Nat. Hazards Earth Syst. Sci., 16, 1449–1463, 2016
www.nat-hazards-earth-syst-sci.net/16/1449/2016/
doi:10.5194/nhess-16-1449-2016

Natural Hazards and Earth System Sciences
Open Access

An approach using multi-factor combination to evaluate high rocky slope safety

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Received: 5 December 2015 – Published in Nat. Hazards Earth Syst. Sci. Discuss.: 23 February 2016
Revised: 25 April 2016 – Accepted: 1 June 2016 – Published: 17 June 2016

Abstract. A high rocky slope is an open complex giant system for which there is contradiction among different influencing factors and coexistence of qualitative and quantitative information. This study presents a comprehensive intelligent evaluation method of high rocky slope safety through an integrated analytic hierarchy process, extension matter element model and entropy weight to assess the safety behavior of the high rocky slope. The proposed intelligent evaluation integrates subjective judgments derived from the analytic hierarchy process with the extension matter model and entropy weight into a multiple indexes dynamic safety evaluation approach. A combined subjective and objective comprehensive evaluation process, a more objective study, through avoiding subjective effects on the weights, and a qualitative safety assessment and quantitative safety amount are presented in the proposed method. The detailed computational procedures were also provided to illustrate the integration process of the above methods. Safety analysis of one high rocky slope is conducted to illustrate that this approach can adequately handle the inherent imprecision and contradiction of the human decision-making process and provide the flexibility and robustness needed for the decision maker to better monitor the safety status of a high rocky slope. This study was the first application of the proposed integrated evaluation method in the safety assessment of a high rocky slope. The study also indicated that it can also be applied to other similar problems.

1 Introduction

Nowadays, human beings are facing many serious environmental and natural geological disasters, accompanying the massive construction of important projects (Su et al., 2013a). More and more high and steep rocky slopes are forming and are threatening people's lives and property and the safety of whole projects. This slope safety behavior needs to be urgently analyzed. From an engineering point of view, a high rocky slope is a complex open system and the factors affecting its stability are varying and capricious, in that they have strongly chaotic characteristics. The complexity and uncertainty of these factors leads to contradiction among different factors and the coexistence of qualitative and quantitative information, which may seriously affect the safety assessment of slopes. Therefore, it is very difficult, but important, to carry out a safety assessment of high rocky slopes.

From the viewpoint of expert systems, final evaluations of the safety of one high rocky slope vary from person to person according to their different professional backgrounds, viewpoints, conditions of understanding the project, etc. Accordingly, the fact that the safety evaluation of high rocky slopes includes multiple criteria is problematic, as well as both qualitative and quantitative features being present. It is considered to be a multiple criteria decision-making problem. The paper aims to express artificial reasoning in mathematical forms to mimic the human behavior which is present in expert systems. The combination of the analytic hierarchy process, matter element analysis and entropy weight model presents a fundamental approach to mathematically express human beings' inference and interpretation. The prevailing side of the proposed method in solving the multiple criteria decision-making problem is its capability of more objective and intelligent assessment in mathematical form, combining detected influencing factors without the need of human involvement and interference.

Much research mainly focuses on one specific aspect of slopes' safety and lacks the identification of the whole security of high rocky slopes (Malkawi et al., 2000; Prsilva et al., 2008). Although there are many evaluation methods, the amount of research and number of applications are still few and superficial. Traditional methods always tend to cause contradictions among affecting factors and the coincidence of qualitative and quantitative information, resulting in uncertainty.

In recent years, we have seen the development of the finite element analysis, the fuzzy mathematic method and the artificial neural network method. They all conduct the assessment through combining qualitative and quantitative information, and the factors concerned basically do not change (Su et al., 2013b). For rocky slope safety evaluation, some advanced methods, such as geographic information systems and ground-based radar, have been attempted for slope safety evaluation and warning (Dai and Lee, 2002; Bozzano et al., 2010; Casagli et al., 2010). However, existing interpretation methods typically applied one single index (e.g., surface deformation or rainfall) as a predictor and hence revealed only one aspect of slope performance (Ermini et al., 2005). In the paper, a method is introduced though multiple monitoring indexes and influencing parameters.

For the past 1 year of research from 2014 to 2015, analysis methods mainly focused on the Bayesian network, finite element analysis, genetic algorithms, artificial neural networks, digital elevation models, statistics methods, evolutionary approach, etc. (Abdalla et al., 2015; Jamsawang et al., 2015; Fuchs et al., 2014; Bahsan et al., 2014; Peng et al., 2014; Garg and Tai, 2014; Ji et al., 2015). The disadvantages of present rocky slope safety evaluation method include that it is focused on one or certain factor, local safety analysis, single qualitative evaluation, single quantitative calculation, changeable results, more subjective analysis and so on. A holistic assessment of the slope safety state might not be achieved. Besides, a large portion of monitoring data is often not utilized in these methods.

The geological conditions of high rocky slopes are changeable and the outer environment also changes with time. The evaluation methods and theories still have large limitations and defects which need to be further developed (Pantelidis, 2011). Slope safety evaluation using multiple sources of monitoring information is more reasonable, and it is the topic of the present research. For present studies, a complete evaluation analysis, combining subjective and objective factors and presenting a qualitative evaluation conclusion and quantitative evaluation amount, is desired. An integrated approach is proposed, avoiding the aforementioned disadvantages and enhancing present research which lacks high rocky slope safety evaluation.

The objective of this study is to propose a methodology for identifying and delineating high rocky slope safety using an integrated analytic hierarchy process (AHP)–matter element analysis (MEA)–entropy weight method (EWM). Firstly, previously related research is reviewed systematically. Secondly, the multiple criteria decision-making (MCDM) process of high rocky slope safety evaluation is computerized and an MCDM evaluation system of three layers, four criteria and 15 subcriteria is built by the AHP. Thirdly, MEA is used to determine the factor importance sequence to avoid subjective judgment as much as possible, and the sutra field, controlled field and the matrices of the matter element are set up from each layer. The importance ranking of each factor is finally determined based on the single index correlation, comprehensive correlation and grade variable eigenvalue. The initial weight follows with the multiple comparison and judgment principle and matrix. A second correction with the EWM is conducted to reduce the decision maker's subjectivity on the largest level to improve the scientific nature and accuracy of the evaluation indexes. Lastly, an example of one slope is presented to illustrate the proposed methodology.

2 Literature review

2.1 Multiple criteria decision-making (MCDM)

The problems of MCDM are common occurrences in all kinds of areas, as MCDM refers to decisions being made in the presence of multiple, usually conflicting, criteria (Hwang and Yoon, 1981). Since the safety evaluation of high rocky slopes includes multiple criteria and both qualitative and quantitative features, it is considered to be an MCDM problem. Subjective information and objective information coexist in MCDM. Thus, the subjective and objective approach is promoted to solve MCDM problems. For example, Kersuliene et al. (2010) proposed the new stepwise weight assessment ratio analysis method to allow a more thoughtful application of existing MCDM analytic methodologies. Ginevicius (2011) adopted a new method, namely a factor relationship for MCDM problems. To solve the inherent uncertainty and imprecision of the MCDM, a fuzzy assessment approach was introduced, combining the concept of entropy and interval normalization procedure in a fuzzy AHP (Ozkir and Demirel, 2012). Zolfani et al. (2013) combined stepwise weight assessment ratio analysis and weighted aggregated sum product assessment methods to solve the MCDM problem. The technical analysis results in the theoretical foundations of different MCDM methods and advantages and weaknesses among them were more fully shown by Larichev and

Olson (2001), Belton and Stewart (2002), Hashemkhani et al. (2013) and Figueira et al. (2005).

