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Key Techniques for the Construction of High-Speed Railway Large-Section Loess Tunnels

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ABSTRACT

The successful completion of the Zhengzhou–Xi'an high-speed railway project has greatly improved the construction level of China's large-section loess tunnels, and has resulted in significant progress being made in both design theory and construction technology. This paper systematically summarizes the technical characteristics and main problems of the large-section loess tunnels on China's high-speed railway, including classification of the surrounding rock, design of the supporting structure, surface settlement and cracking control, and safe and rapid construction methods. On this basis, the key construction techniques of loess tunnels with large sections for high-speed railway are expounded from the aspects of design and construction. The research results show that the classification of loess strata surrounding large tunnels should be based on the geological age of the loess, and be determined by combining the plastic index and the water content. In addition, the influence of the buried depth should be considered. During tunnel excavation disturbance, if the tensile stress exceeds the soil tensile or shear strength, the surface part of the sliding trend plane can be damaged, and visible cracks can form. The pressure of the surrounding rock of a large-section loess tunnel should be calculated according to the buried depth, using the corresponding formula. A three-bench seven-step excavation method of construction was used as the core technology system to ensure the safe and rapid construction of a large-section loess tunnel, following a field test to optimize the construction parameters and determine the engineering measures to stabilize the tunnel face. The conclusions and methods presented here are of great significance in revealing the strata and supporting mechanics of large-section loess tunnels, and in optimizing the supporting structure design and the technical parameters for construction.

1. Introduction

A loess stratum contains prominent vertical joints with strong structural characteristics. China has the largest area of loess in the world [1–4]; since the founding of the People's Republic of China, the nation has built a number of highways, railways, and water tunnels in loess areas, and has thereby gained relevant survey, design, and construction experiences [1]. The new Zhengzhou–Xi'an high-speed railway line for passenger traffic (hereinafter referred to as the Zhengxi High-Speed Railway) has a full length of 458 km and a design speed of 350 km·h^{-1}. It passes through a loess area for a considerable distance, necessitating 28 loess tunnels (totaling 53 km in length). Of these, Hanguguan Tunnel is the longest and largest (in terms of excavation section) loess tunnel in the world, with a length of 7851 m and an excavation section of up to 174 m^2. Most loess tunnels on the Chinese railway system have an excavation section of less than 100 m^2 and have encountered major problems such as strata settlement and lining excavation during construction and operation. Existing tunnel support design methods, construction schemes, and technical levels cannot meet the construction requirements of large-section loess tunnels on a high-speed railway. For the large-section loess tunnel on the Zhengxi High-Speed Railway, researchers and engineers from research institutes, the owner, the designer, and the construction contractor worked together to establish a key technical system for the construction of large-section loess tunnels on high-speed railways, thus providing strong support for the safe and successful

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completion and operation of the Zhengxi High-Speed Railway [1,5–7].

Based on an examination of the Zhengxi High-Speed Railway project, this paper systematically expounds on key techniques for the construction of large-section loess tunnels on China's high-speed railway in order to provide a reference for similar engineering construction in future.

2. Technical difficulties

A single-tube double-track tunnel scheme is adopted for most loess tunnels on China's high-speed railway; this scheme is characterized by an extra-large excavation section, a long section in loess, a strict requirement for settlement control, and a tight schedule. The following technical problems are typically encountered during construction using this scheme [1,8–13].

2.1. Classification of surrounding rock for a large-section loess tunnel

Classifying the surrounding rock provides a basis for the design of the supporting structure. The existing surrounding rock classification method for a loess tunnel is based on mechanical mechanisms, deformation property characteristics, and the physical and mechanical properties of a small-section loess tunnel. Tunnel works are influenced by a significant scale effect. Thus, the research results from a small-section loess tunnel cannot simply be applied to the stratum deformation mechanism of a large-section loess tunnel on a high-speed railway; rather, they need to be improved or corrected. Therefore, it is necessary to study the classification of the surrounding rock for large-section and super-large-section tunnels in order to lay a foundation for the design of supporting structures for large-section loess tunnels on high-speed railways.

