Technical Status Evaluation of River Training Works Based on the Improved DS Evidence Theory

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Abstract. A large number of river training works have been built in the inland waterway regulation projects to improve ship navigation conditions. However, water damages to river training works happen frequently in practice. Technical status evaluation of river training works is regarded as a fundamental content of inland waterway maintenance. Due to the various influencing factors and complex mechanisms, the content involved in the standard files is recognized as qualitative and no quantitative evaluation method is recommended so far. The technical status of river training works is currently evaluated through on-site investigation which is time-consuming and individual-dependent. By means of multi-source sensors, massive status data of river training works could be obtained instantaneously. Study on the technical evaluation model based on the multi-source information fusion theory attracts more attention in recent years. The classical DS evidence theory could fail as evidence conflict occurs. Thus, the Pearson's correlation coefficient is calculated and utilized to update the probability distribution in the present study. A novel technical status evaluation model based on the improved DS evidence theory is established. The model is further verified through three case studies of traditional river training works (spur dike and flexible mattress belt) in the Yangtze River, China. The model outputs are consistent with the technical survey reports as well as the published research article. Quantitative and accurate evaluation of river training works could be accomplished by applying the proposed evaluation model. Moreover, the model could be embedded in the Inland Electronic Chart Display and Information System. The present study would provide theoretical basis for inland waterway maintenance and infrastructure monitoring in the future.

Keywords: River training works · DS evidence theory · Technical status evaluation · Pearson correlation coefficient · Inland waterway

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1 Introduction

River training works have been widely applied in the inland waterway regulation projects to provide better navigation conditions. Common river training works including dams (Macfarlane et al. 2017), spur dikes (Kiani et al. 2017), dredging works (Mendes et al. 2016), etc. would facilitate navigation conditions improvement and transport safety. In the upper reach of Yangtze river, the stochastic characteristics of turbulent flows and gravel bedload transport are highlighted (Cui et al. 2021). Severe river bank erosion results in the riverbed declination as well as the riverbank retreat. Meanwhile, the flood discharge capacity would decrease as siltation occurs. Except for some water conservancy projects to promote social economy and human activities (Ren et al. 2020), majority of river training works are performed for the purpose of maintaining the navigable conditions and the riverbank stability. Since the 21st century, a large number of river training projects have been conducted in China, e.g. the Yangtze estuary deep water waterway regulation project and Jingjiang waterway regulation project, among which spur dikes and flexible mattress belts have been widely applied. Due to the nonlinear and complex flow conditions, the failure mechanism differs for river training works (Crotti and Cigada 2019). Failures of river training works would lead to riverbank retreat and deteriorate navigation conditions. In view of aforementioned situation, reasonable maintenance strategies and solutions are required. Following the annual survey report of Wuhan Waterway Bureau (*Ministry of Communication*, China) of Yangtze River, 5 sites of river training works are seriously damaged and 17 sites are damaged to a certain degree. Intuitive evaluation of training works would be achieved through in situ investigation. However, it is known as subjective and time-consuming. The common qualitative evaluation methods include analytic hierarchy process and expert judgment method (Fan et al. 2016), which are usually straightforward but arbitrary in some cases. Quantitative evaluation methods include fuzzy comprehensive evaluation method and principal component analysis method (Gu et al. 2020; Wu et al. 2019), which require numerous fundamental information and calculations. The DS evidence theory-based model combines characteristics of both qualitative and quantitative methods, and provides a comprehensive evaluation of river training works through multi-source information fusion.

Since 1967, DS evidence theory (Dempster 1967; Shafer 1967) has been widely used in different fields, such as information fusion, fault diagnosis, expert identification, and target identification (Gao et al. 2021; Khan and Anwar 2019; Wickramarathne et al. 2013). In the absence of prior information, the DS evidence method could complete multi-sensor data fusion and judgment. Since information conflicts occur between different sensors, the information fusion results would be greatly affected. Therefore, DS evidence conflicts need to be properly resolved in the case of technical status evaluation. Interval assignment method is introduced to evaluate impacts of different factors. The improved DS evidence theory is therefore applied and validated in the technical status evaluation of river training works.

2 Technical Evaluation Model

2.1 Framework of Technical Evaluation Model

The technical evaluation framework of river training works presented by Li et al. (2020) are adopted and reproduced in Fig. 1. A total number of 14 indexes are classified as functional and structural indicators.

