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Research Article

Study on Excavation Stability of Loess Tunnel in Geological Weak Areas Exploring Excavation Stability of Loess Tunnels in Geologically Vulnerable Regions

Aizhong Luo, Juan Fang*, Changlu Chen, Biao Hu

School of Civil Engineering and Architectural Engineering, Guizhou University of Engineering and Science, Bijie, China

Abstract

As western development progresses, extensive infrastructure construction can be conducted in the Loess Region. During infrastructure construction, particularly in tunnel excavation, traversing through extensive loess formations poses a significant challenge. It is imperative to ensure the stability and integrity of the tunnel while crossing weak geological zones in loess regions. This issue should be comprehensively addressed during tunnel construction. Geological and numerical analyses were employed to analyze the impact of weak geological areas on loess tunnel excavation. These analyses focused on the mechanisms of weak geology and assessed the efficacy of advanced support measures in loess tunnel construction, specifically addressing the issues encountered within weak geological zones during the construction process. First, we examined the formation mechanism of weak geological zones in loess, which is primarily attributed to water infiltration. Subsequently, based on this formation mechanism, a finite difference numerical analysis was utilized to investigate the potential failure modes of loess tunnels passing through weak geological zones. The destruction of the tunnel in the weak geological zone resulted from sliding erosion of the surface soil, leading to the complete collapse of the soil above the tunnel. During tunneling through weak geological zones, The soil in front of the excavation initially exhibited instability, causing the overall subsidence of the entire weak band, with the formation of a trap on the surface. Finally, the effectiveness of treatment measures was assessed according to the failure pattern of the loess tunnel in the weak geological zone. The analysis results indicated that with the implementation of appropriate advanced reinforcement measures, successful crossing can be achieved during the construction of a loess tunnel traversing the weak geological zone.

Keywords

Loess Tunnel, Excavation Stability, Geological Weak Areas, Mechanism of Instability, Advance Support

1. Introduction

Loess is prevalent in northwest and north China. In loess regions, adverse geological phenomena such as landslides, soil caves, and weak geological zones are widely distributed due to the unique sedimentary environment and semi-arid conditions [1, 2]. The weak geological zone within the loess zone refers to the areas where the shear strength of the soil decreases, and its loose quality decreases owing to water infiltration or other external factors. As western development progresses, extensive infrastructure construction can be conducted in the Loess Region. During infrastructure

*Corresponding author: 568641755@qq.com (Juan Fang)

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construction, particularly in tunnel excavation, traversing through extensive loess formations poses a significant challenge. It is imperative to ensure the stability and integrity of the tunnel while crossing weak geological zones in loess regions. This issue should be comprehensively addressed during tunnel construction [3-5]. Chang-yu Yang [6] focused on the mud section of the Liangshan Tunnel of the Xiamen-Shenzhen Railway. The instability of excavation surfaces and their formation mechanisms were investigated through engineering geological analysis and numerical simulation methods. The main factors contributing to excavation failure include the physical and mechanical properties as well as the spatial distribution characteristics of the weak zones. Zhang Yong et al. [7] have developed a new method for determining the deformation modulus of weak rock zones based on the analytical solution for the deformation modulus of inferior weak rock bands. Additionally, Zhang Zhiqiang [8] elucidated the deformation patterns concerning the vertical relationship between the maximum displacement direction and maximum main stress direction in weak surrounding rock tunnels under high ground stress conditions. Sun Kiguo et al. [9] investigated the mechanism of long tunnels. Based on research by Ma Gang [10] on the typical physical and mechanical characteristics and the laws of formation occurrence, four typical risks were discussed along with the proposed risk control measures. It was emphasized that the presence of large pore structures and water-induced soil instability were fundamental causes of risks in urban subway tunnel engineering, whereas water-loss-induced deformation was the root cause of environmental risks. Gou Zhiqiang [11] analyzed the weak loess surrounding rock of high-pressure jet grouting piles, covering the aspects such as reinforcement scheme, reinforcement process, and reinforcement effectiveness. Fan Haobo et al. [12] analyzed the impact of tunnel base strengthening in weak loess areas, studying the influence of pile length and diameter on tunnel foundation settlement and structural mechanical response characteristics. Li Jun et al. [13] established a model for calculating the tunnel surrounding pressure with the consideration of the influence from the development of vertical joint fissure of new loess on the basis of the relevant investigation result of the surface fissure of loess tunnel and the vertical joint fis- sure distribution characteristics of loess. Wang mingnian et al. [14] analyzed the surrounding rock pressure data obtained at different loess stratum, YANG Jianmin [15] Based on the research on the ground cracks and surrounding rock pressure during the excavation of loess tunnel, based on the research on the ground cracks and surrounding rock pressure during the dividing line of deep and shallow submersion, computing method of surrounding rock pressure and designing principle of secondary lining of large sectional loess tunnel on Zhengzhou-Xi'an Passenger Dedicated Line are presented.

