

# Vulnerability evaluation method of inland waterway revetment project subjected to wave and current

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## ABSTRACT

The flood damage of inland waterway revetment project has become one of the most serious disasters that affect the water transportation, municipal environment, human life and property safety. Scientific and reasonable evaluation of the vulnerability of waterway revetment project subjected to wave and current can effectively prevent and reduce disaster losses. According to the characteristics of multi factors and fuzziness in the vulnerability evaluation of waterway revetment project subjected to wave and current, a two-level fuzzy comprehensive evaluation mathematical model for vulnerability assessment is established by using fuzzy mathematics method. Based on the field investigation and observation data of the waterway revetment project in the middle and upper reaches of the Yangtze River and the relevant measurement of laboratory experiments, four main factors affecting the stability of the waterway revetment project, including design and construction, protective measures, wave-current characteristics and river waterway factors, are selected based on the establishment of vulnerability evaluation index system. Analytic hierarchy process (AHP) is used to determine the weight of evaluation factors and their sub factors, which improves the objectivity and scientificity of vulnerability assessment of waterway revetment project subjected to wave and current.

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## 1. Preface

The damage degree of inland waterway revetment project is closely related to climate, geology, hydrology, hydraulic, river environmental conditions, engineering design and construction, and improvement of protective measures. The disaster-bearing body of different bank protection projects suffers from the same intensity of water damage, and the loss degree may be different. The same disaster-bearing body suffers from different intensity of water damage to the same extent, that is, the vulnerability is different. The so-called vulnerability of the disaster-bearing body refers to the degree of difficulty of the disaster-bearing body suffering from different intensities of water damage. The vulnerability evaluation of inland waterway revetment project and its water damage protection facilities is to find out the advantages and disadvantages of the waterway revetment project's ability to resist the wave-current loading, so as to take effective preventive and remedial measures in time, which is of great significance to ensure the safety of human economic activities and reduce disaster losses.

At present, there are many researches on the hazard or risk assessment of geological disasters such as landslides, collapses, and mudslides (Ali et al., 2014; Erener & Düzgün, 2013; Liu et al., 2012). There are also lots of investigations on risk analysis and evaluation of flood disaster, especially on flood resistance capacity of highway and waterway and flood damage assessment (Chen, 2012; Wang, Yang & Wang, 2015; Wang et al., 2018). However, the research on vulnerability evaluation of waterway revetment project subjected to wave and current is relatively less. Among all kinds of disaster risk and vulnerability assessment, the commonly used and mature evaluation methods mainly include comprehensive index method, fuzzy comprehensive evaluation method and chromatography analysis method. As one of the comprehensive evaluation methods, fuzzy mathematics method has the advantages of simple mathematical model, easy operation, and good evaluation effect for complex problems with multi factors and multi-level. Therefore, when the evaluation factors or levels of some specific problems are fuzzy, the comprehensive evaluation is called fuzzy

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comprehensive evaluation, also known as fuzzy comprehensive evaluation (Li, 2004). Fuzzy comprehensive evaluation is a kind of evaluation based on the principle of fuzzy transformation and the principle of maximum subordination. Fuzzy comprehensive evaluation has the advantages of simple calculation and strong practicability. It is an effective mathematical method to deal with fuzzy evaluation problems. It is widely used in the risk assessment of geological disasters such as debris flow in various engineering construction, landslide stability evaluation, water conservancy engineering stability evaluation and highway engineering risk assessment (He et al., 2011; Liao et al., 2013, 2015; Ma, 2008; Slingerland & VoightPaolo, 1982; Wang et al., 2004; Yang, 2014; Zhao & Tan, 2017; Zou et al., 2019). According to the characteristics of multi factors and fuzziness in the vulnerability evaluation of waterway revetment project subjected to wave and current, a two-level fuzzy comprehensive evaluation mathematical model for vulnerability evaluation is established by using fuzzy mathematics method. The evaluation factor set, comment set and weight set are determined by combining with engineering examples, and the vulnerability of waterway revetment project under wave and current is evaluated.

## 2. Overview of fuzzy comprehensive evaluation method

Fuzziness is a kind of uncertainty, that is, it is difficult to determine whether an object conforms to the concept of something. Fuzzy comprehensive evaluation method is a comprehensive evaluation method based on fuzzy mathematics. According to the membership degree theory of fuzzy mathematics, the comprehensive evaluation method transforms qualitative evaluation into quantitative evaluation. Thus, fuzzy mathematics is used to make an overall evaluation of things or objects restricted by many factors. It has the advantages of clear results and strong systematicness, and can solve the fuzzy and difficult to quantify problems, which is suitable for solving all kinds of non deterministic problems. The disadvantage is that the calculation is relatively complex and the determination of index weight vector is subjective. In 1965, Zadeh, an expert in automatic control theory, put forward the concept of fuzzy set and used membership function to describe the fuzziness of the object. This approximates accuracy to fuzziness. Therefore, it is necessary to introduce the fuzzy theory to study the vulnerability of river revetment.

