# ANALYSIS OF FACTORS CAUSING WATER DAMAGE TO LOESS DOUBLE-ARCHED TUNNEL BASED ON TFN-AHP

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## ABSTRACT

In order to analysis the factors causing water damage to loess double-arched tunnel, this paper conducts field investigation on water damage to tunnels on Lishi-Jundu Expressway in Shanxi, China, confirms its development characteristics, builds an index system (covering 36 evaluation indexes for construction condition, design stage, construction stage, and operation stage) for the factors causing water damage to loess double-arched tunnel, applies TFN-AHP (triangular fuzzy number-analytic hierarchy process) in calculating the weight of indexes at different levels, and obtains the final sequence of weight of the factors causing water seepage to loess double-arched tunnel. It is found out that water damage to loess double-arched tunnel always develops in construction joints, expansion joints, settlement joints, and lining joints of tunnel and even around them; there is dotted water seepage, linear water seepage, and planar water seepage according to the trace and scope of water damage to tunnel lining. The result shows that water damage to loess double-arched tunnel mainly refers to linear water seepage, planar water seepage is also developed well, and partition and equipment box at the entrance and exit of tunnel are prone to water seepage; construction stage is crucial for controlling water damage to loess double-arched tunnel, atmospheric precipitation is the main water source, and the structure defect of double-arched tunnel increases the possibility of water seepage; the final sequence for weight of various factors is similar to the actual result.

## KEYWORDS

Tunnel engineering, Double-arch tunnel, Loess; Triangular fuzzy numbers, Analytic hierarchy process, Water damage

# 1. INTRODUCTION

China has built plenty of tunnels in loess regions and accumulated rich experience in construction of loess tunnel engineering. As a kind of particular soil with collapsibility and vertical joints development, loess can lead to collapse, big surface settlement, surface crack, low bearing capacity of tunnel base, large deformation of primary support, and vertical settlement after free face results from the excavation of tunnel. Damage to loess tunnel mainly includes lining deformation, body cracking, chipping and collapse of roof, water seepage and leakage, crack, sinkhole and karst cave of surface, vault settlement, etc. Water damage caused by surface water and groundwater's directly or indirectly percolating through or flowing into tunnel affects and threatens the safety, comfort, and normal operation of loess double-arched tunnel seriously. Currently, researches on water damage to double-arched tunnel are mainly conducted through field investigation and statistic analysis, but few of them are about water damage to loess double-arched tunnel.

Wang Yuhua et al. [1] proposed treatment measures for water seepage on the basis of investigating the current status of damage to Jinzhulin double-arched tunnel and analyzing the causes of damage; Lai Jinxing et al. [2] classified water burst in loess and soft rock tunnel, put forward design principles for waterproofing and drainage of tunnel, designed waterproofing and drainage structures, and discussed their application condition through the investigation on water seepage of as-built loess and soft rock tunnels in Gansu Province and Shaanxi Province of China; Wang Jianxiu et al. [3] researched Sangongqing Tunnel on Yuanjiang-Mohei Expressway (Yunnan Province), arranged crack monitoring points, monitored crack movement, and analyzed its characteristics with time. Ding Zhaomin et al. [4] considered that the primary causes for damage are the features of loess engineering, surface water, and burial depth of tunnel based on the investigation and analysis on one loess highway tunnel, and determined the measures for repair and reinforcement of lining crack, treatment of arch foot foundation, and grouting reinforcement for tunnel roof through finite element analysis. Taking the loess double-arched tunnel on Lishi-Jundu Expressway as an example, Hu Jinchuan et al. [5] monitored the surface settlement, geological and supporting conditions, vault crown settlement and horizontal convergence on site, utilized finite element software to analyze the variation law of vault crown settlement and horizontal convergence of surrounding rock, and thus confirmed the law and factor for deformation of surrounding rock resulting from construction of loess double-arched tunnel by the three-pilot drift method. Wang Daoliang et al. [6] counted the major water seepage parts of one integral double-arched tunnel through field investigation, adopted AHP to sort the factors causing water seepage, and confirmed that the major factors causing water seepage are the structure and construction management of integral double-arched tunnel. Through field investigation on water seepage in seven double-arched tunnels on Hangzhou-Anhui Expressway, Dou Fengguang et al. [7] discovered that water seepage mainly occurred in construction joints and tunnel entrances, which was mainly affected by topography and geology, construction, and design; epoxy resin grouting materials, epoxy thickening coating, and polymer cement mortar should be used to block off the seepage parts. Lai Jinxing et al. [8] took Qijia Mountain Highway Tunnel as an example, adopted geological radar to detect the lining thickness, cavity behind the lining, and crack water, made use of sonic detector to detect lining materials, and proposed a reinforcement treatment scheme based on the detection result. Shi Jianxun et al. [9] employed the improved AHP to determine the major factors causing water seepage on the basis of field investigation on water seepage in tunnels on Hangzhou-Huizhou Expressway; Liang Dexian et al. [10] carried out a physical simulation test for water burst due to tunnel excavation, analyzed the variation laws of stress, displacement, and pore water pressure, divided the whole water burst process into two stages of accumulation and instability, and established water burst judging criteria in combination with the actual engineering and mutation theory. By revealing the deformation features of long-span loess expressway tunnels in China, Li Pengfei et al. [11] took advantage of field monitoring and numerical simulation to determine the best construction method for excavation of surrounding rock in different orders, and analyzed two side-wall pilot tunnel method in detail. Mao Zhengjun et al. [12] proposed a modular waterproofing and drainage partition for double-arched tunnel as well as its design method.