In loess tunnel projects, the excavation surface is frequently unstable and susceptible to damage owing to weak geological zones [16, 17]. However, there is limited literature on loess tunnels passing through weak geological zones. This study mainly analyzes the causes of the formation of weak geological zones in loess. Through numerical analysis and research on the instability and damage of loess tunnels passing through weak geological zones, it is found that the instability and damage forms of tunnels that reach the weak zone and pass through the entire weak zone during the construction process are the collapse of the palm face and the collapse of the weak geological zone at the top of the tunnel. In response to the instability and damage mode of loess tunnels passing through weak geological zones, a double-layer advanced large pipe shed is proposed to provide advanced support for the weak geological zone.

2. Loess Tunnel Through the Weak Geological Zone Instability Damage

2.1. Formation Mechanism of Loess Weak Geological Zone

2.1.1. Formation of Submerged Weak Zone Under Water Flow

The formation of soft and weak geological zones [18, 19] in loess areas was attributed primarily to water activity. In the loess region, stress release at the tableland, ridge edges, gully edges, and near loess profiles, combined with vertical joint development under dry-wet cycles, led to collapsibility and structural disintegration. This interaction results in the localized loosening of the loess body, significantly reducing the shear strength and forming weak geological zones (Figure 1). Concurrently, local surface precipitation deposition and soil near the liquid limit, coupled with evaporation-induced cracking, contributed to crack formation, indicating preliminary stages of weak geological zone development. Subsequent dry-wet cycles further induced disturbance, forming both disturbed and undisturbed areas, with subsidence between the two regions.

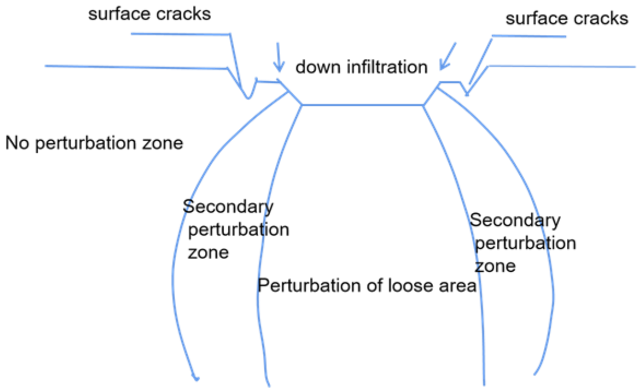


Figure 1. *Formation of weakness bond with water infiltration.*

2.1.2. Formation of Submerged Weak Zone on Water Flow

Simultaneously, alterations in groundwater levels occurred due to construction activities, such as rainfall or artificial lake creation. Through the rise of underground capillary water at dry-wet boundary surfaces, the groundwater induced reverse upward immersion. The upward wetting of groundwater caused subsidence, due to the deformation and collapse of the subsidence area. The upper loess layers within the loess body may develop voids, holes, or collapse owing to additional ground loading. Subsequently, a relatively loose and low-shear-strength weak geological zone formed locally in the loess. This weak zone was characterized by disturbances in some areas and undisturbed conditions in other areas. Subsidence between these areas can further create secondary disturbance zones (Figure 2).

