Research on Long-Term Performance Evaluation Technology of Loess Tunnel Based on Extension Theory

Guang Yao

Shanxi Intelligent Transportation Institute Co. Ltd, Taiyuan, 140102, China
typeeasy2009@sina.com

Abstract. The long-term service performance of loess tunnels is jointly affected by deformation of the surrounding ground, the mechanical response of the initial support, the working condition of the anchorage system, and damage to the secondary lining. Building on an existing five-index extension-evaluation framework, this study retains the same indicators, grade boundaries, and AHP weight vector so that the methodological improvements can be directly compared with the previous approach. The novelty of the present study lies in two newly introduced procedures: an AHP–entropy combined-weighting scheme that incorporates the dispersion of field monitoring data into the weights, and a rolling-window procedure that embeds high-quantile levels and adverse temporal trends into the original five indicators. The resulting entropy weights, combined weights, and comprehensive correlation degrees are newly obtained in this study. The proposed method can integrate structural monitoring indicators with different dimensions and quantify the proximity of an evaluated tunnel section to adjacent performance grades, providing a practical basis for identifying critical sections, adjusting monitoring frequency, and prioritizing maintenance.

Keywords: loess tunnel; long-term performance; Extenics.

1 Introduction

Loess is highly structured and exhibits pronounced collapsibility and water sensitivity. Changes in the external water environment or long-term loading can reduce the strength and stiffness of the surrounding ground, which may further redistribute loads to the initial support, anchorage system, and secondary lining. During operation or long-term monitoring, evaluation based on only one indicator, such as crack width or displacement, may overlook inconsistent states such as “small deformation but increasing support stress” or “narrow cracks but continuously increasing lining stress”, as illustrated in Fig. 1-2. Therefore, long-term performance evaluation should jointly consider ground response, initial-support response, anchorage response, and lining damage.

© The Author(s) 2026
H. Wu et al. (eds.), *Proceedings of the 2026 3rd International Conference on Civil Engineering Structures and Concrete Materials (CESCM 2026)*, Advances in Engineering Research 312,
https://doi.org/10.2991/978-94-6239-865-8_15



Fig. 1. Damage to the initial tunnel support



Fig. 2. Softening damage

Numerous studies have investigated the long-term performance of tunnels. Yao [1] established a multi-index evaluation system for loess tunnels based on extension theory, using displacement rate, initial-support steel arch stress, anchor-bolt axial force, lining stress, and lining crack width, together with field monitoring, to classify tunnel performance. Xue et al. [2] evaluated the reliability of lining cracks in water-rich loess tunnels using extension theory. Li et al. [3] applied a matter-element extension method to durability evaluation of tunnel linings. Yang et al. [4] evaluated the service performance of operating loess railway tunnels using a Bayesian network. Wu et al. [5] used three-dimensional laser scanning to characterize refined deformation features of loess tunnels, while Deng et al. [6] further investigated loess-tunnel stability under groundwater conditions. These studies demonstrate that multi-source structural monitoring and comprehensive evaluation are important directions for loess-tunnel performance assessment. The five-indicator system, Grade I–V boundaries, and AHP weight vector adopted in the present paper are intentionally retained from Yao [1] and are not claimed as new contributions. Relative to Ref. [1], the new developments are: (i) the entropy-weight calculation and AHP–entropy combination in Eq. (3) and the subsequent combined-weighting procedure, which introduce objective information from the observed dispersion of monitoring data; (ii) the rolling-window long-term feature in Eq. (4), which combines the 95th-percentile level with an adverse trend term without adding a sixth indicator; and (iii) a new evaluation workflow of rolling-window feature extraction → entropy weighting → AHP–entropy combination → matter-element extension assessment. The entropy weights, combined weights, and correlation-degree results reported for the monitored sections are newly calculated in this study.

2 Long-Term Performance Evaluation Indicators and Data Acquisition

The five indicators are denoted as C1–C5. They are all cost-type indicators, meaning that a larger value corresponds to a less favorable condition. Together, they represent the complete response chain from ground deformation to support loading and finally to lining damage. A monitoring system was established in the tunnel to measure the above mechanical indicators, as illustrated in Fig. 3-4.