### 2.1. Fuzzy sets and membership functions

Let the total objects under discussion be called the field, denoted by  $U$ . Objects in the domain are called elements

and are represented by  $U$ . A part of the elements in universe  $U$  is called a set on universe  $U$ , which is called  $A$ . According to general set theory, there are only two relations between element  $u$  and set  $A$  in universe  $U$ , either  $u \in A$ , or  $u \notin A$ . Both must occupy one and only one of them. However, the attribution of many things is 'one or the other', that is, there are not only two relations between the element  $u$  and set  $A$  in the field  $U$ , and some of them belong to this relation, that is fuzziness. This kind of set which contains some elements or whose boundary is not clear is called fuzzy set, which is usually represented by  $\tilde{A}$ .

Then, a given universe  $U$ ,  $\tilde{A}$  is a fuzzy set over  $U$ , if for any  $u \in U$ , it can be determined a number  $\mu_A(u) \in [0, 1]$ , which indicates the degree to which  $u$  belongs to  $\tilde{A}$ , which means that a mapping is made:

$$\begin{aligned} \mu_A(u): U &\rightarrow [0, 1] \\ u &\rightarrow \mu_A(u) \end{aligned}$$

The mapping  $\mu_A$  is called the membership function of  $\tilde{A}$ , and the number  $\mu_A(u)$  is called the membership degree of element  $u$  in  $U$  to Fuzzy Set  $\tilde{A}$ . The degree of membership can also be recorded as  $\tilde{A}(u)$ .

It can be seen from this definition that fuzzy sets are completely characterized by membership functions. The determination of membership function is the basis of fuzzy theory, but so far there is no unified method to determine membership function. The determination of membership function is based on subjective factors of human beings, but can never be arbitrary, and must be based on objective laws. Usually, the rough membership function is initially determined, and then, through constant practical tests, it is gradually revised and improved to achieve the final agreement between the subject and the objective. There are many methods available for the determination of membership function, such as subjective determination method (expert experience method), typical function method, fuzzy statistics method, example method, multidimensional scale method, etc.

### 2.2. Steps of fuzzy comprehensive evaluation

(1) Establish the factor set

The factors that affect the main indexes of the waterway revetment to resist the damage caused by wave-current are composed of factor set  $U$ , and the factors in  $U$  are divided into  $m$  categories according to their properties, namely,  $m$  subsets:

$$u = \{u_1, u_2 \dots, u_m\} \quad (1)$$

where  $u_i (i = 1, 2, \dots, m)$  is the  $i$ th factor subset. Let each factor subset include  $n$  factors:

$$u_1 = \{u_{i1}, u_{i2}, \dots, u_{im}\} \tag{2}$$

Among them,  $u_{ij} (i = 1, 2, \dots, m; j = 1, 2, \dots, n)$  is the  $j$ th factor of the  $i$ th factor subset, and different  $i$  may have different  $n$ . Each factor  $u_{ij} (i = 1, 2, \dots, m; j = 1, 2, \dots, n)$  is divided into  $p$  levels according to its degree. If the design level is divided into five grades: high, relatively high, general, relatively low, low, it can be expressed as the following factor level set:

$$u_{ij} = \{u_{ij1}, u_{ij2}, \dots, u_{ijp}\} \tag{3}$$

Among them,  $u_{ijk} (k = 1, 2, \dots, p)$  is the  $k$ th rank of factor  $u_{ij}$ . The factor hierarchy set should be regarded as a fuzzy subset on the hierarchy universe:

$$u_{ij} = \frac{\mu_{ij1}}{u_{ij1}} + \frac{\mu_{ij2}}{u_{ij2}} + \dots + \frac{\mu_{ijp}}{u_{ijp}} \tag{4}$$

Among them,  $u_{ijk}$  is the membership degree of  $u_{ij}$ 's  $k$ th grade to the factor.

(2) Set up a collection of comments

Before the vulnerability evaluation of waterway revetment, the evaluation set should be established. Evaluation set is given by the review of each level evaluation index set of comments (language), is all kinds of possible results in various evaluation factors for the elements of a collection of  $V_l (l = 1, 2, \dots, q)$ , that is,  $V = v_1, v_2, \dots, v_q$  as the comment set, where  $v_q$  is the  $q$ th possible evaluation result.