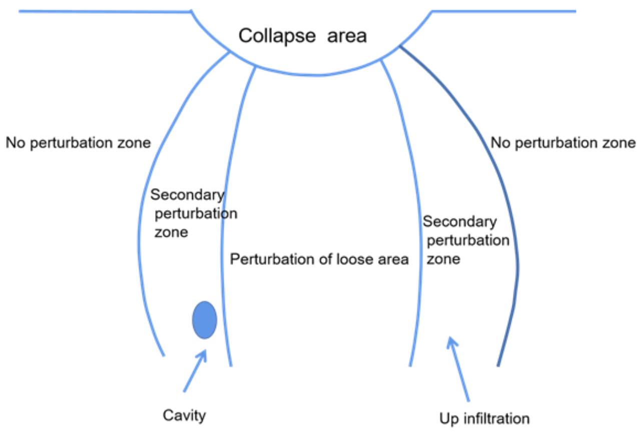


Figure 2*. Formation of weakness bond with groundwater rise.*

2.1.3. Formation of Weak Zone on Rock Surface

In the typical loess distribution areas of northwest and north China, the presence of numerous strata at soil-rock junctions often leads to a stratigraphic phenomenon, commonly observed in shallow buried broken surrounding rocks. Through field investigation and geological analysis [20, 21]. it was generally observed that the formation age of the soil and rock boundary was relatively short, characterized by large, loose pores in the overlying soil and varying rock properties, including mudstone, shale, and granite, with varying degrees of weathering. This distinctive geological feature not only altered the mechanical properties of the surrounding rock of the tunnel, but also affected the hydrogeological conditions at the soil-rock interface. At this interface, there was a significant increase in water content. Historically, soil-rock boundary strata has not attracted sufficient attention from researchers and engineers, resulting in frequent landslides and surrounding rock deformation incidents, severely affecting project implementation or operation and posing risks to life and property safety. At the junction of the rock and loess, differences in soil strength and geological movements, coupled with water interactions, induced soil loosening at the interface, causing a sharp reduction in shear strength. With the duration of action and the continuation of the force, a weak geological zone was eventually formed within a specific range of the rock interface in the loess body (Figure 3).

