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Evaluation of Hydraulic-Tunnel-Lining Durability Based on ANP and Cloud-Model-Improved Matter–Element Theory

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Abstract: Compared with highway tunnels, hydraulic tunnel linings are in the water environment for a long time, and their lining materials and structures are more vulnerable to damage. Therefore, a comprehensive scientific durability evaluation of hydraulic tunnel linings is of great significance for the safe operation and daily maintenance of hydraulic tunnels. This paper proposes a new method for evaluating the durability of hydraulic tunnel linings. The paper first constructs a hydraulic tunnel concrete lining durability evaluation system, taking into account the feedback between the indices, and using the analytic network process (ANP) to calculate the weights of each index, as well as multiple-expert scoring to reduce its one-sidedness and subjectivity. Considering the randomness and fuzzy nature of the evaluation, the cloud model was used to modify the matter–element theory to evaluate the durability of the hydraulic tunnel lining. Finally, an example application was carried out, and the durability classes of five segments of the Nawei Tunnel were calculated as III, II, II, II, and III. The results were compared with the evaluation results of the method in the related literature, which proved that the method has good accuracy in evaluating the durability of hydraulic tunnel linings.

Keywords: ANP; cloud-model-improved matter–element theory; hydraulic tunnels; concrete lining; durability evaluation

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1. Introduction

The shortage and uneven spatial distribution of water resources are key factors that limit the development of some cities, for which China has built a series of inter-regional water transfer projects, such as the South–North Water Transfer Project, in which hydraulic tunnels have an irreplaceable role. The hydraulic tunnel lining is mainly made of a reinforced-concrete structure, which is in the water environment for a long time and under high ground stress, high head pressure, as well as various physical and chemical effects. It will gradually deteriorate in performance due to the permeability pressure, acidic substances, and aggressive ions and carbonization, resulting in its durability and bearing capacity decreasing, and the structural function not meeting the design requirements, thus affecting its normal operation, and even threatening the safety of its operation. For some of the early construction of hydraulic tunnels, due to the limitations of the technical conditions at this time, the design is poor, the construction quality is not good, and after a long period of operation, the durability problem is more prominent. The factors that affect the durability of hydraulic tunnel linings are complex and diverse, and as the tunnel operation period increases, tunnel diseases inevitably emerge, thus putting forward higher requirements for tunnel maintenance and reinforcement. Therefore, it is necessary to make a scientific and objective evaluation of the damage level through an inspection of the tunnel-lining-structure condition so as to formulate a targeted treatment plan. At present, many scholars have conducted a lot of in-depth research. In a tunnel evaluation, Arends, B.J. [1] proposed a method for tunnel safety evaluation using probabilistic risk assessment based on three aspects: personal, social, and economic risks, and applied it in a Dutch tunnel project. Jin, N.G. [2] proposed a measurement method for a tunnel-lining risk analysis based on the fault tree theory and entropy method by establishing a lining fault-tree-analysis model and discussing the calculation method and evaluation criteria of the lining risk entropy. Jifei, W. [3] proposed an assessment method for evaluating and managing the risks associated with postlining voids in mountainous tunnels, and illustrated the validity of the method with examples. Wang, Y. [4] combined exponential scaling with triangular fuzzy numbers to propose an improved scale based on the fuzzy-analysis-network process, and applied it to the risk analysis of the Humaling Tunnel; the results showed that it could accurately reflect the actual situation. Qi, Y. [5] used the ANP and the gray correlation TOPSIS method to construct a safety-evaluation model of water-diversion tunnel diseases in Northwest China, and applied the model to the Pandaoling Tunnel of the Water Diversion Project from Datong River to Qinwangchuan District to verify the scientific rationality of the proposed index system and model. Qiu, W. [6] established an index system for evaluating the sustainability of railroad tunnels based on three main dimensions: policy management, supporting structures and auxiliary facilities, and the regional ecological environment. Xu, J. [7] proposed a new method for a systematic seismic-risk assessment for mountain tunnel planning using the extension theory and the hierarchical analysis method, improved based on the extension theory, and applied the method to a mountain tunnel in Southwest China, illustrating the rationality and flexibility of its application in mountain tunnel projects. Han, W. [8] explored the safety state and damage law of the tunnel structure under composite diseases by establishing a three-dimensional numerical model of a tunnel lining. In a study on the durability of hydraulic buildings and tunnels, Chatveera, B. [9] studied the effect of sludge water on the mechanical properties and durability of concrete by replacing tap water with sludge water. Jeon, J.K. [10] experimentally investigated the durability-enhancement effect of nylon fiber on tunnel concrete lining and evaluated its durability. By evaluating the structural and durability performances of conventional reinforced concrete (RC) versus steel-fiber-reinforced concrete (SFRC), Abbas, S. [11] found that conventional RC PCTL (precast concrete tunnel lining) pipe sheets are more susceptible to corrosion damage compared with SFRC pipe sheets. Li, K. [12] evaluated the durability of an immersed tunnel by experimentally simulating a concrete immersed tunnel exposed to seawater with nondestructive testing, using a fully probabilistic approach, and gave preliminary maintenance recommendations in conjunction with the accidental conditions of seawater infiltration. Akula, P. [13] evaluated the long-term durability of the broken concrete lining of the Friant-Kern Canal treated with lime from the engineering and mineralogical points of view, and preliminarily investigated the effect of lime on the repair of hydraulic buildings. Li, Q. [14] proposed a highway tunnel lining structure durability evaluation method based on the object-expansion simple-correlation-function cloud model considering the fuzzy and random nature of the lining-structure-durability evaluation indices, and verified the feasibility of the method through engineering cases. Zhang, H. [15] established a structural-durability-evaluation model of a pier by combining the topologic theory and entropy weight method, and applied the evaluation model to a beam–slab pier; the results showed that the evaluation results were consistent with the actual situation.

From the abovementioned research status, it can be seen that the research on the evaluation of concrete tunnel lining is mainly focused on road and railroad tunnels, and less on hydraulic tunnels, which are subjected to long-term water erosion. The research content is mainly focused on tunnel safety and risk evaluation, and not enough attention is paid to durability evaluation. The research method makes it difficult to consider the actual situation comprehensively, and it cannot solve the ambiguity, randomness, and mutual incompatibility of the concrete-tunnel-lining condition well. In general, the current index system and existing evaluation model of hydraulic tunnel lining durability evaluation are not perfect and need to be further studied. Based on this, this paper proposes a new method for hydraulic tunnel lining durability evaluation, adding the multiexpert scoring method to the ANP to reduce the subjectivity of the weight calculation. Combining the cloud model with the matter–element theory, a cloud-model-improved matter–element evaluation method is proposed, so that qualitative concepts that can only be described by natural language values can be represented by quantitative matter–elements, which, in turn, allows the model to handle stochasticity and ambiguity in complex uncertain analysis problems. Finally, the theory is validated by relevant cases in order to obtain more scientific and reasonable evaluation results. The evaluation process of this paper is shown in Figure 1.

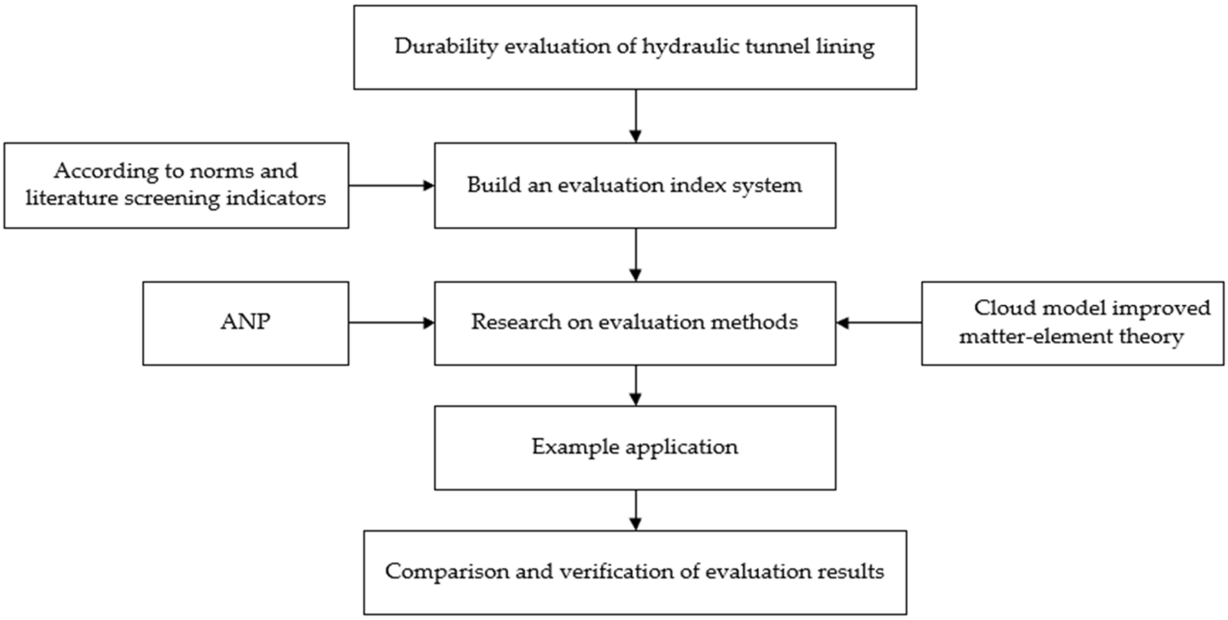

Figure 1. Evaluation flow chart.

