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Fuzzy Synthetic Evaluation of the Long-Term Health of Tunnel Structures

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Abstract: A tunnel is a coupled system of the surrounding rock and the supporting structure. The health status of a tunnel structure is complex and is influenced by various factors. In addition, these factors are coupled and interacted with each other, which calls for the linguistic description of the tunnel safety level. In this paper, we describe the health status of a highway tunnel structure in terms of four levels: safe; basically safe; potentially unsafe and unsafe. Based on the analysis of the safety characteristics of the tunnel structure and its proposed safety level, this research develops a multi-level fuzzy synthetic evaluation model for the long-term safety evaluation system of a tunnel structure. The Cang Ling Tunnel, which has embedded sensors to measure the stress values of the secondary lining and the contact pressure, is used as an example to study the proposed method. The results show that the structure of the entire Cang Ling Tunnel is in almost a safe condition under the current conditions, which is consistent with the actual operational situation.

Keywords: long-term safety monitoring; structure health monitoring; fuzzy synthetic evaluation; Cang Ling Tunnel

1. Introduction

Over the past two decades, China has observed the rapid development of highway and railway transportation systems, including many tunnels. In recent years, with the increase of the service time of these tunnels, various problems, such as lining cracks, water leakage, and even falling linings, have been widely observed and attracted attention from practicing engineers and academic researchers. The concepts of "prevention" and "early discovery" have been developed and gradually put into practice. Specifically, the long-term structural monitoring of tunnels that pass through complex and special environmental conditions has received additional attention in recent years. One example is the research on the application of structural health monitoring in Hangzhou Qiantang River Tunnel done by Wu et al. [1]. Ke et al. studied the structural health monitoring system for Nanjing Yangtze River Tunnel [2]. The stress of the secondary lining was selected as a long-term monitoring project and was successfully applied in Cang Ling Tunnel in Zhejiang province [3]. Li et al. successfully established a long-term health monitoring system for the Mo Tianling Extra-long Highway Tunnel [4]. Effective monitoring techniques were adopted to ensure the operation security of Xiamen Xiang'an Subsea Tunnel [5]. Located in Antwerp, Belgium, the Liefkenshoek tunnel was studied in terms of the structural health response to tidal fluctuations [6]. Due to their particular and complex engineering environment, Su et al. studied the long-term structural health monitoring of subsea tunnels [7]. A tunnel monitoring system was set up to monitor joint movements in the concrete tunnel lining of an existing London underground tunnel [8]. Structural monitoring is also used in a typical metro tunnel located in Rome, Italy [9].

With the development of sensors and other monitoring techniques, new monitoring methods are gradually applied to structural health monitoring of tunnels. Zhang et al. presented an automatic crack detection and classification methodology for subway tunnel safety monitoring [10]. The application of the fiber Bragg grating (FBG) sensing technology for safety monitoring during railway tunnel construction was researched [11]. Tunnel structural health monitoring can also be achieved by terrestrial laser scanning [12].

Since a tunnel is a coupled system of the surrounding rock and the supporting structure, the health status of the tunnel structure is influenced by the stability of the surrounding rock. Hence, the stability of the surrounding rock is of great importance. The stability of the surrounding rock is usually influenced by the lithology, the geological conditions, the initial geostress field conditions, the topography, the ground water conditions, etc. Therefore, there is enormous uncertainty about the stability of the surrounding rock. In addition, the structural health status is influenced by the shape and size of the tunnel section, the support type, and the construction method. Furthermore, the factors that influence the health of the tunnel structure interact with each other, together determining the long-term health status of the tunnel structure [3]. Thus, the tunnel structural health monitoring is a complex system. In the literature, intelligent methods, including neural networks [13–15], genetic algorithms [16,17], fuzzy logic methods [18–20], Analytic Hierarchy Processes (AHP) [21,22], etc., have been developed to deal with complex systems. Among these methods, the fuzzy logic method is of particular interest in monitoring structural or tunnel safety, which is commonly described by linguistic variables, such as safe, basically safe, potentially unsafe, and unsafe. In the fuzzy logic family, the fuzzy synthetic evaluation method is frequently used. The synthetic evaluation method is a general evaluation of phenomena affected by a variety of factors. If this evaluation process involves fuzzy factors, then it is called a fuzzy synthetic evaluation method. The fuzzy synthetic evaluation method is widely used in civil engineering, such as structural health evaluation, engineering quality, engineering performance, structural variation, etc. Since these problems are influenced by complex and uncertain factors, it is difficult to make a quantitative evaluation using an analytic method. However, by using the fuzzy synthetic evaluation method, these problems can be solved. In addition, this method can combine qualitative factors with quantitative factors, making the evaluation results more objective and in accordance with the actual accident situation. Consider that the fuzzy synthetic evaluation method has been widely used in bridge, slope, and other engineering fields with success. For instance, Shang used multi-level fuzzy synthetic evaluation to evaluate a bridge's structural health [23]. According to the theory of fuzzy synthetic evaluation, the multi-level fuzzy synthetic evaluation model of bridge maintenance is extended [24]. Wu and Wang applied the fuzzy comprehensive evaluation method to slope stability [25]. Based on the method of fuzzy mathematics, a slope stability analysis of the fuzzy synthetic evaluation model is established and the grading index of the slope stability is determined [26]. The fuzzy synthetic evaluation is also widely adopted around the world and in many academic fields. For instance, the fuzzy synthetic evaluation was used to assess the urban air quality in Istanbul [27]. The fuzzy synthetic evaluation was also used in pipe inspection [28]. In addition, it can be used in decision-making for drilling waste discharges [29]. Therefore, in order to the long-term health monitoring data to evaluate the structural safety of the tunnel and ensure it is in good working condition, the fuzzy synthetic evaluation method is used to evaluate the structural health status of the tunnel in this paper.

In view of this, through the long-term health monitoring system of the Cang Ling Tunnel, the real-time values of structural stress can be acquired. Based on the latest data of the structural stress, the health status of the structure of the tunnel is evaluated using the multi-level fuzzy synthetic evaluation method. Thus, the structural safety of the Cang Ling Tunnel during the operation can be evaluated and corresponding measures can be taken.

2. Determination of the Evaluation Methods and Ideas for the Tunnel Structural Health

2.1. Selection of Evaluation Method for Tunnel Structural Health

Up to now, for the quantitative safety evaluation of tunnel structures in China, the formulas recommended in the Code for Design of Highway Tunnel [30] and the Code for Design of Railway Tunnel [31] have frequently been applied. Using the formulas, the stress status of a certain section of the tunnel structure can be obtained (the axial force and bending moment). Though this method can meet the requirements of the safety evaluation of the structure to a certain extent, as mentioned above, the health monitoring of a tunnel structure is a complex system, influenced by various factors such as the geological condition, the section types, and the construction method. The influencing factors include qualitative and quantitative indices, which are related and interact with each other. Thus, it is obviously inappropriate to evaluate the health status of the tunnel structure with the above simple quantitative evaluation method [3]. Moreover, many of these factors are coupled and interact with each other. It is difficult to obtain a reasonable evaluation using the common method of one-level fuzzy synthetic evaluation. The so-called one-level fuzzy synthetic evaluation means that, during the evaluating process, a number of influencing factors can be listed. Then each factor can be seen as a single evaluation factor. However, if the influencing factors of each factor in one-level fuzzy synthetic evaluation are further listed, then that makes it a two-level or multi-level fuzzy synthetic evaluation. Therefore, the method of multi-level fuzzy synthetic evaluation is more suitable to evaluate the health status of a tunnel structure. The steps of this method are illustrated in Figure 1.

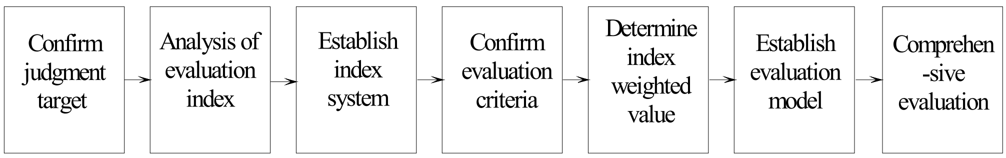


Figure 1. Steps of the fuzzy comprehensive evaluation method.