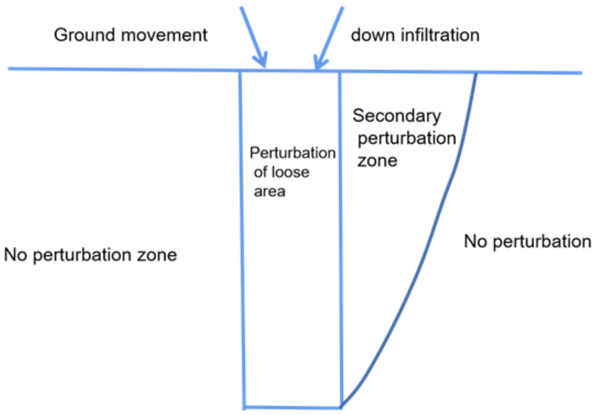


Figure 3*. Formation of the weakness bond by the interface of loss and rock.*

2.2. Numerical Analysis Model and Calculation Parameters

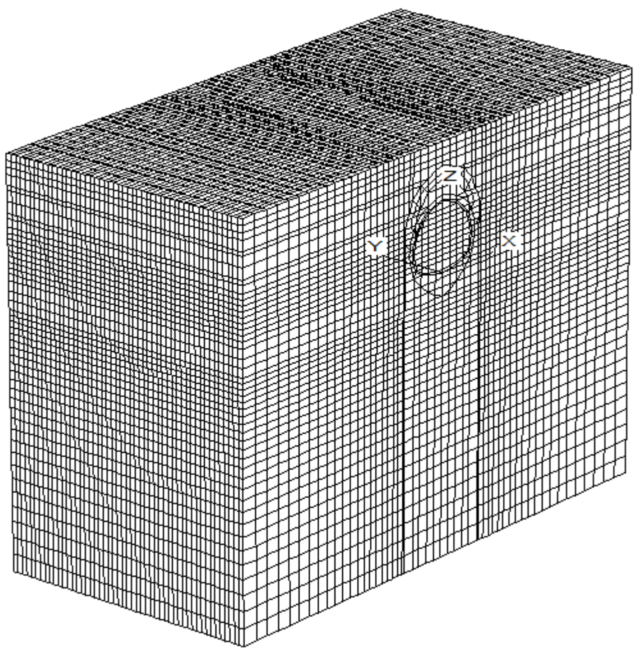


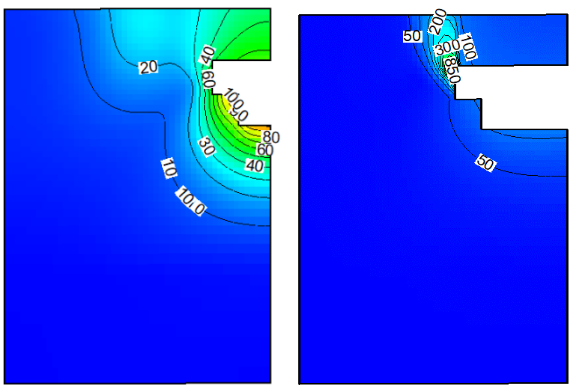
Figure 4*. Numerical analysis model.*

The mechanism underlying the formation of the loess weak geological zone adversely affected the stability of the loess tunnel. To assess its influence, this study employed numerical simulations performed using the finite-difference method. The simulated tunnel measured 100m × 50m × 73m (in the x, y, and z directions, respectively) and featured a horseshoe shape with dimensions of 10 m burial depth, 15.5 m diameter, and 12.57 m height. The model comprised 124,200 units and 130,305 nodes. The initial lining consists of hanging net shotcrete, followed by the secondary lining of an inverted arch and arch wall. The weak geological zone, positioned in the middle of the tunnel, was set using the soil column method within designated area of 20 m (x-axis: -10 to 10), 10 m (y-axis: 20 to 30), and extended to the tunnel burial depth along the z-axis. The numerical analysis model depicted in Figure 4 employed the Moore–Coulomb model for soil and an elastic-plastic model for the lining. The key parameters used for the calculations are presented in Table 1.

Table 1*. Material parameters used in the calculation.*

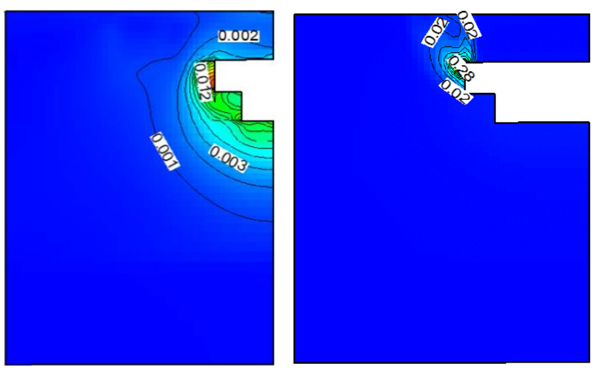
solum	Natural severe / (kN m^{-3})	bulk modulus /MPa	modulus of shearing /MPa	cohesive strength /kPa	internal friction angle /(°)
Q3	14.2	4.45	0.3	32	17.1
A line	25	1.15e3	0.58e3	-	-
Second line	25	1.15e4	0.58e4	-	-

2.3. Analysis of the Simulation Results



(A) 10 m palm excavation (B) 20 m

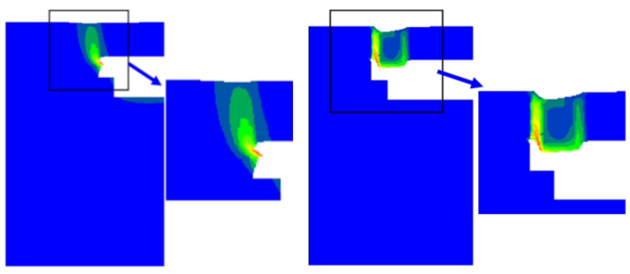
Figure 5*. Total displacement nephograms.*



(A) 10 m palm excavation (B) 20 m

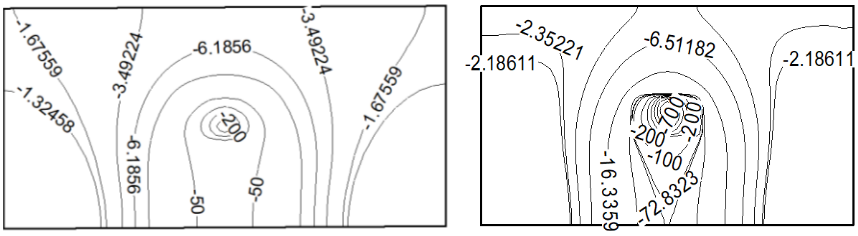
Figure 6*. Shear strain nephograms.*

Figures 5 and 6 depict the total displacement cloud map and shear deformation cloud map, respectively, showing displacements at 10 m and 20 m forward on the excavated palm surface. As shown in Figure 5, with a 10 m advance, the tunnel excavation remained stable under the current support conditions. In contrast, Figure 6 illustrates that when the tunnel face reached a distance of 20 m, it encountered a weak geological zone. the tunnel exhibited sliding towards the palm surface side, as evident from the total displacement and shear strain patterns. Figure 7 illustrates the destruction mode of the tunnel at the top of the weak geological zone. The destruction of the tunnel in the weak geological zone resulted from the sliding failure of the soil from the palm surface to the overall collapse at the top of the tunnel. During the tunnel's traversal of the weak geological zone, the soil ahead of the excavation initially became unstable, causing complete subsidence of the weak zone and ultimately forming a depression on the surface.