(3) First-level fuzzy comprehensive evaluation

The fuzzy comprehensive evaluation was carried out according to the grade of each factor,  $\mu_{ijk}$  could be evaluated according to the standard designated by  $K$ -level, which is subordinated to  $j$ -factor in  $i$ -category, the membership degree of the first factor in the evaluation set is as follows:  $r_{ijkl} (i = 1, 2, \dots, m; j = 1, 2, \dots, n; k = 1, 2, \dots, p; l = 1, 2, \dots, q)$ , then the evaluation matrix of factor  $u_{ij}$  is as follows:

$$\tilde{R}_{ij} = \begin{bmatrix} r_{ij11} & r_{ij11} & \dots & r_{ij1q} \\ r_{ij21} & r_{ij22} & \dots & r_{ij2q} \\ \dots & \dots & \dots & \dots \\ r_{ijp1} & r_{ijp2} & \dots & r_{ijpq} \end{bmatrix} \tag{5}$$

In order to make each factor have a common evaluation matrix  $R_{ij}$  to simplify the calculation, the grade of each factor should be arranged according to the consistency of the evaluation objects.

In order to reflect the influence of a factor on the value of the evaluation object, the weight assigned to each level of the factor is called the weight set of the factor level. If the weight of factor grade  $u_{ijk}$  is  $a_{ijk}$ , the weight set of factor  $u_{ij}$  is as follows:

$$\tilde{A}_{ij} = (a_{ij1}, a_{ij2}, \dots, a_{ijp}) \tag{6}$$

Among them,  $a_{ijk} = \mu_{ijk} / \sum_{k=1}^p \mu_{ijk} (i = 1, 2, \dots, m; j = 1, 2, \dots, n)$

The first level fuzzy comprehensive evaluation set is as follows:

$$\tilde{B}_{ij} = \tilde{A}_{ij} \cdot \tilde{R}_{ij} = (b_{ij1}, b_{ij2}, \dots, b_{ijl}) \tag{7}$$

Among them,  $b_{ijl} = \sum_{k=1}^p a_{ijk} \cdot r_{ijkl} (i = 1, 2, \dots, m; j = 1, 2, \dots, n; l = 1, 2, \dots, q)$ ,  $b_{ijl}$  is a general fuzzy comprehensive evaluation index, which represents the membership degree of the evaluation object to the  $l$ th element in the comment set when fuzzy comprehensive evaluation is carried out according to all levels of factors.

(4) Multi-level fuzzy comprehensive evaluation

According to all factors  $u_{ij} (i = 1, 2, \dots, m; j = 1, 2, \dots, n)$  of the prime subset  $u_i$ , fuzzy comprehensive evaluation is carried out. The single factor evaluation set  $B_{ij}$  of  $u_{ij}$  should be the first level fuzzy comprehensive evaluation set  $B_{ij}$ , so the single factor evaluation matrix of  $u_i$  is as follows:

$$\tilde{R}_i = \begin{bmatrix} B_{i1} \\ \tilde{B}_{i2} \\ \dots \\ B_{in} \end{bmatrix} \tag{8}$$

If  $a_{ij}$  is the weight of factor  $u_{ij}$ , the weight set of subset  $u_i$  is as follows:

$$\tilde{A}_i = (a_{i1}, a_{i2}, \dots, a_{in}) \quad i = (1, 2, \dots, n) \tag{9}$$

The primary fuzzy comprehensive evaluation set is as follows:

$$\tilde{B}_i = \tilde{A}_i \cdot \tilde{R}_i = (b_{i1}, b_{i2}, \dots, b_{iq}) \tag{10}$$

Among them,  $b_{il} = \sum_{j=1}^n a_{ij} b_{ijl} (i = 1, 2, \dots, m; l = 1, 2, \dots, q)$ ,  $b_{il}$  is the primary fuzzy comprehensive evaluation index, which represents the membership degree of the first element in the alternative set when the evaluation object is comprehensively evaluated according to all the sub factors of the  $u_i$  of the factor subset.

The single factor evaluation set  $R_i$  of type  $i$  should be the primary fuzzy comprehensive evaluation set  $B_i$ , so the single factor evaluation matrix of  $V$  is as follows:

$$\tilde{R} = \begin{bmatrix} B_1 \\ \tilde{B}_2 \\ \tilde{B}_3 \\ \dots \\ B_n \\ \tilde{B}_n \end{bmatrix} = [b_{ij}]_{m \times q} \quad (11)$$

If the weight of the  $i$  factor of class  $u_i$  is  $a_i$ , the weight set of the factor set  $U$  is:

$$\tilde{A} = (a_1, a_2, \dots, a_p) \quad (12)$$

The second-level fuzzy comprehensive evaluation set is:

$$\tilde{B} = \tilde{A} \cdot \tilde{R} = (b_1, b_2, \dots, b_q) \quad (13)$$

Among them,  $b_l = \sum a_i \cdot r_{il} (l = 1, 2, \dots, q)$ .  $b_l$  is the total fuzzy comprehensive evaluation index, which represents the membership degree of the  $l$ th element in the comment set when the evaluation object is evaluated according to all factors.