2.2. Evaluation Idea for Tunnel Structural Health

Due to the great differences in the geological conditions, hydrogeology, topography, and geomorphology features along the full length of the tunnel, especially for long tunnels, different types of lining structures, section types, and construction methods must be designed. The entire tunnel is virtually divided into different segments with the same characteristics. In these segments, the rock condition, the characteristics of the stress field, the development of the groundwater, the tunnel depth, the support types and parameters, the section shapes, and the construction methods are basically the same.

In order to scientifically evaluate the health status of a tunnel structure, it is necessary to obtain the in situ long-term monitoring data. However, it is neither realistic nor necessary to embed long-term monitoring elements within the entire range of the tunnel to obtain the information. From the perspectives of economics and the similar characteristics of some segments of a tunnel, it is only necessary to select limited typical sections, which can reflect the characteristics of all the segments of the tunnel project to conduct the long-term monitoring.

The basic idea behind the evaluation of the long-term health status of a tunnel structure is shown in Figure 2. It is based on the structural stress information from sensors embedded in typical sections. Through the comprehensive analysis of many factors that influence tunnel structural safety, the multi-level fuzzy synthetic evaluation method was adopted to evaluate the structural safety of each typical monitoring section that represents the overall safety status of each segment. Those segments all have the same conditions as the typical monitoring section. Then the long-term safety status of the entire tunnel can be evaluated.

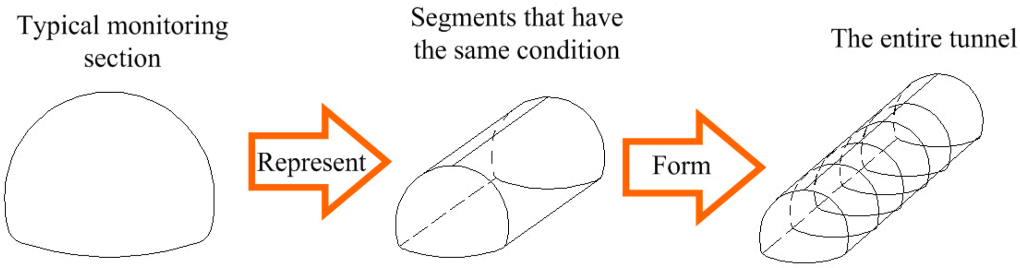


Figure 2. The evaluation processing diagram of long-term health of the tunnel structure.

3. Application of the Fuzzy Synthetic Evaluation Method to Cang Ling Tunnel Structural Health Evaluation

3.1. General Situation of Application Engineering

The Cang Ling Tunnel is located in the middle of Zhejiang province. The full length of this highway tunnel is about 7500 m, which means the tunnel is extra-long. The maximum buried depth of the tunnel is 768 m. Moreover, the tunnel is located in the high initial geostress field (the maximum principle stress is about 20 MPa). The tunnel passes through the ground, which is made up of granite porphyry and ignimbrite. The surrounding rock is rated as graded II, III according to the Code for Design of Highway Tunnels [30]. The geological structure of this region is relatively simple and the rock mass integrity is good (Figure 3). Considering the special conditions, such as the extra-long length and the deep buried depth, the concept of long-term health monitoring is developed and put into practice gradually. At the beginning of 2009, when the tunnel began operations, the long-term health monitoring system for the tunnel structure was basically established.

In order to know the initial geostress field and its influence on the stability of the tunnel, the hydraulic fracturing technique was used near the axis of the tunnel. Three holes were drilled to carry out the initial geostress testing work. Combined with multiple regression analysis, the stress distribution on the axis of the tunnel is obtained [32], providing basic data for the long-term structural health evaluation of Cang Ling Tunnel (Figure 4).

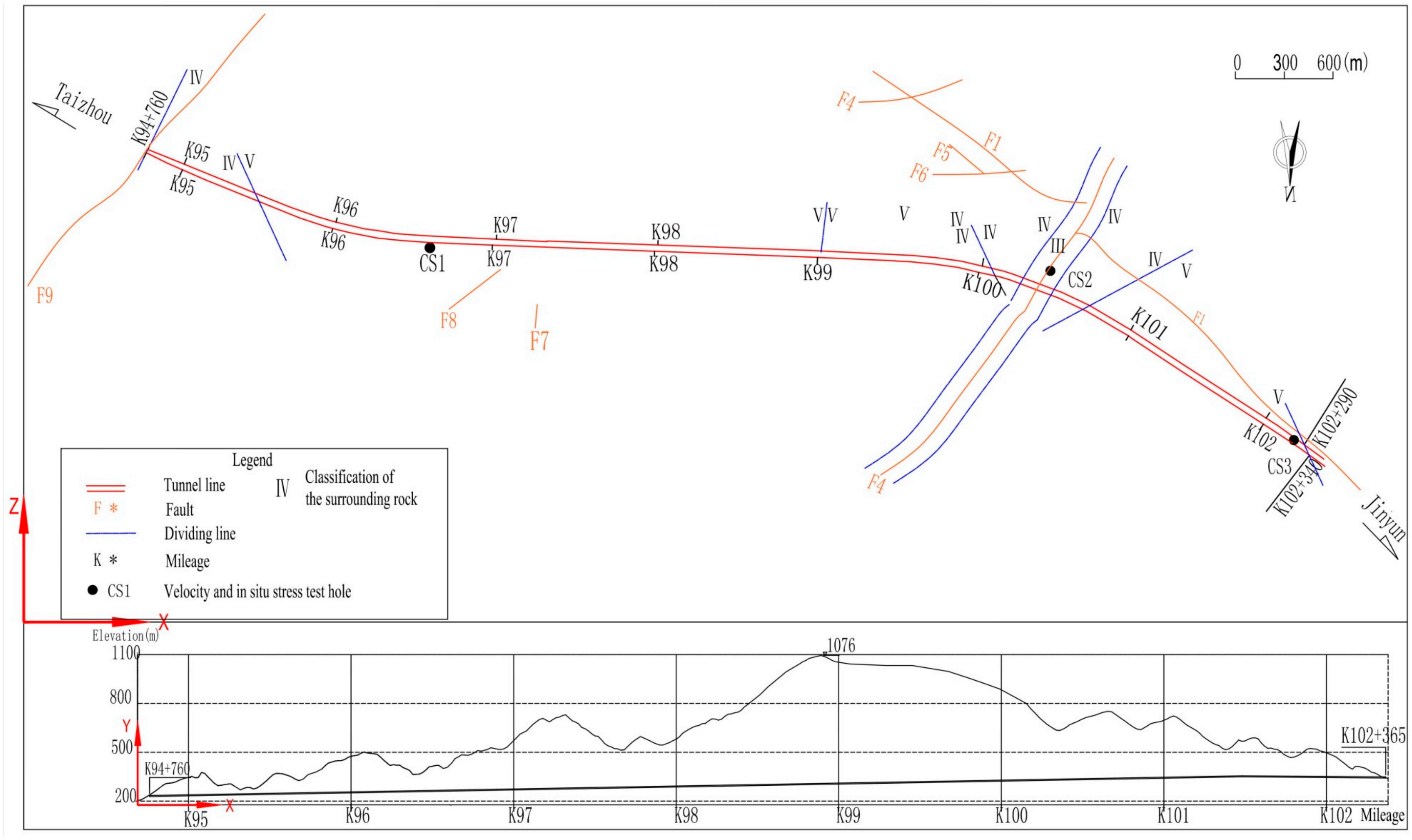


Figure 3. Plane and vertical sectional diagram of Cang Ling Tunnel.

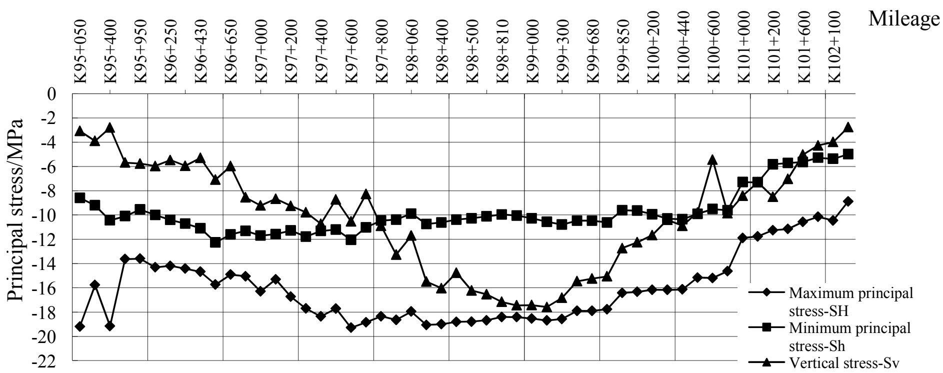


Figure 4. The principal stress field distribution along the axial direction of Cang Ling Tunnel.