Fig. 3. Installation of locking-foot anchor bolts



Fig. 4. Steel arch stress monitoring

Table 1. Reference classical domains for Grades I–V of the five indicators

Indicator	Unit	I	II	III	IV	V
C1 Displacement rate	mm/d	0–1	1–3	3–6	6–8	8–10
C2 Initial-support steel arch stress	MPa	0–0.12	0.12–0.30	0.30–0.60	0.60–0.90	0.90–1.20
C3 Anchor-bolt axial force	kN	0–33.75	33.75–67.5	67.5–135	135–202.5	202.5–270
C4 Lining stress	MPa	0–2.06	2.06–4.13	4.13–8.25	8.25–12.38	12.38–16.5
C5 Lining crack width	mm	0–1	1–2	2–3	3–4	4–5

The case study adopts the published Grade I–V boundaries reported by Yao [1] as the classical domains, as listed in Table 1. Grades I–V represent good, relatively good, moderate, poor, and dangerous conditions, respectively. In practical applications, the boundaries should be calibrated according to the steel grade, lining-concrete strength, anchor-bolt specifications, monitoring arrangement, and design control values.

3 Matter-Element Extension Evaluation Model with Combined Weighting

3.1 Matter Element, Extension Distance, and Correlation Function

Let N denote the tunnel section to be evaluated, and let x1–x5 denote the five long-term characteristic values. The matter element of the evaluated section is expressed as:

$$R = (N, C, X) = [(C_1, x_1), (C_2, x_2), (C_3, x_3), (C_4, x_4), (C_5, x_5)]^{\mathrm{T}}. \quad (1)$$

For the classical domain of Grade j, $X_{0ij} = [a_{ij}, b_{ij}]$, and the nodal domain $X_{pi} = [a_{pi}, b_{pi}]$, the interval distance is defined as:

$$\rho(x, X) = |x - \frac{a+b}{2}| - \frac{b-a}{2}. \quad (2)$$

If x lies within the classical domain, $K_j(x) = -\frac{\rho(x, X_{0j})}{b-a}$; otherwise, $K_j(x) = \frac{\rho(x, X_{0j})}{\rho(x, X_p) - \rho(x, X_{0j})}$. A larger correlation degree indicates that the indicator is closer to the corresponding grade. For an indicator exceeding the upper bound of Grade V, the engineering risk is not attenuated by mathematical extrapolation; instead, the indicator is directly flagged as out of range and a special structural review is triggered.

3.2 Combined AHP–Entropy Weighting

AHP incorporates engineering experience, but the resulting weights may be affected by expert judgment. The entropy method determines objective weights from the dispersion of monitoring data across different sections. In this study, the AHP weight vector $W^{\mathrm{a}} = \{0.3951, 0.1263, 0.0542, 0.1263, 0.2981\}$ from Ref. [1] is retained as the subjective weighting basis. Entropy weights are newly calculated using the monitoring data from Sections A, B, and C. Let z_{ki} denote the nonnegative value of indicator i for section k used in the entropy calculation; then:

$$p_{ki} = \frac{z_{ki}}{\sum_k z_{ki}}, \quad e_i = -\frac{1}{\ln m} \sum_k p_{ki} \ln p_{ki}, \quad w_i{}^{\mathrm{e}} = \frac{1 - e_i}{\sum_i (1 - e_i)} \quad (3)$$

The combined weight is defined as $w_i = \alpha w_i{}^{\mathrm{a}} + (1 - \alpha) w_i{}^{\mathrm{e}}$, with $\alpha = 0.5$ in the present case study. This formulation retains the importance assigned from structural-mechanism knowledge while allowing the monitoring data to adjust the weights objectively. When a larger engineering dataset becomes available, α can be re-determined through sensitivity analysis or cross-validation.

3.3 Rolling Embedding of Long-Term Monitoring Information

To keep the evaluation system strictly limited to C1–C5, no additional "degradation-trend indicator" is introduced. Instead, long-term behavior is represented by the temporal characteristics of each indicator itself. For the indicator series $x_i(t)$ within a recent rolling window Δt, the long-term characteristic value is defined as:

$$x_i^{\mathrm{L}} = Q_{0.95}[x_i(t)] \cdot [1 + \lambda \cdot \max(0, r_i)] \tag{4}$$

Here, $Q_{0.95}$ denotes the 95th percentile within the recent time window, r_i is the dimensionless adverse trend, and λ is the trend-sensitivity coefficient. Because the tunnel is in the operational stage and its mechanical responses generally vary slowly over short periods under normal conditions, $Q_{0.95}$ is used instead of a simple mean to retain a relatively unfavorable but representative response level; the trend term further captures gradual deterioration. For low-frequency inspection indicators such as crack width, the maximum value within the time window may be used instead of $Q_{0.95}$. When the historical series is insufficient, λ is set to 0 and the model reduces to a static extension evaluation. The comprehensive correlation degree for Grade j is $K_j(N) = \sum_i w_i K_j(x_i^{\mathrm{L}})$, and the maximum determines the long-term performance grade.