2. Hydraulic Tunnel Lining Durability Evaluation Index System

Tunnel lining diseases reflect the durability condition of tunnels [16], and various diseases in tunnels generally do not exist alone, but affect and interact with each other [17]. Water is involved in almost all tunnel diseases, and hydraulic tunnels work in water environments for a long time, so their disease problems are even more prominent. In summary, the types of lining diseases in hydraulic tunnels during operation mainly include lining cracks, water leakage, lining-structure deterioration, and lining-material deterioration [18].

Lining cracks are mainly caused by the cross effect of the load, temperature, and frost damage, and the presence of cracks in the lining indicates that the lining is subjected to stresses that exceed its own strength [19]. Superficial cracks have less impact on the structural bearing capacity, deep cracks reduce the structural bearing capacity, while large cross cracks can cause structural instability and collapse. The crack-length, crack-width, and crack-depth ratio (crack depth/lining thickness) reflects the condition of the lining cracks [20].

When the tunnel passes through or near the water-bearing strata, tunnel leakage disease will occur due to the imperfect waterproofing and drainage facilities of the lining, unqualified waterproofing materials, or improper laying construction. Different locations of leaks have different effects on the lining safety, and when leaks are accompanied by strong acidity and frost damage, this will also accelerate the deterioration of the lining material and structure. The main indices of water leakage are classified as the arch leakage status, sidewall leakage status, freezing status, and pH value [21–23].

Subject to the effects of construction methods, mechanical problems, human factors, geology, and the surrounding environment, lining-thickness loss, cavities behind the lining, lining deformation, lining spalling, and other problems [24,25] occur from time to time, and the structural deterioration of the lining will cause a redistribution of these stresses within it and reduce the lining structural-bearing capacity. It is worth noting that the shape and size of the tunnel, the direction of the lining cracks, and the bond strength of the lining to the tunnel also affect the structural durability of the tunnel lining. Different shapes and sizes of hydraulic tunnels have different effects on the deterioration of the lining structure, but the current durability state of tunnel linings cannot be judged directly based on their shapes and sizes; the effect of the direction of lining cracks on the durability of tunnel lining needs to be considered, together with the length–width–depth of the tunnel, and there are different combinations of them, which do not facilitate the direct calculation of the effect on the durability of the lining. The bond between the lining and tunnel strength has a certain influence on the durability of the tunnel lining structure, but, in this study, it was difficult to measure it directly due to limited conditions. These factors are either difficult to correspond directly to the durability of the lining, or are difficult to measure and count, and so this paper adopts indicators such as the insufficient-thickness ratio (insufficient thickness/design thickness), depth of the void behind, deformation speed, spalling diameter, and spalling depth to indicate the degree of the lining-structure deterioration, which are not only easy to measure, but also either directly or indirectly reflect the influence of each factor on the durability of the lining structure.

The deterioration of the lining material is due to the long-term exposure of the lining material to water, air, and the corrosive substances it contains, and the resulting chemical reactions have caused damage to its physical, chemical, and mechanical properties [26]. Lining-material deterioration can be reflected by the lining-strength ratio (actual strength/design strength), rebar-section-loss rate, carbonization coefficient, etc. For hydraulic tunnels, the secretion of shellfish organisms on the lining surface also accelerates material deterioration [27], and thus shellfish thickness is also used as one of its indices.

The hydraulic tunnel lining durability evaluation index system is constructed as shown in Figure 2.

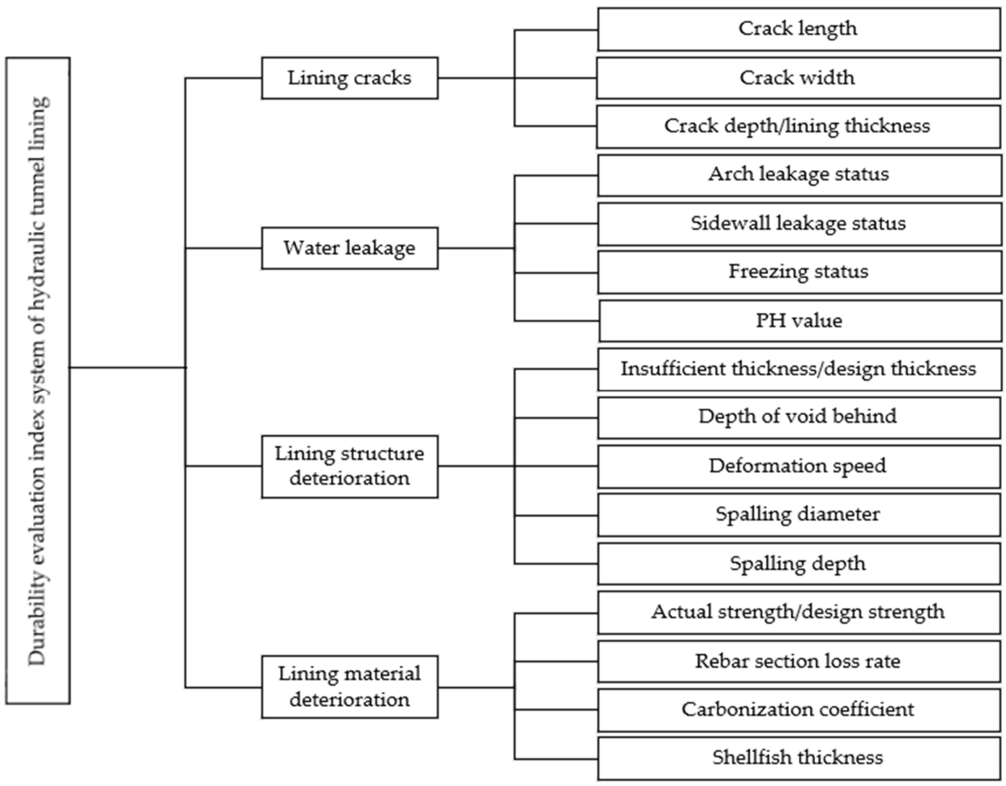

Figure 2. Hydraulic tunnel lining durability evaluation index system.

3. Evaluation Methods

In the 1980s, Saaty proposed the hierarchical analysis method (AHP) [28], the core of which is to divide the evaluation index system into levels, and to consider only the dominance of the upper-level elements on the lower-level elements, while the same-level elements are independent of each other. This model greatly facilitates the evaluation processing process, and it has been widely used in system decision analysis; however, it is also limited in its accuracy in dealing with complex problems because, in actual problems, many evaluation-index elements have feedback and are not independent of each other, and the structure of the system at this point is more similar to a network structure. In 1996, Saaty systematically proposed the ANP [29] on the basis of the AHP, which better reflects the existence of mutual feedback between the hierarchical structures and their internal elements. A two-by-two comparison of the relative importance of the index elements is an important part of the ANP calculation, which requires scoring according to a preagreed-upon scale; however, due to the existence of factors such as differences in the perceptions and preferences of different experts on the same issue, and the level of the experts, the judgments given by each expert may be very different. In order to avoid the one-sidedness and negativity caused by the subjective judgments of individual experts, this paper introduces multiexpert scoring into the ANP. The various diseases that exist in hydraulic tunnel lining structures generally do not exist alone but affect and interact with each other. For example, to a certain extent, the crack length affects the lining-deformation speed, the water-leakage status affects the lining steel cross-sectional area, etc. Therefore, it is feasible to use the ANP to calculate the evaluation-index weights of the hydraulic-tunnel-lining durability.

Founded by Chinese scholar Professor Cai, W. [30], the matter–element model is mainly used to solve complex problems of incompatibility and is suitable for multifactor evaluation, and, after years of development, the matter–element theory has been successfully applied in the comprehensive evaluations of many fields. The matter–element model takes the ordered triad $R(N, C, V)$ as the basic element that describes things, where N denotes things, C denotes the feature name of the things (N), and V denotes the feature quantity value of the N. The basic steps of the theory are as follows: first, determine the thing element to be evaluated; divide the thing element into different index levels, classical domains, and section domains; determine the membership function; calculate the degree of membership according to the known index weights; determine the evaluation level.

The cloud model was proposed by Li, D. [31,32], who was a member of the Chinese Academy of Engineering in 1995, as a mathematical model for converting the uncertainty between qualitative and quantitative. A cloud is composed of a large number of cloud drops, and each cloud drop is a specific realization of a certain qualitative concept with uncertainty and ambiguity in the quantity. Let D be a quantitative domain represented by exact values, and let I be a qualitative linguistic value on D. If any quantitative value (x) on D corresponds to a random realization of I, and x has a degree of membership ($\mu(x) \in [0,1]$) to I, then each x is called a cloud droplet, and its distribution over the domain (D) is called the membership cloud [33].