In addition, a fundamental problem of MCDM is the derivation of the weight for a set of activities according to importance. Thus, scaling numbers from 1 to 9 were introduced to the weights of the elements in each level of the hierarchy with respect to an element of the next higher level in MCDM (Saaty, 1977). Weights based on a subjective approach reflect subjective judgements from one person, and objective weights obtained by mathematical methods are based on the analysis of the initial data. Both of them are not perfect and an integrated approach could be most appropriate for determining the weights of the attributes. Therefore, a subjective and objective integrated approach was introduced to determine attribute weights in multiple attribute decision-making problems (Ma et al., 1999). As the quantitative criteria were precisely defined, the developed quantitative multiple criteria decision-making method can be successfully applied (Ustinovichius et al., 2007). In terms of qualitative and quantitative criteria, decision-making techniques were applied, including Technique for Order of Preference by Similarity to Ideal Solution, Simple Additive Weighting and mixed methods, as well as AHP and entropy methods, for defining the importance of weights of the attributes (Karami and Johansson, 2014).

2.2 Analytic hierarchy process (AHP)

According to advantages of applied techniques, it is expected that the AHP method can provide closer results to real decisions made (Saaty, 2003). Saaty's AHP is a popular MCDM technique and is widely used. Thus, the AHP method is firstly chosen as the basic analysis approach in this paper. The AHP was proposed by Thomas L. Saaty (Saaty, 1972, 1986, 1988, 1994; Shannon, 1948; Vaidya and Kumar, 2006) and reflects the natural behavior of human thinking. Its major innovation is the introduction of pairwise comparisons. The pairwise comparison technique represents a theoretically founded approach to compute weights, representing the relative importance of criteria. Therefore, AHP has been considered as a very useful tool for dealing with complex MCDM problems by the international scientific community.

In civil engineering, especially for the situations with incomplete or ambiguous data due to great inherent uncertainty in construction projects, a risk assessment model using AHP was developed (Abdul-Rahman et al., 2013). Li et al. (2013) analyzed the inconsistent comparison matrix in AHP and proposed a way to improve comparison matrix consistency by using a sorting and ranking methodology. To manage crises in the reconstruction of the damaged areas, the AHP method for weighing the important criteria and a novel complex proportional assessment of alternatives with gray relations for evaluating the alternatives were successfully applied (Bitarafan et al., 2012). Li and Zou (2011) proposed a fuzzy AHP method to deal with the public–private partnerships in infrastructure projects. Eshtehardian et al. (2013) applied the analytical network process and AHP methods to select appropriate construction suppliers and civil engineering companies, and achieved a satisfied result. An AHP-based MCDM approach was presented for pedestrian zone selection in the absence of quantitative data (Sayyadi and Awasthi, 2013). However, the models considered present some difficulties for application and are far from being perfect, therefore requiring further analysis (Triantaphyllou, 2000).

2.3 Matter element analysis (MEA)

Based on previous reviews and summaries, the AHP is proven to be a well-known decision support tool used for complex MCDM problems by providing a multi-level hierarchical structure. However, it is also indicated that it is difficult for a single mathematical method to complete the final decision-making process because of some drawbacks of the AHP. Thus, this paper adopts an integrated method to evaluate high rocky slope safety.

During the AHP process, the index importance rule is influenced seriously by artificial disturbance and it is difficult to establish a reasonable and precise index importance sequence. The incompatibility problem is very evident. To solve these problems, the matter element analysis (MEA) method based on extension theory is introduced and primarily used to study the problem of incompatibility (Cai, 1983).

Matter element analysis is a new theory to find out the regular patterns of incompatibility problems. It can better reflect the variation characteristics of the objects of analysis and aid in qualitative analysis and quantitative calculation. Extenics theory differs from the fuzziness concept described in fuzzy mathematics and certain concepts from classical mathematics. It concentrates on the changeability of the research objects and further describes the pros and cons from the qualitative level to the quantitative level. It can be used for solving multiple parameters evaluation problem by formalizing the problem and establishing the corresponding matter element.

While solving the MCDM problem, three factors of MEA, namely events, features and values, are used to describe and represent the objects to be assessed, and together form the matter element. It can better reflect the variation characteristics of the objects of the analysis and aid in qualitative analysis and quantitative calculation, which is very suitable for the decision maker to give a more precise safety assessment. Based on the matter element method, Cheng (2001) investigated a practical case study of blasting classification of rock and Tang et al. (2009) evaluated soil nutrients in an ecological fragile region. There are also other detailed applications of the matter element method, such as weather forecasting and evaluating financial security (Feng and Hong, 2014; Li et al., 2014). To expand the application of MEA, Wang et al. (2015) proposed a model that predicted rockburst intensity based on the fuzzy matter element theory.

This paper is based on the matter element concept, combining the evaluation objects, indexes and index values, and the extension nature of the matter element is used to assess the whole safety of the high rocky slope.

2.4 Entropy weight method (EWM)

However, the safety evaluation weight of the slope founded on the AHP-extension matter model might be subjective, which might affect the objective analysis about its safety. In addition, for the integrated AHP and MEA, a minor factor can have a great influence on the ranking of the alternatives. Hence, the entropy approach is introduced for determining the objective weight (Ustinovichius, 2001). AHP depends on experts to different extents, and therefore contains strong subjectivity. Slight weight differences can dramatically change the order of the alternative preference. Consequently, the appropriate weight for each criterion in MCDM is critical to achieve a precise qualitative evaluation and quantitative safety amount. An objective weight correction method is an important guarantee.

As we all know, entropy is the one of the most important concepts in social science, physics and information theory. The entropy weight method (EWM) is used to determine the weights of influence indexes as a better way of avoiding subjective influence. EWM can be quantified and simulated to represent the objective information contained in an MCDM system and the subjective information possessed by a decision maker. In the literature of information theory, the concept of entropy, was firstly introduced by Shannon (1948). Shannon's entropy served as a useful method for evaluating data structures and patterns. Then, EWM was introduced in determination of criteria weights for MCDM problems (Shemshadi et al, 2011; Ye, 2010; Kildiene et al, 2011). Ge et al. (2013) established a fuzzy optimization model based on EWM to select a typical flood hydrograph in the design flood, and this model was relatively better at designing flood computation compared with the traditional typical flood hydrograph. European country management capabilities within the construction sector in the time of crisis were investigated, applying a proposed method determined via the entropy method (Susinskas et al., 2011). Assessment and selection of appropriate solutions for occupational safety were classified as an MCDM problem, and EWM was used to determine the relative significance of evaluation criteria (Dejus and Antucheviciene, 2013).

