

PAPER • OPEN ACCESS

A Comprehensive Evaluation Method of Safety Behavior of Concrete Face Rockfill Dam Based on Regression Relationship Method and Fuzzy Recognition Model

To cite this article: Lifeng Wen *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **643** 012070

View the [article online](#) for updates and enhancements.

You may also like

- [Numerical simulation and operation characteristics analysis of folded line concrete face rockfill dam: case study of Yimeng Pumped storage power station](#)
Qiang Ren, Guoying Li and Kuangmin Wei
- [Stress and Deformation Analysis of High Concrete Face Rockfill Dam Based on COMSOL Multiphysics](#)
Runying Wang and Keping Yu
- [Simulation of creep deformation of faced rockfill dam based on secondary development of ABAQUS](#)
Hui Chen and Yanyi Zhang



ECS
The
Electrochemical
Society
Advancing solid state &
electrochemical science & technology

DISCOVER
how sustainability
intersects with
electrochemistry & solid
state science research

A Comprehensive Evaluation Method of Safety Behavior of Concrete Face Rockfill Dam Based on Regression Relationship Method and Fuzzy Recognition Model

Lifeng Wen^{1*}, Ying Yang¹ and Yanlong Li¹

¹State Key Laboratory of Eco-hydraulics in Northwest Arid Region of China, Xi'an University of Technology, Xi'an, Shaanxi, 710048, P.R. China

*Corresponding author's e-mail: wenlifeng@xaut.edu.cn

Abstract. The concrete face rockfill dam (CFRD) generally encounters structural health problems during long-term operation. Therefore, it is necessary to study the safety evaluation of CFRDs. This paper proposes a comprehensive evaluation method for the safety behavior of CFRDs on the basis of regression relationship method and fuzzy recognition model. The method of sub-index safety evaluation is established by using regression relationship method. The multiplication scale method was adopted to determine the sub-indexes weight. In combining of sub-index safety evaluation value and sub-indexes comprehensive weight, the fuzzy recognition model is used to determine the comprehensive evaluation grade of dam safety. Safety evaluation of several CFRDs were evaluated by the method proposed in this paper and existing safety evaluated method to verify reasonable and rationality of the method.

1. Introduction

The concrete face rockfill dam (CFRD) has the advantages of good safety, convenient construction, and short construction period. It has been widely used in water conservancy and hydropower projects[1]. At present, the development of CFRDs is facing a leap from 200m to 300m in height. As the age of the CFRDs increase, a considerable number of dams have safety problems, such as face slab cracks, dam embankment cracks, and excessive leakage[2]. These problems will endanger the safety of the dam and even cause immeasurable losses. Therefore, it is very essential to carry out safety evaluation research on CFRDs.

The safety evaluation method of CFRD includes single index and multiple indexes of the dam. Single index evaluation usually establishes a mathematical model for a single measurement point. Single index evaluation methods include random forest method and catastrophe theory. The single index evaluation model can well reflect the deformation concerned and the safety status of the measuring point. However, it cannot reflect the overall safety of the dam.

The multiple indexes evaluation method studied several indexes at different locations of the dam. It can reasonably consider the relationship between various indicators. Multiple indexes evaluation methods include analytic hierarchy process, grey model, fuzzy theory, etc. The determination of index weights is the most critical issue in the evaluation method. At present, the methods for determining index weights include expert consultation, principal component analysis, and analytic hierarchy process. However, each method has certain applicable conditions and limitations. Therefore, the evaluation method of dam safety behavior needs further research.

This paper analyzes the measured data of 87 CFRDs[3]. Firstly, a safety evaluation method for



sub-index of CFRD is proposed, which based on regression theory. Secondly, the multiplication scale method was adopted to determine the weight of sub-indexes. Then, considering the overweight and the index weight, the calculation method of the sub-index comprehensive weight is determined. Finally, the fuzzy recognition model is used to establish a comprehensive evaluation method for the measured behavior of the CFRD.

2. A quantitative evaluation method of CFRDs behavior

This section establishes a quantitative evaluation method for the safety performance of a CFRD. Firstly, the regression relationship method is used to establish a sub-index safety evaluation method. Secondly, the weights of sub-indexes are determined by the multiplication scale method. Then, the fuzzy recognition model is used to process the sub-index security evaluation value and sub-index weight. Finally, a comprehensive evaluation method for the safety performance of the CFRDs can be successfully established.