After getting the evaluation index  $b_l$ , when determining which comment the comprehensive evaluation result belongs to, the principle of maximum membership degree is adopted. In other words, the value of the comment set corresponding to  $\max b_l$  is taken, and then the evaluation result is determined as a certain comment according to the evaluation set.

### 3. Fuzzy comprehensive evaluation method for vulnerability of river revetment project subjected to wave and current

#### 3.1. Determination of evaluation factor set and comment set

In view of the complex system of flood damage of waterway revetment subjected to wave and current, there are a lot of uncertainties in the evaluation factors due to the diversity, variability and complexity of the natural environmental conditions in which it is located. This kind of uncertainty has randomness and fuzziness, and the factors are often divided into different levels. If the first level evaluation is adopted, it is difficult to compare the good and bad order of the things in the system, and no meaningful evaluation results can be obtained. Therefore, the fuzzy comprehensive evaluation method is used to evaluate the vulnerability of waterway revetment project to water damage. In the process of fuzzy evaluation, the selection of evaluation factors and the construction of subsection function should be carried out in combination with the characteristics of river revetment.

#### (1) Determination of evaluation factor set

According to the principles of objectivity, scientificity, rationality and integrity, the vulnerability evaluation index of waterway revetment project subjected to wave and current should be selected. It is required that the assessment factor set should include the main factors which have significant impact on the vulnerability of revetment works to water damage as comprehensively as possible, and the influence factors are independent of each other, without inclusion relationship, so as to avoid repetition. In addition, the vulnerability assessment of bank revetment project needs to distinguish the primary and secondary factors while considering all the influencing factors systematically and comprehensively. In order to avoid complicated evaluation and analysis, some minor factors which have no obvious influence can be ignored.

In the selection of the evaluation index of the flood damage vulnerability of the waterway revetment subjected to wave and current, not only the factors of the project itself, but also the protection and maintenance measures, flood, wave and other factors that have important influence on the project vulnerability should be considered, which makes the selection of evaluation factors involve many factors. The strength of vulnerability is determined by the function of each influencing factor, and each influencing factor is determined by the action characteristics of its sub factors. Therefore, the comprehensive evaluation of vulnerability is a multi-factor and multi-level comprehensive evaluation problem. However, subjective factors often account for a large proportion in the comparison and selection of evaluation factors, most of which are fuzzy and difficult to describe with quantitative data.

Under the wave-current loading, the water damage of waterway revetment project is the result of interaction and interaction among revetment project, wave-current dynamics and sediment erosion and deposition. The erosion damage of bank protection engineering is the main type of water damage, and the scouring intensity and depth will directly affect the safety of bank protection engineering. In practice, it is generally not allowed to have a large degree of scouring to affect the integrity and stability of the revetment project. Therefore, riprap, soft mattress, permeable frame, hydraulic plug-in board and spur dike are usually used to resist the scour and erosion induced by wave and current (Ma, 2008; Wang et al., 2018).

In this study, the appropriate evaluation factors are selected from the angle of bank protection damage caused by lash and collision. The selection of evaluation index is based on the data of field investigation

and indoor experiment observation, and widely absorbing the research results of relevant experts. According to the fuzzy mathematics theory, after comprehensive induction, analysis and research comparison, the evaluation index is established. Then, many factors are divided into four categories. The factor set  $U$  that affects the vulnerability of waterway revetment works is divided into four sub-factors, specifically:

- (1) Design and construction ( $u_1$ ): the anti-impact capacity of revetment project largely depends on its own strength and stability, and the design and construction factors play a key role in the strength and stability of the project itself.

It can be analysed from four aspects:

- (a) Geological composition of bank slope ( $u_{11}$ ): The natural geological composition of bank slope or the quality of artificial fillings affect the stability of bank revetment project. For revetment project, the bearing capacity as well as the permeability of natural geological composition or human engineering filler should be considered. Therefore, the slope geological type often determines the anti-erosion characteristics and stability of the slope surface.
- (b) Design rationality ( $u_{12}$ ): the ability of the waterway revetment to resist the wave-current impact damage is related to the flood control standard and waterway grade, and the ability to resist the damage is also different when the flood control standard and waterway grade are different. In addition, the design of cross-section and vertical section, drainage design, filling water content and treatment of slope toe of revetment all have influence on the stability of the project. The optimization of design scheme can effectively reduce the occurrence of water damage.
- (c) The slope of the upstream surface of bank slope ( $u_{13}$ ): the slope of the upstream surface of protective structures such as river revetment and retaining wall (slope coefficient  $m$ ), which is also an important parameter affecting the maximum scouring depth of the river bank. The increase of slope coefficient can largely reduce the impact capacity of current and wave, and reduce the depth and scope of scour pit. When  $m = 0$  and other conditions remain unchanged, the maximum scouring depth reaches its maximum, and the maximum scouring depth decreases with an increase of  $M$ . Generally, under the vertical condition of the side wall ( $m = 0$ ), the maximum erosion depth of the river bank is multiplied by the erosion reduction coefficient  $K_m$  of the previous

slope to reflect the influence of slope coefficient  $m$  on the erosion depth.

