A Comprehensive Evaluation Model of Dam Failure Consequences Based on Combined Weighted Cloud Model

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Abstract: In order to solve the uncertainty and fuzziness of various factors, the cloud model theory is introduced to establish evaluation indexes from four aspects of life loss, economic loss, social impact and environmental impact. AHP and grey correlation method are applied to subjective and objective weight respectively, and a combination weight based on cloud model is proposed the evaluation model of dam break consequence. According to the evaluation index system and evaluation standard of dam breach, the cloud model parameters of different accident levels under the evaluation index are determined in the model; the combined weight of each index is calculated based on AHP and correlation degree method, and the comprehensive evaluation model of dam breach consequences is constructed. Taking five reservoirs in Jiangxi Province as an example, the results show that the model is effective and feasible, which provides a new way for the comprehensive evaluation of the consequences of dam break.

1. Preface
Currently, more than 98,000 dams have been built in China. The establishment and operation of these dams provide fundamental guarantee for China’s economic and social development. However, most dams were built in the early period of People’s Republic of China’s establishment, and the technological level of dam building was low, so there exist many problems in the project quality, and even unfortunate accidents of dams also accidentally occur. Besides, since the new century began, some world-class high dams and large dams have been built in China. How to guarantee the safe operation of these mega projects also imposes challenges to the risk management of dams.

During risk management of dams, scholars make research on comprehensive evaluation on consequence of dam break from the perspective of life loss, economic loss, social influence and environmental influence, etc. Currently, some achievements have been made for the research on the above aspects. Especially a lot of achievements on the life loss have been made, including calculation approaches and evaluation criteria. However, there is little research on comprehensive evaluation of dam break because the evaluation indicators of social and environmental influence lack quantitative numerical characterization. The comprehensive model of consequence evaluation on dam break, built by Li et al.\textsuperscript{[1]}, was built on the basis of three influencing factors including life, economy and social & environmental influence from the logarithmic non-linear and logarithmic linear perspective, and then the comprehensive evaluation model on consequence of dam break was built; Zhao et al.\textsuperscript{[2]} graded and analyzed the above influencing factors, took "very severe, severe, intermediate, ordinary and slight" as the alternative set, determined the grading criteria, and determined the indicator weight with asymptotic normalization coefficient, built the comprehensive evaluation model on the consequence of dam break on the basis of grey-fuzzy theory, provided solutions of fuzzy problems of influencing
factors; Sun and Li et al. built the comprehensive evaluation model on consequence of dam break on the basis of fuzzy mathematics theory[3], principal component analysis[4], linear weighted sum method[5] and grey relational analysis[6]. Cheng et al. [7] probed new channel of comprehensive evaluation model on consequence of dam break apart from conventional mathematical model, introduced attribute theory into comprehensive evaluation approach, and built the model of evaluating the consequence severe degree of dam break; Zou et al. [8] built comprehensive evaluation model of dam break with attribute interval recognition theory in order to solve the fuzzy problem of evaluation indicator system. It can be found in the previous study process that the weight of influencing factors shall be defined and the comprehensive evaluation model of uncertainty, fuzziness and correlation of influencing factors shall be built for comprehensive evaluation study on consequence of dam break.

This thesis applies cloud model into the comprehensive evaluation on consequences of dam break, adopts analytic hierarchy process to define the subjective weight of all factors, defines the objective weight with grey relational analysis, makes combination weighting for subjective and objective weight, proposes the consequence evaluation model of dam break based on the combination weighing cloud model.

2. Evaluation model

2.1 Evaluation indexes

Dam risk management is a process for management of adverse conditions in the human life and property in the dam influencing scope and social environment and resources. Risk is uncertain and fuzzy, so are its influencing factors and severe degree. In the risk management of water projects, the main influencing factors shall be recognized, classified and selected, the project risk indicator system shall be established, and the implementation shall be evaluated, monitored and early warned accordingly.

The comprehensive evaluation of dam break consequence is the overall evaluation on consequence severe degree of dam break. Among studies in China and abroad, scholars made some research on life loss, economic loss, social influence and environmental influence, etc. after dam break, especially some research is made on life loss and economic loss, and some research achievement are made. Currently, as regards the comprehensive evaluation on consequence of dam break, it is a mainstream practice that the above four aspects are used as the evaluation scope of consequence of dam break. This thesis also defines the comprehensive evaluation indicator system of risk and consequence of dam break on the basis of previous studies[9][10].