2.5 Integrated method

A single method effect is weak for the solution of MCDM problem and may be dangerously inaccurate for complex decision problems. An integrated approach brings a comprehensive and objective result based on previous reviews. Thus, the integrated approach is an effective evaluation method. AHP and EWM are often used to implement the safety evaluation of hydraulic or civil engineering (Kok et al., 2009; Rahman et al., 2013). Tavana and Hatami-Marbini (2011) developed an MCDM framework based on AHP and EWM for the human spaceflight mission planning. For the selection of the best material for the tool holder used in hard milling, Caliskan et al. (2013) applied the AHP and EWM to confirm criteria weighting so that a new decision model was developed. For the pursuing the goal of selecting the best transportation investment project portfolio, a fuzzy assessment approach was presented by utilizing the concept of entropy and fuzzy AHP (Ozkir and Demirel, 2012).

This paper adopts an AHP–MEA–EWM integrated method to assess the safety of high rocky slopes. It sets up the comprehensive multi-layer and multi-objective safety evaluation model for high rocky slopes from the aspects of geological condition, engineering condition, external environment and internal and external monitoring behavior. AHP is firstly used to construct a multi-layer and multi-index MCDM framework. Then, the importance ranking of all influential factors of high rocky slopes is determined based on the single index correlative degree, comprehensive correlative degree and grade variable eigenvalue of the matter element matrix. The initial weight is obtained based on the above analyses, and a second correction with the entropy weight method is made. Finally, the quantitative safety amount and qualitative safety level are determined by overlapping application of integrated methods and recursive calculation from the criteria level to the goal level.

3 Multi-level and multi-index evaluation system of high rocky slope safety

A single index of a complex high rocky slope is not enough for the evaluation of its safety. Additionally, the stability of the high rocky slope is obviously influenced by its inner characteristics and outer environment. Therefore, it is necessary to set up a multi-level and multi-index evaluation structure. Each level plays a dominant role, with its adjacent subsequent level covering multiple indices, and each forming a layer-by-layer dominant relationship from top to bottom. Following the method above, the hierarchy of an open-cut construction of a high rocky slope has been established as shown in Fig. 1. There are lots of factors related to the rocky slope safety. Some of these factors are still unknown and a few factors are neglected for their ignorable influences to the rocky slope safety. Therefore, the dotted arrows are added to denote the unknown and ignorable factors for a more complete rocky slope safety evaluation process in Fig. 1. The highest level (level 1) of the hierarchy represents the overall goal of evaluating the high rocky slope safety. The second level (level 2) consists of all factors on the high rocky slope safety, such as geological conditions, engineering conditions, outer environment and inner and outer monitoring. The general criteria constitute the lowest level (level 3).

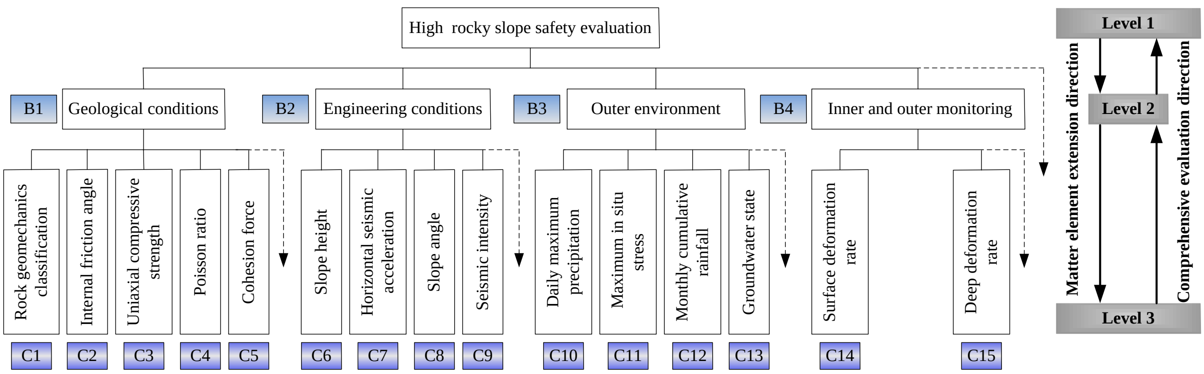

Figure 1. Safety evaluation hierarchy of high rocky slopes.

According to the specification and national standard of the water conservancy and hydropower slope engineering about the rocky slope safety classification and existing research results on the ranking standard, the differences of different areas and different projects are comprehensively considered (Wu and Chen, 2009; Zhao et al., 2011). Combined with numbers of engineering cases, the safety grade of high rocky slope can be divided into five levels shown in Table 1; I means very stable, II means stable, III means basically stable, IV means unstable and V means extremely unstable.

In order to eliminate the shortcomings of incommensurability brought by the dimension and dimensional unit for evaluation index values under different factors, the dimensionless method is used to process the evaluation indexes on different grade levels. For indexes such as the cohesion force, the larger the value, the better the tendency.

$$c'_{ij} = \left(c_{ij} - c_{i\max}\right) / \left(c_{i\max} - c_{i\min}\right) \tag{1}$$

For indexes such as slope height, the smaller the value, the better the tendency.

$$c'_{ij} = \left(c_{i\max} - c_{ij}\right) / \left(c_{i\max} - c_{i\min}\right), \tag{2}$$

where $c_{i\max}$ and $c_{i\min}$ are the maximum and minimum indicators at different levels of one indicator. c_{ij} and c'_{ij} are the initial index value and the final result calculated by a self-developed algorithm of range method under one indicator level. The dimensionless result is shown in Table 1.

4 The proposed integrated method evaluating high rocky slope safety

4.1 The identification of evaluation indexes' importance on high rocky slopes

Comprehensive stability evaluation in terms of high rocky slopes is based on the extensibility of the matter element for stability evaluation. Its core is to determine the extension domain, and the matter element transformation of factors is the implementation means in the extension domain. For extenics, the matter element is the logic cell. The stability of high rocky slope is called event N. The feature of high rocky slope stability is called C, including the geological conditions, the engineering conditions, the external environment and the internal and external monitoring behavior. The eigenvalue of each factor in the every level is called the magnitude V. The ordered triple $R = \{N, C, V\}$ is known as the most basically described element, also named the matter element. Introduction of the matter element provides a viable tool for solving the formalization of stability comprehensive evaluation questions of high rocky slopes.

Extension evaluation will be established including every level based on the matter element extensibility. Sutra field, controlled field and the matrices of matter element for appraising will be set up from each layer. The importance ranking of each factor is finally determined in the corresponding level basing on the single index correlation, the comprehensive correlation and the grade variable eigenvalue. Through this, it can avoid subjective judgments as far as possible and provide an important basis for the improved AHP.

