{RI_2} = CR_1 + \frac{\sum_{i=1}^n CI_{2i} W(A/B_i)}{\sum_{i=1}^n RI_{2i} W(A/B_i)} \quad (4)$$

In this way, the total random consistency ratio CR values of parameters in level C can be obtained.

2.1.3. Expert scoring method

The results using expert judgment system are scored for different parameters with various weight ratios and ratings. Various parameters values are summarized and represented through expert assessment in a way of semi-quality and semi-quantity. The factors constituting the engineering geological conditions are determined based on relative standards or specifications. Practically, the expert scoring method based on experiential judgment of interactions and synthetic evaluation of geo-engineering conditions is widely applied in engineering practice but mostly qualitatively. Thus, it should be noted that the weight ratio of expert judgment results is theoretically different, so the selection of expert, who is familiar with the actual engineering geological situations and has the mandatory knowledge of corresponding theory, is critically important.

2.2. Identification of UGB

Classification and zonation are the main approaches for identifying various site-specific UGBs. Classification of UGBs and corresponding measurements associated with different kinds of UGBs are illustrated in Fig. 1.

The UGB can be divided into 3 types, i.e. soft rock and hard soil, karst cavern, and weak discontinuity, each composed of different media and components. In sites, risks and geohazards have a close relationship with UGB (see Fig. 1), where the scientific adjustment

