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Safety Evaluation Approach for Hydropower Construction Based on Intuitionistic Fuzzy Set

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Abstract

Owing to the complex construction environment for hydropower construction (HC) and the differences in evaluation experts, there is uncertainty involving in the evaluation information, which is prone to produce evaluation deviation. Describing uncertain information accurately and adequately is difficult for traditional safety evaluation approaches, which results in the inconsistency of the assessment with actual situations in most cases. Therefore, a novel safety evaluation approach for HC based on intuitionistic fuzzy set (IFS) was proposed to describe and handle the imprecise or not totally reliable evaluation information. Firstly, the limitations and irrationalities of existing score functions were illustrated through numerical examples, and a novel score function was constructed according to the characteristics of the safety assessment process and the IFS theory. Then the properties of the mentioned score function were discussed, and the superiority of the proposed score function were exhibited by comparison with existing score functions. Furthermore, the safety evaluation index system of HC was established, and a safety evaluation approach based on IFS was proposed with the novel score function. Lastly, the evaluation approach was applied to the case of Maojiahe hydropower station in Guizhou Province of China. Results indicate that the safety evaluation approach based on IFS can deal with the uncertain evaluation information effectively and properly; the evaluation results are in accordance with the actual construction conditions; the approach is characterized by flexibility and can be extended to solve other uncertain decision-making problems. The findings in this study indicate that the proposed approach is feasible and valid for the safety evaluation for HC, which has a significant meaning in providing decision support for enhancing the management of construction safety.

Keywords: Hydropower construction, Safety evaluation, Intuitionistic fuzzy set, Score function

1. Introduction

Hydropower projects are usually constructed in the mountainous and gorge areas with complicated geological and hydrological conditions. Multi-type cross operation and multi-process continuous operation run through the entire construction cycle. Influenced by adverse operational environments, hydropower construction (HC) is prone to collapse, explode, catch fire, fall, collide with vehicles, and other construction accidents, which often result in heavy casualties. In addition, construction accidents delay the construction period and bring about the increase of construction costs. Therefore, project managers attach great importance to construction safety, and carry out safety evaluation periodically to prevent accidents and ensure quality.

However, for each hydropower construction section, different unsecure factors exist in geology, hydrology, multi-type interchange operation. Confronted with the complexities, the evaluators tend to generate intuitive dependence, which results in assessment deviation due to insufficient knowledge and experience[1]. Thus, the corresponding safety evaluation information of HC is often ambiguous and uncertain, such as errors in data acquisition, randomness from the quantification of qualitative assessment and so on, which make it difficult for traditional evaluation approaches to be applied in reality.

The traditional safety evaluation approaches for HC, such as AHP (Analytic Hierarchy Process), gray relational assessment method, and fuzzy comprehensive evaluation, mostly represent evaluation information with crisp numbers or fuzzy numbers. These evaluation values can only describe the degrees of affirmation and negation, but ignore the degree of hesitation. The uncertainty of information is not accurately depicted. Also, these approaches usually perform an unjustified transformation from fuzzy numbers into real numbers, which may suffer from the excessive loss of information and reduce reliability and rationality of the results. Considering the advantages of intuitionistic fuzzy set in an uncertain information field, a novel safety evaluation approach for HC was proposed in the context of intuitionistic fuzzy environment, which is expected to solve the problem of uncertainty reasonably and effectively. Meanwhile relevant conclusions can provide a useful theoretical reference for decision-making related to safety management.

2. State of the art

As an active research topic, the study of safety evaluation concerning HC has captured increasing attention. Currently,

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scholars present different safety evaluation approaches, such as ANP (Analytic Network Process), AHP, and DEMATEL (Decision Making Trial and Evaluation Laboratory), mainly from the viewpoint of information representation and influencing factors. Based on a study of 186 hydropower accidents, Zhou et al. analyzed the interactive relationships of 18 factors influencing construction safety via ANP and DEMATEL model, and concluded that safety supervision and inspection were the most important factors in HC safety[2]. By studying the relationship and effect among indices, Rosso et al. obtained the weights of safety evaluation indices by means of AHP, and finally determined the level of risk for the hydropower project[3]. The researches mentioned above solved the problem of interdependence and feedback in indices, but the evaluation information is represented in crisp numbers only. In fact, the desired accuracy is hard to achieve in reality. Therefore, the type of deterministic evaluation methods cannot accurately reflect the safety status of complex HC, and have limitations in the scope of practical application.