The matter–element theory can well solve the problem of the incompatible contents of evaluation objects by quantitatively calculating the characteristics of things through membership functions, but it ignores the randomness and fuzziness of the quantity values at the same time, and so its calculation results often have deviations. Cloud-modeling theory uses natural language to describe qualitative concepts and build uncertainty-transformation models between them and their given values, which can precisely make up for the deficiencies of the matter–element-theory models. The cloud model is used to improve the traditional matter–element theory and to build a cloud-based matter–element-coupled model, which can take advantage of the combination of the matter–element theory and cloud model to deal with the randomness and ambiguity in complex uncertain analysis problems in a more scientific and comprehensive way. For ease of reading, the parameters used in the paper and their meanings are summarized in Table 1, in order of appearance.

Table 1. Meanings of each parameter.

Parameter	Meaning	Parameter	Meaning
$R(N, C, V)$	Matter–element model	w	Global-weight vector
D	Quantitative domain	$\overline{w}$	Combined-weight vector
I	Qualitative language values in D	E_x	Expectation
x	Actual measurement value	E_n	Entropy
$\mu(x)$	Degree of membership of x to I	H_e	Hyperentropy
G	General objective	$T_{\min}$	Minimum value of the constraint interval
m	Number of elements in the criterion layer	$T_{\max}$	Maximum value of the constraint interval
n	Number of network-layer-element groups	k	Hyperentropy-constant value
N	Number of network-layer elements	E'_n	Normal random number with E_n as expectation value
P_s	Criterion-layer elements	d	Standard-normal-distribution random numbers
X_i	Network-layer-element group	E	The intersection of two clouds
$X_{j\text{-}l}$	Network layer element group elements	F	The union of two clouds
$\boldsymbol{w}_i^{(j-l)}$	Normalized eigenvectors of X_i judgment matrix under $X_{j\text{-}l}$ criterion	U	Membership matrix
W_{ij}	Matrix of supermatrix subblocks composed of normalized eigenvectors	$\boldsymbol{B}$	Comprehensive-evaluation vector
W_s	Supermatrix under the criterion P_s	r	Comprehensive-evaluation score
a_j	Normalized eigenvectors of the judgment matrix of each element group under X_j criterion	b_j	The element in the comprehensive-evaluation vector (B)
a_{ij}	Weighting factor	h_j	Assigned score of durability class (j)
A	Weighting matrix	$E_{x,r}$	Expectation of comprehensive-evaluation score
$\overline{W_{ij}}$	Weighted supermatrix subblock	t	Number of simulation calculations
$\overline{W_s}$	Weighted supermatrix under the criterion P_s	$E_{n,r}$	Standard deviation of comprehensive-evaluation score
w_{ij}	Elements of $\overline{W_s}$, reflecting the one-step dominance of element i over element j	β	Confidence factor
$\overline{W_s}^{\infty}$	Limit supermatrix		

note: vectors in bold.

3.1. The Analytic Network Process

The ANP divides the system elements into a control layer and network layer, and its typical structure [29] is shown in Figure 3. The control layer consists of problem objectives and decision criteria, which are independent of each other and governed only by the objective elements, as in the traditional AHP structure. It is worth noting that, unlike the goal element, the presence of a decision criterion is nonessential. The elements in the network layer are all dominated by the control-layer elements, and they may also dominate and be dominated by each other, forming the network structure, which is the difference between the ANP and AHP. Instead of a two-by-two comparison of the network-layer elements based on their independence from each other, the target weight coefficients of each element are determined by comparing the degree of influence of the third element (also called the subcriteria) under a certain criterion through indirect dominance.

Let the control layer in the ANP include the total objective (G) and criterion elements ($P_1, P_2, \ldots, P_m$), and there are element groups ($X_1, X_2, \ldots, X_n$) in the network layer, where the element group (X_i) includes the elements $X_{i-1}, X_{i-2}, \ldots, X_{i-n_i}$($I$ = 1, 2, ..., n), and the total number of elements in the network layer is denoted as N. Under the control-layer criterion (P_s) (s = 1, 2, ..., m), the elements $X_{j\text{-}l}$ (l = 1, 2, ..., n_j) in the element group (X_j) at the network layer are used as subcriteria, and the influence of each element of the element group (X_i) on $X_{j\text{-}l}$ is compared in terms of the indirect dominance, and the 1–9-scale method [28] (see Table 2) is used to constitute the judgment matrix of the X_i under the criterion P_s and $X_{j\text{-}l}$, and its normalized eigenvector ($\boldsymbol{w}_i^{(j-l)}$) is calculated, as shown in Equation (1):

$$\boldsymbol{w}_i^{(j-l)} = \left(w_{i-1}^{(j-l)}, w_{i-2}^{(j-l)}, \ldots, w_{i-n_i}^{(j-l)}\right)^T \quad (1)$$

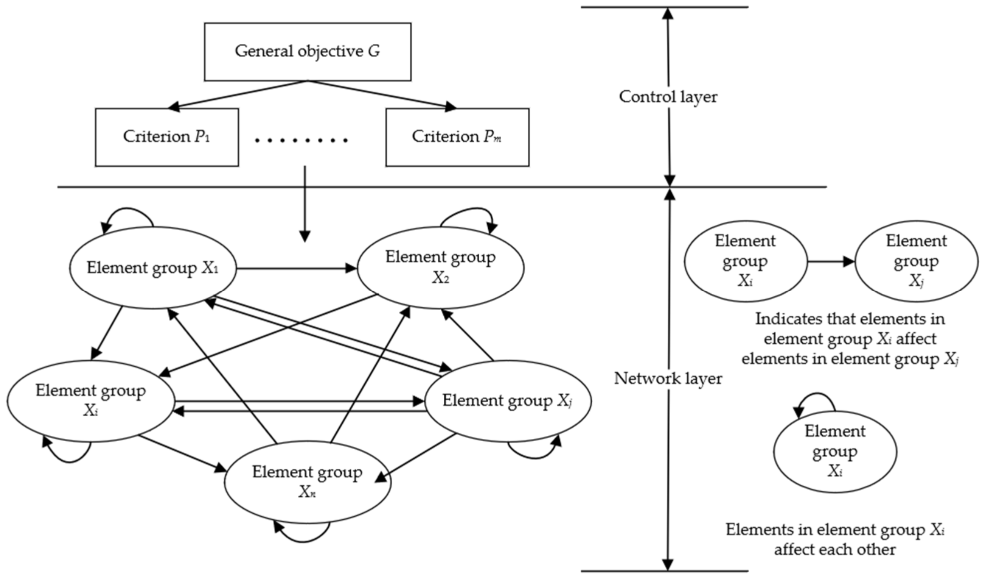

Figure 3. Typical structure of ANP.

Table 2. Meanings of the 1–9 scale.

Scale	Meaning
1	The elements have the same importance as the element being compared.
3	The element is slightly more important than the element being compared.
5	The element is significantly more important than the element being compared.
7	The element is more strongly important than the element being compared.
9	The element is extremely more important than the element being compared.
2, 4, 6, 8	The middle value of the above adjacent judgments.
Countdown	The significance of the above elements when swapped with the elements being compared.

The normalized eigenvectors of the judgment matrix of the X_i obtained under the criterion P_s and all the subcriteria in X_j are formed into a new matrix, denoted W_{ij}, which is obviously nonnegative and column-normalized, as shown in Equation (2):

$$W_{ij} = \begin{bmatrix} w_{i-1}^{(j-1)} & w_{i-1}^{(j-2)} & \ldots & w_{i-1}^{(j-n_j)} \\ w_{i-2}^{(j-1)} & w_{i-2}^{(j-2)} & \ldots & w_{i-2}^{(j-n_j)} \\ \vdots & \vdots & \vdots & \vdots \\ w_{i-n_i}^{(j-1)} & w_{i-n_i}^{(j-2)} & \ldots & w_{i-n_i}^{(j-n_j)} \end{bmatrix} \quad (2)$$

In turn, the supermatrix (W_s) under the criterion P_s can be obtained by Equation (3):

$$W_s = \begin{bmatrix} W_{11} & W_{12} & \ldots & W_{1n} \\ W_{21} & W_{22} & \ldots & W_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ W_{n1} & W_{n1} & \ldots & W_{nn} \end{bmatrix} \quad (3)$$

Similarly, it is possible to obtain m supermatrices under different criteria, which are nonnegative and non-column-normalized, and the weighting matrix must now be calculated to normalize the columns.