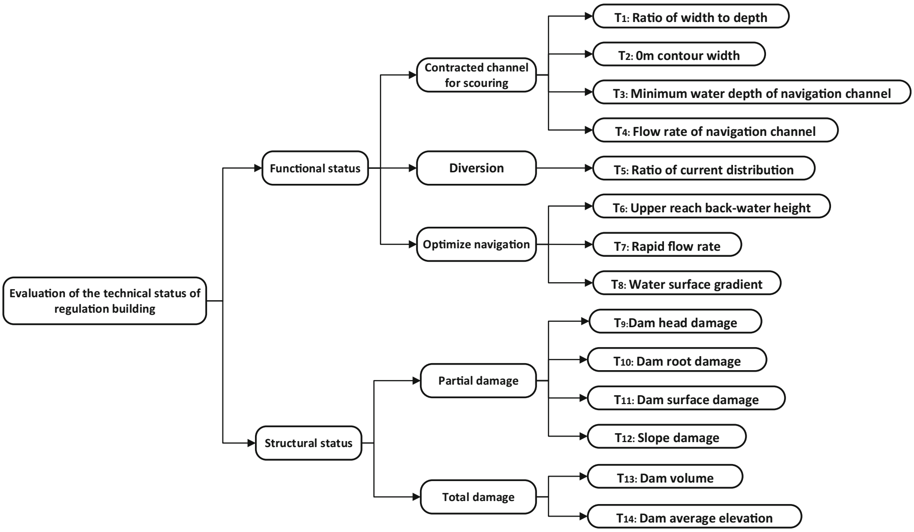

Fig. 1. Index evaluation system for technical status of inland river training works

In the middle reaches of the Yangtze River, the river training works include flexible mattress belts, riverbank revetments, spur dikes, etc. Enrockment method has been used to protect river training works from severe erosion. Following the Technical Code of Waterway Maintenance (JTS/T 320–2021, China), the technical status of river training works is categorized as five levels and the corresponding maintenance recommendations are tabulated (Table 1).

Table 1. Evaluation level definition for river training works

Evaluation level	Score	Maintenance recommendations
Level 1	100	No countermeasure is required
Level 2	85	Follow-up monitoring and analysis is necessary
Level 3	70	Timely maintenance is required
Level 4	55	Countermeasures are required urgently
Level 5	40	No countermeasure is needed

2.2 Improved DS Evidence Theory

DS evidence theory is actually an evidence combination method. The basic probability distribution directly affects the credibility of the evidence theory function (mass function). The identification framework expressed as: $\Theta = \{\theta_1, \theta_2, \ldots, \theta_3\}$ is noted as the foundation of model establishment. $\theta_i (i = 1, 2, \ldots, n)$ represents a single element in the frame, and n denotes the number of elements. For $\forall A \subseteq \Theta$, the Dempster composition rule of the two basic probability distribution functions m_1, m_2 on Θ is written as:

$$m_1 \oplus m_2(A) = \frac{1}{K} \sum_{B \cap C = A} m_1(B) \cdot m_2(C) \tag{1}$$

For A, the composite basic probability distribution function is the sum of the products of all two hypotheses that intersect with A. As the two basic probability distribution functions are calculated, they are divided by the normalization coefficient K. The K algorithm is defined as follows:

$$K = \sum_{B \cap C \neq \emptyset} m_1(B) \cdot m_2(C) = 1 - \sum_{B \cap C = \emptyset} m_1(B) \cdot m_2(C) \tag{2}$$

Although DS evidence theory has been widely applied in the field of information fusion, evidence conflict would occur when two evidences are interrelated. There are four common evidence conflict types named as complete conflict, 0 confidence conflict, 1 confidence conflict, and high conflict. The composition rule is highly sensitive to the hypothetical probability (i.e. the evidence is 0 and 1) which often causes conflicts of evidence and inaccurate evaluation results.

The evidence conflict in DS evidence theory is caused when two evidence units are not independent with each other. The main reason of evidence conflicts is that the certain hypothetical probability with greater difference occupies a dominant position when the evidence is fused. Taking 0 confidence conflict as an example, the result of the synthesis with a probability of 0 is only due to the 1 probability factor of 0 in the hypothesis, which accounts for 100% of the weight ratio of the fusion result of the evidence unit. The Pearson correlation coefficient is therefore used to calculate the weight of each evidence body in the overall weight. The correlation degree between two evidence bodies is clarified and the BPA value is updated through modifying the weight ratio. An improved DS evidence theory model based on Pearson's correlation coefficient is proposed, which solves the problem of evidence conflict in the classic DS synthesis rules. The model can be further utilized in a multi-index fusion evaluation system for the purpose of technical status evaluation of river training works in the Yangtze river. The flowchart of the proposed improved DS evidence theory-based model is shown in Fig. 2.