Many scholars employed fuzzy set (FS) theory to represent the uncertain assessment information, and proposed uncertain safety evaluation methods. Kucukali adopted fuzzy logic to evaluate the safety of hydropower projects and obtained the safety risk ranking according to logical reasoning results[4]. Taylan et al. calculated the weights of attributes based on fuzzy numbers and constructed a model combination of AHP and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) to assess the degree of risk in construction projects[5]. Later on, Ji et al. applied the Fuzzy Entropy to formulize the objective weights of attributes and analyzed the risk level of 10 hydropower stations[6]. However, with regard to safety evaluation for HC under an uncertain environment, a problem that arises in the aforesaid methods that the approach should not only consider the affirmative information (assentient degree) and the negative information (dissentient degree) but also the unknown or hesitation information (abstention degree). For example, the case of abstention often occurs during the process of evaluation, but FS theory fails to take this into account. Also, these approaches based on FS often convert fuzzy numbers into crisp numbers without strict proof, which could reduce accuracy and reliability of the results.

The key to safety evaluation of HC lies in the choice of rational and appropriate tools for depicting the imprecise or not totally reliable evaluation information. Intuitionistic fuzzy set (IFS), which was proposed by Atanassov, is capable of describing the degrees of affirmation, negation, and hesitation simultaneously through increasing a non-membership characteristic function[7]. Benefiting from this, IFS has been widely used in risk investment[8], threat assessment[9], supplier selection[10], and other areas of decision-making in recent years. Meanwhile, in some sense, IFS also can reflect cognition deviation according to the vote model and the concept of net predisposition[11]. Thus, IFS can be regarded as an appropriate tool for expressing and dealing with uncertainty in safety evaluation problem of HC.

Score function is widely applied to represent the aggregated influence of positive and negative assessments in performance rankings based on IFSs, which was presented primarily by Chen and Tan[12]. Due to the fact that the score function of Chen and Tan is invalid in some cases, Hong and Choi developed improved score functions[13]. However, there are still invalid or irrational results when these score functions are applied. One of the important reasons is that hesitation information failed to be taken into full account. Consequently, there is an insufficient usage of IFS information. Although several scholars[14,15] considered the effect of π_α on the score function, the division of hesitation degree was too one-sided. Liu et al. demonstrated the influence of hesitation information by setting parameters, the determination of parameters was the lack of an objective method[16]. In order to settle the drawbacks of existing score functions, it is necessary to propose a reasonable and effective score function to solve the ranking problem.

In conclusion, the existing safety evaluation approaches for HC could not make full use of uncertain evaluation information, which could result in evaluation deviation from the actual situation. Therefore, for the sake of ensuring the rationality and accuracy of the evaluation results for HC, a novel safety evaluation approach was proposed in this study, which depicted the uncertain information with IFS and determined the sorting through an improved score function.

The remainder of this study is organized as follows. Section 3 introduces the basic concepts of IFS and reviews existing score functions. Furthermore, a novel score function of IFS is proposed and an index system of safety evaluation for HC is built. Thereafter, a safety evaluation approach based on IFS is presented for HC. Section 4 presents the case of Maojiahe hydropower project to illustrate the feasibility and validity of the proposed approach. Section 5 concludes this study and recommends it for future research.

3. Methodology

3.1 Preliminary concepts

IFS is an extension of the ordinary FS. A brief review of some basic concepts related to IFS is described below.

Definition 1[13,17]: An IFS A is defined in the universe X as an object of the following form:

$$A = \{< x, \mu_A(x), \nu_A(x) > | x \in X\} \quad (1)$$

whereanddenote the degrees of membership and non-membership of in , and with the condition of $0 \le \mu_A(x) + \nu_A(x) \le 1$.

For each x, an intuitionistic fuzzy index (or a hesitation degree) of x to A is computed as

$$\pi_A(x) = 1 - \mu_A(x) - \nu_A(x) \quad (2)$$

which expresses a lack of knowledge of whether x belongs to A or not. It is obvious that $0 \le \pi_A(x) \le 1$ for each $x \in X$. Notice that for the fuzzy set of Zadeh, $\pi_A(x)$=0 for all $x \in X$. If $\mu_A(x)$ and $1-\nu_A(x)$ are both equal to 1 or 0, the IFS is reduced to a crisp set.

The ordered pair $< \mu_A(x), \nu_A(x) >$ is also called an intuitionistic fuzzy value (IFV). For convenience of notation, we denote an IFV by $\alpha =< \mu_\alpha, \nu_\alpha >$.