2.1. Sub-index evaluation method

Sub-index evaluation is the basis of comprehensive evaluation of dam safety. Based on the statistical data of engineering examples, this paper establishes the evaluation method of crest settlement, internal settlement, face slab deflection and seepage rate. This method uses the regression relationship method.

The specific process is as follows:

(1) Regression relationship fitting. First of all, this paper analyzes the deformation and seepage monitoring data of 87 existing CFRDs. At the same time, the regression relationship between the sub-indexes and the main influencing factors is established. Multiple functional relationships are selected for regression fitting. The regression curve with larger R^2 and smaller RMSEP is selected as the optimal regression model curve.

(2) Sub-index evaluation method and grade. The vertical distance between the sample and the regression curve is calculated. One of the sample points is selected as the reference point in the normal state. Then determine the actual range of sub-index $[-a, b]$. And convert the actual range of sub-indexes to the standard range of $[0,5]$. According to the standard value range, each sub-index is divided into 5 security levels. The optimal regression curve between each sub-index and the corresponding main influencing factor calculated in this paper is shown in Table 1, and the conversion relationship of each sub-index is shown in Table 2.

Table 1. The optimal relationship between sub-index and the corresponding main influencing factor.

Sub-index	Fitting function	Expression	R^2	RMSEP
Internal settlement	Exponential function	$y = 0.1154e^{0.0147x}$	0.5313	0.4175
Crest settlement	Power function	$y = 0.0004x^{1.2892}$	0.4541	0.0967
Face slab deflection	Power function	$y = 0.0003x^{1.3524}$	0.4640	0.1240
Seepage rate	Power function	$y = 0.0237x^{1.5847}$	0.5709	19.3721

Table 2. The actual range and conversion relationship of sub-indexes for CFRD safety evaluation.

Sub-index	Actual range	Reference point	Reference	Conversion function
Internal settlement	$[-1.32, 2.36]$	Bakun	-0.19	$y = -1.3587x + 3.2065$
Crest settlement	$[-0.20, 0.75]$	Hongjiadu	-0.002	$y = -5.2632x + 3.9474$
Face slab deflection	$[-0.22, 0.81]$	Daao	0.10	$y = -4.8544x + 3.9320$
Seepage rate	$[-105.7, 337.1]$	Jiudianxia	81.97	$y = -0.0113x + 3.8035$

^a x is the value of the factor corresponding to each sub-index, and y is the value of the sub-index.

2.2. Determine sub-index weight

The determination of the weights of sub-indexes is the core issue in the comprehensive evaluation of the measured behavior of dam structures. He et al.[4] proposed the multiplication scale method on the basis of analytic hierarchy process. This method compares the importance of each index in pairs, considers the relative importance of the indexes more flexibly, and scientifically obtains the weight of each index.

The multiplication scale method is adopted to determine the weight of sub-indexes. The steps are as follows: (1) According to experience or measured data, qualitatively rank the importance of m evaluation indexes. (2) Compare the evaluation indexes A and B in pairs to determine the importance of the two evaluation indexes. When the importance of indexes A and B are the same, the weight is $(w_A, w_B) = (0.5, 0.5)$. (3) When the importance of indexes A and B are not the same, use the equation 1 to calculate the weight:

$$(w_A : w_B) = (1.354^n \div (1 + 1.354^n), 1 \div (1 + 1.354^n)) \quad (1)$$

In equation 1, the 1.354 is the "slightly larger" scale value of the product scaling method. The values of n are 1, 2, 3, and 4 when the importance of the two indexes is "slightly large, obviously large, intensely large, and extremely large".

2.3. A quantitative evaluation method based on fuzzy theory

The safety of dams is a relatively vague concept. There is no clear boundary between safety and danger. Therefore, this paper introduces fuzzy mathematics theory into the safety evaluation of CFRD[5]. The sub-index safety evaluation value and the index weight are comprehensively dealt with the correlation, which uses the fuzzy recognition model.