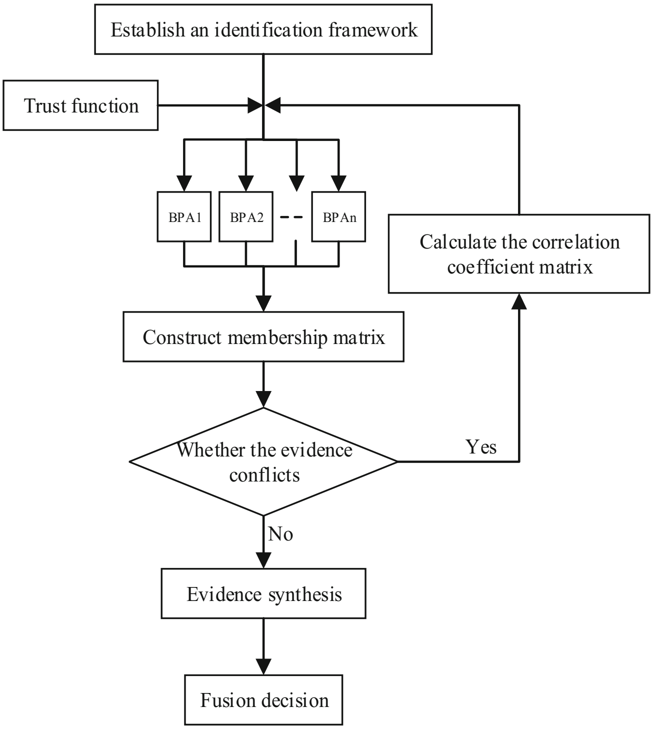

Fig. 2. Flowchart of improved DS evidence theory-based model.

The membership function is the basis of fuzzy statistics, which calculates the probability of each indicator under different evidence units and denotes the membership degree. The correlation coefficient matrix is constructed to modify the probability of the membership matrix of each indicator, combining with the zero-factor correction. A threshold value of 0.001 is introduced to replace the zero-factor in the matrix, and later subtracted from the evidence body with the highest probability.

For improved DS evidence theory based model, the correlation coefficient between the two evidence units is calculated by Eq. (3).

$$s_{ij} = \frac{\mathrm{cov}(m_i, m_j)}{\sigma_{m_i}\sigma_{m_j}} = \frac{E((m_i - \mu_{m_i})(m_j - \mu_{m_j}))}{\sigma_{m_i}\sigma_{m_j}} \tag{3}$$

E is the mathematical expectation; μ and σ denote the mean and variance respectively. Their relationship with the mathematical expectation E is demonstrated as follows:

$$\mu_{m_i} = E(m_i) \tag{4}$$

$$\sigma_{m_i} = \sqrt{E(m_i^2) - E^2(m_i)} \tag{5}$$

By calculating the correlation coefficient of evidence units m, the evidence correlation coefficient matrix S_{ij} could be constructed as follows:

$$S_{ij} = \begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1n} \\ s_{21} & s_{22} & \cdots & s_{2n} \\ \vdots & \vdots & & \vdots \\ s_{n1} & s_{n2} & \cdots & s_{nn} \end{bmatrix} \tag{6}$$

To avoid zero confidence factor in the DS synthesis rules, a zero factor correction is adopted. Then the initial credibility *cred* of the evidence body m_i can be obtained by Eq. (7).

$$cred(m_i) = \frac{\sum_{j=1}^{n} s_{ij}(m_i, m_j)}{\sum_{i=1}^{n} \sum_{j=1, i \neq ,}^{n} s_{ij}(m_i, m_j)} \tag{7}$$

Considering the influence of the decimal point of the credibility value in the basic probability of the evidence unit, $m_i^*(X)$ is derived through Eq. (8):

$$m_i^*(X) = m_i(X) * cred(m_i) \tag{8}$$

The reasonableness of each evidence $D[m_i(A)]$ is calculated after updating the evidence value.

$$D[m_i(A)] = \frac{2m_i(A)\overline{m}(A)[1 - dm_i(A)]}{m_i^2(A) + \overline{m}^2(A)} \tag{9}$$