Definition 2[18]: Let $\alpha_i \in \text{IFV}, (i = 1, 2, \text{L}\ , n)$, the intuitionistic fuzzy weighted average operator ($IFWA_\omega$) is defined as follows：

$$IFWA_{\omega}(\alpha_1,\alpha_2,\ldots\alpha_n) = <1-\prod_{i=1}^{n}(1-\mu_{\alpha_i})^{\omega_i}, \prod_{i=1}^{n}\nu_{\alpha_i}^{\omega_i}> \quad (3)$$

where ω_i is the weight of α_i, $\omega_i \in [0,1]$ and $\sum_{i=1}^{n}\omega_i = 1$.

The aggregation result of $IFWA_{\omega}$ is still an IFV. The $IFWA_{\omega}$ is often applied to aggregate information in an IF environment.

3.2 Score function

Chen and Tan defined the score function primarily to rank the IFVs[12]. In recent years, the research on the score function has attracted increasing attention of scholars, and several types of score functions were proposed. However, invalid or irrational results exist in applying these score functions in some cases. Therefore, it is necessary to pay attention to this issue and propose an improved score function.

In this section, numerical examples were given to show the deficiencies and limitations of several existing score functions[12-15]. In order to modify the evaluation deviation, a novel score function was proposed, which can reflect the aggregated effects of affirmation, negation, and hesitation degrees. Thereafter, the properties of the novel score function were discussed to ensure the rationality, and the validity of the novel score function was demonstrated by comparison examples.

3.2.1 The limitations of the existing score functions

(I). The score function of Chen and Tan[12]: Considering the degrees of membership and non-membership, they defined the score function as follows:

$$S_{CT}(\alpha) = \mu_\alpha - \nu_\alpha \quad (4)$$

where $S_{CT}(\alpha) \in [-1,1]$. The larger the value of $S_{CT}(\alpha_i)$ is, the higher the priority of the α_i is, i.e., if $S_{CT}(\alpha_1) \geq S_{CT}(\alpha_2)$, $\alpha_1 \succ \alpha_2$.

Example 1: If $\alpha_1 = <0.89,0.09>$ and $\alpha_2 = <0.80,0.00>$, we can then obtain $S_{CT}(\alpha_1) = S_{CT}(\alpha_2) = 0.80$ by applying Eq. (4). Therefore, the score function of Chen and Tan fails to rank the IFVs in this case.

(II). The score function of Hong and Choi[13]: Noticing the limitation of the score function of Chen and Tan, Hong and Choi added an accuracy function H to assist in sorting, which was defined as follows:

$$H(\alpha) = \mu_\alpha + \nu_\alpha \quad (5)$$

where $H(\alpha) \in [0,1]$. If the score values $S_{CT}(\alpha_i)$ are equal, the conclusion can be drawn on account of the values $H(\alpha_i)$, which is $\alpha_1 \succ \alpha_2$ in the case of $H(\alpha_1) > H(\alpha_2)$.

Example 2: In Example 1, $S_{CT}(\alpha_1) = S_{CT}(\alpha_2) = 0.80$. We can obtain $H(\alpha_1) = 0.98$ and $H(\alpha_2) = 0.80$ by applying Eq. (5). Then, we obtain $\alpha_1 \succ \alpha_2$. However, in reality, people are more sensitive to losses than to gains. People often prefer unopposed α_2 according to prospect theory[19], and arrive at $\alpha_1 \prec \alpha_2$. Thus, the method of Hong and Choi give a counter-intuitive result.

(III). The score function of Lin and Yuan[14]: Lin and Yuan et al. defined a score function consisting of determinate and indeterminate information from the viewpoint of optimist:

$$S_{LY}(\alpha) = S_{CT}(\alpha) + \frac{\pi_\alpha}{2} = \frac{1}{2}\mu_\alpha - \frac{3}{2}\nu_\alpha + \frac{1}{2} \quad (6)$$

Example 3: If $\alpha_3 = <0.3,0.2>$ and $\alpha_4 = <0.0,0.1>$, the result obtained by applying Eq. (6) is $S_{LY}(\alpha_3) = S_{LY}(\alpha_4) = 0.35$, thus in this case, the order of the IFVs would not be got. In fact, when the degrees of non-membership are close, people often prefer α_3 because of the noticeably higher degree of membership, and arrive at $\alpha_3 \succ \alpha_4$.

(IV) The score function of Ye[15]: Ye took the influence of abstention part π_α into account and believed that people in hesitance was more inclined to vote against. Therefore, he defined score function as follows:

$$S_Y(\alpha) = \mu_\alpha(1+\pi_\alpha) - \pi_\alpha^2 \quad (7)$$

Different from the score function of Lin and Yuan, Ye held a pessimistic attitude, and the corresponding results were sometimes invalid or inconsistent with reality.