Therefore, we adopts TFN-AHP in this paper to analyze the factors causing water damage to loess double-arched tunnel based on the field investigation on water damage to Lishi-Jundu Expressway Tunnel (Shanxi Province, China) in operation. And the result of the research is of great practical significance and reference value for prediction and control of water damage to loess double-arched tunnel.

## 2. OVERVIEW OF LISHI-JUNDU EXPRESSWAY IN CHINA

Located in mid-low mountain area of Lvliang Mountains in loess plateau in Shanxi Province and Shaanxi Province, Lishi-Jundu Expressway (Shanxi Province, China) runs from east to west. It starts from Qiaojiata Village in Lishi District of Lvliang City of Shanxi Province, and stops at Jundu Town in Liulin County of Lvliang City connecting with Wubu-Zizhou Expressway (Shaanxi Province, China), which is 38.55kms long. As a main artery for transportation in the east and west of Shanxi Province, it is of great significance for facilitating the development of regional transportation. There are eight tunnels on Lishi-Jundu Expressway, such as Lishi Tunnel, Wangjiahui Tunnel, Shangbaishuang Tunnel, Dayuliang Tunnel, Shipogou Tunnel, Yanjiatiao Tunnel, Miaoliang Tunnel, and Bapanshan Tunnel. Lishi Tunnel and Wangjiahui Tunnel are respectively called as the first and second loess double-arched tunnels in China, Dayuliang Tunnel, Shipogou Tunnel, Yanjiatiao Tunnel, and Miaoliang Tunnel are loess highway tunnels with small clear distance, and Shangbaishuang Tunnel and Bapanshan Tunnel are rock tunnels. The geographic location of Lishi-Jundu Expressway is shown in Figure 1.

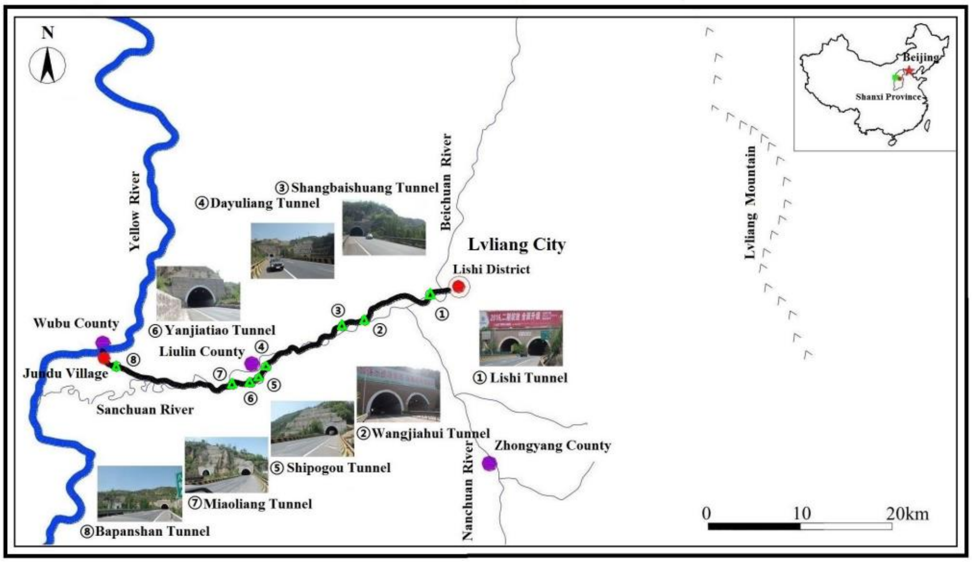


*Fig. 1 - The geographic location of Lishi-Jundu Expressway*

## 3. DEVELOPMENT CHARACTERISTICS OF WATER DAMAGE

It is found out that water damage always develops in construction joints, expansion joints, settlement joints, and lining joints of tunnel and even around them through the field investigation on water damage to tunnels on Lishi-Jundu Expressway in Shaanxi Province, China.