3.2. Choice and Implementation of Long-Term Health Monitoring Project

The concept of structural safety based on stress is clear, and stress monitoring can easily and directly reflect the mechanical characteristics of the surrounding rock and supporting structure compared with the traditional deformation monitoring. Therefore, the tunnel structural health monitoring system based on long-term stress monitoring has been proposed and established gradually in recent years [3,4]. At the same time, with the increase of tunnel service time, lining structures, especially primary supports, will deteriorate gradually during the operation. The load will be transferred to the secondary lining, which will gradually become an important bearing unit. Final tunnel safety will be reflected in the existing status of the secondary lining. Based on the above idea, the variation characteristics of the contact pressure (contact pressure means the pressure between the primary support and the secondary lining, similarly hereinafter) and the internal force of the secondary lining are major concerns for the long-term monitoring project of Cang Ling Tunnel (Figure 5). The embedded sensors, including pressure cells and strain gauges, are respectively located on vaults, both sides of the spandrel, and the side walls of the secondary lining. The pressure cells are located between the primary support and the secondary lining. They are fixed on the primary support with cross buckles before the secondary lining is applied. Two strain gauges are symmetrically buried in the inside and outside of each monitoring section. The embedding process is as follows: Firstly, the embedded strain gauges should be symmetrically strapped in the middle of the secondary lining main rebar with tying wires. Then, the wires should be guided along the waterproof to the reserved cavity located on the side walls of weak cable channel, which is convenient for networking and to subsequently transmit the monitoring data to the LAN. The variation of the contact pressure and the secondary lining stress are the focus when monitoring the entire life cycle of the Cang Ling Tunnel, which can help with judging the safety of the supporting structure. Figures of the reserved cavity, pressure cell, and strain gauge in the field are shown in Figure 6.

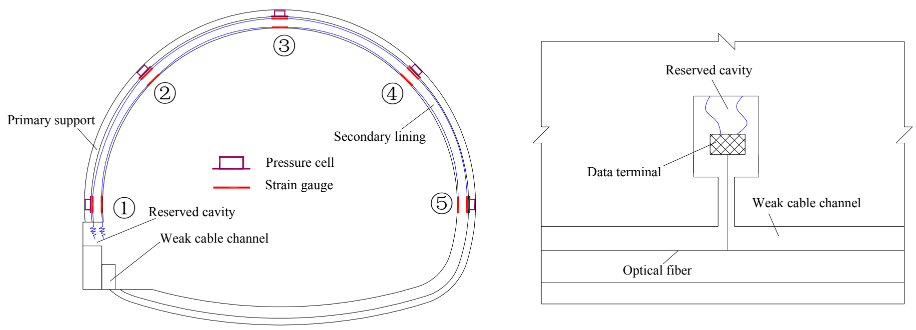
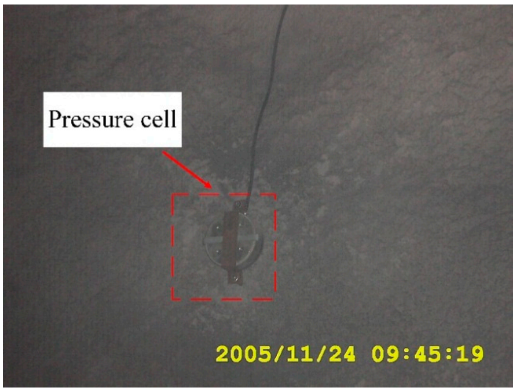
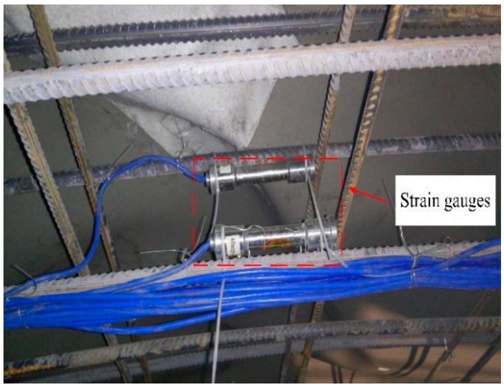


Figure 5. Layout diagram of the long-term monitoring sensors in Cang Ling Tunnel.



(**a**)



(**b**)

(**c**)

Figure 6. Embedding figures of the reserved cavity, pressure cell, and strain gauge in the field. (**a**) Pressure cell; (**b**) Strain gauge; (**c**) Reserved cavity.

According to the rock condition, the grade of the surrounding rock, the section type, and the support parameters, the Cang Ling Tunnel is divided into 20 segments (Table 1). The characteristics of hydrogeology, stress field status, support types, and parameters are basically the same in each segment. In each segment, sensors are embedded in typical sections to carry out long-term monitoring.

Table 1. Segment classification and typical monitoring sections in Cang Ling Tunnel.

Serial Number	Mileage of the Segment	Typical Monitoring Section	Serial Number	Mileage of the Segment	Typical Monitoring Section
1	ZK94+760~ZK95+400	ZK94+900	11	K95+304~K95+850	K95+350
2	ZK95+400~ZK96+350	ZK95+609	12	K95+850~K96+650	K96+000
3	ZK96+350~ZK97+073	ZK96+370	13	K96+650~K97+650	K96+790
4	ZK97+073~ZK97+550	ZK97+093	14	K97+650~K98+469	K98+000
5	ZK97+550~ZK98+600	ZK97+655	15	K98+469~K99+100	K98+490
6	ZK98+600~ZK99+400	ZK98+895	16	K99+100~K99+969	K99+240
7	ZK99+400~ZK100+160	ZK99+521	17	K99+969~K100+719	K100+000
8	ZK100+160~ZK100+900	ZK100+220	18	K100+719~K101+150	K100+740
9	ZK100+900~ZK101+700	ZK101+050	19	K101+150~K102+300	K101+535
10	ZK101+700~ZK102+200	ZK101+900	20	K102+300~K102+365	K102+340

3.3. The Classification of Health Levels for a Tunnel Structure

The structural health status of a tunnel is a very abstract concept. It is necessary to divide the health status into several measurable safety levels. At present, the main methods are the three-class classification method, the four-class classification method, the five-class classification method, and the 10-class classification method.

Of these classification methods, the three-class classification method is relatively simple. It is mainly used for the evaluation of the results of the tunnel inspection (the daily inspection, the regular inspection, and the special inspection). The five-class classification method is based on the four-class classification method. However, the classification of the 10-class classification method is too detailed. In the health evaluation of the highway tunnel structure, some conditions are not necessary. Therefore, on the basis of the existing tunnel health level classification method, considering the wide application of the four-class classification method, the health status of the structure of the Cang Ling Tunnel is divided into four levels. There are: $V = \{v_1, v_2, v_3, v_4\}$ = {I,II,III,IV}. Among them, v_1 means the structure is safe, v_2 means the structure is basically safe, v_3 means the structure is potentially unsafe, and v_4 means the structure is unsafe. The meanings of each level are shown in Table 2.

Table 2. Health levels of a tunnel structure.

Health Levels	Evaluation
Level I (Safe)	The structure is safe. The structure is intact or has tiny cracks. In this stage, pedestrians and traffic safety will not be affected. Maintaining daily monitoring is enough
Level II (Basically Safe)	The structure is basically safe. The structure is slightly damaged or has tiny cracks. In this stage, pedestrians and traffic safety will not be affected. Maintaining daily monitoring is enough. Whether the structural stress will develop further or not should be determined by the combined judgment of the long-term monitoring project. Strengthening the monitoring frequency and daily maintenance are suggested
Level III (Potentially Unsafe)	The structure is potentially unsafe. The structure is seriously damaged or has cracks. In this stage, pedestrians and traffic safety will be affected sooner or later. Further development will lead to the decrease of the structure function or even the failure of the structure. Increasing the monitoring frequency and taking strengthening measures as soon as possible are suggested
Level IV (Unsafe)	The structure is unsafe. The structure is seriously damaged and the damage continues to develop. In this stage, pedestrians and traffic are endangered. Immediately increasing the monitoring frequency and taking reinforcement measures are suggested

3.4. Application of Fuzzy Synthetic Evaluation of Long-Term Structural Health in Cang Ling Tunnel

3.4.1. Establishment of the Evaluation Model

When using the fuzzy method to evaluate the health status of a tunnel structure, one of the key points is establishing the evaluation model. Through the in-depth analysis of the various factors affecting the health status of the tunnel structure, coupled with the long-term monitoring project carried out in the Cang Ling Tunnel, the two-level fuzzy synthetic evaluation model of the structural health status for the Cang Ling Tunnel is established. This model is shown in Figure 7.