Example 4: If $\alpha_5 = <0.5,0.2>$, $\alpha_6 = <0.5,0.3>$, by applying Eq. (7), we can obtain $S_Y(\alpha_5) = S_Y(\alpha_6) = 0.56$. Therefore, it cannot be determined which one is better.

In sum, the existing score functions have some limitations or do not perform well in actual situations. In Eqs. (4) and (5), the influence π_α is neglected, which causes information loss. In Eqs. (6) and (7), the role of indeterminacy π_α is considered, but Ye and Lin et al. believed that evaluators always held a certain attitude preference, which results in limited application of these score functions.

3.2.2 Novel score function

The key to the determination of an effective score function is to divide the uncertain information π_α rationally and objectively. $<\mu_\alpha,\nu_\alpha>$ can be interpreted by a vote model[11]: the values μ_α, ν_α and π_α denote the proportions of the assentients, dissenters and abstainers in the votes, respectively. Thus, we analyzed the effects of π_α on score function based on the vote model.

During the process of evaluation, some evaluators are unable to give accurate assessment because of lack of sufficient professional knowledge, and choose to abstain or lie in a condition of irresolution. Influenced by conformist mentality, these evaluators who are hesitant are prone to make the same judgment with others rather than to rely on their own judgement. Therefore, when voting for the second time, the proportions tending to assent, dissent and abstain in the abstention group should be μ_α, ν_α and π_α. The proportion π_α should be divided into three parts: $\mu_\alpha\pi_\alpha$, $\nu_\alpha\pi_\alpha$ and $\pi_\alpha - \mu_\alpha\pi_\alpha - \nu_\alpha\pi_\alpha = \pi_\alpha^2$, and the reformed proportions of assentients, dissenters, and abstainers are $\mu_\alpha+\mu_\alpha\pi_\alpha$, $\nu_\alpha+\nu_\alpha\pi_\alpha$ and π_α^2, respectively, after voting twice. In general, project managers typically vote three times. Thus, in accordance with this law, the final proportions of assentients and dissenters are likely to be $\mu_\alpha+\mu_\alpha\pi_\alpha+\mu_\alpha\pi_\alpha^2$, $\nu_\alpha+\nu_\alpha\pi_\alpha+\nu_\alpha\pi_\alpha^2$, respectively, and the proportion of maintaining abstention are π_α^3.

Next, we consider the effect of π_α^3 on the result. In reality, some hesitant evaluators are often elicited a certain attitude deviation, which is consistent with the group deviation. In the concept of net predisposition, group deviation is measured by the deviation between the overall membership and non-membership, so the deviation can be formulated as follows:

$$\frac{1}{n}\sum_{i=1}^{n}(\mu_{\alpha_i}-\nu_{\alpha_i}),(i=1,2,\cdots,n) \tag{8}$$

where $\mu_{\alpha_i},\nu_{\alpha_i}\in[0,1],\frac{1}{n}\sum_{i=1}^{n}(\mu_{\alpha_i}-\nu_{\alpha_i})\in[-1,1]$.

For simplicity, formula (8) is denoted by β, i.e. $\beta=\frac{1}{n}\sum_{i=1}^{n}(\mu_{\alpha_i}-\nu_{\alpha_i})$. When $\beta>0$, the number of assentients is higher than that of dissenters, which means that a majority of evaluators choose to vote for it. By comparison, when $\beta<0$, the influence of dissenters is greater than that of assentients on the whole, and a majority of evaluators choose to vote against it. When $\beta=0$, the evaluators are neutral. Therefore, we believe that the aggregated effect degree of π_α^3 on the result is likely to be $\beta\pi_\alpha^3$.

Based on the discussion above, a novel score function is proposed as follows.

Definition 3: Let $\alpha_i=<\mu_{\alpha_i},\nu_{\alpha_i}>\in IFV$, $(i=1,2,\mathrm{L}\ ,n)$, the score function $S_{new}(\alpha_i)$ is defined as follows:

$$S_{new}(\alpha_i)=(\mu_{\alpha_i}-\nu_{\alpha_i})(1+\pi_{\alpha_i}+\pi_{\alpha_i}^2)+\frac{1}{n}\pi_{\alpha_i}^3\sum_{i=1}^{n}(\mu_{\alpha_i}-\nu_{\alpha_i}) \tag{9}$$

The larger the value of $S_{new}(\alpha_i)$ is, the higher the priority of the α_i is, i.e., the more the suitability to which the alternative α_i satisfies the requirement of the evaluator.

The score function $S_{new}(\alpha_i)$ has the following properties.