4 Representative Case Study

To demonstrate the calculation procedure of the proposed five-indicator model, three actual field-monitored tunnel sections, A, B, and C, are considered. The C1–C5 values in Table 2 are not synthetic data or simple time averages; they are the long-term characteristic quantities x_i^{L} obtained from the corresponding field-monitoring series according to Eq. (4) and used in the entropy-weight and extension-evaluation calculations.

Table 2. Long-term characteristic values and evaluation results for the representative sections

Section	C1 (mm/d)	C2 (MPa)	C3 (kN)	C4 (MPa)	C5 (mm)	Grade
A	1.50	0.18	50.0	3.00	1.50	II
B	4.00	0.45	100.0	6.50	2.50	III
C	0.50	0.08	25.0	1.50	0.60	I

Using the data in Table 2, the entropy-weight vector is $W^{\mathrm{e}} = \{0.2950, 0.2316, 0.1535, 0.1737, 0.1462\}$. Equal combination with the AHP weights gives $W = \{0.3450, 0.1790, 0.1038, 0.1500, 0.2222\}$. C1 and C5 retain relatively high weights, indicating that displacement response and lining cracking are the main direct descriptors of long-term performance. At the same time, the objective dispersion of the monitoring data gives steel arch stress and lining stress more data-responsive contributions to the final assessment. It should be noted that only the three monitored sections in Table 2 were used to calculate the entropy weights in the present case study. Therefore, these objective weights should be regarded as case-specific and preliminary rather

than universal weights for loess tunnels. Future work will incorporate monitoring data from a larger number of sections and different operating conditions, and will examine the stability of the entropy and combined weights through sensitivity analysis and repeated validation.

The comprehensive correlation-degree vectors of Sections A, B, and C with respect to Grades I–V are $A = \{-0.248, 0.375, -0.368, -0.656, -0.754\}$, $B = \{-0.409, -0.216, 0.429, -0.256, -0.469\}$, and $C = \{0.389, -0.389, -0.735, -0.856, -0.898\}$, respectively. Accordingly, Sections A, B, and C are classified as Grades II, III, and I, respectively.

The Grade II correlation degree of Section A is clearly higher than those of the other grades, indicating a relatively good condition. However, C1, C2, C3, C4, and C5 have all entered the Grade II ranges; routine monitoring should therefore be maintained, with particular attention to whether the indicators continue to increase. All five indicators of Section B fall within the Grade III ranges, and its Grade III correlation degree is 0.429, indicating consistent deterioration of the structural system. The monitoring frequency should be increased, and particular attention should be given to whether ground deformation has induced load redistribution among the initial support, anchorage system, and secondary lining. All indicators of Section C fall within Grade I, with a comprehensive correlation degree of 0.389, indicating a good condition.

5 Conclusions

(1) The five indicators, their Grade I–V boundaries, and the baseline AHP weights are retained from Ref. [1] to ensure direct comparability. The present contribution does not lie in redefining this index system, but in extending it with a data-informed and temporally aware evaluation procedure.

(2) Combined AHP–entropy weighting is introduced to integrate expert knowledge with the observed dispersion of field monitoring data, while a rolling time window uses high-quantile features and adverse trends to construct long-term characteristic quantities. These procedures constitute the principal methodological developments relative to Ref. [1].

(3) For the three actual monitored sections, the proposed procedure yields Grades II, III, and I, respectively, and provides the proximity to adjacent grades through comprehensive correlation degrees. Because the entropy weights are presently based on only three sections, the resulting objective weights are case-specific; broader validation using additional monitored sections is required in future work.

Acknowledgments

This work was financially supported by the Research Project of Shanxi Transportation Holdings Group Co., Ltd. [2022-JKKJ-2].

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