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Water damage to tunnel is classified as dotted water seepage, linear water seepage, and planar water seepage according to its trace and scope on lining. Water damage to tunnels on Lishi-Jundu Expressway mainly refers to linear water seepage, and planar water seepage is also developed well. Besides, partition and equipment box at the entrance and exit of tunnel are prone to water seepage.

### 3.1 Circular linear water seepage

Circular linear water seepage is the most common and serious water damage to loess tunnel. It not only exists in loess double-arched tunnel, but also stands out in separated loess tunnel. Circular linear crack mainly results from nonuniform vertical load, geological change of surrounding rock, and improper treatment of settlement joint, etc., and it often occurs at tunnel portal or joint of unfavorable geologic zone and complete rock stratum. Circular linear water damage to loess double-arched tunnel develops along the circular linear crack from vault, spandrel, hance, and side wall to arch foot. See Figure 2 for the development of circular linear water seepage in tunnels on Lishi-Jundu Expressway.

*Fig. 2 - Circular linear water seepage*

### 3.2 Vertical linear water seepage

Vertical linear water seepage is accompanied by the vertical crack of lining parallel to tunnel axis, with small amount of water seepage. However, it is the most fatal to tunnel structure, and its development may lead to clipping and even collapse of vault. See Figure 3 for the development of vertical linear water seepage in tunnels on Lishi-Jundu Expressway.

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*Fig. 3 - Vertical linear water seepage*

### 3.3 Slant linear water seepage

Slant linear water seepage usually appears at arch foot and the junction of side wall and arch foot. See Figure 4 for the development of slant linear water seepage in tunnels on Lishi-Jundu Expressway.

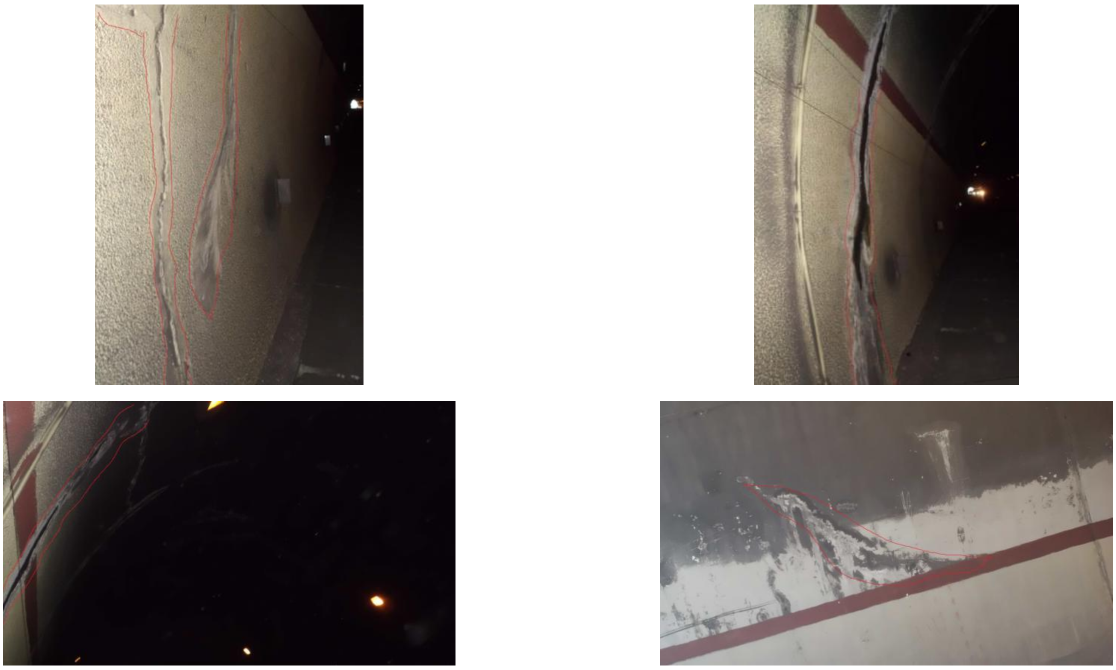

*Fig. 4 - Slant linear water seepage*

### 3.4 Planar water seepage

For the as-built loess tunnels, planar water seepage generally occurs at the vault and expands along circular linear cracks. See Figure 5 for the development of planar water seepage in tunnels on Lishi-Jundu Expressway.