- (d) Construction quality ( $u_{14}$ ): mainly including foundation treatment, groundwater, treatment of filling and excavation joint, treatment of adverse geological conditions, compaction and levelling of filling materials, construction technology, etc. The higher the construction quality, the better the stability of the project.
- (2) Protective measures ( $u_2$ ): the common anti-scour structures of slope toe and foundation of revetment project mainly include riprap and soft rock body row, permeable frame, hydraulic plug plate, spur dike and their combination forms. Due to the long-term lashing, dashing, scouring and erosion induced by current and wave, the irrational selection of protection form and plane layout are also important reasons for water damage. Therefore, the setting and use of protective structures are very important to evaluate the vulnerability of revetment and the ability to resist wave and current.
    - (a) Layout perfection ( $u_{21}$ ): including the type, size, masonry materials, strength, quantity (scale), layout location, foundation buried depth and rationality of its own protection. These factors affect the impact resistance, erosion resistance and wear resistance of protective structures.
    - (b) Maintenance and maintenance ( $u_{22}$ ): it refers to whether the engineering stability is inspected regularly, whether the maintenance are timely and reasonable, the intensity of the implementation of the disaster control project, maintenance and maintenance technology and the establishment of archives, etc. This is related to the effectiveness and durability of the protection project.
  - (3) Wave-current characteristics ( $u_3$ ): mainly considered from two aspects of local velocity and wave height.
    - (a) Local flow velocity ( $u_{31}$ ): the shape of river section (Canyon / open reach) has significant influence on the cross-section distribution of velocity. Water conservancy facilities, river regulation and development and utilization activities (river dredging, sand excavation and earth rock piling) change the local topography of the riverbed, disturb the flow, and increase the cross-section heterogeneity of flow velocity. When the velocity is small, the bank slope is gentle and the revetment building blocks are large, which can resist the scour and impact of the current and maintain the stability of the project. However, in the case of high flow velocity, the structures on the bank slope are easy to be impacted



and scoured and become unstable. At the same time, the greater the local flow velocity, the stronger the ability to carry sand and gravel in the riverbed, and the more likely to cause erosion damage to the bank slope and its protective structures. Therefore, in practice, the local flow velocity and the threshold velocity of revetment block stone and surrounding riverbed sediment can be determined, while the ratio was calculated and judged.

- (b) Wave height ( $u_{32}$ ): the wind-induced wave, ship travelling wave, flood discharge wave of dam and surge wave formed by landslide will have significant impacts and scouring effect on revetment project, leading to instability and damage of the project. The higher the wave height, the greater the impact force on the bank slope, and the more likely to cause damage to the bank slope and its protective structures. According to the requirements of discharge wave height in 'emergency plan for storm surge, wave, tsunami and sea ice disaster' issued by the State Oceanic Administration (State Oceanic Administration, 2012) and the general design code for ship lock (Industry standards of the People's Republic of China, 2001), considering that the inland river is a non-open narrow water area, the early warning division of wave risk for inland waterway project safety is carried out. When the wave height is greater than 2 m, it is extremely dangerous. When the wave height is between 1.5 and 2 m, it is a high dangerous area. When the wave height is between 1 and 1.5 m, it is a medium dangerous area. When the wave height is between 0.5 and 1 m, it is a low risk area. When the wave height is less than 0.5 m, it is a low risk area.
- (4) Waterway factors ( $u_4$ ): it is mainly evaluated from two aspects of waterway morphology and riverbed composition.
- (a) Waterway morphology ( $u_{41}$ ): The curved and straight plane shape of the river makes the flow pattern different. The flow in curved waterway is related to the change of geometric boundary conditions. The main parts of bank revetment project are as follows: concave bank of river bend and straight section of concave bank near the outlet of river bend; Canyon reach and its upstream and downstream; oblique and top scour points of wave and current caused by topography and nearby downstream, which indicates that river morphology has significant influence on the location of water damage. The influence of waterway shape on revetment can

**Table 1.** Vulnerability evaluation index system of revetment project.

Indicator System	Influence Factor	Factor Subset
Vulnerability index system of revetment project $U$	$u_1$ Design and construction	$u_{11}$ Geological composition of bank slope
		$u_{12}$ Rationality of design
		$u_{13}$ Bank slope
		$u_{14}$ Construction quality
	$u_2$ Protective measures	$u_{21}$ Layout integrity
		$u_{22}$ Maintenance and repair
	$u_3$ Wave-current characteristics	$u_{31}$ Local flow velocity
		$u_{32}$ Wave height
	$u_4$ Waterway factors	$u_{41}$ River configuration
		$u_{42}$ Riverbed composition

be comprehensively evaluated according to the bending degree of river waterway, compression ratio of cross section and local terrain change.