2.2. Design of supporting structures for loess tunnels

The basic composition of a composite lining for a loess tunnel is the same as that for a conventional mountain tunnel. However, for Chinese engineers with experience in the construction of loess tunnels, the mechanical mechanism and effect of the systematic rock-bolting, as an important part of the primary support, have always been a source of debate [10]. Similarly, there is an urgent need for systematic and in-depth research into problems directly related to the design of supporting structures for large-section loess tunnels on high-speed railways, including determining the design load for loess tunnels, the mechanism of action, and the application conditions for the profile steel frame and grid steel frame [11].

2.3. Surface settlement and cracking control

As typical earth tunnels, most loess tunnels have a shallow buried depth and poor stability of the surrounding rock. Excavation for such tunnels usually causes serious surface settlement and surface cracking, thereby endangering the tunnel structure and existing buildings or structures around the tunnel; this is especially the case for large-section loess tunnels on high-speed railways. The question of how to effectively control surface settlement and surface cracking is a prominent issue facing engineers and builders [14].

2.4. Safe and rapid construction technology for super-large-section loess tunnels

In cases with poor surrounding rock conditions, most Chinese large-section tunnels are excavated in parts using the cross diaphragm (CRD) method, the center diaphragm (CD) method, or the double side-wall heading method. In these methods, the large section is divided into several smaller sections by adding a temporary inverted arch or vertical support. Such methods involve numerous construction processes and have a high requirement for the node connection process, which is not suitable for mechanized operation; as a result, they lead to low efficiency and slow progress [15–20]. For three-lane highway tunnels (with an excavation width of 15 m), the monthly progress of construction using the CD and double side-wall heading methods is about 45 m and 30 m, respectively; for ordinary two-track railway tunnels, the monthly progress of construction by the CRD method is about 40 m [1].

In comparison with loess tunnels on a normal-speed railway, the large-section loess tunnel on the Zhengxi High-Speed Railway required an excavation section of up to 174 m^2 and an excavation width of up to 15 m, performed on a tight schedule. In building a large-section loess tunnel on such a large scale, the question of how to achieve rapid construction while ensuring the safety of the tunnel structure and construction economy was a technical problem that had to be solved by engineering professionals [1].

3. Key design techniques

3.1. Classification of the surrounding rock for a loess tunnel

Based on the current understanding of loess strata for the classification of surrounding rock, and considering the level of influence of the buried depth on the mechanical properties of the surrounding rock and on parameter variability and availability, the classification idea and indicators for the surrounding rock are determined after a comparison of various parameters of loess. The main design indicators are obtained after the effect of buried depth is corrected on the basis of loess age, with the focus being placed on the plastic index and water content [1].

Using the existing classification system for the surrounding rock of a tunnel, we classified the surrounding rock, as shown in Table 1. It is notable that Table 1 gives 11% as the threshold water content of Late Pleistocene (Q_3) sandy loess; this is because experience has shown that Q_3 sandy loess usually has a water content of about 11% or below, and that its mechanical property will worsen markedly when the water content exceeds 11%. Therefore, this threshold water content is used as a classification indicator.

3.2. Stratum deformation characteristics and surface-cracking mechanism

3.2.1. Stratum deformation characteristics

(1) Large deformation with long duration. Field monitoring has been conducted on stratum deformation for large-section loess tunnels on the Zhengxi High-Speed Railway; for most of these tunnels, surface settlement and interior deformation exceed 100 mm and reach as high as 600 mm. Monitoring data for several tunnels on the Zhengxi High-Speed Railway revealed the following: Interior convergence is obvious 3–4 d after excavation; convergence then continues at 1 mm·d^{-1} for 20–30 d. In other words, the deformation tends to stabilize after the tunnel support is completed. For shallow loess tunnels that are subject to support, the surface settlement is still obvious in rainy weather, and is up to 1–3 mm·d^{-1}.

(2) Rapid deformation, with sudden failure. Q_3 and Holocene (Q_4) loess are called neo loess, and are characterized by large porosity and developed vertical joints, with loose soil and a water content ranging from 5% to 15%. Neo loess is normally distributed in a superficial layer at a depth of 30–50 m. Due to the large porosity and developed vertical joints of neo loess, tunnel excavation is likely to cause the cutting of vertical joints to form vertical weak faces, leading to differential settlement in the area affected by

Table 1
Classification of surrounding rock for loess tunnel.