*Fig. 5 - Planar water seepage*

### 3.5 Partition and equipment box

Water seepage mainly occurs at the partition in tunnel entrance and exit. See Figure 6 for the development of water seepage in tunnel partition on Lishi-Jundu Expressway. Water seepage is common for equipment box. See Figure 7 for the development of water seepage in the equipment box of tunnels on Lishi-Jundu Expressway.

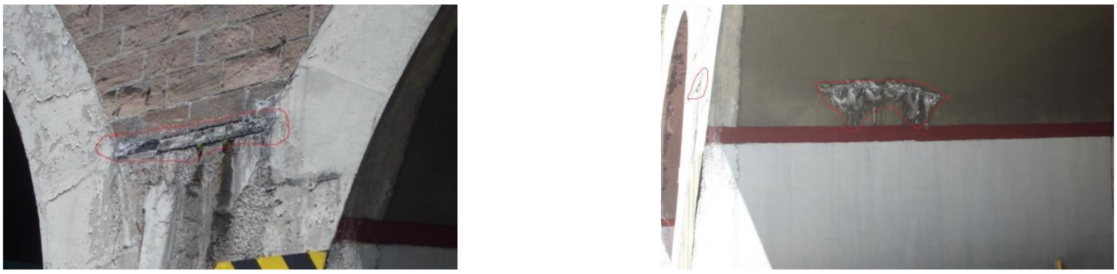

*Fig. 6 - Partition water seepage*

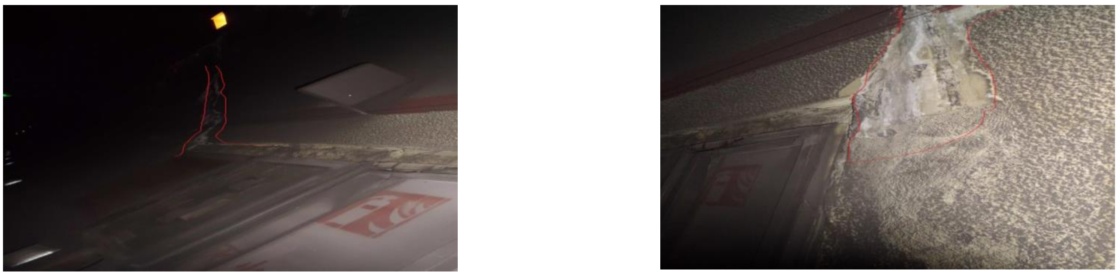

*Fig. 7 - Equipment box water seepage*

## 4 ANALYSIS ON FACTORS CAUSING WATER DAMAGE

### 4.1 TFN and its property

Definition 1: Given that $l$, $m$ and $n$ respectively mean the minimum probable value, most probable value and maximum probable value of one fuzzy variable, three numbers $(l, m, n)$ form triangular fuzzy numbers (TFN). Let $\tilde{M} = (l, m, u)$, $l \le m \le u, l, m, u \in R$, and see the definition of membership function in Formula (1) [13, 14]:

$$\mu_m(x) = \begin{cases} 0 & x < l \\ x - l/m - l & l \le x \le m \\ u - x/u - m & m \le x \le u \\ 0 & x > u \end{cases} \tag{1}$$

$|l-u|$ indicates the fuzzy degree as shown in Figure 8. When $|l-u| < \frac{1}{2}$, the fuzzy degree is too low to reflect the fuzziness recognized by people; when $|l-u| > 1$, the fuzzy degree is too high, so that the degree of confidence is lowered. The practice result shows that when $\frac{1}{2} < |l-u| < 1$, the result is more realistic [15-17].

Definition 2: The possibility of $M_1 \ge M_2$ is defined as:

$$V(M_1 \ge M_2) = \sup_{x \ge y}\left(\min\left(\mu_{M_1}(x), \mu_{M_2}(y)\right)\right) \tag{2}$$

Based on Formula (2), the necessary and sufficient conditions for $V(M_1 \ge M_2) = 1$ is $m_1 \ge m_2$ [13].