$d[m_i(A)]$ represents the BPA distance between each evidence and the average value as defined in Eq. (10):

$$d[m_i(A)] = |m_i(A) - \overline{m}(A)| \tag{10}$$

$\overline{m}(A)$ is the average evidence obtained by multiplying the credibility and the original evidence value, as shown in Eq. (11):

$$\overline{m}(A) = \sum_{i=1}^{n} [m_i * cred(m_i)] \tag{11}$$

The credibility value of the fusion evidence is finally obtained:

$$F_{cred}[m_i(A)] = \frac{D[m_i(A)]}{\sum_{q=1}^{N} D[m_i(A_q)] + D[m_j(A_q)]} \tag{12}$$

3 Case Study

Case study has been performed for technical status evaluation of river training works in the Yangtze River, China. Two types of river training works (spur dike and flexible mattress belt, as shown in Fig. 3) are considered in the present study. Spur dikes are frequently applied to protect river banks while the flexible mattress belts are used to combat beach erosion. Following the aforementioned evaluation index system and index scoring rules, the evaluation index scores of three cases are calculated and presented in Table 2.

Fig. 3. Classic river training works (left: spur dike; right: flexible mattress belt).

Table 2. Evaluation index calculations for case studies in the Yangtze River, China.

Evaluation index	Dongxikou spur dike	Taipingkou flexible mattress belt	Majiazui flexible mattress belt
Ratio of width to depth (T_1)	100	100	50
0 m contour width (T_2)	100	100	100
Minimum water depth of navigation channel (T_3)	100	100	100
Flow rate of navigation channel (T_4)	80	80	80
Ratio of current distribution (T_5)	100	50	60
Upper reach back-water height (T_6)	100	80	80
Rapid flow rate (T_7)	60	60	60
Water surface gradient (T_8)	100	100	100
Dam head damage (T_9)	80	100	40
Dam root damage (T_{10})	60	100	80
Dam surface damage (T_{11})	60	100	50
Slope damage (T_{12})	100	100	60
Dam volume (T_{13})	80	100	80
Dam average elevation (T_{14})	100	100	80

4 Results

4.1 Dongxikou Spur Dike

The evaluation results of Dongxikou spur dike are shown in Table 3. The results showed that the technical status of spur dike is generally well, which is consistent with conclusions drawn by Li et al. (2020). The authors presented a coupled model of fuzzy mathematical theory and Bayesian network for river training works in the upper reaches of Yangtze River. The uncertain nature of evidence is characterized by probability, which is generally similar to the improved DS evidence theory in this study. However, the probability calculation between different levels is not remarkable (approximately 0.06) in the literature (Li et al. 2020). Therefore, misinterpretation might occur in the technical status evaluations. The present study demonstrated that quantitative evaluation of river training works could be accomplished by both improved DS evidence theory-based model and Bayesian evaluation model. Considering the probability calculations, the improved DS evidence theory-based model is more recommended in the practices.

Table 3. Probability calculations for Dongxikou spur dike

Evaluation level	Probability value
Level 1	0.64
Level 2	2.79×10^{-5}
Level 3	0.36
Level 4	2.79×10^{-5}
Level 5	3.36×10^{-11}

4.2 Taipingkou Flexible Mattress Belt

The Taipingkou channel located at the middle reaches of the Yangtze River, China. The north riverbank is straight and protected by the artificial structures. The Lalinzhou shoal locates at the south riverbank. Three flexible mattress belts have been deployed to protect Lalinzhou shoal from erosion. The length of flexble mattress belt is approximately 360 m. Following the technical survey report after the flood season of year 2019, the sediment has been silted up in the lower beaches of the Lalinzhou shoal. No significant variations have been observed in the downstream areas of the revetment works. The flexible mattress belt is recognized as functional well and structural complete. Therefore, the technical status is evaluated as level 1 in the field survey of year 2020. The BPA values are calculated and presented in Table 4. It is noted that the probability values of each evidence are not independent and evidence conflict could occur in the application of classic DS theory. The calculated reliability value is shown in Table 5. Based on the evaluation model established in the Sect. 2.2, the Pearson correlation coefficient matrix is calculated and the basic probability distribution updated. Finally, a diagonal matrix of correlation coefficients is obtained. The revised BPA matrix is presented in the Table 6.