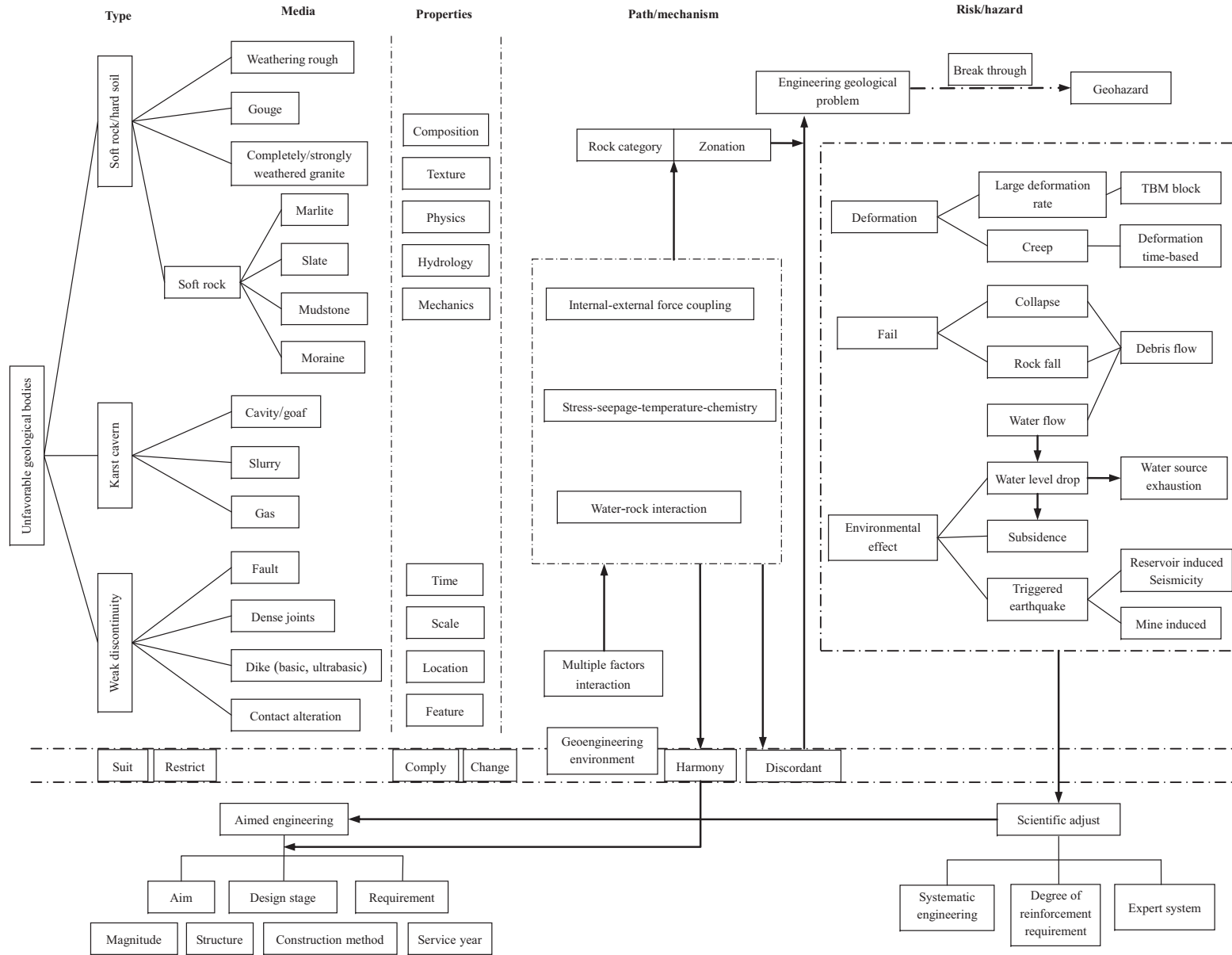


Fig. 1. Classification of unfavorable geological bodies and corresponding measurements.

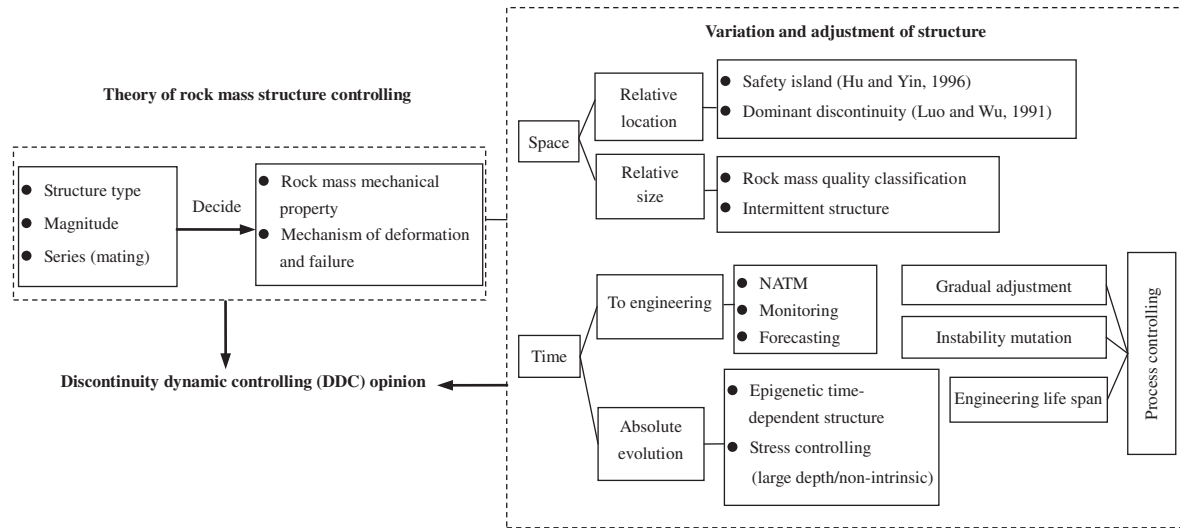


Fig. 2. Chart showing formation of the discontinuity dynamic controlling opinion.

for geohazards prevention should be adopted in order to gain a desirable result.

In order to identify site-specific UGB, regional investigation and comparison are important. In practice, the analogical analysis (Langer, 1999) and precedent typical analysis method (PTA) (Li et al., 1998) are used for identification of the UGB, which often constitute the observation and monitoring in the construction stages followed, aiming to feasible excavation and reinforcement (Shang et al., 1996).