Under the criterion P_s, the degree of influence of each element group (X_i) on the sub-criterion (X_j) is compared to obtain the judgment matrix, which, in turn, yields the eigenvector $\boldsymbol{a_j} = (a_{1j}, a_{2j}, \ldots, a_{nj})^{\mathrm{T}}$, composed of the weighting factor (a_{ij}), which forms the weighting matrix (A), as shown by Equation (4):

$$A = \begin{bmatrix} a_{11} & a_{12} & \ldots & a_{n1} \\ a_{21} & a_{22} & \ldots & a_{n2} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n1} & \ldots & a_{nn} \end{bmatrix} \tag{4}$$

The weighted supermatrix subblock ($\overline{W_{ij}}$) can be obtained according to Equation (5):

$$\overline{W_{ij}} = a_{ij} \times W_{ij} \tag{5}$$

Then, the normalized weighted supermatrix is obtained, as in Equation (6):

$$\overline{W_s} = \begin{bmatrix} \overline{W_{11}} & \overline{W_{12}} & \ldots & \overline{W_{1n}} \\ \overline{W_{21}} & \overline{W_{22}} & \ldots & \overline{W_{2n}} \\ \vdots & \vdots & \vdots & \vdots \\ \overline{W_{n1}} & \overline{W_{n2}} & \ldots & \overline{W_{nn}} \end{bmatrix} \tag{6}$$

The size of the element (w_{ij}) of the weighted supermatrix ($\overline{W_s}$) reflects the one-step dominance of element i over element j. The element $\sum w_{ik} \cdot w_{kj}$ of $\overline{W_s}^2$ represents the two-step dominance of element i over element j. Objectively, the degree of dominance of element i over element j should be deterministically unique, and so the stability of the weighted supermatrix of the ANP is required. If $\overline{W_s}^\infty = \lim_{t \to \infty} \overline{W_s}$ exists, then the column (x) of the limit supermatrix ($\overline{W_s}^\infty$) is the limit relative ordering of the elements of the network layer under the criterion P_s for element j. When the column vectors of $\overline{W_s}^\infty$ are the same, any of its columns are the global weight vector ($\boldsymbol{w}$) of the evaluation indices.

The following theorems make it easy to determine whether $\overline{W_s}^\infty$ exists or not [34].

Theorem 1. *If the largest eigenvalue of a nonnegative column random matrix (W) is 1 and is a single root, and all the other eigenvalues have a mode less than 1, then* W^∞ *exists and all its columns are the same.*

Theorem 2. *If W is a nonnegative irreducible column random matrix, then the necessary and sufficient condition for the existence of* W^∞ *is that the W is a prime matrix.*

Finally, in order to reduce the influence of subjective factors, several experts were consulted to judge the index system, and the expected value of the global-weight vector was used as the combined-weight vector ($\overline{\boldsymbol{w}}$).

3.2. Cloud-Model-Improved Matter–Element Theory

3.2.1. Transforming Matter–Element Model with Cloud Model

To transform the matter–element model with the cloud model is to make the numerical features (E_x, E_n, H_e) of the universal normal cloud model [35] replace the thing-feature measure (V) in the (E_x, E_n, H_e) model ($R(N, C, V)$) [30], and when the thing (N) has q features, the cloudified matter–element model can be represented as Equation (7):

$$R = \begin{bmatrix} N & c_1 & (E_{x_1}, E_{n_1}, H_{e_1}) \\ & c_2 & (E_{x_2}, E_{n_2}, H_{e_2}) \\ & \vdots & \vdots \\ & c_q & \left(E_{x_q}, E_{n_q}, H_{e_q}\right) \end{bmatrix} \tag{7}$$

where the expectation (E_x) is the most typical sample point on the domain, representing the cloud center of gravity; the entropy (E_n) is the measurable granularity of a qualitative concept, reflecting the range of values that can be accepted by this concept on the domain, and the larger the entropy, the greater the degree of ambiguity of the qualitative concept represented by the cloud; H_e is the hyperentropy, which is the entropy of the entropy, which reflects the randomness of the sample, and the greater the hyperentropy, the greater the thickness of the cloud droplets on the cloud chart. The cloud model realizes the conversion between qualitative and quantitative through these three numerical features [36].

After transforming the matter–element model with the cloud model, there is ambiguity at the boundary of each level. The degree of membership of each index to each level is random, and some overlap of the level range is allowed.

3.2.2. Cloud-Model Parameters

Using the fuzzy and stochastic nature of the cloud model, each level is considered as a double-constraint index [$T_{\min}$, $T_{\max}$], and each cloud-model parameter [33] is calculated according to Equations (8) and (9):

$$E_x = \frac{T_{\min} + T_{\max}}{2} \tag{8}$$

$$H_e = k \tag{9}$$

where the expectation (E_x) takes the cloud center-of-gravity point value. k is a constant, and the smaller its value, the thinner the cloud, and the smaller the dispersion of the degree of membership, the more comparable the results, but it will ignore many boundary cloud drops, and the larger its value, the greater the randomness of the cloud drops, and the less comparable the results. The value can be adjusted according to the ambiguity of each level, the randomness, and the actual situation. Referring to related research [37], in this paper, we take $k = 0.1E_n$.

The entropy (E_n) is calculated in the following two ways.

When there is less overlap of the adjacent-level membership clouds, the boundary value is a transition from one class to another, which is a fuzzy boundary and should belong to the corresponding two classes at the same time, so that the degree of membership is $\mu = \exp\left(-\frac{(x-E_x)^2}{2(E_n)^2}\right) = 0.5$ at the adjacent-level boundary, substituting $x = T_{\min}$ or $T_{\max}$, and Equation (10) can be introduced:

$$E_n = \frac{T_{\max} - T_{\min}}{2.355} \tag{10}$$

According to the rule of the spatial distribution of cloud drops in normal clouds, 99.74% of the cloud drops fall on ($E_x - 3E_n$, $E_x + 3E_n$) (that is, $6E_{\mathrm{n}}$ = 99.74% ($T_{\max} - T_{\min}$)), and Equation (11) can be obtained:

$$E_n = \frac{T_{\max} - T_{\min}}{6} \tag{11}$$

Obviously, the entropy qualitative concept obtained by the former covers a larger range than the latter, and the boundary between the adjacent levels is more blurred, which is suitable for general situations, while the latter is more suitable for situations with clear boundaries, such as danger and safety. The boundaries of the durability grades of hydraulic tunnel linings are relatively vague, and so the former is used to calculate the entropy value in this paper.

3.2.3. Degree of Membership of Evaluation Index

By considering the deterministic value of the evaluation index as a cloud droplet (x), and generating a normal random number ($E_n' = E_n + H_e \times d$), with E_n as the expected value and H_e as the standard deviation, where d denotes a standard normally distributed random number, the degree of membership between the thing index represented by this value and the thing index represented by this cloud can be calculated by Equation (12):

$$\mu = \exp\left(-\frac{(x - E_x)^2}{2(E_n')^2}\right) \tag{12}$$

The degree of membership between the index represented by normal clouds can be calculated according to the 3σ criterion of normal distribution. Assuming the existence of cloud a and cloud b, the intersection (E) and the union (F) of them are shown in Equations (13) and (14), respectively, and the degree of membership between the two clouds is shown in Equation (15):

$$E = (E_x^a - 3E_n^a, E_x^a + 3E_n^a) \cap \left(E_x^b - 3E_n^b, E_x^b + 3E_n^b\right) \tag{13}$$

$$F = (E_x^a - 3E_n^a, E_x^a + 3E_n^a) \cup \left(E_x^b - 3E_n^b, E_x^b + 3E_n^b\right) \tag{14}$$

$$\mu = \frac{E}{F} \tag{15}$$

To calculate the degree of membership between the index represented by interval values and the index represented by clouds, the interval is first converted into a cloud representation using Equations (8)–(11), and then the calculation method of the cloud–cloud degree of membership is applied.

The cloud degree of membership between the calculated indices to be evaluated and the standard normal clouds of each class are formed into a cloud membership matrix (U), as shown in Equation (16):

$$U = \begin{bmatrix} \mu_{11} & \mu_{12} & \mu_{13} & \mu_{14} \\ \mu_{21} & \mu_{22} & \mu_{23} & \mu_{24} \\ \vdots & \vdots & \vdots & \vdots \\ \mu_{N1} & \mu_{N2} & \mu_{N3} & \mu_{N4} \end{bmatrix} \tag{16}$$

The matrix element is the degree of membership between the index (c_i) to be evaluated and the durability class (j), where i = 1, 2, ..., N, is the number of evaluation indices, and the number of elements of the network layer in this paper (N) is 16; j is the durability-class serial number and, in this paper, it is an integer from 1 to 4, corresponding to four classes: I, II, III, and IV.

3.2.4. Durability-Class Calculation

The combined weight vector ($\overline{\boldsymbol{w}}$) of each index calculated from the previous ANP is multiplied with the membership matrix (U) to obtain the comprehensive-evaluation vector ($\boldsymbol{B}$), as shown in Equation (17):

$$\boldsymbol{B} = \overline{\boldsymbol{w}} \cdot U \tag{17}$$

According to Equation (18), the weighted-average method is applied to obtain the comprehensive-evaluation score (r) of the evaluation event:

$$r = \frac{\sum b_j h_j}{\sum b_j} \tag{18}$$

where b_j is the element in the comprehensive-evaluation vector ($\boldsymbol{B}$), and h_j is the assigned score of the durability class (j). The nearest score of the calculated comprehensive-evaluation score (r) is the durability class corresponding to it.