- (b) Riverbed composition ( $u_4$ ): the riverbed composition can be generally divided into clay and non-clay, leading to different scour resistance. For non-clay riverbed (sandy river bed, sandy pebble bed), the main parameters affecting riverbed deformation and scouring depth are sediment particle size and sediment gradation. Due to the non-uniformity of sediment in natural rivers, the influence of sediment heterogeneity on local scour depth of revetment works or protective structures should be considered. For clay riverbed, it is related to the type and content of cohesive soil, clay characteristics and clay compression and consolidation state. The size and classification of sediment particles adopt the classification method of China's Hydrologic Engineering field (Qian & Wan, 1983). Combined with the above analysis, the vulnerability assessment factors of river revetment project subjected to wave and current are listed in Table 1.
- (2) Determination of comment set

Before the vulnerability assessment of waterway revetment project, a set of comments should be established. The evaluation set is a collection of comments (language description) given by the reviewers for each level of evaluation indicators, and it is also a set composed of various possible results of each evaluation element.

In order to better describe the nature and degree of advantages and disadvantages of each factor or sub-factor in the evaluation, this study divides the evaluation of the vulnerability evaluation model into five levels, which can be expressed as:

That is,  $V = \{v_1, v_2, v_3, v_4, v_5\} = \{\text{extremely high vulnerability, high vulnerability, medium vulnerability, low vulnerability, very low vulnerability}\}$ .

**Table 2.** Grading standards for each evaluation factor.

Factor set		Rating scale				
		10	8	6	4	2
Design and construction $u_1$	Geological Composition of bank slope $u_{11}$	Other weak Banks	Clayey soil or silty soil	Gravel soil with good water permeability	Drift (block) stone soil, pebble soil, gravel soil or gravel soil, etc.	Hard rock that is not easily weathered
	Rationality of design $u_{12}$	Extremely poor: the cross-section and drainage design of the project is extremely unreasonable	Poor: poor design of cross-section and drainage of the project	General: the horizontal and vertical sections and drainage design of the project are basically feasible	Good: the cross-section and drainage design is reasonable	Excellent: the cross-section and drainage design schemes have been compared and selected Superior scheme
	Bank slope $u_{13}$ Construction quality $u_{14}$	$m = 0$ Extremely poor: improper foundation treatment measures and poor construction technology	$0 < m \leq 0.75$ Poor: unreasonable base treatment and poor construction technology	$0.75 < m \leq 1.25$ General: the foundation treatment of the project is basically reasonable, and the construction technology is general	$1.25 < m \leq 2.0$ Good: good foundation treatment and good construction technology	$m > 2.0$ Excellent: the foundation treatment measures are reasonable and the construction technology is good
Anti-erosion measures $u_2$	Layout perfection $u_{21}$	Extremely poor: no anti-scour prevention measures	Poor: the anti-scour type and structural strength are unreasonable	General: the anti-scour type and structural strength are reasonable	Good: the anti-scour type and structural strength are generally good	Excellent: good anti-scour type and structural strength
	Maintenance $u_{22}$	Extremely poor: no maintenance and disaster control measures	Poor: the maintenance is not timely, and the treatment measures are unreasonable	General: temporary subgrade maintenance and treatment measures	Good: the maintenance and repair is timely, and the treatment measures are feasible	Excellent: timely maintenance and repair, reasonable treatment measures
Wave-current characteristics $u_3$	Local flow velocity $u_{31}$	It is higher than the threshold velocity of revetment block stone and surrounding riverbed sediment	It is slightly higher than the threshold velocity of revetment block stone and surrounding riverbed pebble	It is equal to the starting velocity of revetment block stone and surrounding riverbed pebble	It is smaller than the starting velocity of the larger block stones and the pebbles in the riverbed around the revetment	It is far less than the threshold velocity of revetment block stone and surrounding riverbed pebble
Riverway factor $u_4$	Wave height $u_{32}$	$H > 2$ m	$1.5 \text{ m} < H \leq 2$ m	$1 \text{ m} < H \leq 1.5$ m	$0.5 \text{ m} < H \leq 1$ m	$H \leq 0.5$ m
	Riverway morphology $u_{41}$	Sharp bend reach ( $\theta \geq 90^\circ$ ); The local topography of the river waterway causes the obvious top or oblique scour of water flow; Section compression ratio $\geq 45\%$	Highly curved reach ( $60^\circ < 90^\circ$ ); The results show that the local topography of the river causes obvious top or oblique scour, and the compression ratio of river section is 30–45%	The results show that the river section is moderately curved ( $30^\circ < \theta \leq 60^\circ$ ); the local topography of the river waterway causes obvious water crest or oblique scour; the compression ratio of river section is 15–30%	The results show that there is a slight bend section ( $\theta \leq 300$ ); the local topography of the river waterway does not cause the water top rush or oblique scour; the section compression ratio of the reach is $\leq 15\%$	There is no local abrupt topography in the waterway
	Riverbed composition $u_{42}$	Mainly boulders (particle size greater than 200 mm)	Mainly pebbles (20–200 mm)	Mainly gravels (2–20 mm)	Mainly sandy soil (0.05–2 mm)	Mainly fine grained soil (particle size less than 0.05 mm)