Theorem 1: Given that $M_1 = (l_1, m_1, u_1), M_2 = (l_2, m_2, u_2)$ are two TFNs, recorded as $V(M_2 \ge M_1) = \mu(d)$, and $d$ is the horizontal ordinate of points $(M_1, M_2)$ of intersection as shown in Figure 9,

$$V(M_2 \ge M_1) = \mu(d) = \begin{cases} \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & , l_1 \le u_2 \\ 0 & , others \end{cases} \tag{3}$$

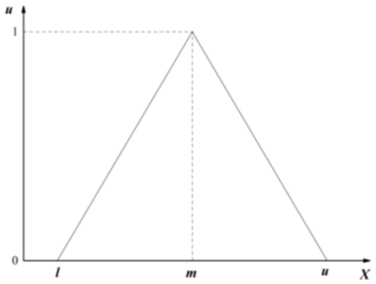


*Fig. 8 - Triangular fuzzy numbers*

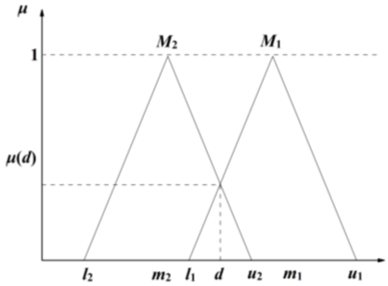


*Fig. 9 - Intersection of* $M_1, M_2$ [15]

Theorem 2: Given that $M_1=(l_1,m_1,u_1), M_2=(l_2,m_2,u_2)$ is two TFNs,

$$M_1\oplus M_2=(l_1,m_1,u_1)\oplus(l_2,m_2,u_2)=(l_1+l_2,m_1+m_2,u_1+u_2) \tag{4}$$

$$M_1\otimes M_2=(l_1,m_1,u_1)\otimes(l_2,m_2,u_2)=(l_1l_2,m_1m_2,u_1u_2) \tag{5}$$

$$M^{-1}=\frac{1}{M}=\left(\frac{1}{u},\frac{1}{m},\frac{1}{l}\right) \tag{6}$$

$$\forall\lambda,\exists R,\lambda M=\lambda(l,m,u)=(\lambda l,\lambda m,\lambda u) \tag{7}$$

Theorem 3: According to Theorem 1, the formula below is established [15]:

$$\begin{aligned}&V(M\geq M_1,M_2,...,M_k)=V\left[(M\geq M_1),(M\geq M_2),...,(M\geq M_k)\right]\\&=\min V(M\geq M_i)\qquad i=1,2,...,k\end{aligned} \tag{8}$$

### 4.2 Establishment of index system

An index system is established for the factors causing water damage to loess double-arched tunnel according to the field investigation on water damage to tunnels on Lishi-Jundu Expressway in Shanxi, China and the development characteristics of water damage in combination with relevant research results related to loess tunnel [18-20]. See Table 2 for the analysis model for hierarchical structure of factors causing water damage to loess double-arched tunnel.

### 4.3 Comparison between indexes

Scale numbers 1-9 are adopted for scores of indexes after comparison. The form and scoring method of investigation table is the same as the traditional AHP and based on this, TFN is applied for fuzzy expansion, as shown in Table 1.

*Tab. 1 - Connotation and fuzzy expansion of scale number*

| Scale numbers $a_{ij}$ | Connotation | TFN expansion |
|---|---|---|
| 1 | Factor $i$ is as important as factor $j$ | (1, 1, 2) |
| 3 | Factor $i$ is more important than factor $j$ | (2, 3, 4) |
| 5 | Factor $i$ is important than factor $j$ | (4, 5, 6) |
| 7 | Factor $i$ is much more important than factor $j$ | (6, 7, 8) |
| 9 | Factor $i$ is more important than factor $j$ absolutely | (8, 9, 10) |
| 2, 4, 6, 8 | Scale number for the status between the two of the above judgments | ($m$-1, $m$, $m$+1) |
| Reciprocal | When factor $j$ is compared with factor $i$, the result is $1/a_{ij}$ | (1/$u$, 1/$m$, 1/$l$) |

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*Tab. 2 - The analysis model for hierarchical structure of factors causing water damage*