The degree of membership (μ_{ij}) is influenced by the normal random number (E_n'), and so several simulations are needed to reduce the influence of random factors and finally obtain the expectation ($E_{x,r}$) and standard deviation ($E_{n,r}$) of the comprehensive-evaluation score (r), as shown in Equations (19) and (20), respectively:

$$E_{x,r} = \frac{\sum r(d)}{t} \tag{19}$$

$$E_{n,r} = \sqrt{\frac{1}{t}\sum[r(d) - E_{x,r}]^2} \tag{20}$$

where t is the number of simulation calculations, which is taken as 1000 in this paper.

The expectation ($E_{x,r}$) expresses the final evaluation result, and the standard deviation ($E_{n,r}$) reflects the dispersion of the evaluation result. The confidence factor (β) is now defined as Equation (21):

$$\beta = \frac{E_{n,r}}{E_{x,r}} \tag{21}$$

The smaller the value of the confidence factor (β), the smaller the dispersion of the evaluation results, and the higher its credibility; in general, if $\beta < 0.05$ [37], then the evaluation results can be considered credible.

The flow chart of the specific evaluation method in this paper is shown in Figure 4.

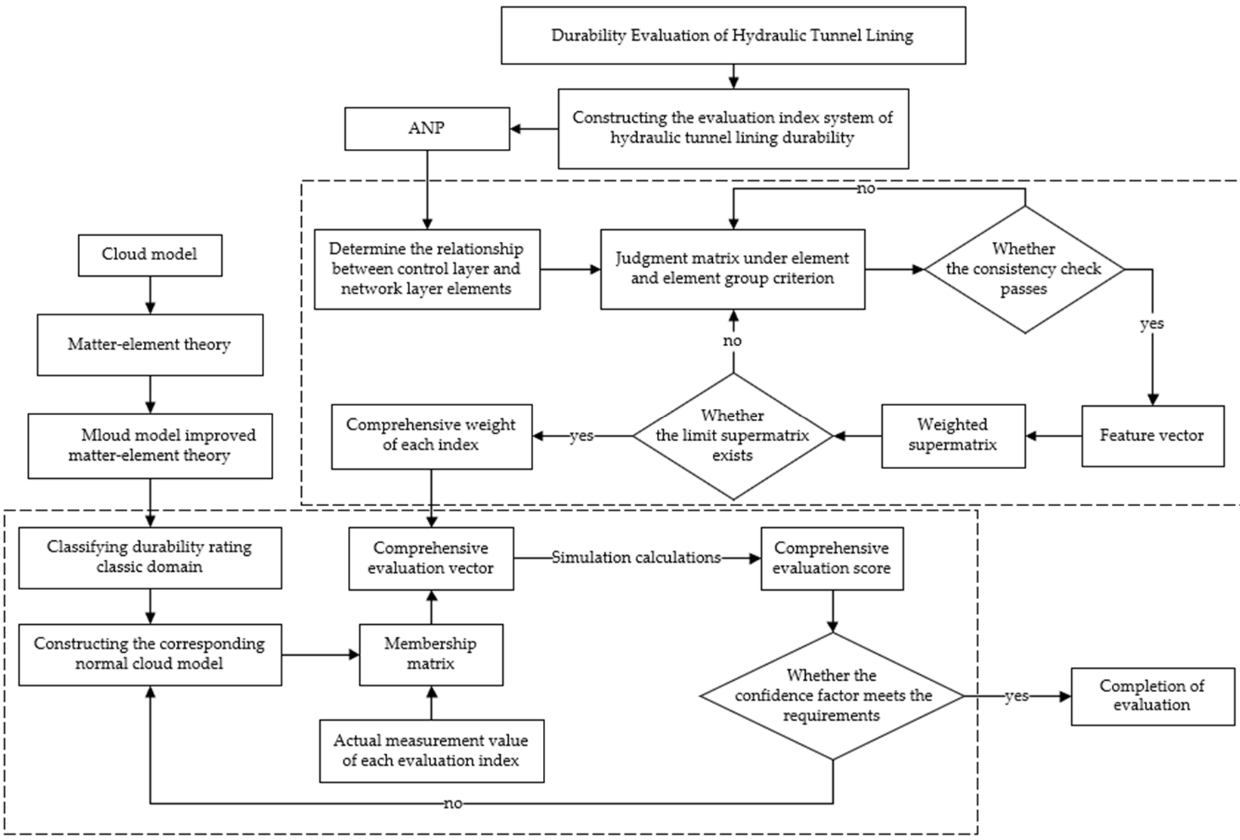

Figure 4. Flow chart of evaluation method.

4. Example Application and Analysis

4.1. Engineering Background

The Water Diversion Project from Datong River to Qinwangchuan District is a large-scale interbasin water transfer project that brings water from the Daitong River at the junction of Gansu and Qinghai provinces into the water-scarce Qinwangchuan Basin, covering an area of 2800 km^2. The climate of the project passing area is cold, and it belongs to the semiarid climate in the cold-temperate zone. The annual average temperature is 3 °C, and the annual temperature is lower than −5 °C for 95 days. The annual precipitation is 413~483 mm, the annual evaporation is 1323 mm, and the maximum frozen soil depth is 1.48 m in this area.

The Nawei Tunnel is an important nonpressure diversion tunnel connecting the canal head diversion hub and the tunnel group [38,39]. The tunnel length is 2099.25 m (pile number: 4 + 247.01~6 + 346.26), with a round-arch straight-wall section, as shown in Figure 5. The top arch radius is 2.4 m, the central angle of the top arch is 180°, the height of the side wall is 2.4 m, the design flow rate is 31.2 m^3/s, the design longitudinal slope is 1/1500, and the lining-structure type is cast-in-place concrete and reinforced concrete. The geological conditions of the section that the Nawei Tunnel passes through are complex and diverse. Under the influence of groundwater erosion, water-flow scouring in the tunnel, and freezing action, the lining structure of the tunnel has suffered from lining cracks, water leakage, the deterioration of the lining structure and materials, and other diseases during the operation period. According to their typical characteristics, the tunnel is divided into five sections for evaluation and analysis. The division and salient characteristics of each section are shown in Table 3.

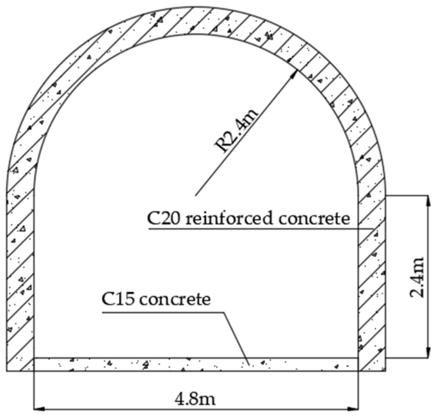

Figure 5. Cross-sectional view of Nawei Tunnel.

Table 3. The Nawai Tunnel sections and their characteristics.

Pile Segment	Notable Characteristics
4 + 247.01~4 + 281.6	The bottom plate is seriously damaged, with 5~10 cm pits (the deepest is 21 cm). The concrete-surface layer below the water-crossing surface of the sidewall is seriously peeling off, and the concrete aggregate is exposed.
4 + 362~4+402	There are many cracks in the bottom plate.
4 + 757.5~4 + 797	The water leakage is serious. Concrete cracks are developed in the range of 3.3~4.3 m on the left wall, the length is 1~4 m, and most of them are closed. There are white precipitates in the cracks, of which the 0.2 m water leakage on the right wall of 4 + 773 is dripping.
5 + 071~5 + 135	The water leakage on the two walls is serious. There are water-leakage points in the range of 0~4.3 m, mostly at the junction of the vault and side wall, and especially the 5 + 120 full-arch seepage, which is dripping.
6 + 240~6 + 346.26	The frost-heave damage of the bottom plate is serious, and there are many cracks. The concrete surface is mostly pitted and honeycombed, which seriously falls off.

4.2. Determination of Evaluation-Index Weights

By consulting the literature [5,38] and consulting experts, we summarized the survey results, and finally obtained the mutual-influence-relationship table of the hydraulic tunnel lining durability indices (namely, Table 4). We then established the hydraulic tunnel lining durability index ANP structure model, as shown in Figure 6.

Table 4. Interaction relationship between durability indices of hydraulic tunnel lining.