In order to facilitate the evaluation, score values are assigned to each impact factor respectively, and it is proposed to establish the evaluation grade comment set  $V = \{v_1, v_2, v_3, v_4, v_5\} = \{10, 8, 6, 4, 2\}$  in the form of a 10-point scale. The upper limit of each grade is used in the evaluation.

Through investigation and analysis, combined with expert consultation and evaluation, the basis and

standards for determining the different rating levels of each evaluation factor are shown in Table 2.

### 3.2. Determination of membership function

Membership degree refers to the degree of membership of the factor set to the comment set, and is the contribution of various evaluation factors to vulnerability.

The factor membership function is constructed by the method of half trapezoid.

(1) Determination of membership function of quantitative element evaluation index set

According to the optimal value and the worst value of the scoring results,  $v_j$  ( $j = 1, 2, 3, 4$ ) is discretized as the comment set according to the equal step size. The results show that  $v_j$  and  $v_{j+1}$  are the two adjacent classification criteria. If  $v_j > v_{j+1}$ , the membership function of factor to  $v_j$  is:

$$r(x) = \begin{cases} 0, & x > v_j, x < v_{j+1} \\ (x - v_{j+1}) / (v_j - v_{j+1}), & v_{j+1} \leq x \leq v_j \end{cases} \quad (14)$$

If  $v_j < v_{j+1}$ , then the membership function of the factor to  $v_j$  level is:

$$r(x) = \begin{cases} 0, & x > v_{j+1}, x < v_j \\ (v_{j+1} - x) / (v_{j+1} - v_j), & v_j \leq x \leq v_{j+1} \end{cases} \quad (15)$$

In the equation:  $r(x)$  is the membership function;  $X$  is the score of the index.

(2) Determination of membership function of qualitative factor evaluation index set

The qualitative factor evaluation index is based on the same evaluation grade standard after comprehensive comparison and analysis of the same element in each scheme by experts. The score of a certain element is set as  $X$ , and the calculation method of its membership function is the same as Equations (14) and (15).

### 3.3. Determination of weight set

In fuzzy comprehensive evaluation, the determination of weight will have a great impact on the final evaluation results. There are many methods which can be used to determine the weight, such as expert estimation method, analytic hierarchy process (AHP), etc. No matter which method is used, whether the weight is reasonable or not mainly depends on the detailed understanding of the disaster investigation of river revetment project and the experience of experts. In this study, based on the field investigation, the weight of the evaluation factor set and the factor subset in the evaluation index system is determined by the conventional AHP, which is a multi-objective decision analysis method combining quantitative and qualitative methods (Wang, 2016; Xu, 1988). Finally, the factor weight sets of sub elements corresponding to various elements are calculated by using AHP:

(5) The weight set of each kind of factor

$$\tilde{A}_1 = (0.2, 0.5, 0.1, 0.2), \quad \tilde{A}_2 = (0.667, 0.333)$$

$$\tilde{A}_3 = (0.333, 0.667), \quad \tilde{A}_4 = (0.667, 0.333)$$

(6) Factor class weight set

$$\tilde{A} = (0.275, 0.513, 0.138, 0.074)$$

According to the above method, the vulnerability assessment can be carried out for specific river revetment. In practice, the evaluation index can be increased or decreased flexibly, and the weight set can also be adjusted appropriately.

## 4. Application examples of evaluation methods

In this study, the vulnerability of the waterway revetment project in Nanxi urban section of Yibin City is evaluated. Nanxi urban area of Yibin City is located on the left bank of the Yangtze River, which is 42 km downstream of the confluence of Jinsha River and Minjiang River. The Yangtze River is 55 km long in Nanxi area, and the river course is distributed in 'S' shape. The river section of the revetment project is located on the left bank of the upper section of the Dananmen bend. The river surface is narrowed, with an average width of 855 m. The left bank is a terrace of the Yangtze River, and the right bank is a steep mountain. The total length of the revetment project is 5603 m, and the waterway revetment project is constructed with local gravel. The natural slope angle of the engineering area is 15°–25°, and the surface layer is mainly silty soil, with a thickness of 1–5 m. The lower part is sand and gravel layer. The riverbed in this reach is composed of pebbles and bedrock. The flow velocity is high and the flood season high water level lasts for a short period. Affected by the flood discharge wave from the upstream to Xiangjiaba Water Conservancy project, a wave about 2.1 m high is formed in this reach. The embankment body of the project is filled with rolled sand and gravel, and the upstream slope ratio is 1:1.8. The cast-in-place concrete slope protection is adopted, and the diameter of drainage hole is 3 cm. The slope protection surface is added with concrete lattice green plants, and the upstream water toe protection adopts the steel wire cage with the gravel particle size of no less than 10 cm. The riverbed evolution analysis and model test are used to study the engineering design scheme. The engineering construction technology and construction technology are good, and the maintenance is timely. The comprehensive ability of the project to resist wave and current disasters is improved, and the ecological landscape effect is good (Lu et al., 2017), as shown in Figure 1.