Theorem 1: Let $\alpha=<\mu_\alpha,\nu_\alpha>\in IFV$, $\mu_\alpha,\nu_\alpha\in[0,1]$ and $0\le\mu_\alpha(x)+\nu_\alpha(x)\le 1$, then

(i) $\alpha=<1,0>$ if and only if $S_{new}(\alpha)=1$;

(ii) $\alpha=<0,1>$ if and only if $S_{new}(\alpha)=-1$.

Proof. (i) Necessity is obvious, we only proof the sufficiency in the following.

Since $S_{new}(\alpha)=1$, according to Eq. (9), we obtain

$$(\mu_\alpha-\nu_\alpha)(1+\pi_\alpha+\pi_\alpha^2)+(\mu_\alpha-\nu_\alpha)\pi_\alpha^3=1$$

For $\mu_\alpha+\nu_\alpha+\pi_\alpha=1$, we get

$$(\mu_\alpha-\nu_\alpha)(1+\pi_\alpha+\pi_\alpha^2)+(\mu_\alpha-\nu_\alpha)\pi_\alpha^3=\mu_\alpha+\nu_\alpha+\pi_\alpha$$

$$2\nu_\alpha(1-\pi_\alpha)+(1-(\mu_\alpha-\nu_\alpha))\pi_\alpha^3=0$$

Since $\nu_\alpha\ge 0,1-\pi_\alpha\ge 0,1-(\mu_\alpha-\nu_\alpha)\ge 0,\pi_\alpha\ge 0$, we obtain $\pi_\alpha=0,\nu_\alpha=0$ and $\mu_\alpha=1$, i.e., $\alpha=<1,0>$.

(ii) Similarly, we can proof $\alpha=<0,1>$ if and only if $S_{new}(\alpha)=-1$. □

Theorem 2: Let $\alpha_i=<\mu_{\alpha_i},\nu_{\alpha_i}>\in IFV$, $(i=1,2,\cdots,n)$, then the score function $S_{new}(\alpha_i)$ increases monotonically with increasing μ_{α_i} and decreases monotonically with increasing ν_{α_i}.

Proof. It follows from the fact that $\frac{1}{n}\sum_{i=1}^{n}(\mu_{\alpha_i}-\nu_{\alpha_i})$ is a constan for the given $\alpha_i(i=1,2,\cdots,n)$, and we denote it by β for simplicity. According to the Definition 3, we get

$$\begin{aligned}\frac{\partial S_{new}(\alpha_i)}{\partial\mu_{\alpha_i}}&=1+\pi_{\alpha_i}+\pi_{\alpha_i}^2+(\mu_{\alpha_i}-\nu_{\alpha_i})(-1-2\pi_{\alpha_i})-3\beta\pi_{\alpha_i}^2\\&=1-\mu_{\alpha_i}-\nu_{\alpha_i}+2\nu_{\alpha_i}+(1-2\mu_{\alpha_i}+2\nu_{\alpha_i})\pi_{\alpha_i}+(1-3\beta)\pi_{\alpha_i}^2\\&=2\nu_{\alpha_i}+(2-2\mu_{\alpha_i}+2\nu_{\alpha_i})\pi_{\alpha_i}+(1-3\beta)\pi_{\alpha_i}^2\\&=2\nu_{\alpha_i}+2(\pi_{\alpha_i}+2\nu_{\alpha_i})\pi_{\alpha_i}+(1-3\beta)\pi_{\alpha_i}^2\\&=2\nu_{\alpha_i}+4\nu_{\alpha_i}\pi_{\alpha_i}+3(1-\beta)\pi_{\alpha_i}^2.\end{aligned}$$

Since $\nu_{\alpha_i}\ge 0,\pi_{\alpha_i}\ge 0,1-\beta\ge 0$, we get $\frac{\partial S_{new}(\alpha_i)}{\partial\mu_{\alpha_i}}\ge 0$.

Thus $S_{new}(\alpha_i)$ increases monotonically with increasing μ_{α_i}.

In the same way, the partial derivatives of $S_{new}(\alpha_i)$ to ν_{α_i} is computed as

$$\frac{\partial S_{new}(\alpha_i)}{\partial\nu_{\alpha_i}}=-2\mu_{\alpha_i}-4\mu_{\alpha_i}\pi_{\alpha_i}-3(1+\beta)\pi_{\alpha_i}^2.$$

Since $\mu_{\alpha_i}\ge 0,\pi_{\alpha_i}\ge 0,1+\beta\ge 0,$ then $\frac{\partial S_{new}(\alpha_i)}{\partial\nu_{\alpha_i}}\le 0$. Therefore $S_{new}(\alpha_i)$ decreases monotonically with increasing ν_{α_i}. □

Theorem 3: Let $\alpha_i=<\mu_{\alpha_i},\nu_{\alpha_i}>\in IFV$, $(i=1,2)$, if $\mu_{\alpha_1}>\mu_{\alpha_2},\nu_{\alpha_1}<\nu_{\alpha_2}$, then $S_{new}(\alpha_1)>S_{new}(\alpha_2)$.