Classification		Type of loess	Water content	Main engineering geological conditions of surrounding rock	Stability state after excavation of surrounding rock	Elastic longitudinal wave velocity in surrounding rock, v_P (km·s^{-1})
IV	IVa	Q_1 clayey loess Q_2 clayey loess	— < w_P	Largely hard soil; multiple layers of paleo soil, stable horizon; high calcareous content, localized layer of calcareous concretion; undeveloped joints	Chip off-falling and small collapse at the arch without support	1.5–3.0
	IVb	Q_2 clayey loess Q_1 sandy loess	> w_P < w_P	Largely hard plastic soil; multiple layers of paleo soil, unstable horizon; relatively low calcareous content in the soil layer, with calcareous concretion distributed sporadically; developed joints	Chip off-falling and collapse at the arch without support; occasional stability failure of side wall	
V	Va	Q_3 clayey loess	< w_P	Hard–hard plastic neo loess; relatively loose; undeveloped joints	Collapsible surrounding rock; large collapse may occur as a result of improper treatment	1.0–2.0
		Q_1 sandy loess Q_2 sandy loess	> w_P < w_P	Largely hard plastic soil; multiple layers of paleo soil, unstable horizon; low calcareous content in the soil layer; developed joints	Side wall prone to collapse	
	Vb	Q_2 sandy loess	> w_P	Hard–soft plastic soil; multiple layers of paleo soil, highly unstable horizon; low calcareous content in the soil layer; developed joints	Collapsible arch and side wall, with possible large collapse as a result of improper treatment; prone to surface settlement or collapse to surface when buried depth is shallow	
		Q_3 clayey loess Q_3 and Q_4 sandy loess	> w_P < 11%	Hard plastic–soft plastic soil; loose; developed joints		
VI		Saturated neo loess		Soft plastic–flow plastic soil; largely exhibiting a wriggly and soft structure	Extremely prone to collapse and deformation; prone to surface settlement or collapse to surface	< 1.0

Q_1—Early Pleistocene; Q_2—Middle Pleistocene; Q_3—Late Pleistocene; Q_4—Holocene.
w_P is the water content when the plastic limit $I_L = 0$.

tunnel construction. This will result in surface cracking, or even tunnel collapse. Engineering experience with large-section loess tunnels on the Zhengxi High-Speed Railway has indicated that when a tunnel passes through shallow neo loess, large surface settlement and transverse/longitudinal surface cracking tend to appear during construction; the cracking develops as the excavation face advances, until the tunnel support is completed.

(3) Acute stability problem at the arch springing. The low strength and developed vertical joints of loess strata result in a prominent plastic failure zone in the surrounding rock at the arch springing of the supporting structure after the excavation support is erected. More specifically, large settlement of the arch springing may occur to the extent of causing tunnel collapse; in addition, when the tunnel excavation section is large, the control of arch springing deformation is more crucial to the stability of the entire tunnel.

3.2.2. Surface-cracking mechanism

(1) Structural characteristics of loess strata. The structural characteristics of the developed vertical joints of a loess stratum tend to cause many vertical planes. Tunnel excavation will disturb the stratum, causing loosening around the tunnel due to excessive deformation; in particular, when the tunnel excavation section is large and the buried depth is shallow, tunnel excavation will cause obvious differential settlement of the upper strata, inducing stratum cracking.

(2) Anisotropy of the mechanical properties of loess strata. At the site on top of the exit of Hejiazhuang Tunnel on the Zhengxi High-Speed Railway, four undisturbed soil samples (each taken from a different direction at the same height) were obtained from the side wall of an artificial trial pit approximately 11 m deep. Indoor vertical and horizontal specimens were prepared and tested for loess anisotropy. The test results are summarized as follows: The average compression moduli E_{1-2} in the vertical and horizontal directions are 5.82 MPa and 6.83 MPa, respectively; the average vertical and horizontal coefficients of collapsibility of the loess are 0.026 and 0.019, respectively; and both the triaxial test and the direct shear test suggest that horizontal cohesion is greater than vertical cohesion, while the internal friction angle varies slightly. Therefore, loess has a greater tensile strength and a more prominent deformation and mechanical anisotropy than ordinary soil. The difference between the compression moduli of loess in the vertical and horizontal directions is about 15%; the difference between its cohesion in the vertical and horizontal directions (21.2 kPa and 23.7 kPa, respectively) is about 10%.