	$X_{1\text{-}1}$	$X_{1\text{-}2}$	$X_{1\text{-}3}$	$X_{2\text{-}1}$	$X_{2\text{-}2}$	$X_{2\text{-}3}$	$X_{2\text{-}4}$	$X_{3\text{-}1}$	$X_{3\text{-}2}$	$X_{3\text{-}3}$	$X_{3\text{-}4}$	$X_{3\text{-}5}$	$X_{4\text{-}1}$	$X_{4\text{-}2}$	$X_{4\text{-}3}$	$X_{4\text{-}4}$
$X_{1\text{-}1}$	1 *	1	1	1	1	1	−2	−2	−2	1	0	0	1	1	−2	0
$X_{1\text{-}2}$	1	1	1	1	1	1	−2	−2	−2	1	0	0	1	1	1	0
$X_{1\text{-}3}$	1	1	1	0	0	0	−2	−2	−2	1	0	2	1	1	1	0
$X_{2\text{-}1}$	1	1	0	0	0	2	0	0	1	2	0	0	0	0	1	0
$X_{2\text{-}2}$	1	1	0	0	0	2	0	0	1	2	0	0	0	0	1	0
$X_{2\text{-}3}$	1	1	0	−2	−2	0	2	2	0	0	2	2	0	0	0	2
$X_{2\text{-}4}$	2	2	2	0	0	0	0	0	1	0	0	0	2	2	2	0
$X_{3\text{-}1}$	2	2	2	0	0	−2	0	0	0	2	−2	−2	0	1	0	−2
$X_{3\text{-}2}$	2	2	2	1	1	0	1	0	0	2	0	0	0	0	0	0
$X_{3\text{-}3}$	1	1	1	−2	−2	0	0	−2	−2	0	1	1	−2	−2	0	0
$X_{3\text{-}4}$	0	0	0	0	0	-2	0	2	0	1	1	1	1	2	2	0
$X_{3\text{-}5}$	0	0	−2	0	0	−2	0	2	0	1	1	1	1	2	1	0
$X_{4\text{-}1}$	1	1	1	0	0	0	−2	0	0	2	1	1	0	0	−2	−2
$X_{4\text{-}2}$	1	1	1	0	0	0	−2	1	0	2	−2	−2	0	0	−2	−2
$X_{4\text{-}3}$	2	1	1	1	1	0	−2	0	0	0	−2	1	2	2	1	0
$X_{4\text{-}4}$	0	0	0	0	0	−2	0	2	0	0	0	0	2	2	0	1

* 0 means that the two indexes do not affect each other, 1 means that the two indexes affect each other, 2 means that the row index affects the vertical index in one direction, and −2 means that the vertical index affects the horizontal index in one direction.

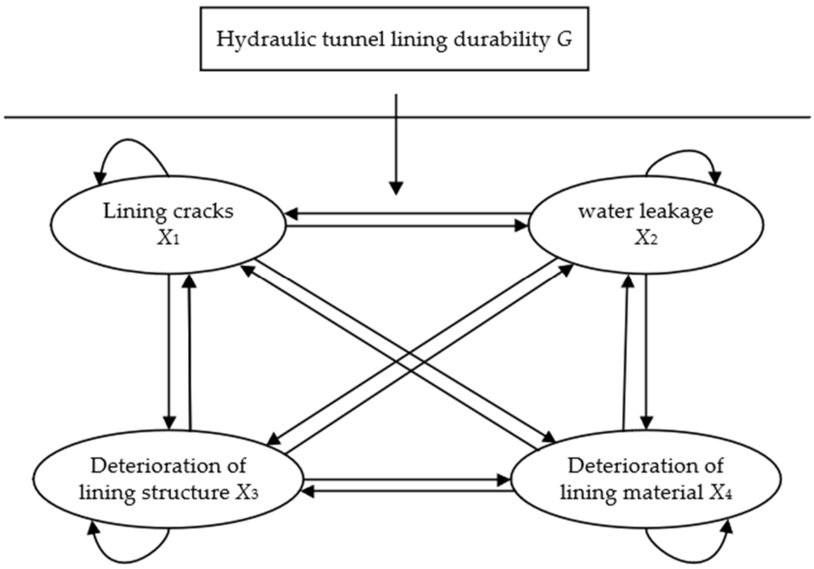

Figure 6. ANP structural model of hydraulic tunnel lining durability indices.

According to Table 4 and Figure 6, and consulting relevant experts (E_1, E_2 and E_3), the judgment matrices under each criterion can be obtained. Due to space limitations, only judgment matrices are listed, which take the lining cracks (X_1) and crack length ($X_{1\text{-}1}$) as the criterion elements, as shown in Tables 5–8. In order to improve the accuracy of the weights of each index as much as possible, the eigenvector elements of the judgment matrix are retained to four decimal places here.

Table 5. Judgment matrices of element groups under the criterion of lining cracks (X_1).

	E_1					E_2					E_3				
	X_1	X_2	X_3	X_4	a_1	X_1	X_2	X_3	X_4	a_1	X_1	X_2	X_3	X_4	a_1
X_1	1	1/2	2	3	0.2995	1	1/2	3	4	0.3358	1	1/2	3	4	0.3056
X_2	2	1	2	2	0.3889	2	1	2	3	0.4004	2	1	4	5	0.4918
X_3	1/2	1/2	1	2	0.1881	1/3	1/2	1	3	0.1777	1/3	1/4	1	2	0.1248
X_4	1/3	1/2	1/2	1	0.1235	1/4	1/3	1/3	1	0.0862	1/4	1/5	1/2	1	0.0778
CR *	0.0536					0.0789					0.0181				

* Consistency ratio: when its value is less than 0.1, the inconsistency of the judgment matrix is within the allowable range, and the consistency test is satisfied.

Table 6. Judgment matrices of lining-cracks group (X_1) under the criterion of crack length ($X_{1\text{-}1}$).

	E_1				E_2				E_3			
	$X_{1\text{-}1}$	$X_{1\text{-}2}$	$X_{1\text{-}3}$	$w_1^{(1\text{-}1)}$	$X_{1\text{-}1}$	$X_{1\text{-}2}$	$X_{1\text{-}3}$	$w_1^{(1\text{-}1)}$	$X_{1\text{-}1}$	$X_{1\text{-}2}$	$X_{1\text{-}3}$	$w_1^{(1\text{-}1)}$
$X_{1\text{-}1}$	1	2	3	0.5396	1	3	4	0.6250	1	3	3	0.6000
$X_{1\text{-}2}$	1/2	1	2	0.2970	1/3	1	2	0.2385	1/3	1	1	0.2000
$X_{1\text{-}3}$	1/3	1/2	1	0.1634	1/4	1/2	1	0.1365	1/3	1	1	0.2000
CR	0.0088				0.0176				0.0000			

Table 7. Judgment matrices of water-leakage group (X_2) under the criterion of crack length ($X_{1\text{-}1}$).

	E_1				E_2				E_3			
	$X_{2\text{-}1}$	$X_{2\text{-}2}$	$X_{2\text{-}3}$	$w_2^{(1\text{-}1)}$	$X_{2\text{-}1}$	$X_{2\text{-}2}$	$X_{2\text{-}3}$	$w_2^{(1\text{-}1)}$	$X_{2\text{-}1}$	$X_{2\text{-}2}$	$X_{2\text{-}3}$	$w_2^{(1\text{-}1)}$
$X_{2\text{-}1}$	1	2	4	0.5584	1	1	3	0.4286	1	2	3	0.5278
$X_{2\text{-}2}$	1/2	1	3	0.3196	1	1	3	0.4286	1/2	1	3	0.3325
$X_{2\text{-}3}$	1/4	1/3	1	0.1220	1/3	1/3	1	0.1429	1/3	1/3	1	0.1396
CR	0.0176				0.0000				0.0516			

Table 8. Judgment matrices of lining-material-deterioration group (X_4) under the criterion of crack length ($X_{1\text{-}1}$).

	E_1			E_2			E_3		
	$X_{4\text{-}1}$	$X_{4\text{-}2}$	$w_4^{(1\text{-}1)}$	$X_{4\text{-}1}$	$X_{4\text{-}2}$	$w_4^{(1\text{-}1)}$	$X_{4\text{-}1}$	$X_{4\text{-}2}$	$w_4^{(1\text{-}1)}$
$X_{4\text{-}1}$	1	3	0.7500	1	2	0.6667	1	3	0.7500
$X_{4\text{-}2}$	1/3	1	0.2500	1/2	1	0.3333	1/3	1	0.2500
CR	0.0000			0.0000			0.0000		

According to the normalized eigenvectors calculated by each judgment matrix, the supermatrix (W), the weighted supermatrix ($\overline{W}$), and the limit supermatrix ($\overline{W}^{\infty}$) can be obtained, and the calculation results of each expert are arithmetically averaged to finally determine the combined weight vector ($\overline{w}$) of the hydraulic tunnel lining durability evaluation system, as shown in Table 9. It can be seen that the first three are the crack width ($X_{1\text{-}2}$) (0.1297), crack length ($X_{1\text{-}1}$) (0.1198), and deformation rate ($X_{3\text{-}3}$) (0.1197). Therefore, the crack width ($X_{1\text{-}2}$) is the most sensitive parameter to the durability of the tunnel lining.

Table 9. Comprehensive weight and sequence of each index.

Index	Weight	Sequence	Index	Weight	Sequence
$X_{1\text{-}1}$	0.1198	2	$X_{3\text{-}2}$	0.0145	15
$X_{1\text{-}2}$	0.1297	1	$X_{3\text{-}3}$	0.1197	3
$X_{1\text{-}3}$	0.0823	6	$X_{3\text{-}4}$	0.0876	5
$X_{2\text{-}1}$	0.0640	7	$X_{3\text{-}5}$	0.0993	4
$X_{2\text{-}2}$	0.0430	11	$X_{4\text{-}1}$	0.0469	10
$X_{2\text{-}3}$	0.0496	8	$X_{4\text{-}2}$	0.0309	13
$X_{2\text{-}4}$	0.0159	14	$X_{4\text{-}3}$	0.0477	9
$X_{3\text{-}1}$	0.0376	12	$X_{4\text{-}4}$	0.0116	16

4.3. Durability Evaluation of Example

Based on the current research results on the durability of concrete structures [27,40,41], the durability statuses of hydraulic tunnel linings are classified as normal, basically normal, reaching the durability limit, and reaching the bearing-capacity limit, as shown in Table 10 below.