(A) 20 m (B) 30m

Figure 7*. Failure modes of weaken bond.*



(A) 20 m (B) 30 m

Figure 8. *Earth settlements before supporting.*

3. Analysis of the Advanced Support and Effect of Crossing the Weak Geological Belt in Loess Tunnel Excavation

3.1. Reasonable Selection of the Form of Advance Support

The analysis in the previous section revealed that without specific measures, the tunnel was susceptible to collapse and surface subsidence when it traversed the weak geological zone, thereby impeding the tunnel excavation process. Various methods of advance support and reinforcement have been employed in tunnel engineering construction. Typically, these include advanced pipe shed grouting reinforcement, advanced curtain grouting reinforcement, and palm surface horizontal rotary spray reinforcement. Notably, advanced pipe shed grouting supports and advanced curtain grouting reinforcements have been frequently utilized. To ensure effective advance reinforcement, it is essential to consider the diverse mechanisms and applicable conditions of advance support and reinforcement to select appropriate advanced support measures. In advance pipe shed grouting supports, steel pipes are positioned around the tunnel excavation outline at specific intervals and inserted along the hole axis at a certain angle. These steel pipes serve a dual purpose: they function as both advance pipe sheds and grouting pipes. This arrangement strengthens the surrounding rock through grouting, reinforcement, and compaction of the vault to create a solid structure, thereby enhancing the overall stability. Additionally, the scaffolding function of the pipe shed helps achieve optimal excavation conditions. This method is appropriate for water-bearing sandy-soil strata, crushing zones, and shallow-buried tunnel sections. After the analysis of various advanced support types, a double-layer advanced large pipe shed support was selected. The support principle is illustrated in Figure 9. Constructed with φ108 mm steel pipes, the pipe shed, grouting consolidation body, and excavation support system collectively constituted a composite support system, extending at least 200 mm beyond the excavation surface.

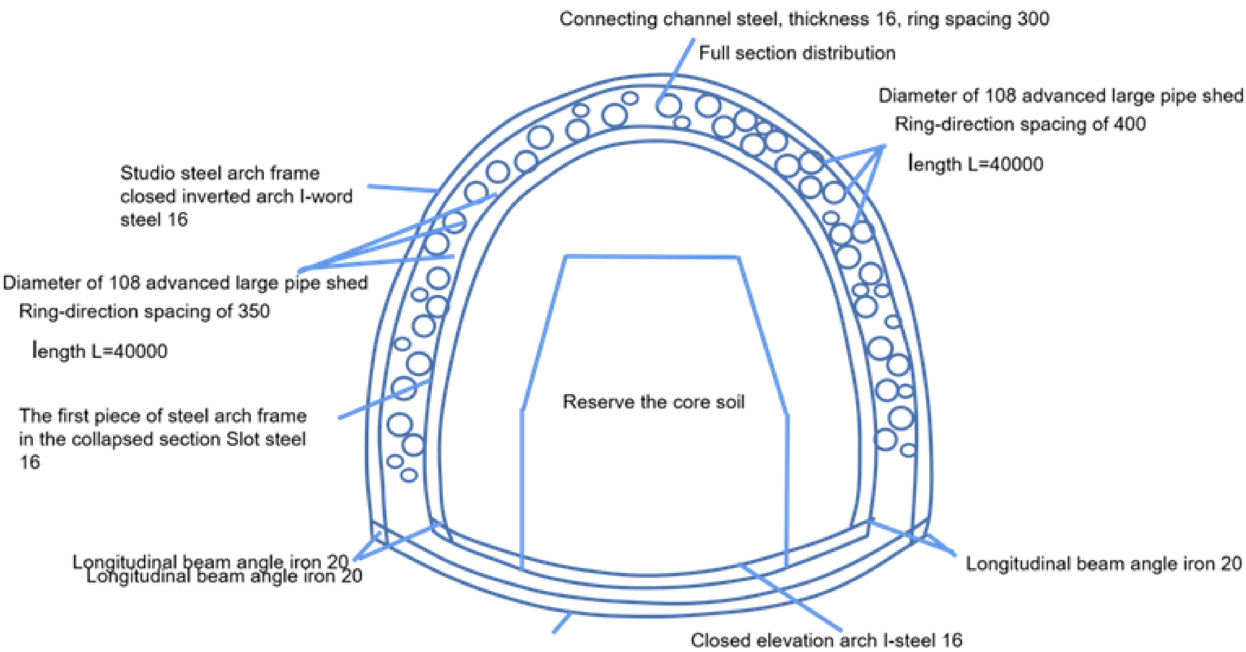
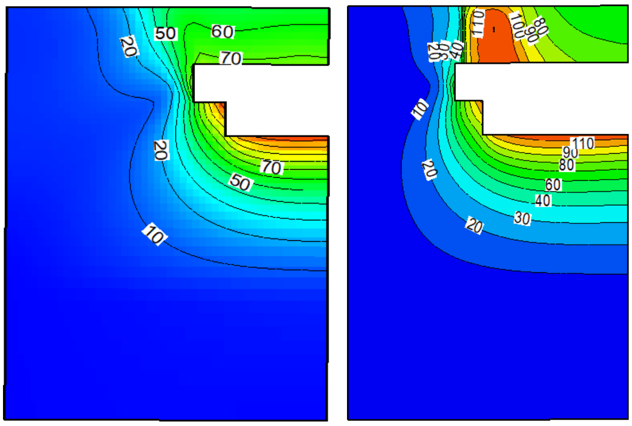