From Figure 7, it can be seen that the multi-level fuzzy synthetic evaluation model of the tunnel structural health is divided into three layers. The first layer is the target layer, including a target object. The target object is the health evaluation system of the tunnel structure. The second layer is the control layer, including the factors that may influence the health status of the tunnel structure. The factors are the stress characteristics of the structure U_1, the engineering geological characteristics U_2, the initial geostress characteristics U_3, the tunnel section characteristics U_4 and other influencing factors U_5. The third layer is the index layer, consisting of 14 indices that may influence the control layer factors (Figure 6).

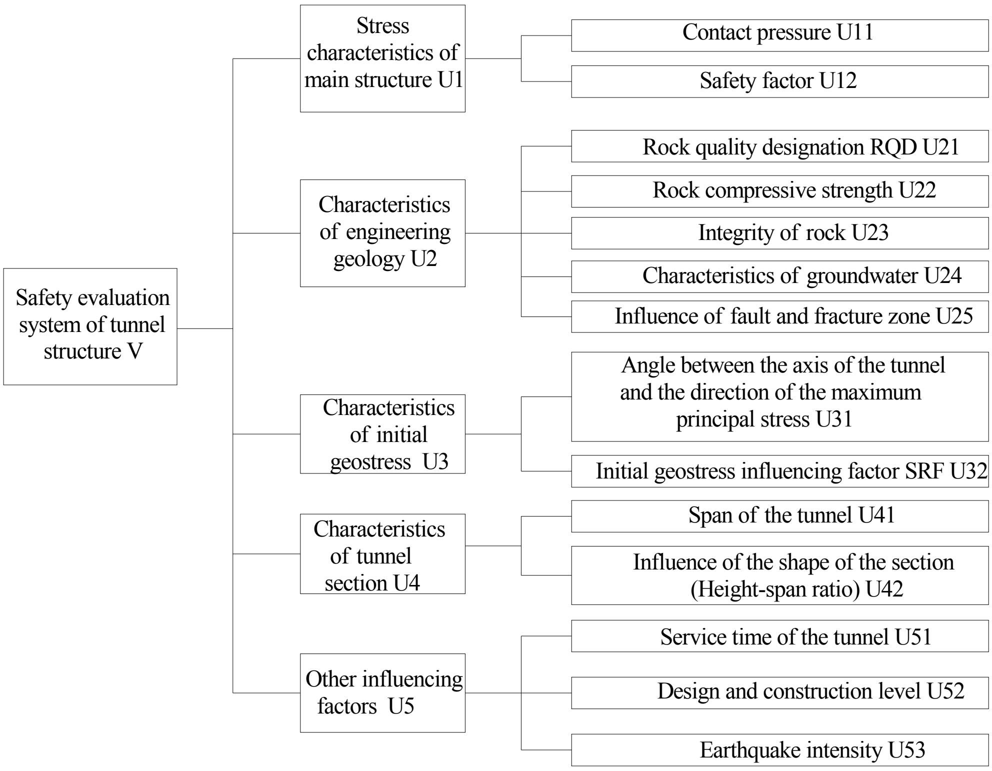


Figure 7. Fuzzy synthetic evaluation model.

It should be noted that in order to quickly determine the current status of the health and safety of the tunnel structure, the internal force (the axial force and the bending moment) of the secondary lining obtained by long-term monitoring are converted into safety factors U_{12} in the evaluation model according to the conventional safety formulas (Equations (1) and (2)) in the Code for Design of Highway Tunnels [30]:

(1) When the eccentricity $e_0 \leq 0.2h$, where "h" is the thickness of the secondary lining, the section of the concrete is an axial compression member or a compression member with a small eccentricity. The bearing capacity is controlled by the compressive strength. The safety factor is calculated as follows:

$$K \leq \phi \alpha R_a bh/N, \quad (1)$$

where: R_a: The ultimate compressive strength of the concrete, which is applied according to the Code for Design of Highway Tunnel [30]. K: The safety factor. N: The axial force of the section (KN). B: The width of the secondary lining. Take b = 1 m. h: The thickness of the secondary lining (m). ϕ: The longitudinal bending coefficient of the member, ϕ can be taken as ϕ = 1. α: The eccentric influencing coefficient of the axial force that is applied according to the Code for Design of Highway Tunnels [30].

(2) When the eccentricity $e_0 > 0.2h$, the section of the concrete is a compression member with a large eccentricity. The bearing capacity is controlled by the tensile strength. The safety factor is calculated as follows:

$$K \leq \phi \frac{1.75 R_l bh}{(\frac{6e_0}{h} - 1)N}, \quad (2)$$

where R_l is the ultimate tensile strength of the concrete, which is applied according to the Code for Design of Highway Tunnels [30]. Other symbols are the same as in Equation (1).

3.4.2. The Determination of Criteria and Weight of Each Index in the Evaluation Model

In order to scientifically evaluate the structural health status of Cang Ling Tunnel, it is necessary to establish the relationship between each index in the fuzzy synthetic evaluation model and the health level of the structure. In other words, it is necessary to establish the evaluation criteria for each factor.

1. Research on the evaluation criteria of the internal force and contact pressure for the tunnel structure.

With the increase of service time of the tunnel, the primary support will deteriorate gradually, as has been mentioned before, or the bearing capacity of the primary support will gradually decrease due to corrosion and other reasons. From now on, the load of the surrounding rock will gradually transfer to the secondary lining. The secondary lining will become an important bearing unit. The safety of the tunnel structure will also be reflected in the safety of the secondary lining. Therefore, the internal force of the secondary lining is the most important information for the safety of tunnel structure during the operational period. In the tunnel structure safety evaluation system that is based on the values of the internal force of the secondary lining (the axial force and bending moment), the key point is scientifically defining the bearing capacity of the supporting structure under different safety conditions. Therefore, based on the self-designed horizontal loading device, and taking the Cang Ling Tunnel as the prototype, the authors carried out a destructive model test for the surrounding rock-supporting system of the tunnel over the entire life cycle (Figure 8) [13]. The whole test bench is 5.34 m × 5.44 m × 2.4 m, including the 3.64 m × 3.64 m × 0.3 m test trough and the 3 m × 3 m × 0.3 m model specimen. The model specimen is laid between two 25 mm thick steel plates. The upper and lower boundary of the cover plate is confined by two box beams whose sizes are 0.6 m × 0.4 m. In order to keep the specimen in the plane strain state in the loading process, two sets of 4–6 high precision hydraulic jacks of 60 t in total are connected with the upper two boxes beam to control the vertical displacement of the specimen. The initial geostress field is achieved by eight high precision hydraulic 60-t jacks. Two jacks are applied in each direction of the load in the way of surface force through the load distribution beam. The oil pressure is driven by the air pressure through an electric pump. After using the WY-300/V type hydraulic regulator to adjust the hydraulic pressure, two sets of different loads are exported, according to the predetermined value. This system can guarantee the stability accuracy of the load applied at each level.