Proof. According to Theorem 2, the result is obvious. □

The above theorems indicate that the higher proportion of the assentients or the lower proportion of the dissenters is, the larger value of $S_{new}(\alpha_i)$ is, and the higher priority of the α_i. Noticeably, the novel score function conform to the intuitive judgment standard in practical life.

In the following, we rank the IFVs in examples 1-4 according to the novel score function. The results and comparison explanations are shown in Table 1.

Table. 1. The sorting results of IFVs

IFV	Example	$S_{new}(\alpha_i)$	Sorting	Explanation
$\alpha_1 =< 0.89, 0.09 >$ $\alpha_2 =< 0.80, 0.0 >$	Examples 1, 2	$S_{new}(\alpha_1) = 0.8163$ $S_{new}(\alpha_2) = 0.9984$	$\alpha_1 \prec \alpha_2$	The order cannot be obtained by Eq. (4) It is a contradictory result with reality by Eq. (5)
$\alpha_3 =< 0.3, 0.2 >$ $\alpha_4 =< 0.0, 0.1 >$	Example 3	$S_{new}(\alpha_3) = 0.1875$ $S_{new}(\alpha_4) = -0.3439$	$\alpha_3 \succ \alpha_4$	The order cannot be obtained by Eq. (6)
$\alpha_5 =< 0.5, 0.2 >$ $\alpha_6 =< 0.5, 0.3 >$	Example 4	$S_{new}(\alpha_5) = 0.4251$ $S_{new}(\alpha_6) = 0.2496$	$\alpha_5 \succ \alpha_6$	The order cannot be obtained by Eq. (7)

The results in Table 1 show that the novel score function is able to settle the limitations existing in the score functions[12-15] , and the results drawn by which are in accordance with actual situations. Therefore, the novel score function is superior in validity and accuracy compared with these score functions.

3.3 Safety evaluation approach concerning the hydropower construction based on IFS

3.3.1 Problem descriptions

Let $A = \{A_1, A_2, \cdots, A_m\}$ be a set of construction sections and $C = \{C_1, C_2, \cdots, C_n\}$ be a set of index. The evaluation information of each construction section A_i $(i = 1, 2, \cdots, m)$ with respect to each index C_j $(j = 1, 2, \cdots, n)$ is represented by IFSs:

$$A_i = \{< C_1, \mu_{A_i}(C_1), \nu_{A_i}(C_1) >, < C_2, \mu_{A_i}(C_2), \nu_{A_i}(C_2) >, \cdots, < C_n, \mu_{A_i}(C_n), \nu_{A_i}(C_n) > \mid C_j \in C\} \tag{10}$$

For simplicity, $< C_j, \mu_{A_i}(C_j), \nu_{A_i}(C_j) >$ is denoted by IFV $< \mu_{ij}, \nu_{ij} >$, where μ_{ij} indicates the degree to which the construction section A_i satisfies the index C_j, and in contrast ν_{ij} indicates the degree to which the construction section A_i does not satisfy the index C_j. Let $\gamma_1, \gamma_2, \cdots, \gamma_n$ be the subjective weights of $C_1, C_2, \cdots, C_n$, respectively, where $\gamma_1, \gamma_2, \cdots, \gamma_n \in [0,1]$ and $\sum_{i=1}^{n} \gamma_i = 1$.

3.3.2 An index system of safety evaluation for hydropower construction

The HC is characterized by a large construction scale, great investment, long construction period, and complicated technology. Therefore, safety evaluation for HC consists of multiple factors and targets. At present, a scientific and consistent evaluation index system is lacking. Based on the field survey and consulting literature, an index system of safety evaluation for HC was established, as shown in Fig. 1.