(1) Matter element

For the evaluation level of the matter element, evaluation event N_{0k} corresponds to composition elements of the evaluation level. The indexes composing evaluation levels correspond to matter element feature C_i including $C_1, C_2, \ldots, C_n$ and the index value is called the matter element feature of the magnitude $V_{0ik} = < a_{0ik}, b_{0ik} >$. $R_{0k} = (N_{0k}, C_i, V_{0ik})$ is the evaluation level matter element, and its sutra field matrix is expressed as

Table 1. Value rank of evaluation index under different grades.

Index	Normal index value [dimensionless index value]				
	I	II	III	IV	V
Rock geomechanics classification	80–100 [0.80–1.00]	60–80 [0.60–0.80]	40–60 [0.40–0.60]	20–40 [0.20–0.40]	0–20 [0.00–0.20]
Internal friction angle (°)	60–90 [0.67–1.00]	50–60 [0.56–0.67]	39–50 [0.43–0.56]	27–39 [0.30–0.43]	0–27 [0.00–0.30]
Uniaxial compressive strength (MPa)	150–200 [0.74–1.00]	125–150 [0.61–0.74]	90–125 [0.42–0.61]	40–90 [0.16–0.42]	10–40 [0.00–0.16]
Poisson ratio	0–0.20 [0.60–1.00]	0.20–0.25 [0.50–0.60]	0.25–0.30 [0.40–0.50]	0.30–0.35 [0.30–0.40]	0.35–0.50 [0.00–0.30]
Cohesion force (MPa)	0.22–0.32 [0.69–1.00]	0.12–0.22 [0.38–0.69]	0.08–0.12 [0.25–0.38]	0.05–0.08 [0.16–0.25]	0.00–0.05 [0.00–0.16]
Slope height (m)	0–75 [0.93–1.00]	75–175 [0.83–0.93]	175–300 [0.70–0.83]	300–500 [0.50–0.70]	500–1000 [0.00–0.50]
Horizontal seismic acceleration (g)	0.00–0.05 [0.88–1.00]	0.05–0.10 [0.75–0.88]	0.10–0.15 [0.63–0.75]	0.15–0.20 [0.50–0.63]	0.20–0.40 [0.00–0.50]
Slope angle (°)	0–10 [0.89–1.00]	10–20 [0.78–0.89]	20–30 [0.67–0.78]	30–40 [0.56–0.67]	40–90 [0.00–0.56]
Seismic intensity	0–2 [0.83–1.00]	2–4 [0.67–0.83]	4–6 [0.50–0.67]	6–8 [0.33–0.50]	8–12 [0.00–0.33]
Daily maximum precipitation (mm)	0–20 [0.87–1.00]	20–40 [0.73–0.87]	40–60 [0.60–0.73]	60–100 [0.33–0.60]	100–150 [0.00–0.33]
The maximum in situ stress (MPa)	0–2 [0.92–1.00]	2–8 [0.68–0.92]	8–14 [0.44–0.68]	14–20 [0.20–0.44]	20–25 [0.00–0.20]
Monthly cumulative rainfall (mm)	0–50 [0.83–1.00]	50–100 [0.67–0.83]	100–150 [0.50–0.67]	150–250 [0.17–0.50]	250–300 [0.00–0.17]
Groundwater state (L min^{-1} $(10\,\mathrm{m})^{-1}$)	0–25 [0.83–1.00]	25–50 [0.67–0.83]	50–100 [0.33–0.67]	100–125 [0.17–0.33]	125–150 [0.00–0.17]
Surface deformation rate (mm day^{-1})	0–2 [0.80–1.00]	2–3 [0.70–0.80]	3–5 [0.50–0.70]	5–8 [0.20–0.50]	8–10 [0.00–0.20]
Deep deformation rate (mm day^{-1})	0.00–0.20 [0.90–1.00]	0.20–0.30 [0.85–0.90]	0.30–0.50 [0.75–0.80]	0.50–1.00 [0.50–0.75]	1.00–2.00 [0.00–0.50]

$$R_{0k} = (N_{0k}, C_i, V_{0ik}) = \begin{bmatrix} N_{0k} & C_1 & V_{01k} \\ & C_2 & V_{02k} \\ & C_3 & V_{03k} \\ & \vdots & \\ & C_n & V_{0nk} \end{bmatrix} = \begin{bmatrix} N_{0k} & C_1 & < a_{01k},\ b_{01k} > \\ & C_2 & < a_{02k},\ b_{02k} > \\ & C_3 & < a_{03k},\ b_{03k} > \\ & \vdots & \\ & C_n & < a_{0nk},\ b_{0nk} > \end{bmatrix}. \quad (3)$$

Its controlled field can be expressed as

$$R_p = \left(P, C_i, V_{pi}\right) = \begin{bmatrix} P & C_1 & V_{p1} \\ & C_2 & V_{p2} \\ & C_2 & V_{p3} \\ & \vdots & \\ & C_n & V_{pn} \end{bmatrix} = \begin{bmatrix} P & C_1 & < a_{p1},\ b_{p1} > \\ & C_2 & < a_{p2},\ b_{p2} > \\ & C_2 & < a_{p3},\ b_{p3} > \\ & \vdots & \\ & C_n & < a_{pn},\ b_{pn} > \end{bmatrix}, \quad (4)$$

where R_p means controlled field matter element; P means the composition of evaluation level elements and $V_{pi} = < a_{pi}, b_{pi} >$ means the maximum magnitude range of the controlled field matter element and $< a_{0ik}, b_{0ik} > \subset < a_{pi}, b_{pi} >, (i = 1, 2, \ldots, n)$.

Furthermore, the matrices of matter element for appraising can be expressed as

$$R_t = (N_t, C_t, V_t) = \begin{bmatrix} N_m & C_1 & d_1 \\ & C_2 & d_2 \\ & C_2 & d_3 \\ & \vdots & \\ & C_n & d_n \end{bmatrix}, \tag{5}$$

where R_t means the matter element of high rocky slope safety to be evaluated; N_t means elements of evaluation level to be evaluated; C_t means evaluating planning index of evaluation level elements; $V_t = d_i$ $(i = 1, 2 \ldots n)$ means the actual value of C_m.