2.3. Discontinuity dynamic controlling in construction stages

At present, the NATM is widely used in modern tunnel design and construction, and it emphasizes to some extent the essential integration of monitoring, rapid determination of surrounding rock instability boundaries, shotcrete protection and quick closing of fractured surrounding rocks timely at primary stage, and geological forecast followed by advanced supports. The greatest uncertainty or risk we encounter during excavation comes from the discontinuity dynamic controlling (DDC) which is put forward

(Fig. 2) Luo and Wu, 1991 based on practice and experiences in construction. In order to understand rock mass structure discontinuity, some theories in terms of adjustment measures are developed such as safety island theory (Hu and Yin, 1996) for selecting suitable engineering site in tectonic-active areas. With respect to variation and adjustment of structures in space and time, we adopt principle for dominant discontinuity identification to describe structural effects on engineering project in space, and the NATM to control surrounding rock stability in time. The former focuses on spatial controlling and comparison, while the latter is on process controlling.

The minimum disturbance induced by excavation to UGB is desirable in managing excavation rate, reinforcement measures and speed, which can be implemented with the help of field monitoring and forecast obtained from index thresholds or DRRC (Shang et al., 2013). To determine the mechanical parameters of surrounding rocks, back analysis of monitored data is usually adopted to obtain lateral stress coefficient and elastic modulus to numerically evaluate surrounding rock stability in project design (Shang et al., 2002).

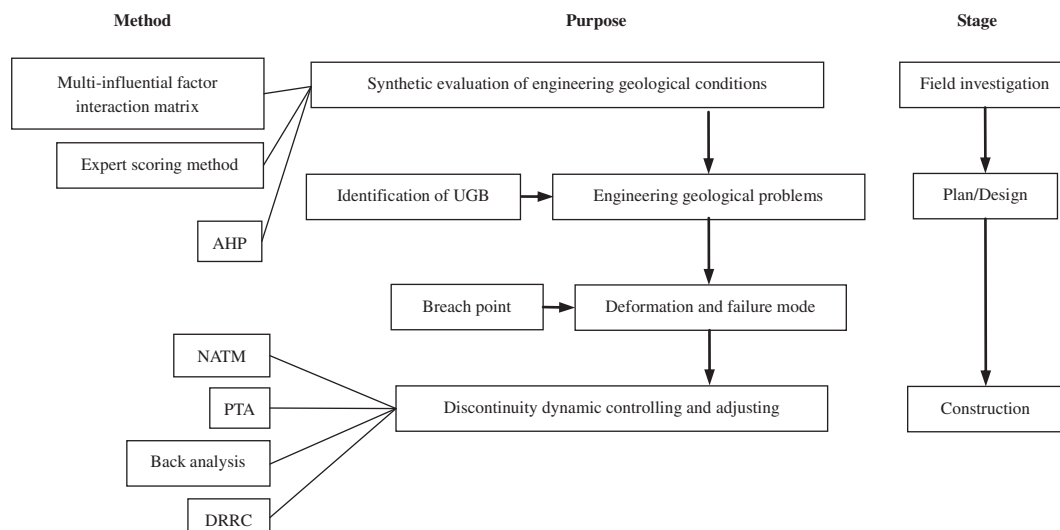


Fig. 3. Flow chart for engineering geological work at various stages.