The model test steps are as follows:

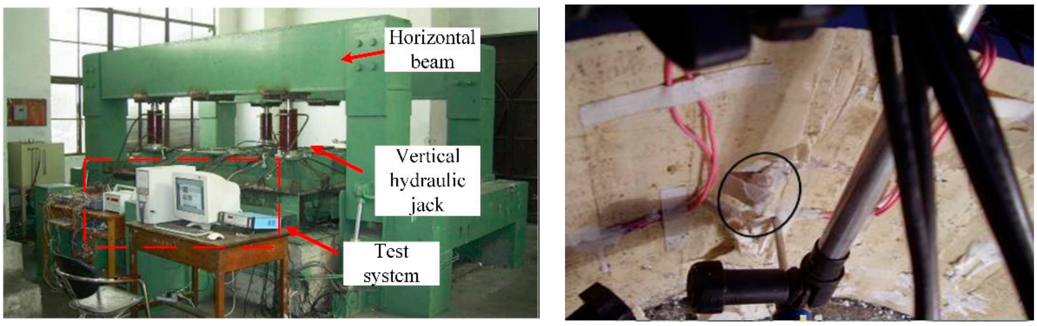
(1) In order to keep the plane strain state and reduce the friction between the test tank and the simulated surrounding rock, the upper and lower steel plate and the distribution beam are buttered. Then the film is pasted on the upper and the lower steel plate to isolate the surrounding rock and the butter;
(2) According to the different factors of surrounding rock, wires are pulled around the test tank to control the feeding quantity. After artificial leveling, a compaction rammer is used. Compacted density is controlled by the cutting ring method. The upper steel plate is lifted after compaction, then the vertical jack is installed to restrain the vertical displacement;
(3) According to the initial geostress field of each section in the similarity comparison tests, the specimen is loaded with the initial geostress before the excavation of the tunnel. Then the tunnel is excavated in the middle of the surrounding rock under the initial geostress field. Rock bolts are inserted and a steel arch is installed when necessary;
(4) The primary support is constructed and the pressure cells are fixed to it with cross buckles. Then, the secondary lining with strain gauges is placed in the excavated model tunnel to simulate the construction process of the tunnel;
(5) The wires of the pressure cells and the strain gauges are connected to the strain acquisition instrument and the displacement meters are displayed. When the strength of the primary support reaches the design strength, the specimen is loaded with the initial geostress fields of different sections, from small to large, until the main structure of the tunnel is destroyed (lateral pressure

coefficient is fixed during the loading process). When the structure is stable after the loading of each level of initial geostress field, corresponding strain, pressure, and displacement are measured by the data acquisition instrument controlled by a computer;

(6) The behavior of the secondary lining from the first crack appearing to the final complete failure is recorded in detail. The structural failure characteristics, damage location, crack width, depth, etc. are paid attention to. After the secondary lining is completely destroyed, the specimen is unloaded and the test is finished;

(7) The data are arranged and analyzed. Based on the data, a study of the mechanical behavior of the main structure of the tunnel under different initial geostress fields during construction and operation can be carried out.

Thus, the corresponding bearing capacity (the axial force and the bending moment) of the secondary lining under different security levels can be acquired, providing the criteria for the rational judgment of the structural health status of the Cang Ling Tunnel (Table 3). The corresponding relationship between the health level and safety factors of the structure can be determined by the following steps. First, the axial force and bending moment of the secondary lining obtained by the tests are converted to safety factor through Equations (1) and (2). According to the appearance of the secondary lining structure during the tests (such as the existence of the cracks and the development of the cracks, etc.) and the rule of the displacement, the health level can be determined. Then the corresponding relationship between the health level and safety factors can be determined according to their values.



(**a**) (**b**)

Figure 8. Entire life cycle loading and destructive model test for the secondary lining. (**a**) Test equipment diagram; (**b**) Failure diagram of lining structure.

Table 3. The evaluation criteria for the stress characteristics of the structure in the evaluation model.

Section Type	Classification	The Thickness of the Lining (cm)	Influencing Factor	Health Level			
				Level I	Level II	Level III	Level IV
Standard section	Surrounding rock of grade IV	45	Contact pressure (kPa) Safety factor	<540 >4.49	540~1012 4.49~2.54	1013~1263 2.55~1.01	>1263 <1.01
		35	Contact pressure (kPa) Safety factor	<420 >4.23	420~720 4.23~2.16	721~878 2.17~1.12	>878 <1.12
	Surrounding rock of grade III	30	Contact pressure (kPa) Safety factor	<390 >4.46	390~640 4.46~2.37	641~814 2.38~0.99	>814 <0.99
	Surrounding rock of grade II	30	Contact pressure (kPa) Safety factor	<482 >4.215	482~709 4.22~1.95	710~810 1.96~1.15	>810 <1.15
Enlarged section	Emergency parking area	40	Contact pressure (kPa) Safety factor	<395 >3.71	395~590 3.71~1.82	591~781 1.83~0.96	>781 <0.96
	Vehicle cross channel	50	Contact pressure (kPa) Safety factor	<443 >3.91	443~626 3.91~2.15	627~874 2.16~1.02	>874 <1.02

2. Analysis of the criteria for other factors in the evaluation model.

As for the acquisition of the evaluation criteria of other indices in the model, plenty of research results about the stability classification of the tunnel at home and abroad are available. Afterwards, combined with the index value of the Code for Design of Highway Tunnel [30] and numerical analysis, the evaluation criteria can be determined and are shown in Table 4 [30,33–35]. The design and construction levels are acquired by consulting construction and design experts and taking a wide range of surveys. The influence of the shape of the tunnel is determined mainly by numerical simulation. The displacement and stress characteristics of tunnels with different section shapes are analyzed to determine the influence of the shape of the tunnel.

Considering the influence of each factor and its index in the evaluation model on the health of the tunnel structure are not the same, in order to reflect the different influencing degree of each factor, a 1–9 scale method in the AHP is applied to analyze the weight of each factor in the evaluation model. It can mainly be divided into four steps by using the AHP to solve the problem. Step 1 is establishing the hierarchical structure of the problem. First, the complex problem is divided into several parts, which are called elements. Then, these elements are divided into several groups according to their properties, forming different layers. The elements in the same layer dominate the elements of the next level, and are governed by the elements of the upper level. These upper and lower dominance relations form a hierarchical structure. The hierarchical relationship of this model is shown in Figure 7. Step 2 is constructing the comparison and judgment matrix. As for the safety of the main structure during the operation of the Cang Ling Tunnel, based on the analysis of the weight of each factor, the scale of the judgment matrix is determined by consulting experts and then comparison and judgment matrices can be constructed. When an element is compared with another element, the more important the former element is compared the latter one, the smaller the scale of the judgment matrix is. The range of the scale is from 1 to 9, which is the 1–9 scale method. The judgment matrices are constructed according to these scales. Step 3: the relative weights of the comparison factors are calculated by the characteristic roots method that is normally used. According to the judgment matrix constructed in Step 2, the characteristic roots can easily be obtained. The characteristic roots method means that the problem of obtaining the weights can be converted into a problem of obtaining the characteristic roots. Step 4 is judging the consistency of the judgment matrix. The weight of each factor and its index in the evaluation model are determined and listed in Table 5, hoping to make it coincide with the actual situation. The judging matrices can be adjusted when it is necessary in this step.

Table 4. Safety criterion value of other factors in evaluation model.

Health Level Influencing Factor		Level I	Level II	Level III	Level IV
Engineering geological characteristics	Rock quality designation RQD/%	100~91	90~76	75~51	50~0
	Rock compressive strength/MPa	200~121	120~61	60~31	30~0
	Rock integrity K_v	1.0~0.76	0.75~0.56	0.55~0.36	0.35~0
	Groundwater conditions/$L \cdot \text{min}/10$ m	0~10	11~25	26~125	126~300
	Influence of the fault fracture zone	No fault or fracture zone nearby	Small fault nearby or the fracture zone is far away	Tunnel is near to the small fault or passes through small fracture zone	Large fault has a certain effect, or the tunnel is near to the large fault or the fracture zone or passes through them
Stress field characteristics	Angle between the axis of the tunnel and the direction of the maximum principal stress	Very favorable (0~$\frac{1}{12}\pi rad$)	Favorable ($\frac{4}{45}\pi$~$\frac{7}{36}\pi rad$)	Generally favorable ($\frac{1}{5}\pi$~$\frac{1}{3}\pi rad$)	Disadvantage (>$\frac{1}{3}\pi rad$)
	Initial geostress influencing factor, SRF	<5	5–10	11–20	>20
Cavity characteristics	Span of the tunnel/m	0~5	6~15	16~20	>20
	Influence of the shape of the tunnel (height-span ratio)	Very favorable	Favorable	Generally favorable	Disadvantage
Other influencing factors	Service time of the tunnel/year	0~10	11~20	21~40	>40
	Design and construction level	High	Relatively high	Normal	Low
	Seismic intensity	1~3	4~5	6~7	8~12

Table 5. Weight of each factor and its relevant indices in the evaluation model.