3.3. Design load for loess tunnel

3.3.1. Field-monitoring results

The spatial-temporal characteristics of the surrounding rock pressure at the Hanguguan DK270+525 section (shallow Class V surrounding rock) and at the Hejiazhuang DK242+960 section (deep Class IV surrounding rock) were monitored. The monitoring results are provided in Fig. 1.

(1) The time-history change of the surrounding rock pressure for loess tunnels can be roughly divided into three stages: rapid increase, slow increase, and stabilization. The monitoring value of the surrounding rock pressure following the end of the rapid

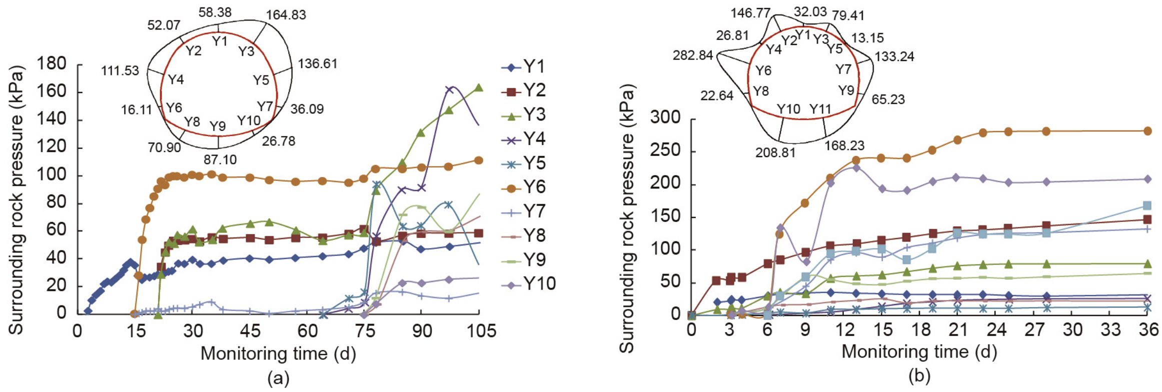

Fig. 1. Field-monitoring results of the surrounding rock pressure for loess tunnels, with a schematic of the monitoring points (Y1, Y2 . . .) on the cross-section at upper left of each figure. (a) Hanguguan DK270+525 section (buried depth: 27 m, Class V surrounding rock); (b) Hejiazhuang DK242+960 section (buried depth: 36 m, Class IV surrounding rock).

increase stage is usually larger than 2/3 of the final result. Surrounding rock pressures on different sections pass through each stage for different lengths of time; however, the monitoring value of the surrounding rock pressure for most sections tends to stabilize three months after tunnel excavation.

(2) In construction using the benching tunneling method, the subsequent erection of excavation support has an obvious effect on previous monitoring results; after excavation of the upper bench, if the support erection is sealed in a timely and rapid manner, the stress relief caused by the excavation will impose high stratum pressure on the primary support. If support erection does not occur in a timely fashion after the excavation of the lower bench, then the upper primary support will lose its foundation for a period of time; this will increase the loosening area of the upper loess strata and aggravate the development of the surrounding rock pressure. Therefore, during construction using the benching tunneling method, the suspending time of the upper supporting structure must be controlled, and the lower bench supporting structure must be erected promptly.

(3) Unlike conventional rock, the obvious rheological characteristics of loess mean that the surrounding rock pressure of loess tunnels changes over a long period of time and convergence stabilizes slowly; this is particularly true for large-section loess tunnels on high-speed railways. Therefore, the supporting structures for large-section loess tunnels on high-speed railways must be designed with consideration of the long-term effect of the rheological load.