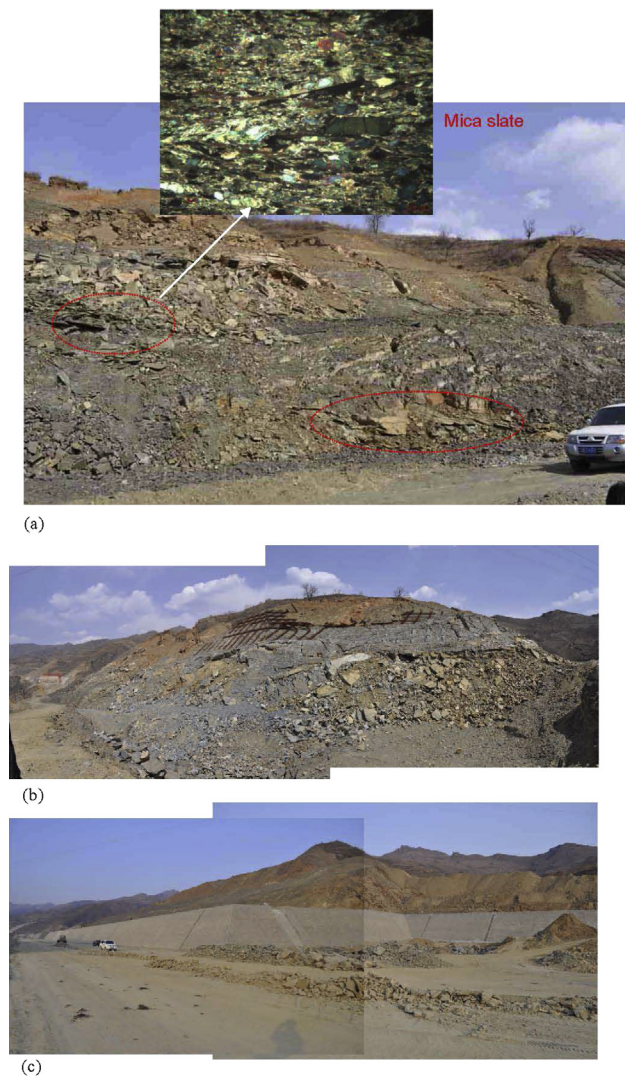


Fig. 4. Slope slipping at an expressway in North China. (a) Landslide controlled by the mica schist (photo taken in NE direction, 22 April 2012); (b) Landslide when installing anchor cables (photo taken in NW direction, 15 April 2012); (c) Cutting of saprolite and shallow layers of mica schist for unloading (26 October 2013).

3. Suggestion of an effective technology roadmap

During the whole procedure of project site selection, design and construction, the engineering geology is dominant in decision making. The whole procedure starts from strategic decision or comparison of engineering candidate sites in order to identify the UGBs to avoid unfavorable problems induced by UGB during construction. When using GEDC method, the problem is now

Table 1
Assessment of slope conditions at different stages.

Stage	Dip direction (°)	Slope structure	Underlying petrology	UGB	Reinforcement	Updated date
Initial (after investigation)	225	Antithetic	Granite-gneiss	Strongly weathered pinal schist in surface	Seven steps with cables	12/2010
Revision (during construction)	225	Antithetic	Biotite plagiogneiss	Five interlayers of pinal schist at different depths	Seven steps with anchor cables and anti-slide piles	12/2011
Consulting (revise design scheme after landslide)	265	Consequent	Biotite plagiogneiss	Five interlayers of schist as cones or with sheared slipped faces	Seven steps with anti-slide piles	6/2012
Mitigation (revised construction)	265	Consequent	Biotite plagiogneiss	Four layers at shallow depth were cut off	Seven steps but with more discharges	10/2013

Table 2
Evaluation of weight ratios of influential factors from the interaction matrix.

Influential factor	Priority in large area α_i (%)	Ratings code N	Weight ratio W_i (%)
Landforms	15.315	2	15.315
Geology	16.216	2	16.216
Precipitation	14.414	2	14.414
Investigation	17.117	2	17.117
Design	16.216	2	16.216
Construction	20.722	2	20.722

transferred to dynamic controlling for diminishing disturbance on weak surrounding rocks, i.e. regular monitoring, smaller advancement rate, weak blasting and excavating, support in advance, etc. (Fig. 3).

At the different stages of field investigation, plan, design and construction, the synthetic evaluation of engineering geological conditions are significantly different from discontinuity dynamic controlling and adjusting (Fig. 3). Consequently, different methods are necessary to deal with various problems encountered to gain an optimal result.