Control Layer	Weight of the Control Layer	Index Layer	Weight of the Index Layer
Stress characteristics of the main structure	0.524	Contact pressure between layers	0.5
		Conventional safety evaluation	0.5
Engineering geological characteristics	0.244	Rock quality designation RQD	0.206
		Rock compressive strength	0.367
		Rock integrity coefficient	0.206
		Situation of the underground water	0.125
		Influence of the fault and the fracture zone	0.096
Stress field characteristics	0.107	Angle between the axis of the tunnel and the direction of the maximum principal stress	0.667
		Initial geostress influencing factor, SRF	0.333
Cavity characteristics	0.063	Span of the tunnel	0.5
		Influence of the shape of the tunnel (height-span ratio)	0.5
Other influencing factors	0.063	Service time of the tunnel	0.320
		Design and construction level	0.558
		Seismic intensity	0.122

3.4.3. Determination of the Membership Function

Another key problem in fuzzy synthetic evaluation is the determination of the membership function. The key to determining the fuzzy relation is to determine the membership degree of each factor, which means determining the quantitative relationship between the evaluation factors and the evaluation levels. The function to measure the membership degree between the evaluation factors and the evaluation levels is called a membership function. Considering the strong subjectivity of experts' opinion, the membership function is determined by mathematical functions. The influencing factors in the evaluation model include qualitative and quantitative indices. As for quantitative indices, they can be obtained directly from the membership function when determining the subordinate degree. As for qualitative indices, they should be properly quantified first. Then, the subordinate degree can be obtained from the membership function.

The stress characteristics of a tunnel structure, through the analysis of the existing data, almost follow the normal distribution [36]. Therefore, it is expressed in the normal form when constructing the membership function. As for the engineering geological characteristics and the seismic intensity, the normal distribution is also commonly used when determining the membership function of each index because of their large discreteness [34,35].

Considering that the types of the index functions are almost the same, the difference is only reflected in the parameters of membership function. This paper takes the structure type of the grade IV standard section whose lining thickness is 45 cm as an example. The membership functions of the contact pressure are:

$$\mu_{\rm I} = \begin{cases} 1 & x < 270 \\ e^{-\left(\frac{x-270}{292.5}\right)^2} & x \geq 270 \end{cases} \quad \mu_{\rm II} = \begin{cases} e^{-\left(\frac{x-776}{292.5}\right)^2} & x < 776 \\ e^{-\left(\frac{x-776}{209}\right)^2} & x \geq 776 \end{cases} \quad \mu_{\rm III} = \begin{cases} e^{-\left(\frac{x-1137.5}{209}\right)^2} & x < 1137.5 \\ e^{-\left(\frac{x-1137.5}{114.4}\right)^2} & x \geq 1137.5 \end{cases}$$

$$\mu_{\rm IV} = \begin{cases} e^{-\left(\frac{x-1335.4}{114.4}\right)^2} & x < 1335.4 \\ 1 & x \geq 1335.4 \end{cases}.$$

As for the determination of three quantitative index membership functions—the ground stress influencing factor (SRF), the span of the tunnel, and the service time of the tunnel—trapezoidal membership functions are constructed. The membership functions of the tunnel span are listed as follows:

$$\mu_{\mathrm{I}} = \begin{cases} 1 & x < 5 \\ 3 - 0.4x & 5 \le x \le 7.5 \\ 0 & x \ge 7.5 \end{cases} \quad \mu_{\mathrm{II}} = \begin{cases} 0 & x < 5 \\ 0.4x - 2 & 5 \le x \le 7.5 \\ 1 & 7.5 \le x \le 10 \\ 5 - 0.4x & 10 \le x \le 12.5 \\ 0 & x \ge 12.5 \end{cases} \quad \mu_{\mathrm{III}} = \begin{cases} 0 & x < 10 \\ 0.4x - 4 & 10 \le x \le 12.5 \\ 1 & 12.5 \le x \le 17.5 \\ 8 - 0.4x & 17.5 \le x \le 20 \\ 0 & x \ge 20 \end{cases}$$

$$\mu_{\mathrm{IV}} = \begin{cases} 0 & x < 17.5 \\ 0.4x - 7 & 17.5 \le x \le 20 \\ 1 & x \ge 20 \end{cases}.$$

As for qualitative indices, they are divided into four levels on the basis of the available information: excellent (0.9), good (0.7), average (0.5), and poor (0.3). The evaluation values can be obtained according to the given evaluation criteria, followed by quantification using the trapezoidal membership function. The membership function is constructed as shown in Figure 9:

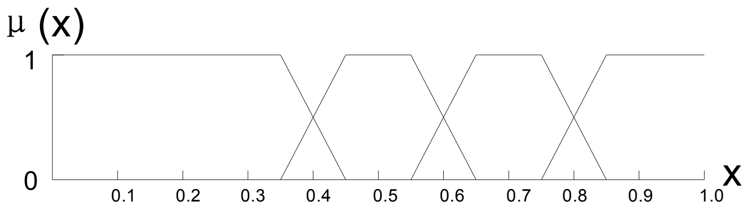


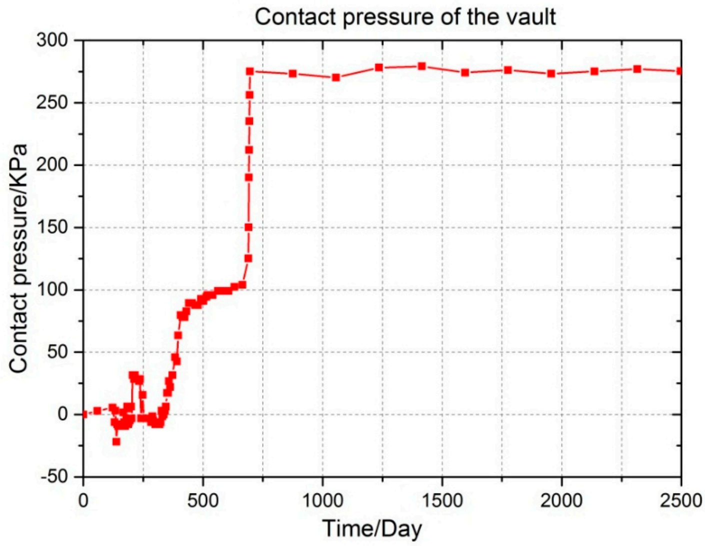
Figure 9. Figure of membership function for qualitative indices.

4. Evaluation of Structural Health Status of Cang Ling Tunnel Based on Filed Data

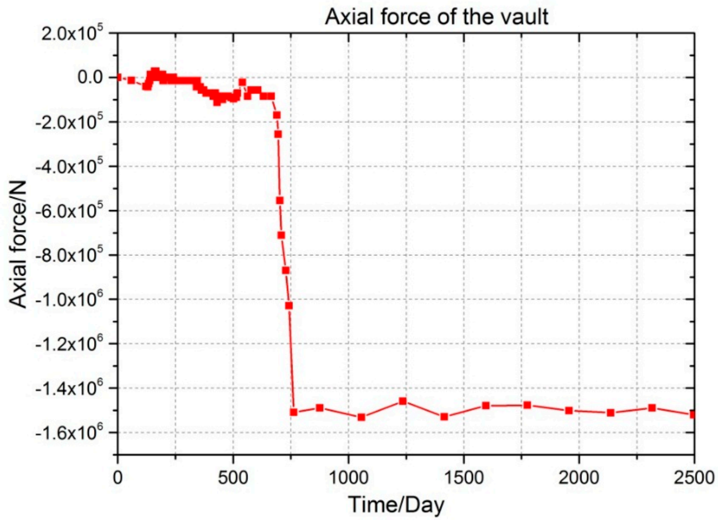
In order to accurately evaluate the current structural safety status, the value of each index in the evaluation model should be obtained. Through the investigation of the design data, construction data, and related research results of the Cang Ling Tunnel, the stress characteristic of the structure is obtained by the long-term monitoring sensors that were embedded during the construction. These data can be obtained by automatic inspection of the established long-term health monitoring network system. Due to the numerous data, this paper only takes the segment of K102+300~K102+365 on the right line as an example to illustrate.

The surrounding rock in this segment is mainly granite–porphyry and the surrounding rock is classified as grade IV. The thickness of the secondary lining is 45 cm. The long-term monitoring sensors embedded in the section of K102+340 acquire the contact pressure and the stress of the secondary lining. The data of the vault are shown in Figure 10.