Figure 9. *Principle of advanced supporting by double pipe-shed.*

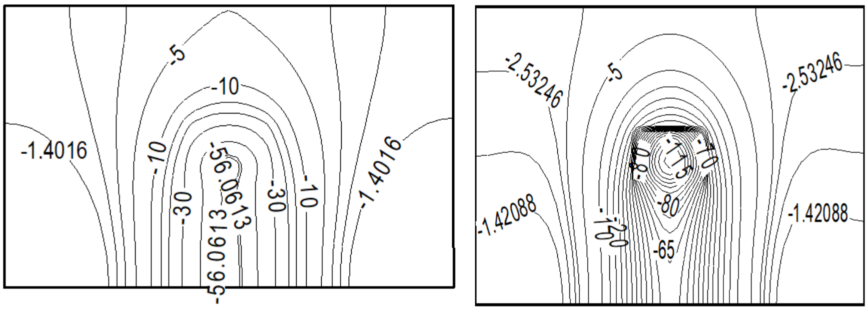
3.2. Analysis of Advanced Support Effect

Figure 10 demonstrates the total displacement cloud map of the tunnel supported by the double-layer advanced large pipe shed. From Figure 9, with the support of the double-layer advanced large pipe shed, soil collapse occurred on the palm surface when the tunnel excavation reached 20 m. The overall displacement remained minimal within the control range. When the palm surface advanced 30 m ahead, the tunnel completed its traversal of a weak geological zone. The maximum displacement occurred above the tunnel in this zone and reached 12 cm. A small depression was formed on the ground owing to the weak geological zone, and the top displacement of the tunnel remained within permissible limits. Figure 11 illustrates the contour diagram of the ground subsidence for the double-advance canopy support tunnel through the weak geological zone. Compared with Figure 8, using the double-advance canopy support significantly reduced ground subsidence in the weak zone. This demonstrates the effectiveness of the proposed support method.



(A) 20 m (B) 30 m

Figure 10. *Displacement nephograms after supporting.*



(A) 20 m (B) 30 m

Figure 11. *Earth settlements after supporting.*

4. Conclusion

Based on the analysis of the formation mechanism of the loess weak zone, the instability failure mechanism of tunneling through this geological formation, and the efficacy of advanced support measures, the following conclusions were drawn:

(1) The formation of the loess soft geological zone was primarily attributed to three factors. The flooding of upper water expanded existing fissures due to long-term dry and wet cycles, rendering the loess weak. Flooding also expanded internal cavities within the loess. The presence of loess at contact surfaces exacerbated the vulnerability of this geological zone.

(2) By conducting numerical analysis and research on the instability failure of loess tunnels passing through weak geological zones, the unstable failure mode of the tunnel entering and traversing the entire weak zone was determined. The main forms of damage included palm surface collapse and the collapse of the weak geological zone above the tunnel.

(3) Considering the unstable failure mode of loess tunnels in weak geological zones, it was suggested to employ a double-layer advanced large pipe shed for advanced support. The results of the numerical analysis indicated that this method yielded favorable outcomes.

Author Contributions

Aizhong Luo: Writing-original draft, Methodology, Data curation, Funding acquisition

Juan Fang: Project administration, Investigation, Funding acquisition

Changlu Chen: Formal analysis, Funding acquisition

Biao Fu: Investigation, Resources

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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