3.3.2. Design load

After a comprehensive analysis of the field-monitoring results and calculation results of various theoretical models, we present the load pattern of surrounding rock pressure for loess tunnels, as shown in Fig. 2. In the figure, q is the vertical pressure from the surrounding rock, and e_1 and e_2 are the horizontal pressure from the surrounding rock. These values are calculated according to buried depth under deep and shallow conditions, respectively.

(1) Deep conditions. The surrounding rock pressure for a deep loess tunnel should be calculated by the corrected Terzaghi formula:

$$q = \frac{b\gamma - c}{\lambda \tan\varphi} \tag{1}$$

$$e_1 = q\tan^2(45^\circ - \varphi/2),\ e_2 = (q + \gamma H)\tan^2(45^\circ - \varphi/2) \tag{2}$$

where γ is the surrounding rock density (kN·m^{-3}), λ is the lateral pressure coefficient, φ is the internal friction angle of the surrounding rock (°), b is half of the loosening width at the tunnel top (m), c is the cohesion of the surrounding rock (kPa), and H is the tunnel excavation height (m).

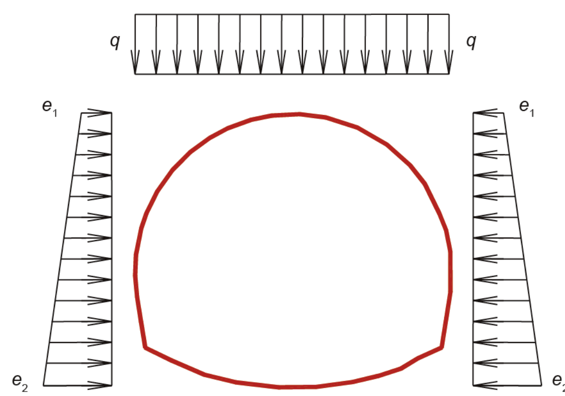

Fig. 2. Load pattern for a loess tunnel.

(2) Shallow conditions. The surrounding rock pressure for a shallow loess tunnel should be calculated using the regular recommended formula:

$$q = \gamma h\left(1 - \frac{\lambda h \tan\theta}{B}\right) \tag{3}$$

$$e_1 = \lambda\gamma h,\ e_2 = \lambda\gamma(h + H) \tag{4}$$

where B is the adit width (m), h is the height from the tunnel top to the ground (m), and θ is the friction angle on both sides of the roof pillar (°). Other symbols have the same meanings as given above.

(3) Determination of deep/shallow buried depth. Both theoretical inferences and field-monitoring results suggest that the range of calculated critical depth for old loess tunnels is 38–45.4 m, and that the critical deep/shallow buried depth is 1.36($H + B$)–1.62($H + B$). The range of the calculated critical depth for neo loess tunnels is 57.4–58.2 m, and the critical deep/shallow buried depth is 2.06($H + B$)–2.08($H + B$). Therefore, the critical deep/shallow buried depth of loess tunnels is proposed to be 1.3($H + B$)–2.1($H + B$); the upper limit of 2($H + B$)–2.1($H + B$) may be taken for neo loess (Q_3 and Q_4 loess) tunnels, while the lower limit of 1.3($H + B$)–1.7($H + B$) may be taken for old loess (Early Pleistocene (Q_1) and Middle Pleistocene (Q_2) loess) tunnels.

3.4. Optimization of design parameters for supporting structure

3.4.1. Systematic rockbolting

To verify the effect of systematic rockbolting, field tests were performed on the mechanical properties of rockbolts in deep and shallow large-section loess tunnels, respectively, on the Hanguguan Tunnel and Hejiazhuang Tunnel on the Zhengxi High-Speed Railway. Comparative tests with and without rockbolts under equivalent conditions showed that for large-section loess tunnels, systematic rockbolting has little effect on improving the stress in composite lining and controlling stratum deformation; in particular, the arch rockbolt is under little stress, whereas the side-wall rockbolt is under some tension. Therefore, it is suggested that no systematic rockbolting be installed in a 130° area at the arch of large-section loess tunnels; full-length cohesive rockbolts (which should be less than 3.5 m long) can be installed from this area down to the arch springing.