2.2 Evaluation criteria

According to Emergency Plan for Major Quality and Safety Accidents in Water Conservancy Project Construction issued by Ministry of Water Resources, the water conservancy projects are evaluated from the perspectives of casualties, economic loss, social influence and environmental influence according to the severe degree and influence scope of accidents. Safety accidents are divided into four grades (i.e. very severe, severe, major and ordinary accident), and each grade is specified by index. The quantitative description is made for casualties and economic loss in each grade, while the qualitative description is made for the social and environmental influence. Li et al. proposed that the quantitative description is made for the above two qualitative indexes with influencing index. This thesis adopts the technical guidance procedure parameters issued by Ministry of Water Resources and Li's influencing index, takes quantitative value and index as the comprehensive evaluation criteria on the consequences of dam break, as shown in Table 1.

| Table 1 Comprehensive evaluation standard of dam accident consequence |
|-----------------------------------------------------|
| Index       | Life loss/person | Economic loss/10,000 yuan | Social influence index | Environment influence index |
| Ordinary accident (Ⅳ) | 1~3             | 10~1000                   | 1~3                    | 1~3                        |
2.3 Cloud model

2.3.1 Brief introduction of cloud model
The cloud model is a quantitative-qualitative conversion model which is proposed by Li Deyi\cite{11}. Through development for more than two decades, it is widely applied in fuzziness and uncertainty problems. The cloud model characterizes randomness and fuzziness of the research objects through three digital features including expectation \( E_x \), entropy \( E_n \) and excess entropy \( H_e \), integrates them and forms quantitative-qualitative mapping relationship.

As regards consequence evaluation of dam break, the cloud model characterizes the digital features of one index with expectation \( E_x \), entropy \( E_n \) and excess entropy \( H_e \) so as to reflect the uncertainty of dam break: \( H_e \) is the expectation of water dust distribution in the domain space and the center value of dam break consequence domain space; \( E_n \) denotes the measurable particle size of qualitative concept, reflects the acceptable digital scope of qualitative concept; \( H_e \) measures the uncertainty of the entropy.

2.3.2 Selection of cloud model parameters
As regards the inference of cloud model parameter \( E_x, E_n, H_e \), the following is the formula according to the cloud digital features proposed by Wang Mingwu et al.\cite{12}

\[
E_x = \frac{M_{\text{max}} + M_{\text{min}}}{2} \tag{1}
\]
\[
E_n = \frac{M_{\text{max}} - M_{\text{min}}}{6} \tag{2}
\]
\[
H_e = \beta \tag{3}
\]

Where \( M_{\text{max}} \) and \( M_{\text{min}} \) are the upper and lower limit of a level index; \( \beta \) is a constant which can be adjusted according to the fuzzy threshold of variables. This thesis takes 0.01.

| Grade | \( E_x \) | \( E_n \) | \( H_e \) |
|-------|----------|----------|---------|
| IV    | \( E_{x1} = (0 + a)/2 \) | \( E_{n1} = (a - 0)/6 \) | 0.01    |
| III   | \( E_{x2} = (a + b)/2 \) | \( E_{n1} = (b - a)/6 \) | 0.01    |
| II    | \( E_{x3} = (b + c)/2 \) | \( E_{n1} = (c - b)/6 \) | 0.01    |
| I     | \( E_{x4} = (c + d)/2 \) | \( E_{n1} = (d - c)/6 \) | 0.01    |

2.3.3 Generation of the cloud model
According to the cloud model theory, the corresponding cloud parameter \( E_x, E_n \) and \( H_e \) are input with forward cloud generator. Each specimen is repeated for 1000 times. The cloud model
corresponding to the dam break consequence indexes such as life loss, economic loss, social influence and environmental influence is generated.

The quantitative and qualitative mapping conversion is realized for dam break consequence evaluation through forward cloud generator. Matlab software is taken as the carrier. The following is the realization procedures of specific algorithm:

① The positive random number \( Y_k = \text{norm}(E_n, H^2_e) \) is generated, where \( E_n \) is the expectation value and \( H^2_e \) is the variance.