Table 10. Classification of durability of hydraulic tunnel linings.

Durability Class	Durability Status	Qualitative Determination Basis
I	Normal	Material and structure functions slightly damaged or intact, and these damages have no effect on the water delivery and do not need to be repaired.
II	Basically normal	Materials and structural functions are basically intact, and there is basically no impact on the water transmission, but minor repairs are required.
III	Reaching the durability limit	The durability cannot meet the applicability requirements, which may endanger the safety of the water transmission, and the necessary preparations and measures should be taken.
IV	Reaching the bearing-capacity limit	The durability cannot meet the safety requirements, which will endanger the safety of the water transmission, and enforcement measures must be taken.

Referring to the Assessment Standard for Structure Deterioration of Railway Bridge and Tunnel—Part 2: Tunnel (Q/CR 405.2-2019) [42], and related literature [20,43], determination criteria, including the lining cracks, water leakage, lining-structure deterioration, and lining-material deterioration, of different grades were established, in which the qualitative indices were transformed into numerical interval representations [44] for the convenience of the cloud-model-improved matter–element calculation, as shown in Table 11 below.

Table 11. Classification of hydraulic tunnel lining durability indices.

First-Level Indices (Element Group)	Secondary Indices (Element)	Durability Classes			
		I	II	III	IV
Lining cracks (X_1)	Crack length ($X_{1\text{-}1}$) (m)	(0,1]	(1,2.5]	(2.5,5]	(5,10]
	Crack width ($X_{1\text{-}2}$) (mm)	(0,0.2]	(0.2,0.3]	(0.3,0.4]	(0.4,0.8]
	Crack depth/lining thickness ($X_{1\text{-}3}$)	(0,0.3]	(0.3,0.5]	(0.5,0.7]	(0.7,1]
Water leakage (X_2)	Arch-leakage status ($X_{2\text{-}1}$ [1])	(0,1]	(1,2]	(2,3]	(3,4]
	Sidewall-leakage status ($X_{2\text{-}2}$ [2])	(0,1]	(1,3]	(3,4]	(4,6]
	Freezing status ($X_{2\text{-}3}$ [3])	(0,1]	(1,2]	(2,3]	(3,4]
	pH value ($X_{2\text{-}4}$)	(6,14]	(5,6]	(4,5]	(0,4]

Table 11. *Cont.*

First-Level Indices (Element Group)	Secondary Indices (Element)	Durability Classes			
		I	II	III	IV
Lining-structure deterioration (X_3)	Insufficient thickness/design thickness, ($X_{3\text{-}1}$)	(0,0.01]	(0.01,0.1]	(0.1,0.5]	(0.5,1]
	Depth of void behind ($X_{3\text{-}2}$) (mm)	(0,50]	(50,100]	(100,500]	(500,1000]
	Deformation speed (X_{3-3}) (mm·a^{-1})	(0,1]	(1,3]	(3,10]	(10,20]
	Spalling diameter ($X_{3\text{-}4}$) (mm)	(0,50]	(50,75]	(75,150]	(150,300]
	Spalling depth ($X_{3\text{-}5}$) (mm)	(0,6]	(6,12]	(12,25]	(25,50]
Lining-material deterioration (X_4)	Actual strength/design strength ($X_{4\text{-}1}$)	(0.8,1]	(0.5,0.8]	(0.3,0.5]	(0,0.3]
	Rebar-section-loss rate ($X_{4\text{-}2}$ (%))	(0,3]	(3,10]	(10,25]	(25,100]
	Carbonization coefficient ($X_{4\text{-}3}$ [4])	(0,0.6]	(0.6,0.8]	(0.8,1]	(1,2]
	Shellfish thickness ($X_{4\text{-}4}$) (mm)	(0,20]	(20,50]	(50,100]	(100,200]

[1] The qualitative language corresponding to classes I–IV are infiltration, hourglass, inrush current, and injection, respectively. [2] The qualitative language corresponding to classes I–IV are infiltration, hourglass, inrush current, injection, and injection, respectively. [3] The qualitative language corresponding to classes I–IV are freeze damage without affecting the flow, freeze damage affecting the flow, freeze damage greatly affecting the flow, and freeze damage severely affecting the flow, respectively. [4] The carbonization coefficient is the ratio of the carbonization depth to the thickness of the protective layer.

According to the class interval and Equations (8)–(10) of each index, the numerical characteristics (E_x, E_n, and H_e) of the normal cloud model are calculated, as shown in Table 12 below.

Table 12. Numerical characteristics of normal cloud model for durability indices.

Durability Class		I	II	III	IV
Evaluation Indices	Numerical Characteristics				
$X_{1\text{-}1}$	E_x	0.500	1.750	3.750	7.500
	E_n	0.425	0.637	1.062	2.123
	H_e	0.043	0.064	0.106	0.212
$X_{1\text{-}2}$	E_x	0.100	0.250	0.350	0.600
	E_n	0.085	0.042	0.042	0.170
	H_e	0.009	0.004	0.004	0.017
$X_{1\text{-}3}$	E_x	0.150	0.400	0.600	0.850
	E_n	0.127	0.085	0.085	0.127
	H_e	0.013	0.009	0.009	0.013
$X_{2\text{-}1}$	E_x	0.500	1.500	2.500	3.500
	E_n	0.425	0.425	0.425	0.425
	H_e	0.043	0.043	0.043	0.043
$X_{2\text{-}2}$	E_x	0.500	2.000	3.500	5.000
	E_n	0.425	0.849	0.425	0.849
	H_e	0.043	0.085	0.043	0.085
$X_{2\text{-}3}$	E_x	0.500	1.500	2.500	3.500
	E_n	0.425	0.425	0.425	0.425
	H_e	0.043	0.043	0.043	0.043
$X_{2\text{-}4}$	E_x	10.000	5.500	4.500	2.000
	E_n	3.397	0.425	0.425	1.699
	H_e	0.340	0.043	0.043	0.170
$X_{3\text{-}1}$	E_x	0.005	0.055	0.300	0.750
	E_n	0.004	0.038	0.170	0.212
	H_e	0.000	0.004	0.017	0.021
$X_{3\text{-}2}$	E_x	25.000	75.000	300.000	750.000
	E_n	21.231	21.231	169.851	212.314
	H_e	2.123	2.123	16.985	21.231

Table 12. *Cont.*

Durability Class		I	II	III	IV
Evaluation Indices	**Numerical Characteristics**				
$X_{3\text{-}3}$	E_x	0.500	2.000	6.500	15.000
	E_n	0.425	0.849	2.972	4.246
	H_e	0.043	0.085	0.297	0.425
$X_{3\text{-}4}$	E_x	25.000	62.500	112.500	225.000
	E_n	21.231	10.616	31.847	63.694
	H_e	2.123	1.062	3.185	6.369
$X_{3\text{-}5}$	E_x	3.000	9.000	18.500	37.500
	E_n	2.548	2.548	5.520	10.616
	H_e	0.255	0.255	0.552	1.0616
$X_{4\text{-}1}$	E_x	0.900	0.650	0.400	0.150
	E_n	0.085	0.127	0.085	0.127
	H_e	0.009	0.013	0.009	0.013
$X_{4\text{-}2}$	E_x	1.500	6.500	17.500	62.500
	E_n	1.274	2.972	6.369	31.847
	H_e	0.127	0.297	0.637	3.185
$X_{4\text{-}3}$	E_x	0.300	0.700	0.900	1.500
	E_n	0.255	0.085	0.085	0.425
	H_e	0.026	0.009	0.009	0.043
$X_{4\text{-}4}$	E_x	10.000	35.000	75.000	150.000
	E_n	8.493	12.739	21.231	42.463
	H_e	0.849	1.274	2.123	4.246

Taking the crack length ($X_{1\text{-}1}$) as an example, according to the numerical characteristics of the cloud model of the evaluation index in Table 12, through MATLAB programming, four normal clouds are generated by the normal cloud generator corresponding to their four durability classes. The standard cloud chart of the crack length is shown in Figure 7.