4. Case study

4.1. Brief description of a cut slope

One rock slope is taken as an example, which sits in the western part of the Taihang Mountain, Yuxian, North China (E113°25'40", N38°28'20"). The stratum of this project belongs to Huili Group of Longhuahe Formation, the Upper Archean (Arlnh), which is basically composed of biotite plagiogneiss (Shanxi Geology Bureau, 1965).

The strike of the Taihang Mountain is nearly SN, and the elevation above sea level is 600–1000 m. The cut slope, located just between two creeks of a gully, is 51.4 m high and 160 m long, with 7 excavation steps (Fig. 4). On 2 July 2011, after a 2-day heavy rainfall (0.4–70.7 mm/d in that region), the slope slipped locally at the SW part (Fig. 4a). On 18 September 2011, when the 2nd step from the slope root was undercut and anchor cables were installed (Fig. 4b), the whole slope slipped and cable installation failed. After field investigation, it was known that the main slipping direction is 265°, and the dip angle of the slipping face is 26°; the frontier margin is 300 m wide, and the main axis is 280 m long, with a coverage area of 42,000 m²; the overburden thickness is 5–15 m, averaging 11 m. The total volume of slipping mass is approximately 460,000 m³.

4.2. Assessment of engineering geological conditions

Different evaluations of the site-specific engineering geological conditions at different stages were carried out for this project. After field investigation, it is clear that the slope, considered as an inse-quent structure, is underlain by granite-gneiss formation. The

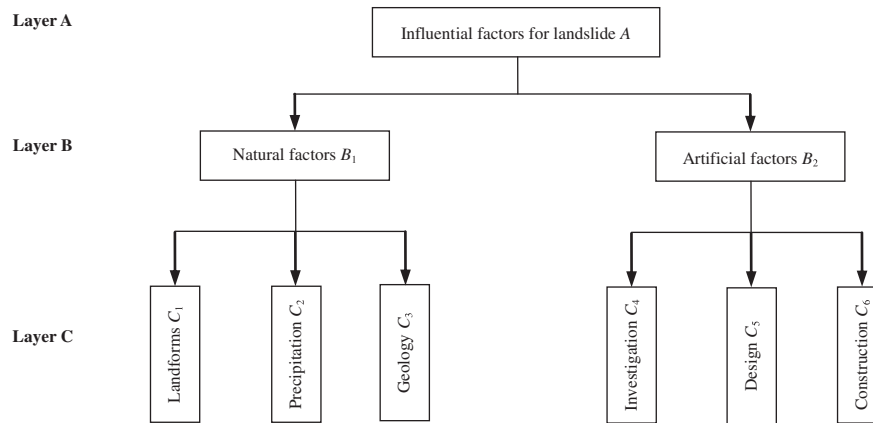


Fig. 5. The hierarchy models affecting stability of the cut slope.

Table 3
Application of the AHP method.

Influential factor	Weight ratio (%)
Landforms C_1	27.507
Precipitation C_2	17.328
Geology C_3	21.832
Investigation C_4	16.667
Design C_5	8.333
Construction C_6	8.333

mechanical parameters of the rock mass, cohesion c and internal friction angle ϕ , of the 3 groups of gneiss samples are 12 MPa and 42.1° , respectively. The design is to cut the slope by 7 steps and to reinforce it using anchor cables within concrete frames. But after slope slipping, field investigation shows that the slope is a typical consequent slope: the dip directions of the slope and the gneissosity are 270° and 265° , respectively; and the dip angles of the cut slope and schistosity are 38° and 25° , respectively. There are 5 interlayers of sericite-schist in the slope, of which the #3 and #4 interlayers (sequential order from the ground surface) constitute the slipping face. The cohesion c and internal friction angle ϕ of the rock mass obtained from back analysis of the slipped slope, using the rigid limit equilibrium method, are 4 kPa and 23.5° , respectively, suggesting that the design revision is needed, and the measures, such as removal of the disintegrated rocks in shallow depth and using anti-slide piles, were put forward. But in 2012, some fissures occurred again in the concrete frames during

construction. Finally, the cut volume is accumulated to such a large value that saprolite and cataclastic rocks at shallow depth were all cut off (Fig. 4c).