② The positive random number \( X_k = \text{norm}(E_x, Y^2_k) \) is generated, where \( E_x \) is the expectation value and \( Y^2_k \) is the variance.

③ The certainty of consequence evaluation index of dam break is calculated:

\[
\mu_k = \exp\left(-\frac{(x_k - E_x)^2}{2(E_n)^2}\right)
\] (4)

④ A cloud dust \((x_k, \mu_k)\) is output;

⑤ The steps from ① to ④ are repeated to produce N cloud dusts.

2.4 Combination weighting

The cloud model constitutes the main body of consequence evaluation model of dam break. In order to fully consider the objectivity of evaluation process and results, this thesis adopts analytic hierarchy process and grey relational analysis to assign a value for the weight of each evaluation index. The analytic hierarchy process is used to derive the subjective weight of each index according to the rich experiences of experts. In order to overcome the human arbitrariness of this weight, grey relational analysis is adopted to derive the objective weight of each index. This weight is derived from the actual measurement value, so it is objective, but it may vary due to the different value of evaluation index. Therefore, in order to get a weighting approach which can fully take advantage of subjective experience and reflect the objectivity of index weight, fully reflect the objective status of each evaluation index, the entropy coupling weighting solution approach which integrates analytic hierarchy process and grey relational analysis is proposed.

(1) AHP determines subjective weight

Analytic hierarchy process (AHP) is a simple and practical quantitative analysis approach for qualitative problems. For more than four decades, it is widely applied in many fields. Refer to Cao [13] et al. approach for specific calculation steps.

① Establish the judgment matrix \( A = \{a_{ij}\} \), compare the relative importance among indexes at the same level, among which \( a_{ij} = 1/a_{ji}, \quad a_{ii} = 1 \)

② Transform \( A = \{a_{ij}\} \) into measurement matrix

\[
\mu = \begin{bmatrix}
\frac{\beta k}{\beta k + 1} & a_{ij} = k \\
\frac{1}{\beta k + 1} & a_{ij} = \frac{1}{k} \\
0.5 & a_{ij} = 1, i \neq j \\
0 & a_{ij} = 1, i = j
\end{bmatrix}
\]

where \( k \geq 1 \) and \( k \in \mathbb{N}, \beta = 1 \)

③ Determination of index weight

Calculate the index weight value \( U = [u_1, u_2, \cdots u_n] \)
Grey relational analysis determines the objective weight

Grey relational analysis adopted in this thesis is based on the grey system theory proposed by Deng Julong. M evaluation indexes \( f_i (1 \leq i \leq m) \) and n items \( a_j (1 \leq j \leq n) \) to be measured are taken, the selection matrix \( X = (x_{ij})_{m \times n} \) is derived and standardized. Different approaches are adopted for different data type when standardized. Normalization is used according to the data in this thesis. When the higher the index value in the matrix, the better it is, (7) normalization is adopted. When the lower the index value in the matrix, the better it is, (8) normalization is adopted.

\[
y_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \quad (1 \leq i \leq m, 1 \leq j \leq n)
\]

(7)

\[
y_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \quad (1 \leq i \leq m, 1 \leq j \leq n)
\]

(8)

After standardization, the matrix \( Y = (y_{ij})_{m \times n} \) is derived. The optimum value in each row may constitute a reference sequence with m elements. In this sequence, the element \( i (1 \leq i \leq m) \) is recorded as \( y_{i,\text{opt}} \) \( (1 \leq j \leq n) \), \( y_{i,\text{opt}} \) is the maximum value in n items. Through formula (9), the matrix \( Z = (z_{ij})_{m \times n} \) can be derived.

\[
z_{ij} = |y_{i,\text{opt}} - y_{ij}| \quad (1 \leq j \leq n)
\]

(9)

Grey relational degree \( \xi_{ij} \) is calculated, \( \rho \) is the identification coefficient, which is often 0.5. After the relational degree corresponding to all elements is calculated, the grey relational degree \( H = \xi_{ij} (1 \leq j \leq n) \) can be derived.

\[
\xi_{ij} = \frac{\min \min(z_{ij})_{m \times n} + \rho \max \max(z_{ij})_{m \times n}}{z_{ij} + \rho \max \max(z_{ij})_{m \times n}}
\]