**Figure 1.** Bank revetment of Nanxi City section of Yibin upper reaches of the Yangtze River.

**Table 3.** Evaluation Form for the vulnerability of the revetment works in Nanxi urban section.

	U									
	u <sub>1</sub>		u <sub>2</sub>		u <sub>3</sub>		u <sub>4</sub>			
Factor	u <sub>11</sub>	u <sub>12</sub>	u <sub>13</sub>	u <sub>14</sub>	u <sub>21</sub>	u <sub>22</sub>	u <sub>31</sub>	u <sub>32</sub>	u <sub>41</sub>	u <sub>42</sub>
Score	5.5	3.5	4.0	3.5	3.0	2.5	8.0	10.0	6.5	7.5

According to the criteria for the grading of each evaluation factor in Table 2, the ratings are shown in Table 3.

According to the score value of each factor, the fuzzy mapping from  $u_i$  to  $V$  is established by the reduced half trapezoid method of constructing membership function, and the fuzzy relation matrix  $R_i$  is determined. According to the factor weight set of various elements and their corresponding sub-elements calculated above. The results of the first level fuzzy comprehensive evaluation can be obtained:

$$\tilde{B}_1 = \tilde{A}_1 \cdot \tilde{R}_1 = (0 \ 0 \ 0.15 \ 0.75 \ 0.1);$$

$$\tilde{B}_2 = \tilde{A}_2 \cdot \tilde{R}_2 = (0 \ 0 \ 0 \ 0.42 \ 0.58);$$

$$\tilde{B}_3 = \tilde{A}_3 \cdot \tilde{R}_3 = (0.667 \ 0.333 \ 0 \ 0 \ 0);$$

$$\tilde{B}_4 = \tilde{A}_4 \cdot \tilde{R}_4 = (0 \ 0.42 \ 0.58 \ 0 \ 0);$$

The results of second level fuzzy comprehensive evaluation are as follows

$$\tilde{B} = \tilde{A} \cdot \tilde{R} = (b_1, b_2, b_3, b_4, b_5) = (0.1 \ 0.08 \ 0.08 \ 0.42 \ 0.32)$$

According to the maximum membership method,  $b_4 = \max b_l = 0.42 (1 \leq l \leq 5)$  can be obtained. Therefore, the fourth evaluation result is determined as 'low vulnerability'. The current actual operation situation (no

water damage) is basically consistent with the completion of the main construction of the project in April 2009.

## 5. Conclusions

- (1) The vulnerability evaluation of inland waterway revetment project should adopt the combination of qualitative and quantitative methods, and the main influencing factors should be selected for objective and scientific comprehensive evaluation. In order to meet the needs of vulnerability analysis, through the comprehensive comparison of a large number of prototype observation data and research results, the design and construction (geological composition of bank slope, rationality of design, slope of upstream surface of bank slope, construction quality), protective measures (layout perfection, maintenance and repair), wave-current characteristics (local flow velocity, wave height) these four main factors that affect the stability of waterway revetment project, including 10 sub factors.
- (2) According to the characteristics of multi factors and fuzziness in the vulnerability evaluation of waterway revetment project subjected to wave and current, a two-level fuzzy comprehensive evaluation mathematical model for vulnerability evaluation of waterway revetment project under wave-current loading is established by using fuzzy mathematics method, and the steps of fuzzy comprehensive evaluation are given. Based on the establishment of vulnerability evaluation index system, AHP is used to determine the weight of evaluation factors and their sub factors.
- (3) The relevant evaluation methods are used to evaluate the vulnerability of the bank revetment project

of Nanxi urban section of Yibin City in the upper reaches of the Yangtze River, the weight of the evaluation index and the vulnerability evaluation results are given. The vulnerability evaluation result of the project is 'low vulnerability', which is consistent with the actual project operation. The fuzzy mathematics method is feasible to evaluate the vulnerability of waterway revetment projects under the action of waves and currents, which provides a reference for the vulnerability assessment and disaster prevention of other similar river revetment projects.

## Disclosure statement

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