Assuming that there are n dams and each dam has m evaluation indexes, there are $m \times n$ sub-indexes safety values. Convert the calculated data of the safety evaluation value of the dam sub-index into a subordinate interval of $[0, 1]$. The matrices X can be obtained. According to the practical experience of CFRDs safety inspection and other factors, the evaluation level of the dam's evaluation index is determined to be 5 levels. Therefore, the composed comment set is $Y = (y_1, y_2, y_3, y_4, y_5) = (\text{good, better, normal, mildly abnormal, severely abnormal})$. It is evaluated by the grading standard is strictly considered in accordance with the grading standard. The matrices Y is equation 2:

$$Y = \begin{bmatrix} 0.8 & 0.7 & 0.5 & 0.3 & 0.2 \\ 0.8 & 0.7 & 0.5 & 0.3 & 0.2 \\ 0.8 & 0.7 & 0.5 & 0.3 & 0.2 \\ 0.8 & 0.7 & 0.5 & 0.3 & 0.2 \end{bmatrix} = (y_{ih})(h = 1, 2, \dots, c; i = 1, 2, \dots, m) \quad (2)$$

Then the matrices X and Y are transfed into the corresponding relative membership matrices R and S :

$$R = \begin{bmatrix} r_{11} & r_{12} & r_{13} & \dots & r_{1n} \\ r_{21} & r_{22} & r_{23} & \dots & r_{2n} \\ \dots & \dots & \dots & \dots & \dots \\ r_{m1} & r_{m2} & r_{m3} & \dots & r_{mn} \end{bmatrix} = (r_{ij}) \quad (3)$$

$$S = \begin{bmatrix} 1 & 0.833 & 0.5 & 0.167 & 0 \\ 1 & 0.833 & 0.5 & 0.167 & 0 \\ 1 & 0.833 & 0.5 & 0.167 & 0 \\ 1 & 0.833 & 0.5 & 0.167 & 0 \end{bmatrix} \quad (4)$$

The weight of the sub-indexes of the CFRD calculated by the scaling method of multiplication and accumulation is $v = [v_1, v_2, \dots, v_m]$. Comprehensively consider the overweight and the index weight, and establish a comprehensive weight matrix of m sub-indexes. The comprehensive weight matrix of sub-index can be calculated as $W = [w_1, w_2, \dots, w_m]^T$. The comprehensive weight matrix can indicate the

influence of sub-indexes on the safety of the measured dam shape.

The fuzzy recognition model used in this article is equation 5:

$$u_h = \begin{cases} 0 & (h < a \text{ or } h > b) \\ \left(\frac{\sum_{k=a}^b \left(\frac{\sum_{i=1}^m w_i (r_i - s_{ih})^p}{\sum_{i=1}^m w_i (r_i - s_{ik})^p} \right)^{2/p}}{\sum_{i=1}^m w_i (r_i - s_{ik})^p} \right)^{-1} & (a \leq h \leq b, d_h \neq 0) \\ 1 & (d_h = 0) \end{cases} \quad (5)$$

Substitute the matrices R and S and matrix W into the fuzzy recognition model. The relative membership degree matrix of the measured safety behavior of the dam is calculated as $U=[u_1, u_2, u_3, u_4, u_5]$. Equation 6 is used to calculate the characteristic value H of the dam. Comparing the calculated characteristic value H with the evaluation grade range, the safety status of the dam behavior can be obtained. The evaluation grade range is $H=([1,1.5), [1.5,2.5), [2.5,3.5), [3.5,4.5), [4.5, 5)]$ =(good, better, normal, mildly abnormal, severely abnormal).

$$H_u = \sum_{h=1}^c \mu_{\tilde{A}}(u) h \quad (6)$$

3. Case study

In order to verify the feasibility of the method proposed in this paper, the Shuibuya CFRD is selected as an engineering example for calculation. The dam crest settlement, internal settlement, face slab deflection, and seepage rate of the Shuibuya concrete faced rockfill dam are selected as evaluation indexes. The calculation results of the safety value of each sub-index are shown in Table 3.

Table 3. Sub-index safety evaluation calculation results of Shuibuya Dam.

Sub-index	Monitoring value	Deformation experience value	Conversion value	Sub-index safety value
crest settlement	0.35m	0.451m	-0.1m	4.47
Internal settlement	2.30m	3.546m	-1.246m	4.90
Face slab deflection	0.28m	0.477m	-0.197m	4.89
Seepage rate	20L/s	125.8 L/s	-105.8 L/s	5.00

Through the case study of the Shuibuya CFRD, the importance of the sub-indexes is determined in order from the heaviest to the least as the face slab deflection (y_1), seepage rate (y_2), crest settlement (y_3), and internal settlement (y_4). Comparing the indicators in pairs, $y_1:y_2=1.354:1$, $y_2:y_3=1.354:1$, $y_3:y_4=1.354:1$. Therefore, the weight of the sub-indexes of Shuibuya CFRD is (crest settlement, internal settlement, face slab deflection, seepage rate) = (0.20, 0.15, 0.37, 0.28).