(10)

Determination of index weight

1. The evaluation matrix which consists of m evaluation objects n is \( X = (x_{ij})_{m \times n} \), (i=1,2,...,n).
2. The matrix standardization is carried out with the following formula:

\[
P_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}
\]

(11)

3. The entropy value \( E_j \) of each index is calculated according to the following formula

\[
E_j = \sum_{i=1}^{m} P_{ij} \ln P_{ij}
\]

(12)

Note: when \( P_{ij} = 0 \), \( P_{ij} \ln P_{ij} = 0 \)
Each index weight $V_j$

$$V_j = \frac{1-E_j}{\sum_{j=1}^{n}(1-E_j)}$$  \hspace{1cm} (13)

$$\sum_{j=1}^{n}V_j = 1$$  \hspace{1cm} (14)

(3) Combination weight

According to objective weight $V$ and subjective $U$ of indexes such as life loss, economic loss, social influence and environmental influence, etc., infer the problem of each index combination weight $W^* = [\omega_1, \omega_2, \ldots, \omega_j, \ldots, \omega_m]^T$. It is required that the distribution of $\omega_j$ in the space approximate to $V_j$ and $U_j$. The following is the principle according to the minimum information entropy.

$$\min F = \sum_{j=1}^{n} \omega_j [\ln \omega_j - \ln u_j] + \sum_{j=1}^{n} \omega_j [\ln \omega_j - \ln v_j]$$  \hspace{1cm} (15)

s.t. $\sum_{j=1}^{n} \omega_j = 1 (\omega_j > 0, j = 1,2,\ldots,m)$

The optimization problem can be solved according to Lagrange multiplier method, and it can be derived that

$$\omega_j = \sqrt{v_j u_j} / \sum_{j=1}^{n} \sqrt{v_j u_j}$$  \hspace{1cm} (16)

(4) Comprehensive certainty

According to the function setting of the cloud generator, the cloud model feature parameters are input. The cloud model of comprehensive evaluation on consequences of dam break is generated. The certainty of each index belonging to the cloud is derived. The combination weight of each index is considered according to formula (17). The comprehensive certainty $\mu^*$ is derived finally.

$$\mu^* = \sum_{k=1}^{m} \mu_k \omega_j$$  \hspace{1cm} (17)

2.5 Evaluation procedures

The cloud model generated by the cloud generator in this thesis is realized by Matlab software. The following is the basic procedures of evaluation on consequences of dam break.

Step 1: determine the evaluation index for consequences of dam break and accident classification criteria;

Step 2: infer the cloud parameter of each index according to the classification criteria of accident grade so as to determine the cloud model of each evaluation index belonging to the accident grade;

Step 3: determine the combination weight of each index according to the proposed coupling weight solution method

Step 4: import the breaking dam sample data to be evaluated into the cloud model, calculated the certainty $\mu$ of breaking dam consequence evaluation index belonging to each grade, obtain the comprehensive certainty $\mu^*$ according to formula (17), and finally determine the accident grade of the dam break.

3. Project case

It is considered to compare the proposed evaluation model and existing research results in this thesis in
order to verify the validity of model. Therefore, Li’s evaluation model is selected as the validity data. After expert on-site examination and safety identification, five reservoir dams including Xialan, Shibikeng, Changlong, Longshan and Lingtan are identified as Category-III dam.

The following is the relevant parameters of life loss, economic loss, social influence and environmental influence for five dams.

| Reservoir name | Life loss/person | Economic loss/0.1 billion yuan | Social influence index | Environmental influence index |
|----------------|------------------|--------------------------------|------------------------|-----------------------------|
| Xialan         | 735              | 25                             | 1.43                   | 13.82                       |
| Shibikeng      | 975              | 41                             | 1.43                   | 9.68                        |
| Changlong      | 454              | 35                             | 1.43                   | 19.28                       |
| Longshan       | 887              | 25                             | 1.43                   | 34.85                       |
| Lingtan        | 1709             | 20                             | 1.43                   | 7.71                        |

3.1 Index weight calculation

(1) AHP weight calculation

The judgment matrix is built according to experts’ evaluation of different indexes, and the subjective weight of each index in the consequence comprehensive evaluation of dam break is derived as follows through consistency test.