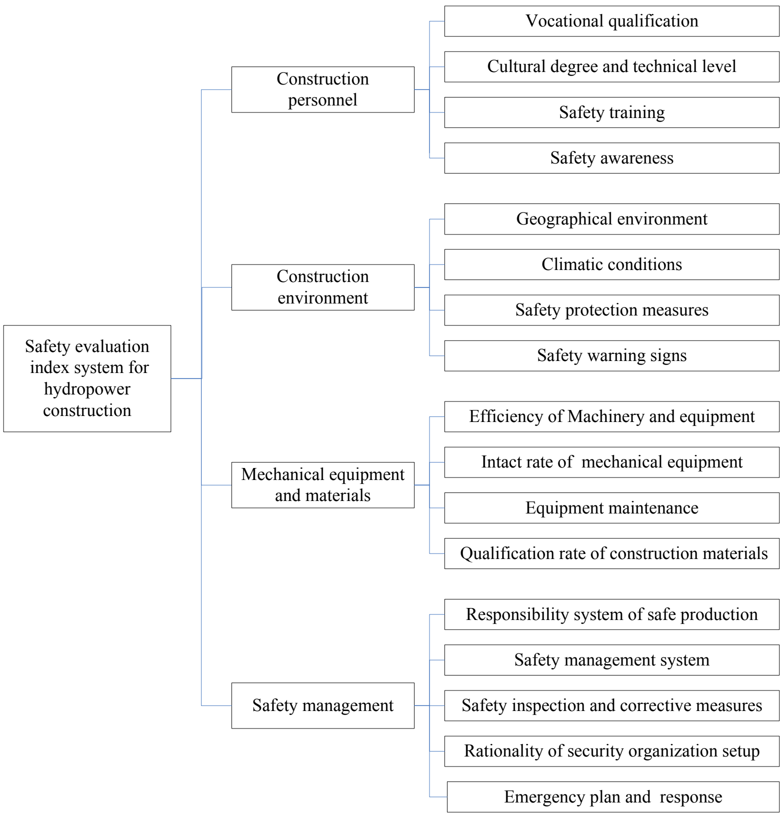

Fig. 1. An index system of safety evaluation for hydropower construction

3.3.3 Procedure of safety evaluation approach for hydropower construction based on IFS

The detailed steps to evaluate security situation of HC can be summarized as follows:

Step-1: Collect safety evaluation information of each construction section A_i, and express the information using IFVs;

Step-2: Calculate the intuitionistic fuzzy entropy $E(C_j)$ of index C_j, which can be derived as follows:

$$E(C_j) = \frac{1}{m}\sum_{i=1}^{m}(1-\mu_{ij}-v_{ij}); \tag{11}$$

Step-3: Calculate the objective weight ρ_j of index C_j, and integrate the comprehensive weight ω_j of C_j with the subjective weight γ_j. The formulae of ρ_j and ω_j are given as follows:

$$\rho_j = \frac{1-E(C_j)}{n-\sum_{j=1}^{n}E(C_j)}, \tag{12}$$

$$\omega_j = \frac{\rho_j\gamma_j}{\sum_{j=1}^{n}\rho_j\gamma_j}; \tag{13}$$

Step-4: Calculate the weighted IFV α_i of each construction section A_i by applying Eq. (3);

Step-5: Calculate the score function $S_{new}(\alpha_i)$ of each construction section by applying Eq. (9);

Step-6: Rank the construction sections according to the values of $S_{new}(\alpha_i)$.

In the Section 4, a case of Maojiahe hydropower construction is presented to validate the proposed safety evaluation approach.

4 Result analysis and discussion

4.1 Case study

The Maojiahe hydropower station is located in Qinshui River Liupanshui City, Guizhou Province of China, which can produce a gross installed capacity of 3×60 MW and total reservoir capacity of 1281.3×10^4 m^3. The crest elevation of RCC gravity dam is 1303.50 m with a maximum height of 74.50 m and total length of 175.04 m. According to “Specifications for Construction Planning of Water Resources and Hydropower Engineering (SL303-2004)”, the main permanent buildings (dam and diversion system) are designed to achieve a III-level standard, and secondary permanent and temporary buildings reach level IV and V, respectively.

The pivotal projects of hydropower station consist of roller compacted concrete dam (RCC), bank spillway, diversion tunnel, and power house (including electromechanical installation), which were denoted by $A_i(i=1,2,3,4)$, respectively. During flood season, safety evaluation is an important and effective means to ensure the construction project. Therefore, it is necessary to analyze and assess the security situation for the four construction sections. For convenience, primary indices comprising construction personnel, construction environment, mechanical equipment and materials, and safety management were chosen and marked by $C_j(j=1,2,3,4)$ correspondingly. The subjective weight set of index was given as $\gamma=\{0.35,0.15,0.30,0.20\}$ in advance.

The safety assessment expert group consisted of 12 project safety management personnel, design technical personnel, construction management personnel, and other related personnel. Two people came from the project owner (Guizhou China Water Energy Co., Ltd.), four people from the construction unit (Sinohydro Bureau 3 Co., Ltd. and Guangdong No.2 Hydropower Engineering Co., Ltd.), two people from the supervision unit (Bei Panjiang Maojiahe Hydropower Station Construction Supervision Project Department), two people from the design unit (Guiyang Hydropower Investigation Design & Research Institute), and two people from the operation management unit (Guizhou Western Energy and Power Construction Co., Ltd.). After the construction site survey, the experts evaluated the performance of four construction sections under each safety index. In order to avoid data loss originating from different scales, the evaluation information included satisfactory score *A* and dissatisfactory score *B*, with integers between 0 and 100 to satisfy $0\le A+B\le100$. Finally, the safety evaluation information was integrated through the method of arithmetic mean and expressed in the form of IFVs according to the vote model, as shown in Table 2.