Table 4. BPA calculations of Taipingkou flexible mattress belt

Evaluation index	Level 1	Level 2	Level 3	Level 4	Level 5
T_1	1	0	0	0	0
T_2	1	0	0	0	0
T_3	1	0	0	0	0
T_4	0	0.667	0.333	0	0
T_5	0	0	0	0.667	0.333
T_6	0	0.667	0.333	0	0
T_7	0	0	0.333	0.667	0
T_8	1	0	0	0	0
T_9	1	0	0	0	0
T_{10}	1	0	0	0	0
T_{11}	1	0	0	0	0
T_{12}	1	0	0	0	0
T_{13}	1	0	0	0	0
T_{14}	1	0	0	0	0

The technical status evaluation by the improved DS evidence theory is shown in Table 7. The technical status of the Taipingkou flexible mattress belt is evaluated as Level 1, which is consistent with the in-site survey report (Changjiang Waterway Institute of Planning and Design 2020).

Table 5. Calculation results of index reliability value

Evaluation index	*Fcred*
T_1	0.046
T_2	0.046
T_3	0.046
T_4	0.155
T_5	0.115
T_6	0.155
T_7	0.115
T_8	0.046
T_9	0.046
T_{10}	0.046
T_{11}	0.046
T_{12}	0.046
T_{13}	0.046
T_{14}	0.046

Table 6. The revised BPA value of Taipingkou flexible mattress belt

Evaluation index	Level 1	Level 2	Level 3	Level 4	Level 5
T_1	0.001	0.001	0.001	0.001	0.046
T_2	0.001	0.001	0.001	0.001	0.046
T_3	0.001	0.001	0.001	0.001	0.046
T_4	0.001	0.001	0.052	0.104	0.001
T_5	0.038	0.077	0.001	0.001	0.001
T_6	0.001	0.001	0.052	0.104	0.001
T_7	0.001	0.077	0.038	0.001	0.001
T_8	0.001	0.001	0.001	0.001	0.046
T_9	0.001	0.001	0.001	0.001	0.046
T_{10}	0.001	0.001	0.001	0.001	0.046
T_{11}	0.001	0.001	0.001	0.001	0.046
T_{12}	0.001	0.001	0.001	0.001	0.046
T_{13}	0.001	0.001	0.001	0.001	0.046
T_{14}	0.001	0.001	0.001	0.001	0.046

Table 7. Evaluation results of Taipingkou flexible mattress belt

Evaluation level	Probability value
Level 1	≈ 1
Level 2	2.77×10^{-15}
Level 3	2.55×10^{-15}
Level 4	2.65×10^{-15}
Level 5	2.26×10^{-15}

4.3 Majiazui Flexible Mattress Belt

According to the technical report of river training works status evaluation, obvious deformation has been observed at the slope foot of the Majiazui flexible mattress belt. The riverbank slope has become even steep. The overall trend is recognized as scouring and undercutting, which seriously affects the stability of the shoal revetment. The experimental data obtained by the field survey indicate that the technical status of Majiazui falls in the category of level 3. The detailed scoring results are shown in the Table 8.

Table 8. Evaluation results of the Majizui flexible mattress belt

Evaluation level	Probability value
Level 1	5.99×10^{-13}
Level 2	0.001
Level 3	0.998
Level 4	4.61×10^{-4}
Level 5	4.31×10^{-11}

It can be seen from the table that the technical status of the Majiazui flexible mattress belt are classified as level 3, which are consistent with the in situ technical survey report. As a result, timely maintenance is required to prevent structural damages of Majiazui flexible mattress belt.

5 Conclusions

The technical status evaluation of inland river training works is necessary for infrastructure maintenance. Owing to the complicated hydrodynamic conditions, their evolutionary characteristics have not yet been revealed. The wide applications of IoT sensors produce massive data of river training works which provide an effective way of big data analysis as well as multi-information fusion.

In view of the evidence conflict of applying classic DS evidence theory, the Pearson's correlation coefficient has been introduced to describe the relationship between two evidence units. The basic probability distribution is thus updated and BPA matrix is revised for multi-information fusion. The improved DS evidence theory-based model is further validated through case studies in the Yangtze River, China. Two types of river training works (spur dike and flexible mattress belt) are discussed in the present study. The results demonstrate that quantitative evaluations of river training works could be accomplished by the improved DS evidence model. Both Dongxikou spur dike and Taipingkou flexible mattress belt fall in the category of level 1, which are consistent with published research article (Li et al. 2020) and in situ survey reports. Due to the complex flow conditions, the technical status of Majiazui flexible mattress belt is evaluated as level 3. Timely maintenance is required to protect the flexible mattress belt from erosion damages. Moreover, the improved DS evidence theory could also be embedded with the Inland Electronic Chart Display and Information System which is the fundamental service platform of water transport. In the future, further studies on the quantification of indicators should be carried out to achieve more reliable evaluations of river training works.

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