| Overall index (target layer) | Grade-I index (criterion layer 1) | Grade-II index (criterion layer 2) | Grade-III index (index layer) |
|---|---|---|---|
| Analysis on factors causing water damage to loess double-arched tunnel A | Construction condition B1 | Physical geography C1 | Landform D1 |
| | | | Atmospheric precipitation D2 |
| | | | Vegetation coverage D3 |
| | | Geological condition C2 | Formation lithology D4 |
| | | | Geological structure D5 |
| | | Hydrogeology C3 | Pore water D6 |
| | | | Fissure water D7 |
| | | | Karst water D8 |
| | Design stage B2 | Design C4 | Advanced forecast of geology D9 |
| | | | Monitoring and measurement D10 |
| | | Tunnel characteristics C5 | Section D11 |
| | | | Burial depth D12 |
| | | | Unsymmetrical pressure D13 |
| | | | Length D14 |
| | Construction stage B3 | Excavation method C6 | Three-pilot drift method D15 |
| | | | Mid-pilot drift method D16 |
| | | | Single tunnel method D17 |
| | | | Parallel double-hole and full-section method D18 |
| | | Support method C7 | Bolt D19 |
| | | | Shotcrete D20 |
| | | | Steel arch D21 |
| | | | Pipe shed support D22 |
| | | Partition type C8 | Integral curved middle wall D23 |
| | | | Integral straight middle wall D24 |
| | | | Combined curved middle wall D25 |
| | | | Combined straight middle wall D26 |
| | | Waterproofing and drainage construction C9 | Waterproofing and drainage construction D27 |
| | | | Construction of three joints D28 |
| | | | Concrete construction for secondary lining D29 |
| | | | Infrastructure construction D30 |
| | Operation stage B4 | Waterproofing and drainage system C10 | Waterproof board damage D31 |
| | | | Blocking of drainage system D32 |
| | | | Failure of partition in waterproofing and drainage D33 |
| | | Major structure of tunnel C11 | Lining crack D34 |
| | | | Seepage of three joints D35 |
| | | | Seepage of equipment box D36 |

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## 4.4 Calculation for weight of grade-I index

### *4.4.1 Fuzzy judgment matrix for establishing grade-I index*

See Table 3 for the fuzzy judgment matrix for the established grade-I index.

*Tab. 3 - The fuzzy judgment matrix for the established grade-I index*

| Fuzzy judgment matrix | B1 | B2 | B3 | B4 |
|---|---|---|---|---|
| | (1, 1, 1) | (2, 3, 4) | (1/4, 1/3, 1/2) | (1, 1, 2) |
| B1 | (1, 1, 1) | (1, 2, 3) | (1/5, 1/4, 1/3) | (1, 1, 2) |
| | (1, 1, 1) | (1, 2, 3) | (1/5, 1/4, 1/3) | (1, 2, 3) |
| | (1/4, 1/3, 2) | (1, 1, 1) | (1/3, 1/2, 1) | (1/3, 1/2, 1) |
| B2 | (1/3, 1/2, 1) | (1, 1, 1) | (1/3, 1/2, 1) | (1/3, 1/2, 1) |
| | (1/3, 1/2, 1) | (1, 1,1) | (1/2, 1, 1) | (1/2, 1, 1) |
| | (2, 3, 4) | (1, 2, 3) | (1, 1, 1) | (2, 3, 4) |
| B3 | (3, 4, 5) | (1, 2, 3) | (1, 1, 1) | (3, 4, 5) |
| | (3, 4, 5) | (1, 1, 2) | (1, 1, 1) | (2, 3, 4) |
| | (1/2, 1, 1) | (1, 2, 3) | (1/4, 1/3, 1/2) | (1, 1, 1) |
| B4 | (1/2, 1, 1) | (1, 2, 3) | (1/5, 1/4, 1/3) | (1, 1, 1) |
| | (1/3, 1/2, 1) | (1, 1, 2) | (1/4, 1/3, 1/2) | (1, 1, 1) |

Summarize the scores in Table 3, utilize the additive operation of TFN, and select the average score of three experts to determine fuzzy judgment matrix $FBM_1$ [21].

$$
FBM_1 = \begin{array}{c} \\ B_1 \\ B_2 \\ B_3 \\ B_4 \end{array}
\begin{array}{c}
\begin{array}{cccc} \quad B_1 \quad & \quad B_2 \quad & \quad B_3 \quad & \quad B_4 \quad \end{array} \\
\begin{bmatrix}
(1,1,1) & (1.33, 2.33, 3.33) & (0.22, 0.28, 0.39) & (1, 1.33, 2.33) \\
(0.31, 0.44, 0.83) & (1,1,1) & (0.39, 0.67, 1) & (0.39, 0.67, 1) \\
(2.67, 3.67, 4.67) & (1, 1.67, 2.67) & (1,1,1) & (2.33, 3.33, 4.33) \\
(0.44, 0.83, 1) & (1, 1.67, 2.67) & (0.23, 0.31, 0.44) & (1,1,1)
\end{bmatrix}
\end{array}
$$

### *4.4.2 Calculation of comprehensive importance of grade-I index*

Utilize Formula (9) for “weight summation” comprehensive fuzziness value to obtain the comprehensive importance value after comparison between grade-I indexes.

$$
S_i = \sum_{j=1}^{n} a_{ij}^{*} \otimes \sum \left[ \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij}^{*} \right]^{-1} \tag{9}
$$