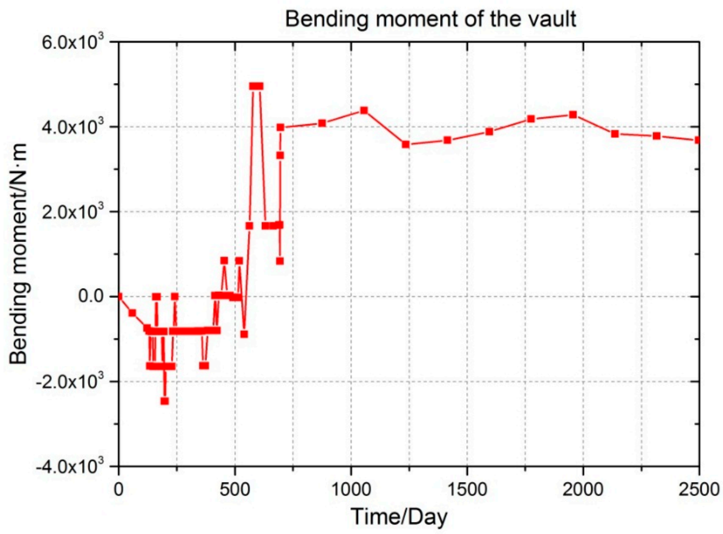
As we can see from Figure 10, the contact pressure and the bending moment tend to gradually converge after about 700 days. The axial force tends to converge after about 750 days. This is because the data of the crown are stable after about 750 days and at this time the values of the crown almost reach the maximum. Therefore, the data at 2500 days are taken as stress indices to evaluate the safety of the structure. The value axial force is 1.52×10^6 N, the bending moment is 3.68×10^3 N·m, and the contact pressure is 275 kPa. Through a series of analyses, the index values are set as: [275, 5.0, 52.5, 98.7, 0.52, 10, 0.7, 54.35, 4.5, 12.22, 0.65, 7.5, 0.75, 5]. Substituting the above index values into the membership functions, the fuzzy relationship matrix R of the index layer can be obtained.



(**a**)



(**b**)



(**c**)

Figure 10. Time-history curve of the contact pressure, axial force, and bending moment of the vault (K102+340 section). (**a**) Contact pressure; (**b**) Axial force; (**c**) Bending moment.

It should be noted that in Figure 10, since the time span of the horizontal coordinate is pretty long, some parts of the time-history curve show a sudden increase. However, the actual variation time is still pretty long. Take the contact pressure of the vault (Figure 10a) for instance: the contact pressure began to increase significantly at day 665 and gradually converges after about 700 days. The increasing stage is about a month. However, compared with the total of 2496 days, this month looks just like a few days.

In this paper, the fuzzy relationship matrix of the stress characteristics of the structure R_1 is given as:

$$R_1 = \begin{bmatrix} 0.9997 & 0.053 & 0 & 0 \\ 0.804 & 0.203 & 0 & 0 \end{bmatrix}. \tag{3}$$

After obtaining the fuzzy relationship matrix R_i, the $U_i = W_i \times R_i$ is used to carry out the fuzzy operation (W_i means the weight matrix of the index layer). Then the fuzzy relationship matrices of the control layer U_i can be obtained:

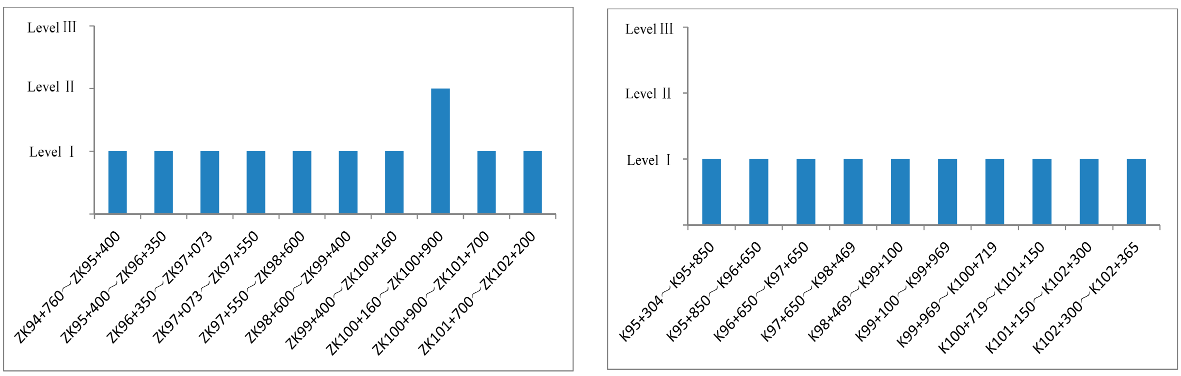
$$U_1 = W_1 \cdot R_1 = \begin{bmatrix} 0.5 & 0.5 \end{bmatrix} \cdot \begin{bmatrix} 0.9997 & 0.053 & 0 & 0 \\ 0.804 & 0.203 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 0.902 & 0.128 & 0 & 0 \end{bmatrix}. \tag{4}$$

Similarly, the fuzzy relationship matrix V of the target layer is

$$\begin{aligned} V = W_i \cdot U_i = \begin{bmatrix} 0.524 & 0.244 & 0.107 & 0.063 & 0.063 \end{bmatrix} \cdot \begin{bmatrix} 0.902 & 0.128 & 0 & 0 \\ 0.114 & 0.553 & 0.321 & 0.046 \\ 0.333 & 0 & 0.667 & 0 \\ 0 & 0.556 & 0.444 & 0 \\ 0.32 & 0.616 & 0.058 & 0.13 \end{bmatrix} \\ = \begin{bmatrix} 0.556 & 0.276 & 0.181 & 0.012 \end{bmatrix}. \end{aligned} \tag{5}$$

According to the principle of maximum membership degree, it can be known that the current health status of the tunnel structure in segment K102+300~K102+365 is level I, which means this segment is safe.

The health status of each segment of the Cang Ling tunnel can be evaluated as above. The current structural health status within the entire range of the tunnel can be obtained (Figure 11): Results reveal that the structure of the Cang Ling Tunnel is almost at level I health status. Only a small number of segments are at level II, which shows that the Cang Ling Tunnel is safe, consistent with the actual operational situation.



(**a**) (**b**)

Figure 11. Structural safety status of Cang Ling Tunnel at present. (**a**) Left line; (**b**) Right line.

5. Conclusions

Based on the application of the fuzzy synthetic method to the long-term health status evaluation of a selected tunnel structure and the associated analysis, the following conclusions can be made:

(1) A tunnel is a coupled system of the surrounding rock and the supporting structure. The safety status of the tunnel structure is a complex system that is influenced by various factors. In addition, these factors are coupled and interact with each other, which calls for a linguistic description of the tunnel safety level. Therefore, the fuzzy synthetic method should be adopted;
(2) According to the investigation and analysis of the safety status classification of tunnels at home and abroad, and combined with the present situation of safety status classification of tunnel structures in China, the health status of a highway tunnel structure is divided into four levels: safe, basically safe, potentially unsafe, and unsafe. In this research, the fuzzy synthetic method is proposed to evaluate the tunnel safety level;
(3) With the increase of service time of the tunnel, the primary support gradually deteriorates. The safety of the tunnel structure will be reflected in the safety of the secondary lining. Therefore, the stress of the secondary lining and the contact pressure between the primary support and the secondary lining are selected as a long-term monitoring project. Long-term monitoring sensors are embedded to acquire structural stress characteristics, providing data for structural safety evaluation. The sensors that monitor the stress of the secondary lining and the contact pressure are embedded in the lining of the Cang Ling Tunnel. From these sensors, the stress data for the safety evaluation of the tunnel structure are obtained;
(4) Through analysis of the various factors affecting the health status of the tunnel structure, coupled with the long-term monitoring project carried out in the Cang Ling Tunnel, the two-level fuzzy synthetic evaluation model of the structural health status for the Cang Ling Tunnel is established. The fuzzy synthetic evaluation model mainly includes the stress characteristics of the tunnel structure, the engineering geological characteristics, the characteristics of the initial geostress, and the characteristics of the tunnel section. Moreover, the factors are refined into 14 specific indices;
(5) As for the tunnel structural health, through the analysis of the distribution characteristics of the influencing indices, the membership functions of indices in the fuzzy synthetic evaluation model are established. The types of membership functions are mainly normal distribution and trapezoidal distribution. The corresponding relationship between each index in the fuzzy synthetic evaluation model and the health level of the tunnel structure and the determination criteria are established using model tests, field tests, and other methods. By using the AHP, the weight of each index in the safety evaluation system of tunnel structure is obtained. According to the membership functions, the determination criteria, and the weight values of the evaluation model, the subordinate degree is obtained using the method of fuzzy mathematics;
(6) According to the principle of maximum membership degree, based on the contact pressure and the stress of the secondary lining acquired by the long-term health monitoring sensors of Cang Ling Tunnel, the health status of the main structure of Cang Ling Tunnel is evaluated using the proposed fuzzy synthetic evaluation. The results show that the current health status of most of Cang Ling Tunnel is at level I safety status. Only a small number of segments are at the basic safety status, which is level II.