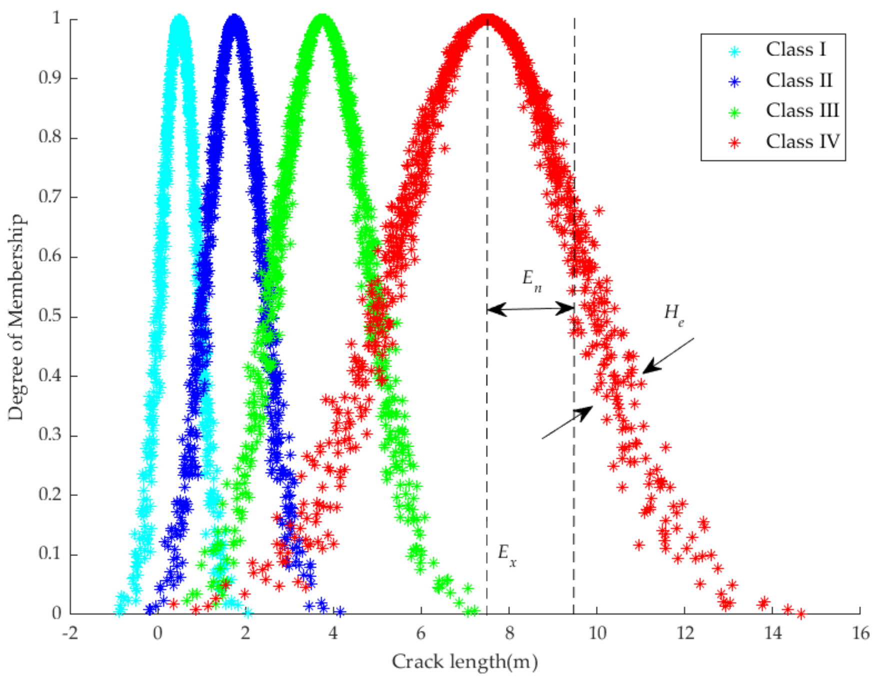

Figure 7. The standard cloud chart of the crack length.

The quantitative detection value and on-site qualitative scoring value of the Nawei Tunnel lining durability evaluation are shown in Table 13.

Table 13. Quantitative detection value and qualitative scoring value of durability indices.

Element Groups	Elements	Pile Segment				
		1	2	3	4	5
X_1	$X_{1\text{-}1}$ (m)	4.5	1	4	2	3.5
	$X_{1\text{-}2}$ (mm)	0.4	0.2	0.25	0.2	0.45
	$X_{1\text{-}3}$	5/12	1/8	1/3	1/3	5/12
X_2	$X_{2\text{-}1}$	0.5	0.5	2.5	2.5	1.5
	$X_{2\text{-}2}$	1.5	0.5	0.5	2.5	2.5
	$X_{2\text{-}3}$	1.5	0.5	0.5	2.5	2.5
	$X_{2\text{-}4}$	4.5	6	5.5	5.5	5
X_3	$X_{3\text{-}1}$	7/12	1/4	5/12	1/3	1/2
	$X_{3\text{-}2}$ (mm)	400	50	150	200	350
	X_{3-3} $(\text{mm}\cdot\text{a}^{-1})$	4	1	2	2	4
	$X_{3\text{-}4}$ (mm)	120	50	60	65	110
	$X_{3\text{-}5}$ (mm)	21	6	13	12	19
X_4	$X_{4\text{-}1}$	0.8	0.85	0.7	0.9	0.8
	$X_{4\text{-}2}$ (%)	15	10	20	19	18
	$X_{4\text{-}3}$	0.8	0.4	0.6	0.6	0.9
	$X_{4\text{-}4}$ (mm)	20	5	5	10	20

According to the quantitative detection value and on-site qualitative scoring value (cloud drop (x)) of the evaluation indices of each section, referring to the cloud-characteristic values in Table 13, the degree of membership (μ) between each evaluation index and the standard normal cloud of different durability classes is calculated according to Equation (12). Taking segment 1 as an example, and assuming a normal random number ($E_n' = E_n$), the cloud-membership matrix (U_1) can be calculated.

$$U_1 = \begin{bmatrix} 0.36851 & 0.77913 & 0.00009 & 0.00000 \\ 0.49995 & 0.49995 & 0.00195 & 0.00195 \\ 0.00307 & 0.09729 & 0.98093 & 0.11180 \\ 0.00000 & 0.00002 & 0.06247 & 1.00000 \\ 0.00021 & 0.00002 & 0.84087 & 0.06247 \\ 0.00002 & 0.06247 & 1.00000 & 0.06247 \\ 0.33851 & 1.00000 & 0.06247 & 0.26964 \\ 0.73483 & 0.24875 & 0.00000 & 0.00000 \\ 0.25698 & 0.84087 & 0.00000 & 0.00000 \\ 0.03490 & 0.70209 & 0.06247 & 0.00000 \\ 0.25698 & 0.97265 & 0.00000 & 0.00004 \\ 0.29882 & 0.90253 & 0.00002 & 0.00000 \\ 0.00000 & 0.00002 & 0.49995 & 0.49995 \\ 0.32881 & 0.92586 & 0.01676 & 0.00000 \\ 0.25698 & 0.49995 & 0.49995 & 0.14577 \\ 0.00922 & 0.03490 & 0.49995 & 0.49995 \end{bmatrix} \quad (22)$$

In order to eliminate the randomness of the evaluation results, 1000 normal random numbers (E_n'), with E_n as the expectation and H_e as the standard deviation, are randomly generated by MATLAB programming for the simulation operation, and then 1000 random membership matrices (U) are obtained. Then, according to Equation (17), the corresponding comprehensive-evaluation vectors are obtained. In this paper, the durability classes I (normal), II (basically normal), III (reaching the durability limit), and IV (reaching the bearing-capacity limit) are assigned 1, 2, 3, and 4 points, respectively, and the expectation and standard deviation of the comprehensive-evaluation score of each section are calculated by Equations (18)–(21), and then the corresponding confidence factor is obtained.

The improved G2-antientropy weight method and the undetermined measure theory are useful evaluation methods, which can fully consider the subjective and objective factors of the evaluation index weight, as well as the uncertainty and ambiguity in the evaluation process. The method in this paper is an improvement of the traditional AHP and matter–element theory model. In order to verify its practicability, the improved G2-antientropy weight method and the undetermined measure theory are used as a comparison. The specific evaluation process is shown in the literature [39]. The evaluation results obtained are shown in Table 14.

Table 14. Evaluation results.

Pile Segment	Expectation	Standard Deviation	Confidence Factor	Evaluation Results of the Method of [39]
1	2.772 (III)	0.057	0.021	III
2	1.580 (II)	0.054	0.034	II
3	2.292 (II)	0.057	0.025	II
4	2.225 (II)	0.054	0.024	II
5	2.880 (III)	0.051	0.018	III

The evaluation results of the method in this paper are in complete agreement with the results obtained by the method in the literature [39], and they are consistent with the actual situation of the tunnel (Table 3). The weight calculation in this paper combines the decision-making results of multiple experts, and it considers the feedback effect between the indices. At the same time, the evaluation model considers the randomness and fuzziness of the durability indices. The evaluation confidence factor of each section is less than 0.05. Therefore, the evaluation results obtained by the method in this paper are highly reliable. The final durability evaluation class of hydraulic tunnels are as follows: the durability class of Sections 1 and 5 is class III, and the durability class of Sections 2–4 is class II.

5. Conclusions and Outlook

The durability evaluation of hydraulic tunnel linings is an important guarantee for the safe and efficient operation of hydraulic tunnels, and thus it is necessary to propose a reasonable and effective lining durability evaluation method. In this paper, based on the review of a large amount of literature, the durability of a hydraulic tunnel lining was evaluated using the ANP and cloud-model-improved matter–element theory, and the main conclusions are as follows:

(1) According to the damage mechanism of hydraulic tunnel linings, the 16 evaluation indices, such as the crack-length, crack-width, and crack-depth ratio, arch-leakage status; sidewall-leakage status, freezing status, and pH value, are divided into four element groups: lining cracks, water leakage, lining-structure deterioration, and lining-material deterioration, forming a scientific hydraulic tunnel lining durability evaluation index system;

(2) Feedback exists between the hydraulic tunnel lining durability evaluation indices, and on the basis of multiexpert scoring, the ANP is used to calculate the weights of each index, which reduces the subjectivity and one-sidedness in the calculation process and obtains the durability index weights that suit the actual situation. The weights of each evaluation index were obtained by calculation, and the first three were the crack width (0.1297), crack length (0.1198), and deformation speed (0.1197);

(3) The cloud-model-improved matter–element theory combines the advantages of the cloud model and matter–element theory, fully considers the randomness and fuzziness in the evaluation process, and provides a new method for hydraulic tunnel lining durability evaluation. The lining durability classes of five sections of the Nawei Tunnel were obtained as III, II, II, II, and III using the method of this paper, which matched with the calculation results of the improved G2-antientropy weight method and unconfirmed measurement theory, thus verifying its accuracy and scientificity.

This paper researches and applies the evaluation method for the durability of hydraulic tunnel linings, but due to the limitation of the data collection and author's knowledge, there are still some problems that need further research and improvement:

(1) The material and structural forms of hydraulic tunnel linings are diverse, and a more complete durability evaluation index system needs to be established for different forms of hydraulic tunnel linings;
(2) The feedback among the hydraulic tunnel lining durability evaluation indices may be asymmetric, and it is necessary to modify the ANP to further reflect the actual situation and improve the accuracy of the indice weights;
(3) The classification criteria of the durability classes and the reasonableness of the durability score have a great influence on the evaluation results. The classification of the durability classes in this paper was obtained on the basis of a large amount of literature, and they are applicable to most shapes and sizes of tunnels, but in order to expand their application, more in-depth and detailed research is still needed to improve the comprehensiveness and objectivity of the evaluation results.

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