The calculation result is as below:

$$
\begin{aligned}
S_{B1} &= (3.55, 4.94, 7.06) \otimes (15.31, 21.19, 28.67)^{-1} \\
&= (0.1238, 0.2333, 0.4608)
\end{aligned}
$$

$$
\begin{aligned}
S_{B2} &= (2.08, 2.78, 3.83) \otimes (15.31, 21.19, 28.67)^{-1} \\
&= (0.0727, 0.1311, 0.2504)
\end{aligned}
$$

$$S_{B3} = (7.00, 9.67, 12.67) \otimes (15.31, 21.19, 28.67)^{-1} \\ = (0.2442, 0.4561, 0.8273)$$

$$S_{B4} = (2.68, 3.81, 5.11) \otimes (15.31, 21.19, 28.67)^{-1} \\ = (0.0934, 0.1769, 0.3338)$$

### *4.4.3 Determination of weight of grade-I indexes*

According to theorem 1, measure the purity of index *i* greater than index $k\left(k = 1, 2, 3\cdots, n; k \neq i\right)$ [14]. The calculation result is as below:

$$V(S_{B1} \geq S_{B2}) = 1 \qquad V(S_{B1} \geq S_{B3}) = 0.4930 \qquad V(S_{B1} \geq S_{B4}) = 1$$

$$V(S_{B2} \geq S_{B1}) = 0.5531 \qquad V(S_{B2} \geq S_{B3}) = 0.0186 \qquad V(S_{B2} \geq S_{B4}) = 0.7640$$

$$V(S_{B3} \geq S_{B1}) = 1 \qquad V(S_{B3} \geq S_{B2}) = 1 \qquad V(S_{B3} \geq S_{B4}) = 1$$

$$V(S_{B4} \geq S_{B1}) = 0.7962 \qquad V(S_{B4} \geq S_{B2}) = 1 \qquad V(S_{B4} \geq S_{B3}) = 0.2448$$

According to theorem 3, $d'\left(A_i\right) = \min V\left(S_i \geq S_k\right)\left(k = 1, 2, 3, \cdots, n; k \neq i\right)$, $A_i$ means the ith index and the calculation result for the possibility that index *i* is better than other indexes is as below:

$$d(B1) = \min V(S_{B1} \geq S_{B2}, S_{B3}, S_{B4}) = 0.4930$$

$$d(B2) = \min V(S_{B2} \geq S_{B1}, S_{B3}, S_{B4}) = 0.0186$$

$$d(B3) = \min V(S_{B3} \geq S_{B1}, S_{B2}, S_{B4}) = 1$$

$$d(B4) = \min V(S_{B4} \geq S_{B1}, S_{B2}, S_{B3}) = 0.2448$$

After normalization of the weight vector $W' = \left[d'\left(A_1\right), d'\left(A_2\right), \cdots, d'\left(A_n\right)\right]^T$, the actual weight vector $W_{A-B} = \left(0.2807, 0.0106, 0.5693, 0.1394\right)^T$ is obtained.

### 4.5 Calculation for index weight of other grades

The calculation for index weight of other grades is conducted by the same method to calculate the weight of grade-I index, and the calculation result for weight of grade-II index is as below:

$$W_{B1-C} = \left(0.5867, 0.0979, 0.3154\right)^T \qquad W_{B2-C} = \left(0.1941, 0.8059\right)^T$$

$$W_{B3-C} = \left(0.1945, 0.0082, 0.3566, 0.4408\right)^T \qquad W_{B4-C} = \left(0.8059, 0.1941\right)^T$$

The calculation result for weight of grade-III index is as below:

$$W_{C1-D} = \left(0.3154, 0.5687, 0.0979\right)^T \qquad W_{C2-D} = \left(0.1941, 0.8059\right)^T$$

$$W_{C3-D} = \left(0.5616, 0.3712, 0.0672\right)^T \qquad W_{C4-D} = \left(0.6636, 0.3364\right)^T$$

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$$W_{C5-D} = (0.1690, 0.3527, 0.4545, 0.0238)^T \quad W_{C6-D} = (0.5073, 0.3545, 0.1356, 0.0025)^T$$

$$W_{C7-D} = (0.4876, 0.0105, 0.1676, 0.3343)^T \quad W_{C8-D} = (0.3700, 0.4199, 0.0356, 0.1745)^T$$

$$W_{C9-D} = (0.3655, 0.4056, 0.1889, 0.0389)^T \quad W_{C10-D} = (0.5616, 0.3712, 0.0672)^T$$

$$W_{C11-D} = (0.2988, 0.5803, 0.1209)^T$$

## 4.6 Final sequence for weight of factors causing water damage

The relative importance between the lowest-leveled factors and the highest-leveled factors (general target) or the final sequence value of relative superiority can be calculated by weight combination based on hierarchical structure, namely the final sequence of weight. See Table 4 for the final sequence for weight of factors causing water damage to loess double-arched tunnel.