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References

1. Wu, S.; Lin, C.; Zhang, Z.; Li, Z. Application of structural health monitoring in Hangzhou Qiantang River Tunnel. In Proceedings of the International Conference on Electric Technology and Civil Engineering, Lushan, China, 22–24 April 2011; pp. 2004–2007.
2. Ke, S.; Zhang, W.; Ding, P.L. The structural health monitoring system for Nanjing Yangtze River Tunnels. In Proceedings of the Second International Conference on Electric Information and Control Engineering, Lushan, China, 6–8 April 2012; pp. 1562–1566.
3. Wang, B.; He, C.; Wu, D.X. Ideas of tunnel structure health monitoring system and its technology application. *J. Railw. Eng. Soc.* **2012**, *1*, 67–72.
4. Li, X.; He, C.; Wang, S.M.; Wang, B. Design and Application of Long-term Safety Monitoring System of Highway Tunnel under Complex Geological Conditions. *China Saf. Sci. J.* **2013**, *23*, 89–95. [CrossRef]
5. Zheng, Z.; Lei, Y. Structural monitoring techniques for the largest excavation section subsea tunnel: Xiamen Xiang'an Subsea Tunnel. *J. Aerosp. Eng.* **2016**, B4016002. [CrossRef]
6. Schotte, K.; Nuttens, T.; Wulf, A.D.; Bogaert, P.V.; Backer, H.D. Monitoring the structural response of the Liefkenshoek Rail Tunnel to tidal level fluctuations. *J. Perform. Constr. Facil.* **2016**, *30*, 04016007. [CrossRef]
7. Su, J.; Zhang, D.; Niu, X.; Fang, Q. Research on design of subsea tunnel structural health monitoring. *Chin. J. Rock Mech. Eng.* **2007**, *26*, 3785–3792.
8. Soga, K.; Amatya, B.; Wright, P.; Bennett, P.J.; Kobayashi, Y.; Cheung, L.L.K. Optical fibre strain measurement for tunnel lining monitoring. *Geotech. Eng.* **2010**, *163*, 119–130.
9. Bursi, O.S.; Tondini, N.; Fassin, M.; Bonelli, A. Structural monitoring for the cyclic behaviour of concrete tunnel lining sections using FBG sensors. *Struct. Control Health Monit.* **2015**, *23*, 749–763. [CrossRef]
10. Zhang, W.; Zhang, Z.; Qi, D.; Liu, Y. Automatic crack detection and classification method for subway tunnel safety monitoring. *Sensors* **2014**, *14*, 19307–19328. [CrossRef] [PubMed]
11. Ye, X.W.; Ni, Y.Q.; Yin, J.H. Safety monitoring of railway tunnel construction using FBG sensing technology. *Adv. Struct. Eng.* **2013**, *16*, 1401–1410. [CrossRef]
12. Lindenbergh, R.; Bucksch, A.; Uchanski, L.; Gosliga, R.V. Structural monitoring of tunnels using terrestrial laser scanning. *Rep. Geod.* **2009**, *z. 2/87*, 231–238.
13. Lopes, V.; Park, G.; Cudney, H.H.; Inman, D.J. Impedance-based structural health monitoring with artificial neural networks. *J. Intell. Mater. Syst. Struct.* **2000**, *11*, 206–214.
14. Wang, H.; Song, G.B. Innovative NARX recurrent neural network model for ultra-thin shape memory alloy wire. *Neurocomputing* **2014**, *134*, 289–295. [CrossRef]
15. Canelon, J.I.; Shieh, L.S.; Song, G.B. A new neural network-based approach for self-tuning control of nonlinear SISO discrete-time systems. *Int. J. Syst. Sci.* **2010**, *41*, 1421–1435. [CrossRef]
16. Guo, H.Y.; Zhang, L.L.; Zhou, J.X. Optimal placement of sensor for structural health monitoring using improved genetic algorithms. *Smart Mater. Struct.* **2004**, *13*, 528. [CrossRef]
17. Li, L.; Song, G.B.; Ou, J. A genetic algorithm-based two-phase design for optimal placement of semiactive dampers for nonlinear benchmark structure. *J. Vib. Control* **2010**, *16*, 1379–1392. [CrossRef]
18. Li, L.; Song, G.B.; Ou, J. Hybrid active mass damper (AMD) vibration suppression of nonlinear high-rise structure using fuzzy logic control algorithm under earthquake excitations. *Struct. Control Health Monit.* **2011**, *18*, 698–709. [CrossRef]
19. Gu, H.; Song, G.B.; Malki, H. Chattering-free fuzzy adaptive robust sliding-mode vibration control of a smart flexible beam. *Smart Mater. Struct.* **2008**, *17*, 4006–4032. [CrossRef]
20. Zhang, W.; Sun, K.; Lei, C.; Zhang, Y.; Li, H.; Spencer, B.F. Fuzzy analytic hierarchy process synthetic evaluation models for the health monitoring of shield tunnels. *Comput. Aided Civil Infrastruct. Eng.* **2014**, *29*, 676–688. [CrossRef]
21. Zhang, Y.; Yan, X.; Yuan, C. The research of optimal monitoring point placement for health monitoring of dredger based on analytic hierarchy process. In Proceedings of the Prognostics and Health Management Conference, Macau, China, 12–14 January 2010; pp. 1–5.
22. Saaty, T.L. How to make a decision: The analytic hierarchy process. *Eur. J. Oper. Res.* **1990**, *48*, 9–26. [CrossRef]
23. Shang, L.; Tan, L.; Yu, C.; Liu, Y. *Bridge Structural Health Evaluation Based on Multi-Level Fuzzy Comprehensive Evaluation*; Springer: Berlin/Heidelberg, Germany, 2011; pp. 661–668.

24. Liu, Y.; Hui, X. Extended multi-level fuzzy comprehensive evaluation model of bridges maintenance based on fuzzy set. *Int. J. Adv. Comput. Technol.* **2012**, *4*, 158–166.
25. Wu, L.M.; Wang, Z.J. Fuzzy comprehensive evaluation method and application of slope stability. *Adv. Mater. Res.* **2011**, *243*, 4969–4974. [CrossRef]
26. Feng, S.J.; Yao, A.M.; Dong, Y.F. Fuzzy comprehensive evaluation of open-pit slope stability. *Adv. Mater. Res.* **2014**, *962*, 1029–1033. [CrossRef]
27. Onkal-Engin, G.; Demir, I.; Hiz, H. Assessment of urban air quality in istanbul using fuzzy synthetic evaluation. *Atmos. Environ.* **2004**, *38*, 3809–3815. [CrossRef]
28. Rajani, B.; Kleiner, Y.; Sadiq, R. Translation of pipe inspection results into condition ratings using the fuzzy synthetic evaluation technique. *J. Water Supply Res. Technol. AQUA* **2006**, *55*, 11–24. [CrossRef]
29. Sadiq, R.; Husain, T.; Veitch, B.; Bose, N. Risk-based decision-making for drilling waste discharges using a fuzzy synthetic evaluation technique. *Ocean Eng.* **2004**, *31*, 1929–1953. [CrossRef]
30. *Code for Design of Highway Tunnel*; China Communications Press: Beijing, China, 2004.
31. *Code for Design of Railway Tunnel*; China Railway Press: Beijing, China, 2005.
32. Wu, C.G.; He, C.; Li, X.; Zhang, F. Model test research on structure mechanics of tunnel in high geostress. *Mod. Tunn. Technol.* **2008**, *S1*, 250–255.
33. Wang, B. *Study on Safety Monitoring Technique for Expressway Tunnel during Period of Construction and Operation*; Southwest Jiaotong University: Chengdu, China, 2008.
34. Vallejo, L.I.G.D. SRC rock mass classification of tunnels under high tectonic stress excavated in weak rocks. *Eng. Geol.* **2003**, *69*, 273–285. [CrossRef]
35. Habibagahi, G.; Katebi, S. Rock mass classification using fuzzy sets. *Iran. J. Sci. Technol. Trans. B Eng.* **1996**, *20*, 273–284.
36. Jing, S.T.; Zhu, Y.Q.; Song, Y.X. *Reliability of Tunnel Structure*; China Railway Press: Beijing, China, 2002.