3.4.2. Applicability of steel frame

To compare and analyze the mechanical characteristics and applicability of profile steel frames and grid steel frames, a field comparison test was conducted on Hejiazhuang Tunnel on the Zhengxi High-Speed Railway. The research results showed that these two steel frames have roughly the same ability to control surrounding rock deformation, and especially to control arch crown settlement. Relatively speaking, the profile steel frame has some advantage in controlling horizontal convergence. Stresses in both frames are within the design strength; relatively speaking, the stress in the grid steel frame is smaller, with more uniform distribution of contact pressure between the primary support and the surrounding rock.

3.4.3. Forepoling

Advanced small pipes can effectively stabilize the working face of a large-section loess tunnel and can be erected on a temporary side support as necessary, in conjunction with pipe-shed construction. A pipe-shed has an obvious effect during loess tunnel construction by transferring the load and constraining deformation of the surrounding rock around the tunnel; therefore, a large pipe-shed is recommended for loess tunnel construction in cases where surface settlement must be controlled. Due to the inadequate effect of grouting, a fiberglass bolt provides limited consolidation to the earth behind the working face, so it should be used with caution in loess tunnels.

4. Key construction technology

4.1. The three-bench seven-step excavation method

Guided by the concept of excavating an arc heading and reserving the central core soil, the three-bench seven-step excavation method (Fig. 3) divides the working face into three benches (upper, middle, and lower) and seven working faces with parallel excavation and support erection so as to achieve safe and rapid construction of large-section loess tunnels on high-speed railways. Its specific characteristics are as follows:

- The large working space facilitates mechanization and enables parallel operation on multiple working faces with high efficiency.
- With a high adaptability to variation in geological conditions, this method enables timely and flexible conversion of operation steps, optimization of platform construction parameters, and timely sealing of primary support when necessary.
- This method can be adapted to various excavation spans and section types, without temporary support or additional construction cost; its engineering economy is good.

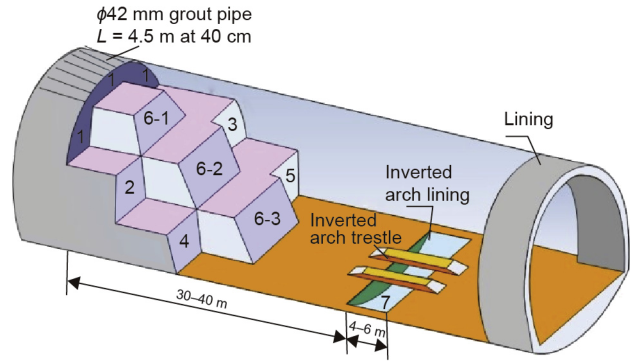

Fig. 3. The three-bench seven-step excavation method.

- The central core soil is fully utilized to guarantee the stability of the excavation face; the arc heading enables timely and convenient erection of the primary support.

4.2. Optimization of bench construction parameters

(1) Bench length. In the three-bench seven-step excavation method, the bench length must be appropriate; excessive length will affect the closure time of the primary support, whereas insufficient length will cause an interior longitudinal fracture plane to affect the working face, leading to sliding of soil at the tunnel top and stability failure of the excavation face. Engineering experience from large-section loess tunnels on the Zhengxi High-Speed Railway showed that when using the three-bench seven-step excavation method, the upper bench should be 3–5 m long, while the middle and lower benches should be 4–6 m long. For water-free old loess with good stability, the bench length can be reduced accordingly in order to facilitate construction.

(2) Bench height. In the three-bench seven-step excavation method, the bench height must be strictly controlled. The height of the upper bench must be minimized while enabling mechanized construction, in order to prevent excessive height from causing too large a scope of sliding mass, which is detrimental to the stability of the working face. In addition, excessive height of the upper bench requires longer small pipes, which will complicate construction. The heights of the middle and lower benches should also be reasonable. According to engineering experience from Zhangmao Tunnel on the Zhengxi High-Speed Railway, the height of the upper bench should not be smaller than 0.3 times its width, and is generally taken as 3–4 m; the heights of the middle and lower benches should have the same heights and are generally taken as 3–3.5 m.