## 4.7 Result analysis

According to Table 4, the percentage of the factors is more than 4%, including construction of three joints, atmospheric precipitation, waterproofing and drainage construction, integral straight middle wall, integral curved middle wall, waterproof board damage, three-pilot drift method, landform, pore water, concrete construction for secondary lining, and blocking of drainage system, which are the major factors causing water damage to loess double-arched tunnel. Therefore, it can be obtained that construction stage is crucial for controlling water seepage during tunnel operation period and especially, construction of three joints and waterproofing and drainage should be in strict accordance with relevant specifications in actual engineering, so as to ensure the quality of tunnel waterproofing and drainage engineering.

*Tab. 4 - Final sequence for weight of factors causing water damage*

| Final sequence | Factors causing water damage to loess double-arched tunnel | Serial number | Percentage /% |
|---|---|---|---|
| 1 | Construction of three joints | D28 | 10.18 |
| 2 | Atmospheric precipitation | D2 | 9.66 |
| 3 | Waterproofing and drainage construction | D27 | 9.20 |
| 4 | Integral straight middle wall | D24 | 8.53 |
| 5 | Integral curved middle wall | D23 | 7.51 |
| 6 | Waterproof board damage | D31 | 6.31 |
| 7 | Three-pilot drift method | D15 | 5.62 |
| 8 | Landform | D1 | 5.19 |
| 9 | Pore water | D6 | 4.97 |
| 10 | Concrete construction for secondary lining | D29 | 4.74 |
| 11 | Blocking of drainage system | D32 | 4.17 |
| 12 | Mid-pilot drift method | D16 | 3.93 |
| 13 | Combined straight middle wall | D26 | 3.54 |
| 14 | Fissure water | D7 | 3.29 |
| 15 | Geological structure | D5 | 2.21 |
| 16 | Vegetation coverage | D3 | 1.61 |
| 17 | Seepage of three joints | D35 | 1.57 |
| 18 | Single tunnel method | D17 | 1.50 |

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| | | | |
|---|---|---|---|
| 19 | Infrastructure construction | D30 | 0.98 |
| 20 | Lining crack | D34 | 0.81 |
| 21 | Failure of partition in waterproofing and drainage | D33 | 0.75 |
| 22 | Combined curved middle wall | D25 | 0.72 |
| 23 | Karst water | D8 | 0.59 |
| 24 | Formation lithology | D4 | 0.53 |
| 25 | Unsymmetrical pressure | D13 | 0.39 |
| 26 | Seepage of equipment box | D36 | 0.33 |
| 27 | Burial depth | D12 | 0.30 |
| 28 | Bolt | D19 | 0.23 |
| 29 | Pipe shed support | D22 | 0.16 |
| 30 | Advanced forecast of geology | D9 | 0.14 |
| 31 | Section | D11 | 0.14 |
| 32 | Steel arch | D21 | 0.08 |
| 33 | Monitoring and measurement | D10 | 0.07 |
| 34 | Parallel double-hole and full-section method | D18 | 0.03 |
| 35 | Length | D14 | 0.02 |
| 36 | Shotcrete | D20 | $\approx$0.00 |

## 5 CONCLUSION

1) Through the field investigation on water damage to tunnels on Lishi-Jundu Expressway in Shanxi Province, China, it is found out that water damage to loess double-arched tunnel always develops in construction joints, expansion joints, settlement joints, and lining joints of tunnel and even around them; there is dotted water seepage, linear water seepage, and planar water seepage according to the trace and scope of water damage to tunnel lining, of which, linear water seepage is the main water damage, planar water seepage is also developed well, and partition and equipment box at the entrance and exit of tunnel are prone to water seepage;

2) According to the field investigation result and development characteristics of water damage, an index system covering 36 evaluation indexes for construction condition, design stage, construction stage, and operation stage is established for the factors causing water damage to loess double-arched tunnel in combination with related research results of loess tunnel;

3) TFN-AHP is applied in calculating the weight of indexes at different levels, and the final sequence of weight of the factors causing water seepage to loess double-arched tunnel is obtained. It is discovered that construction stage is crucial for controlling water damage to loess double-arched tunnel and atmospheric precipitation is the main water source. The possibility of water seepage is incresed by the structure defect of double-arched tunnel;

4) The final sequence for weight of various factors calculated by TFN-AHP is similar to the actual result, so this method is practical to analyze the factors causing water damage to loess double-arched tunnel.

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