\[ u = [0.6429, 0.0769, 0.14401, 0.1401] \]

(2) Grey relational weight calculation

According to grey relational calculation method proposed in this thesis, the objective weight of each index in the consequence comprehensive evaluation of dam break is derived as follows:

\[ v = [0.2549, 0.2479, 0.2478, 0.2495] \]

(3) Combination weight calculation

The subjective and objective weight of comprehensive evaluation index of dam break is derived according to the above calculation, and then the combination weight is calculated according to formula (16).

\[ W^* = [0.4419, 0.1507, 0.2034, 0.2041] \]

3.2 Accident grade evaluation

The comprehensive certainty \( \mu^* \) is derived and the breaking accident grade is finally determined according to the certainty \( \mu \) of each evaluation index and combination weight \( W^* \) of each evaluation index.

| Reservoir name | Comprehensive certainty vector | Maximum value of comprehensive vector |
|----------------|--------------------------------|---------------------------------------|
| Xialan         | [0.1411, 0.0325, 0.0930, 0.5926] | 0.5926                               |
| Shibikeng      | [0.1411, 0.1670, 0.0502, 0.5926] | 0.5926                               |
| Changlong      | [0.1411, 0.0104, 0.1634, 0.5928] | 0.5928                               |
| Longshan       | [0.1411, 0.0103, 0.1361, 0.6214] | 0.6214                               |
| Lingtan        | [0.1411, 0.2139, 0.0358, 0.5926] | 0.5926                               |

The comprehensive evaluation grade of risk consequence of dam break is determined according to comprehensive certainty. Table 4 indicates that the comprehensive evaluation grade of the breaking
consequences of five reservoir dams belongs to a very severe accident (Grade I)

3.3 Result analysis

The comprehensive evaluation results of dam break risks and consequences on the basis of combination weight cloud model are compared with evaluation results in literature [14] and literature [8], as shown in Table 5:

Table 5 Comparison of comprehensive evaluation results of dam break consequences between combined weighted cloud model and set pair analysis and attribute interval identification model

| method                        | Xiailan       | Shibikeng    | Changlong    | Longshan     | Lingtan     |
|-------------------------------|---------------|--------------|--------------|--------------|-------------|
| Set pair analysis             | gradeⅠ (102.1425) | gradeⅠ (73.0794) | gradeⅠ (103.5111) | gradeⅠ (105.0220) | gradeⅠ (59.6688) |
| Attribute interval            | gradeⅠ (3.26649) | gradeⅠ (3.26355) | gradeⅠ (3.29202) | gradeⅠ (3.34237) | gradeⅠ (3.22442) |
| identification model          | gradeⅠ (0.5926) | gradeⅠ (0.5926) | gradeⅠ (0.5928) | gradeⅠ (0.6214) | gradeⅠ (0.5926) |
| Combination weight model      | gradeⅠ (0.5926) | gradeⅠ (0.5926) | gradeⅠ (0.5928) | gradeⅠ (0.6214) | gradeⅠ (0.5926) |

The above table indicates that the comprehensive evaluation result of three evaluation methods including other scholars for five dam break risks and consequences is accident grade I (very severe accident), indicating that the combination weighting cloud model method is feasible in the comprehensive evaluation of dam break consequences.

4. Conclusion

This thesis evaluates the dam break consequences and risks from the perspective of life loss, economic loss, social influence and environmental influence, introduces the cloud model as the main body of comprehensive evaluation model of dam break consequences, considers the subjective and objective influence of grade classification index of dam break accidents, adopts grey relational analysis and analytic hierarchy process for subjective and objective weighting of each evaluation index, integrates them, and proposes the comprehensive evaluation mode of dam break consequences on the basis of the cloud model and combination weight. The project case application indicates that the comprehensive evaluation model of dam break consequences on the basis of the cloud model and combination weight is reasonable and feasible, provides a new approach for comprehensive evaluation of dam break consequences, and it also provides reference for the assessment of other sectors.

Acknowledgments

Fund: JiangXi Engineering Research Center of Water Engineering Safety and Resources Efficient Utilization Open Fund (OF201606); Science and Technology Research Project of Jiangxi Department of Water Resources (201820YBK29); Research project of teaching reform in Colleges and universities of Jiangxi Province (JXJG-19-83-1)

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