In order to understand the landslide mechanism and the suggested countermeasures, the authors combine the variations of evaluations and measurements at different stages (see Table 1).

4.3. Evaluation of influential factors effects

First, a qualitative description is needed to determine different weight ratios of the interaction matrix in investigation, design and construction periods (Table 2). The comparison of influential factors at three levels of A, B and C is carried out (Fig. 5). Then, using the AHP method, the weight ratios of the 6 parameters at level C are computed (Table 3).

In the expert scoring system, there are 4 items with different priorities (Table 4). The sum of different values of influential factors is put into the blanks according to expert group experience. Then different weight ratios of the factors are added to obtain the overall values.

Above all, the weight ratios of the three artificial factors in combination with the natural factors from the interaction matrix, AHP, and expert scoring method are roughly represented as a result of natural factors 55%, investigation 16%, design 9%, and construction 20% (Table 5).

As a result, this assessment method of weight ratios of different influential factors was approved and accepted by the responsible

Table 4
Results of the expert scoring method.

Marking items	Priority	Calculation expression	Natural factors	Artificial factors			Total
				Investigation	Design	Construction	
Not depend on regulations	0.6	Net scores (100 points)	68	20	10	23	121
		Percentage (%)	56.198	16.529	8.264	19.008	100
		Weight ratio (%)	33.179	9.917	4.959	11.405	
Complex geological conditions	0.2	Net scores (100 points)	60	25	15	35	135
		Percentage (%)	44.444	18.519	11.111	25.926	100
		Weight ratio (%)	8.889	3.704	2.222	5.185	
Rainfall effect	0.15	Net scores (100 points)	60	15	10	25	110
		Percentage (%)	54.545	13.636	9.091	22.727	100
		Weight ratio (%)	8.182	2.045	1.364	3.409	
Reference to the division of responsibilities of the similar slope disaster	0.05	Net scores (100 points)	60	20	10	30	120
		Percentage (%)	50	16.667	8.333	25	100
		Weight ratio (%)	2.5	0.833	0.417	1.25	
Overall weight ratio (sum of weights)	1		53.29	16.499	8.962	21.249	100

Note: Percentage is the ratio of net score of an influential factor to total score of all factors.

Table 5
Suggested results of three kinds of methods for evaluation of effects.

Influential factors		Weight ratio (%)			
		AHP	Interaction matrix	Expert scoring method	General mean value
Natural factors	Landform	27.507	15.315	53.29	55
	Precipitation	17.328	16.216		
	Geology	21.832	14.414		
Artificial factors	Investigation	16.667	17.117	16.499	16
	Design	8.333	16.216	8.962	9
	Construction	8.333	20.721	21.249	20

managers. As for the plan effect in this procedure, which is governed by lots of factors during investigation and design, it is strategically important for selection of various schemes in advance. However, in this context, it is not considered due to its complex factors.

5. Conclusions

The assessment of engineering geological conditions is conducted based on synthetic analyses of influential factors with respect to geology and engineering scopes using interaction matrix, AHP, expert scoring method, analogical method, etc. Based on UGB explorations and advance identifications, it is suggested for major project to keep away from the poor geological conditions in space. For determination of weight ratios of different influential factors, different methods can be applied in various conditions. It is desirable if the input data are the same and the output results from different models can be compared and integrated. In this case, field investigation, design and construction are the dominant factors accounting for excavation landslide in expressway in North China.

Conflict of interest

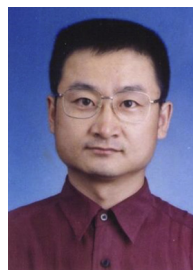
We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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