Table. 2. Safety evaluation information of construction sections

Index / Construction section	C_1	C_2	C_3	C_4
A_1	<0.68,0.21>	<0.46,0.27>	<0.66,0.18>	<0.62,0.18>
A_2	<0.69,0.13>	<0.76,0.16>	<0.43,0.36>	<0.58,0.21>
	<0.47,0.28>	<0.52,0.27>	<0.78,0.12>	<0.55,0.17>
A_4	<0.77,0.16>	<0.69,0.23>	<0.47,0.32>	<0.53,0.15>

4.2 Result analysis

Step-1: Safety evaluation information are represented by IFVs in Table 2.

Step-2: Calculate intuitionistic fuzzy entropy of each index by applying Eq. (11):

$$E(C_1)=0.1525,\ E(C_2)=0.16,\ E(C_3)=0.17,$$
$$E(C_4)=0.2525.$$

Step-3: Acquire objective weight ρ_j and comprehensive weight ω_j of C_j by applying Eqs. (12) and (13). The results are listed in Table 3.

Table. 3. The weights of indices

	C_1	C_2	C_3	C_4
γ_j	0.35	0.15	0.30	0.20
ρ_j	0.2596	0.2573	0.2542	0.2289
ω_j	0.3612	0.1535	0.3032	0.1821

Step-4: Calculate the weighted IFV α_i of each construction section by applying Eq. (3):

$\alpha_1 = <0.6356, 0.2025>$, $\alpha_2 = <0.6211, 0.1995>$, $\alpha_3 = <0.6119, 0.1966>$, $\alpha_4 = <0.6468, 0.2063>$.

Step-5: Calculate the score function $S_{new}(\alpha_i)$ for each construction section, as shown in Table 4.

Table. 4. The score function values of construction sections

	A_1	A_2	A_3	A_4
$S_{new}(\alpha_i)$	0.5162	0.5131	0.5127	0.5159

Step-6: According to Table 4, we obtain $A_1 \succ A_4 \succ A_2 \succ A_3$.

The results show that RCC have the highest level among construction sections in this assessment, followed by the power house, bank spillway, and diversion tunnel. This sorting result was also confirmed by the expert group. The consistence with the actual construction situation demonstrates the feasibility and effectiveness of the approach. Meanwhile, the diversion tunnel is the last in the evaluation sequence. Aside from the disadvantage of complex geological structure, workers in diversion tunnel could not strictly follow the operation standard to inspect and maintain mechanical equipment periodically. Therefore, construction managers are advised to strengthen safety education and training in this construction section.

Although the evaluation approach based on IFS was applied to hydropower construction safety evaluation in this study, it also can be extended to other decision-making problems involving uncertain information. As previously described, β denotes the assessment deviation. Therefore, through setting the different β under decision-making circumstance, the rational and effective results can be acquired. For example, in the case of emergency rescue decision-making, confronted with the losses of life and property, decision-makers usually hold a cautious and conservative attitude. We can choose a parameter $\beta < 0$ according to the degree of aversion in this approach to obtain a reasonable and appropriate rescue plan.

5. Conclusions

Uncertainty existing in the hydropower construction safety evaluation can cause the evaluator to produce evaluation deviation, thereby affecting the precision of results. In order to depict and handle the imprecise or vague evaluation information, a safety evaluation approach for HC based on IFS was proposed. The feasibility and validity of this approach were illustrated in the case of Maojiahe hydropower station. The following conclusions could be drawn:

(1) Safety evaluation approach for HC based on IFS can describe and handle the uncertain evaluation information accurately, which is suitable for applying in practical decision problems.

(2) The evaluation results achieved by this approach are consistent with actual situations, thus this study provide a feasible and effective evaluation method for hydropower project managers.

(3) Safety evaluation approach for HC based on IFS can also be applied in other decision-making problems characterized by uncertainty.

The proposed safety evaluation approach can reflect the safety status of construction accurately and provide a support of method for the project managers to improve the safety level of HC. However, as mentioned before, an index system of safety evaluation for HC was established on the basis of summing up past literatures and field surveys in this study, which lacks opinions of relevant experts. Future research should combine expert investigation with case analysis.

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