(2) Correlation function determination

Based on the extenics theory, the calculation results of simple correlation function of evaluation indexes play an important role in determining the weight coefficient. The expression is

$$K_t(V_m) = \begin{cases} \dfrac{2(d_m - a_{0mt})}{b_{0mt} - a_{0mt}} & d_m < \dfrac{a_{0mt} + b_{0mt}}{2} \\ \dfrac{2(b_{0mt} - d_m)}{b_{0mt} - a_{0mt}} & d_m \geq \dfrac{a_{0mt} + b_{0mt}}{2} \end{cases}. \tag{6}$$

The expression of elementary correlation function is

$$K_t(V_m) = \begin{cases} \dfrac{\rho(d_m, V_{0mt})}{\rho(d_m, V_{pm}) - \rho(d_m, V_{0mt})} & \rho(d_m, V_{pt}) - \rho(d_m, V_{0mt}) \neq 0 \\ -\rho(d_m, V_{0mt}) - 1 & \rho(d_m, V_{pt}) - \rho(d_m, V_{0mt}) = 0 \end{cases}, \tag{7}$$

where

$$\begin{aligned} \rho(d_m, V_{0mt}) &= \left| d_m - \frac{1}{2}(a_{0mt} + b_{0mt}) \right| - \frac{1}{2}(b_{0mt} - a_{0mt}) \\ &= \begin{cases} a_{0mt} - d_m, \ d_m < \dfrac{1}{2}(a_{0mt} + b_{0mt}) \\ d_m - b_{0mt}, \ d_m \geq \dfrac{1}{2}(a_{0mt} + b_{0mt}) \end{cases} \end{aligned} \tag{8}$$

$$\begin{aligned} \rho(d_m, V_{pm}) &= \left| d_m - \frac{1}{2}(a_{pm} + b_{pm}) \right| - \frac{1}{2}(b_{pm} - a_{pm}) \\ &= \begin{cases} a_{pm} - d_m, \ d_m < \dfrac{1}{2}(a_{pm} + b_{pm}) \\ d_m - b_{pm}, \ d_m \geq \dfrac{1}{2}(a_{pm} + b_{pm}) \end{cases}. \end{aligned} \tag{9}$$

In the above correlation function formula, $K_t(V_m)$ expresses the simple correlation function value for the tth classification grade of d_m, which represents the mth $(m = 1, 2, \ldots, n)$ indicator in the evaluating planning matter element. a_{0mt} and b_{0mt} represent the minimum and maximum values of the index grades respectively. $\rho(d_m, V_{0mt})$ and $\rho(d_m, V_{pm})$ represent the interval distance between evaluating planning index value and $< a_{0ik}, b_{0ik} >$, $< a_{pi}, b_{pi} >$ respectively.

(3) Importance ranking of each factor in the same index level

The evaluation index maximum correlation function value $K_{m\max}$ and the associated stability grade $t_{mK\max}$ $(m = 1, 2, \ldots, n)$ are calculated via simple or elementary dependent function. The matrix is composed as follows:

$$T = \{t_{1K\max}, t_{2K\max}, \ldots, t_{nK\max}\}. \tag{10}$$

Then, the maximum grade of t grade matrix can be determined as

$$T' = \{\max(T)\} = \left\{t'_{1t}, t'_{2K\max}, \ldots, t'_{xK\max}\right\}, \tag{11}$$

where x represents the xth indicator in the maximum t grade in the index level, and the maximum value does not exceed n. $t'_{xK\max}$ represents the grade value of the xth indicator in the maximum t grade matrix.

In the maximum grade matrix t, the index x, corresponding to the maximum grade value is the most important factor in the index level followed by the index corresponding to the second maximum value. The rest can be deduced by analogy. In this way, the index sequence of importance at the maximum grade can be determined.

Then, the second largest grade is considered, building the second largest grade matrix and determining the sequence importance of every factor based on the similar process above. At last, the importance sequence of different factors in every indicator layer can finally be determined.

4.2 Weight determination of evaluation indexes on high rocky slope

According to the scale of multiple comparison and judgment principle, A. L. Satty applied fuzzy mathematics theory to establish multiple comparison scale system (Table 2) (Xu, 2013; Chowdary et al., 2013). Considering the factor importance sequence identification in the index level, a comparative judgment matrix of the adjacent upper level is finally established. The judgment matrix is solved by a square root method, and the consistency check is carried out. Then, the factor weight vector of the index level is determined. The index weight is the maximized objective correction based on a comprehensive weight-determining method of the combination of subjective and objective factors of multi-factor entropy weight model. Ultimately the weighted value is determined.

(1) Construct judgment matrix

According to the understanding and preliminary analysis of high rocky slopes, the elements involved in the slope evalu-

Table 2. Standard table of multiple comparison.

Scale value a_{ij}	Implication
1	B_i and B_j are equally important
3	B_i is slightly more important than B_j
5	B_i is obviously more important than B_j
7	Compared with the B_j, B_i is very important
9	Compared with the B_j, B_i is extremely important
1/3	B_j is slightly more important than B_i
1/5	B_j is obviously more important than B_i
1/7	Compared with the B_i, B_j is very important
1/9	Compared with the B_i, B_j is extremely important
2, 4, 6, 8	The importance of B_i compared with B_j is between the corresponding degree above

ation system are arranged hierarchically by nature, including namely the establishment of the overall goal level, criteria level and subcriteria level.

The judgment matrix is the basic information of the AHP. It is also the basis of calculations of the relative importance and level of single sequencing. The method takes a factor of upper level as the criterion and builds a multiple comparison judgment matrix based on the above conclusions about the factor importance sequence and the standard table of multiple comparison in Table 2. The results are listed in Table 3. Every factor of the judging matrix satisfies the following relations:

$$b_{ij} = 1/b_{ji},\ b_{jj} = 1(i,\ j = 1,\ 2 \ldots n). \tag{12}$$

(2) Calculate the eigenvalue and eigenvectors

$MW = \lambda_{\max W}$, W and $\lambda_{\max}$ represent the eigenvector and eigenvalue of the judgment matrix. The square root method is applied while it is a generally approximated solution.

The product E_i $(i = 1, 2 \ldots, n)$ of every row element can be calculated by multiplying the elements in the judgment matrix **M** by row:

$$E_i = \prod_{j=1}^{n} b_{ij}. \tag{13}$$

Calculate the nth root of E_i of each row (n is the order of matrix) as follows:

$$\overline{E}_i = \sqrt[n]{E_i}. \tag{14}$$

Take $\overline{E}_i$ into regularization processing as follows:

$$\boldsymbol{E}'_i = \overline{E}_i / \sum_{k=1}^{n} \overline{E}_k, \tag{15}$$

where $\boldsymbol{E}'_i$ is called the weight vector of the matrix.

Table 3. Judgment matrix of evaluation system for high slope safety.

A	B_1	B_2	$\ldots$	B_j	$\ldots$	B_n
B_1	1	b_{12}	$\ldots$	b_{1j}	$\ldots$	b_{1n}
B_2	b_{21}	1	$\ldots$	b_{2j}	$\ldots$	b_{2n}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
B_i	b_{i1}	b_{i2}	$\ldots$	b_{ij}	$\ldots$	b_{in}
$\vdots$	$\vdots$	$\vdots$	$\vdots$		$\vdots$	$\vdots$
B_n	b_{n1}	b_{n2}	$\ldots$	b_{nj}	$\ldots$	1

Table 4. Different order values of RI.