According to the safety value of the sub-index, the safety evaluation value matrix of the measured sub-index can be determined as $X=[0.89, 0.98, 0.98, 1]^T$. The safety evaluation grade matrix Y is known. Transform the matrix X into the corresponding relative membership matrix $R=[1, 1, 1, 1]^T$. The weights of sub-indexes of Shuibuya CFRD are $v=[0.20, 0.15, 0.37, 0.28]$. Combined with the super-weight matrix R , the comprehensive weight matrix A of 4 sub-indexes can be obtained as:

$$A = vr = \begin{bmatrix} 0.20 & 0 & 0 & 0 \\ 0 & 0.15 & 0 & 0 \\ 0 & 0 & 0.37 & 0 \\ 0 & 0 & 0 & 0.28 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \quad (7)$$

The element values of matrix A are normalized by column, and the comprehensive weight matrix of sub-index can be calculated as $W=[0.20, 0.15, 0.37, 0.28]^T$. And then calculate the relative membership degree matrix $U=[1, 0.848, 0.095, 0.034, 0.024]^T$. Then $U_{-}=[0.500, 0.424, 0.047, 0.017, 0.012]^T$. The comprehensive safety state characteristic value can be calculate by equation 6. The H of Shuibuya CFRD is 1.617, the safety grade is better.

In order to demonstrate the rationality of the method, the results obtained in this paper are compared with the existing results. At the same time, it is compared with the safety evaluation results of the existing literature, as shown in Table 4. The safety evaluation results in this paper are more consistent with the actual safety evaluation results and the existing literature safety evaluation results[6]. It shows that the quantitative evaluation method is reasonable and feasible.

Table 4. Calculation results of comprehensive safety behavior of CFRD.

Dam		Shuibuya	Hongjiadu	Wananxi
Sub-index	Crest settlement	4.47	3.96	5.00
	Internal settlement	4.90	3.72	3.54
	Face slab deflection	4.89	3.86	4.12
	Seepage rate	5.00	3.22	3.74
Comprehensive index characteristic value		1.617	1.686	1.155
Safety grade		better	better	good
Results of other evaluation methods		Dam safety is good	Good operating indexes	Deformation is normal

4. Conclusion

Based on statistical analysis methods, this paper establishes a dam safety performance index quantitative evaluation method based on regression relationship method and fuzzy recognition model. This method is based on actual engineering data and has a clear physical meaning, and it can better evaluate the safety of CFRD sub-indexes. The example shows that the method is reasonable and accurate.

Acknowledgments

The research described in this paper was funded by the National Natural Science Foundation of China (Grant No. 51909215, 52039008, 51979224, and 51722907), the Natural Science Basic Research Program of Shaanxi (Program No. 2020JQ-641), the Scientific Research Program Funded by the Shaanxi Provincial Education Department (Program No. 19JS047), the Young Talent fund of University Association for Science and Technology in Shaanxi, China (Program No. 20200417), and China Postdoctoral Science Foundation (Program No. 2020M683527).

References

- [1] Kim, Y. S, Seo, M. W, Lee, C. W, Kang, G. C. (2014) Deformation characteristics during construction and after impoundment of the CFRD-type Daegok Dam. *Engineering Geology*, 178: 1-14.
- [2] Zhou, W. Hua, J. J, Chang, X. L, Zhou, C. B. (2011) Settlement analysis of the Shuibuya concrete-face rockfill dam. *Computers & Geotechnics*, 38(2):269-280.
- [3] Wen, L. F, Chai, J. R, Xu, Z. G, Qin, Y. Li, Y. L, (2018) A statistical review of the behaviour of concrete-face rockfill dams based on case histories. *Geotechnique*, 68(9):749-771.
- [4] He, J.P, Li, Z. Z, Shi, Y. Q. (2001) Weight question about comprehensive evaluating dam safety monitoring behavior. *Journal of Wuhan University (Engineering Science Edition)*, 03: 13-17.
- [5] Li, Z. K, Jiang, J. S, Wang, G. Y, (2007) Comprehensive assessment of observed behavior of earth-rockfill dams. *Chinese Journal of Geotechnical Engineering*, 02: 255-259.
- [6] Li, F. L, Cai, D. S., Li, W. L, Tang, X, Qin, P. (2014) Discussion on the CFRD Safety Evaluation Method. *Yellow Rive*, 36(04):104-107