(3) Bench slab staggering distance. Construction experience from the large-section loess tunnels on the Zhengxi High-Speed Railway showed that as the bench slab staggering distance increases, the settlement of the arch crown and arch springing increases slightly, while the side-wall convergence decreases significantly. Engineering experience showed that staggering the slabs of the middle and lower benches is conducive to the stability of the supporting structure, and maintains deformation within the allowable range; the staggering length should be 2–3 m.

(4) Appropriate excavation advance. The size of the excavation advance has a major effect on deformation during the construction of large-section loess tunnels. Research shows that when the advance increases from 1 m to 2.4 m, the arch settlement will increase by more than 60%, the horizontal convergence will increase by more than 70%, and the maximum stress on the steel frame will increase by 19%, approaching the yield limit. Engineering experience from the large-section loess tunnels on the Zhengxi High-Speed Railway revealed that for Class IV old loess, one excavation advance should be limited to less than 1 m for the upper

bench, limited to 1.5 m for the middle and lower benches, and limited to 2–3 m for the inverted arch. For neo loess or sandy loess, one excavation advance is recommended to be half the value for old loess.

4.3. Measures to stabilize the working face

(1) Reserving core soil. Engineering experience from the large-section loess tunnels on the Zhengxi High-Speed Railway showed that the core soil of the upper bench should be as long as the upper bench (i.e., 3–5 m) and 1.5–2.5 m high, and that its top width should be 1/3–1/2 of the excavation width of the upper bench (i.e., 3–5 m). The core soil of the middle and lower benches should be 4–6 m long and 1/3–1/2 as wide as the bench.

(2) Early closure of the excavation face. Early closure of the excavation face can effectively stabilize the working face. In particular, during the construction of a water-rich loess tunnel, 5 cm thick shotcrete should be applied as soon as possible after excavation to control the loosening of strata and prevent soil stripping from the excavation face, in order to ensure stability of the working face. Engineering experience from large-section loess tunnels on the Zhengxi High-Speed Railway revealed that the 2 h period after tunnel excavation is crucial to controlling the stability of the working face. In some tunnels, concrete is sprayed at least 5–6 h after excavation; however, in sandy and water-rich loess, this practice reduces the control of the initial displacement of the tunnel.

(3) Installation of advanced small pipes. Engineering experience from large-section loess tunnels on the Zhengxi High-Speed Railway showed that the advanced small pipes must extend about 1 m beyond the fracture plane on the other side of the working face, and that their length should be equal to the height of the upper bench plus 1 m (i.e., 4–5 m). For large-section loess tunnels, installing an advanced small pipe within a 120° scope at the arch is a cost-effective means of support. An advanced small pipe can be rapidly installed by driving it directly into the loess. This driving method does not affect the bearing capacity of the pipe, as it mainly plays the role of a beam. The pre-support effect at the arch may also be reinforced by steel tube grouting if necessary.

5. Conclusions

(1) The loess strata surrounding large tunnels can be classified after the effect of the buried depth is corrected on the basis of loess age by combining the plastic index and the water content.

(2) The stratum deformation characteristics of loess tunnels are large deformation with long duration, rapid deformation with sudden failure, and an acute stability problem at the arch springing.

(3) During tunnel excavation disturbance, if the tensile stress exceeds the soil tensile or shear strength, the surface part of the sliding trend plane can be damaged, and visible cracks can form. The surface-cracking mechanism is based on the structural characteristics and anisotropy of the mechanical properties of loess strata.

(4) This paper presented the critical value separating deep and shallow large-section loess tunnels: The surrounding rock pressure for a deep loess tunnel should be calculated using the corrected Terzaghi formula, whereas the surrounding rock pressure for a shallow loess tunnel should be calculated using the regular recommended formula. The surrounding rock pressure of a large-section loess tunnel should be calculated according to the buried depth, using the corresponding formula.

(5) A three-bench seven-step excavation method of construction was used as the core technology system to ensure the safe and rapid construction of a large-section loess tunnel, following a field test to optimize the construction parameters and determine the engineering measures to stabilize the tunnel face.

Compliance with ethics guidelines

Yong Zhao, Huawu He, and Pengfei Li declare that they have no conflict of interest or financial conflicts to disclose.

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