The order of judgment matrix	Consistency index RI	The order of judgment middle matrix	Consistency index RI
1	0.00	8	1.41
2	0.00	9	1.45
3	0.58	10	1.49
4	0.90	11	1.52
5	1.12	12	1.54
6	1.24	13	1.56
7	1.32	14	1.58

Estimate the maximum characteristic value of judgment matrix as follows:

$$\lambda_{\max} = \sum_{k=1}^{n} \left[(ME')_k / \left(nE'_k \right) \right]. \tag{16}$$

The consistency check index, CI, is introduced to make the result more consistent with the actual situation. The consistency check formula is as follows:

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI}, \tag{17}$$

where $\mathrm{CI} = (\lambda_{\max} - n)/(n-1)$. The mean random consistency index, RI, is different along with the change of the matrix order. The result is shown in Table 4. The judgment matrix is introduced. When $\mathrm{CR} < 0.1$, the consistency of the judgment matrix is acceptable. Otherwise, it needs to adjust the judgment matrix until the consistency test meets the requirements. Especially when $\mathrm{CR} < 0.01$, the consistency of the matrix is a satisfactory result. When $\mathrm{CR} = 0$, it is a complete consistency check.

(3) Determine and correct the weight vector

Through the above process, the judgment matrix meets the requirements of the consistency check. The vector, $\boldsymbol{E}'$, is the weight vector of the judgment matrix constituted by influential factors of high slopes. According to the nature of the entropy, actual information and subjective information of decision makers is quantified and synthesized to build

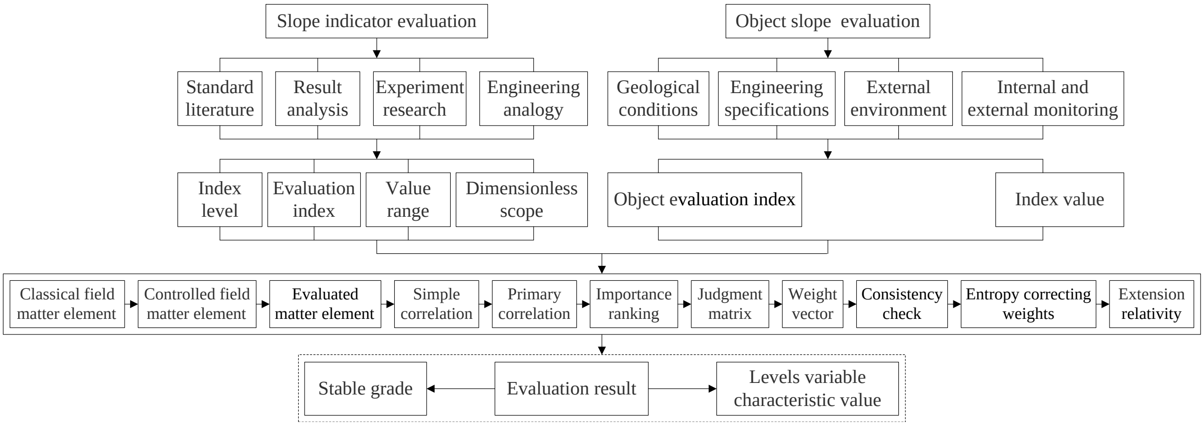

Figure 2. Evaluation flowchart of high rocky slope safety.

up the multi-objective decision entropy weight model from which we can learn how decision makers influence the index weight. Then, the weight indicator of AHP by the entropy weight method is corrected to make the index weight vector more reasonable and accurate. The factor importance ranking method built by the entropy weight method and the matter element extension theory reduces the subjective judgment as a maximization level, making the results more accurate and objective.

The following formula is adopted to determine the entropy value e_i of the ith indicator:

$$e_i = -\frac{1}{\ln(n)} \sum_{j=1}^{n} \left(\frac{c'_{ji}}{\sum_{j=1}^{n} c'_{ji}} \right) \ln \left(\frac{c'_{ji}}{\sum_{j=1}^{n} c'_{ji}} \right), \quad (18)$$

where n is the slope judgment matrix order. c'_{ij} is the slope impact factor index value which has experienced the range treatment.

The difference coefficient g_i of the ith indicator is calculated as follows:

$$g_i = (1 - e_i) \Big/ \left(n - \sum_{i=1}^{n} e_i \right), \quad (19)$$

where $0 \leq g_i \leq 1$.

The information weight value w_i is determined as follows:

$$w_i = g_i \Big/ \sum_{i=1}^{n} g_i. \quad (20)$$

The index weight k_i of AHP is corrected by w_i, and eventually the synthesis weight s_i is determined as follows:

$$s_i = w_i k_i \Big/ \sum_{i=1}^{n} w_i k_i. \quad (21)$$

4.3 High rocky slope safety state determination

With the help of single factor correlation function value $K_t(V_m)$ and the weight vector $\boldsymbol{s}$, the extension correlation $K_t(O)$ of the evaluation planning slope O about the grade of t can be confirmed:

$$K_t(O) = \sum_{i=1}^{n} s_i K_t(V_i), \quad (22)$$

where $\sum_{i=1}^{n} s_i = 1$, n is the matrix dimension.

With extension relativity, the safety state of the high rocky slope can eventually be obtained, namely as follows:

$$K_t(O) = \{k_{11}(O),\ k_{22}(O),\ \ldots k_{ti}(O) \ldots k_{ss}(O)\}, \quad (23)$$

where t is the standard grade; i is the element numbering of the vector $K_t(O)$ at the grade t, and the elements' maximum value in this vector is recorded as

$$k_{it0}(O) = \max(\{k_{11}(O),\ k_{22}(O),\ \ldots k_{ti}(O) \ldots k_{ss}(O)\}). \quad (24)$$

The stability grade of high slope is t_0. The calculation formula for the eigenvalue of classification grade of the evaluation planning index can be expressed as follows:

$$\overline{k}_t(O) = \frac{[k_t(O) - \min(K_t(O))]}{[\max(K_t(O)) - \min(K_t(O))]}, \quad (25)$$

where

$$t' = \sum_{t=1}^{s} t\overline{k}_t(O) \Big/ \sum_{t=1}^{s} \overline{k}_t(O). \quad (26)$$

Figure 2 shows the implementing process of high rocky slope safety evaluation with the proposed approach.

5 Case study

Integrating the aforementioned principles and methods, the calculation procedure for the evaluation of high rocky slope has been compiled in this section. This procedure is designed with the consideration of achieving the real-time dynamic evaluation and internal and external monitoring timeliness. The AHP–MEA–EWM is adopted during the calculation. One high rocky slope in China is used as a typical research project analyzed under the multi-factor evaluation system, as shown in Table 5.

The height of the unique high rocky slope is more than 700 m and the width is 50–290 m for an area of 115 000 m^2. Larger deformations of the surface and inner rocks are caused by challenging geological conditions in complex internal and external environments, such as rainfall and groundwater. The largest cumulative deformation velocity could reach 3.5 mm day^{-1}. At present, the maximum cumulative displacement amount is about 1500 mm for 1 year. Therefore, the present rocky slope is unstable and its safety needs to be analyzed urgently by integrating multiple methods.

5.1 Influencing index importance analysis

On the basis of the ideas explained above, the matter element extension matrix of the index level should be first constructed to determine the element importance ranking. Then simple correlation function values and elementary dependent function values can be calculated through establishing its sutra field, controlled field and the matrices of matter element for appraising. In order to identify the index importance ranking, the improved AHP is used to construct the judgment matrix and the initial weight vector is calculated after a consistency inspection. Finally, the EWM based on multi-objective decision-making is a means of secondary revision of the initial weight vector to build the extension relativity. The final safety state is determined for the high rocky slope, and the dimensionless parameters in this project are shown in Table 5.

This article takes the index evaluation system under geological conditions (B1) criteria in Fig. 1 as an example of carrying out detailed analysis. Other indexes can also be analyzed through a similar analysis process. For the stability classification, the sutra field (R_{01}–R_{05}), the controlled field (R_p) and the evaluating planning matter element (R_0) are respectively shown as follows:

$$R_{01}=\begin{bmatrix} N_{01} & C_1 & <0.80,\ 1.00> \\ & C_2 & <0.67,\ 1.00> \\ & C_3 & <0.74,\ 1.00> \\ & C_4 & <0.60,\ 1.00> \\ & C_5 & <0.69,\ 1.00> \end{bmatrix},$$

$$R_{02}=\begin{bmatrix} N_{02} & C_1 & <0.60,\ 0.80> \\ & C_2 & <0.56,\ 0.67> \\ & C_3 & <0.61,\ 0.74> \\ & C_4 & <0.50,\ 0.60> \\ & C_5 & <0.38,\ 0.69> \end{bmatrix},$$

$$R_{03}=\begin{bmatrix} N_{03} & C_1 & <0.40,\ 0.60> \\ & C_2 & <0.43,\ 0.56> \\ & C_3 & <0.42,\ 0.61> \\ & C_4 & <0.40,\ 0.50> \\ & C_5 & <0.25,\ 0.38> \end{bmatrix},$$

$$R_{04}=\begin{bmatrix} N_{04} & C_1 & <0.20,\ 0.40> \\ & C_2 & <0.30,\ 0.43> \\ & C_3 & <0.16,\ 0.42> \\ & C_4 & <0.30,\ 0.40> \\ & C_5 & <0.16,\ 0.25> \end{bmatrix},$$

$$R_{05}=\begin{bmatrix} N_{05} & C_1 & <0.00,\ 0.20> \\ & C_2 & <0.00,\ 0.30> \\ & C_3 & <0.00,\ 0.16> \\ & C_4 & <0.00,\ 0.30> \\ & C_5 & <0.00,\ 0.16> \end{bmatrix},$$

$$R_p=\begin{bmatrix} P & C_1 & <0.00,\ 1.00> \\ & C_2 & <0.00,\ 1.00> \\ & C_3 & <0.00,\ 1.00> \\ & C_4 & <0.00,\ 1.00> \\ & C_5 & <0.00,\ 1.00> \end{bmatrix},$$

$$R_0=\begin{bmatrix} N_0 & C_1 0.30 & \\ & C_2 & 0.21 \\ & C_3 & 0.53 \\ & C_4 & 0.30 \\ & C_5 & 0.25 \end{bmatrix}. \quad (27)$$

According to Eqs. (6) and (7), the simple correlation function and elementary correlation function values of R_{01} are determined by calculating the correlation procedure developed in this paper. The calculation results are listed in Tables 6 and 7.

The result of importance ranking of different factors according to the above methods is C_2, C_4, C_1, C_5, C_3. Based on the same method, the results of the order of importance of other indexes in Level 3 are C_8, C_6, C_9, C_7; C_{11}, C_{13}, C_{10}, C_{12}, C_{15}, C_{14}. According to the order of importance and Table 2, the judgment matrix of $\mathbf{B}_1-\mathbf{C}$ is shown in Table 8.

$$R_{B1-C}=\begin{pmatrix} 1 & 1/3 & 3 & 1/2 & 2 \\ 3 & 1 & 5 & 2 & 4 \\ 1/3 & 1/5 & 1 & 1/4 & 1/2 \\ 2 & 1/2 & 4 & 1 & 3 \\ 1/2 & 1/4 & 2 & 1/3 & 1 \end{pmatrix} \quad (28)$$

Table 5. Safety evaluation index value of high rocky slopes.

Level 2	Level 3	Values	Dimensionless values
Geological conditions B1	Rock geomechanics classification (RMR)	30.00	0.30
	Internal friction angle (°)	19.30	0.21
	Uniaxial compressive strength (MPa)	110.00	0.53
	Poisson ratio	0.35	0.30
	Cohesive force (MPa)	0.08	0.25
Engineering conditions B2	Slope height (m)	750.00	0.25
	Horizontal seismic acceleration (g)	0.07	0.83
	Slope angle (°)	43.00	0.52
	Seismic intensity	5.00	0.58
External environment B3	Daily maximum precipitation (mm)	54.60	0.64
	Maximum in situ stress (MPa)	23.50	0.06
	Monthly cumulative rainfall (mm)	68.40	0.77
	Groundwater state ($\mathrm{L\,min^{-1}\,(10\,m)^{-1}}$)	75.00	0.50
Internal and external monitoring B4	Surface deformation rate ($\mathrm{mm\,day^{-1}}$)	9.90	0.010
	Deep deformation rate ($\mathrm{mm\,day^{-1}}$)	1.63	0.19

Table 6. Index level results of correlation function under geological conditions criteria for grade I.

Evaluated index	Classic field interval	Controlled field interval	Evaluated matter element	Elementary dependent function	Simple correlation function
C_1	<0.80,1.00>	<0.00,1.00>	0.30	−0.63	−5.00
C_2	<0.67,1.00>	<0.00,1.00>	0.21	−0.69	−2.79
C_3	<0.74,1.00>	<0.00,1.00>	0.53	−0.31	−1.62
C_4	<0.60,1.00>	<0.00,1.00>	0.30	−0.50	−1.50
C_5	<0.69,1.00>	<0.00,1.00>	0.25	−0.64	−2.84

Table 7. The results of elementary dependent function for every grade.

Index	I	II	III	IV	V
C_1	−0.63	−0.50	−0.25	0.50	−0.25
C_2	−0.69	−0.63	−0.51	−0.30	0.75
C_3	−0.31	−0.15	0.21	−0.19	−0.44
C_4	−0.50	−0.40	−0.25	0.00	0.00
C_5	−0.64	−0.34	0.00	0.00	−0.26

Table 8. Standard table of multiple comparison of B_1–C.

B	C_1	C_2	C_3	C_4	C_5
C_1	1	1/3	3	1/2	2
C_2	3	1	5	2	4
C_3	1/3	1/5	1	1/4	1/2
C_4	2	1/2	4	1	3
C_5	1/2	1/4	2	1/3	1

Based on the procedure of calculating weights and eigenvalues developed in this paper, the obtained weight result is 0.16, 0.42, 0.06, 0.26, 0.10, with 5.07 as its eigenvalue. The consistency test ($\mathrm{CR} = 0.015 < 0.1$) shows that the judgment matrix has a satisfactory consistency which shows that the judgment matrix and the weight are reliable. Based on the weight amendment procedure, the result of corrected weight vector is 0.18, 0.55, 0.044, 0.14, 0.083. According to Eqs. (22)–(26) and the program developed in this paper, the extension relativity of each level is calculated (−0.63, −0.53, −0.35, −0.083, 0.33), and the eigenvalue of the classification grade is 4.25.

The results for other index layers are obtained similarly, including the weight vector, final weight result after amendment, eigenvalue, extension relativity and the eigenvalue of the classification grade, which are as follows. $\mathbf{B_2} - \mathbf{C}$ with its weight vector result is 0.28, 0.10, 0.47, 0.16 and the eigenvalue of 4.03 has a satisfactory consistency in the consistency test ($\mathrm{CR} = 0.0096 < 0.01$). The weight after amendment is 0.27, 0.11, 0.44, 0.18 and the extension relativity in each level is −0.48, −0.33, −0.27, −0.26, −0.30. The

Table 9. Evaluation results of criteria level (Level 2).

Index grade	Single index relativity				Comprehensive correlation
	Geological conditions	Engineering conditions	External environment	Internal and external monitoring	
1	−0.81	−0.53	−0.46	−0.64	−0.56
2	−0.75	−0.37	−0.28	−0.52	−0.41
3	−0.63	−0.06	0.07	−0.29	−0.13
4	−0.25	0.06	−0.07	0.43	0.068
5	0.50	−0.32	−0.35	−0.23	−0.22

eigenvalue of the classification grade is 3.11. $\mathbf{B}_3 - \mathbf{C}$ is with its weight vector results in 0.16, 0.48, 0.88, 0.27, and the eigenvalue is 4.00, with a satisfactory result in the consistency test ($CR = 0.0034 < 0.01$) and the weight vector after amendment is 0.17, 0.47, 0.091, 0.27. The extension relativity in each level is −0.63, −0.50, −0.27, −0.46, −0.69, and the eigenvalue of the classification grade is 2.85. $\mathbf{B}_4 - \mathbf{C}$, with its weight vector result of 0.25, 0.75, eigenvalue of 1.99 and matrix order of 2, shows a satisfactory consistency. The extension relativity in each level is −0.84, −0.83, −0.81, −0.70, −0.86, and the eigenvalue of the classification grade is 3.57.

5.2 Final safety evaluation

The analysis program of evaluation system is built on the theory of the integrated AHP–MEA–EWM. For the evaluation system of the overall goal level (Level 1), the analysis steps and ideas are consistent with the criteria level (Level 2) and the classification eigenvalue of the criteria level (Level 2) constructed above is 0, 1; 1, 2; 2, 3; 3, 4; 4, 5. Based on the ideas calculated in this article, the results of the single-index relation degree, integrated incidence degree and grade variable eigenvalue for safety evaluation of high rocky slope are shown in Table 9.

Based on the above methods, the importance order is B3, B4, B2, B1. The initial value of the weight is 0.10, 0.16, 0.47, 0.28, the value of the weight after amendment is 0.11, 0.18, 0.44, 0.27 and the classification eigenvalue is 3.75. The safety state of grade slope is IV, which is fully consistent with the present situation of the high rocky slope under an unstable state with larger and more unstable deformation. It is worth noting that the results of multivariate analysis demonstrate a warning of its precarious state. Based on the results of its internal and external monitoring, this safety evaluation system has provided an important theoretical basis for making rational decisions using a procedural algorithm to assess the security status of the slope in a timely and dynamic manner.

6 Conclusions

An integrated analytic hierarchy process–matter element analysis–entropy weight method for solving the multiple criteria decision-making problem has been proposed and applied in the comprehensive safety assessment of high rocky slope. The proposed method integrates the analytic hierarchy process method, matter element theory, and the entropy weight method within a safety assessment framework. The specific multivariate computational procedures were provided to illustrate the integration process of the above methods. Its evaluation process involves factor input, self-evaluation, dynamic assessment and real-time grade standards' output, etc. The comprehensive assessment results demonstrate that the level eigenvalue of the high rocky slope is 3.75, and its security status IV is fully consistent with the actual situation. Decision makers can conduct flexible and variable response programs for the high rocky slope. This study is the first application of the proposed method in the safety assessment of high rocky slopes.

Compared with the traditional method of solving the MCDM problem, the proposed method not only can assess multi-criteria decision problems in a more objective manner through avoiding subjective effects on the weights, but also, it can simultaneously produce the qualitative evaluation conclusion and quantitative evaluation amount. The effects of subjective errors on safety assessment of the high rocky slope could be avoided to a large extent. The intelligent preliminary evaluation analysis system provides an important theoretical support for making scientific judgments in a timely way based on the feedback of safety state of high rocky slopes. Thus, decision makers can obtain a more objective and flexible evaluation for the high rocky slope. Meanwhile, finding the best method to solve the MCDM problem is an elusive goal that may never be reached. Limitations also exist in this research. For example, this method could not solve the safety state for fuzzy and uncertain factors. The imprecision of the human decision-making process might exist and all the analyses should be conducted before the evaluation of qualitative factors can be consistent as this method is still based on the AHP theory.

The proposed MCDM approach integrates subjective judgments derived from the AHP with MEA and EWM into an intelligent, preferable and subjective and objective and multiple criteria approach. The structured approach presented in this study has some obvious attractive features. (1) It is comprehensive and flexible; the approach combines a comprehensive method covering the AHP, MEA and EWM technique concerning multiple factors, multiple criteria and multiple layers. The number of the all kinds of factors is not limited and this method is flexible for extension. (2) It is structured and analytical; the miscellaneous factors are stratified into a hierarchy to simplify information input and provide a clear framework for the decision maker for such complex problems. The proposed method helps the decision maker decompose a complex problem into manageable steps. (3) It is qualitative and quantitative; the comprehensive approach presents a qualitative evaluation analysis and a quantitative evaluation amount, which can be established for the decision maker to obtain a more precise decision. (4)It is subjective and objective; the subjective evaluation of a finite number of decision alternatives is allowed as the generic nature of the proposed approach of this paper allows a finite number of influencing factors. The objective influencing factors' importance of multiple layers can be obtained by MEA and an objective weight can be achieved by integrating the AHP and EWM. (5) It is computational and intelligent; the proposed method is a mathematical and computational model which can be widely applicable to the MCDM problem.

For future research, it can be conducted in the following directions. (1) The proposed method could be developed in the future based on fuzzy theory for imprecise, ambiguous or unknown data. (2) A more objective evaluation guideline could be introduced to amend the subjective judgment of the AHP. (3) The proposed method could be applied to other MCDM problems, especially for the safety evaluation of other fields. (4) The matter element theory could be more widely applied in solving MCDM problems by integrating other methods.

Acknowledgements. This research has been partially supported by the National Natural Science Foundation of China (SN: 51579083, 41323001, 51139001, 51479054), the Jiangsu Natural Science Foundation (SN: BK2012036), the Doctoral Program of Higher Education of China (SN: 20130094110010), the Open Foundation of State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering (SN: 20145027612), the Fundamental Research Funds for the Central Universities (SN: 2015B25414) and a project funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (SN: 3014-SYS1401).

Edited by: O. Katz
Reviewed by: three anonymous referees

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