Safety Analysis of Building Structures in Shallow-Buried Section of Tunnel under Complex Geological Conditions

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Abstract. This paper focuses on the safety of building structure in shallow-buried section of complex geological tunnel, and takes Banzhulin Tunnel of Xubi Railway as an example, and analyzes the impacts of tunnel construciton on the surface building structures in shallow-buried section using the Midas GTS NX calculation program. Considering the complex geological conditions and various types of building structures, and combining with the surface settlement control standards, the mechanical performance parameters of curtain grouting measures are systematically researched and determined, which provides a theoretical basis and practical guidance for the safe construction of similar tunnels underpassing buildings.

Keywords: complex geological tunnel; shallow-buried section; the safety of building structure; Midas GTS NX simulation; curtain grouting

1 Introduction

With the rapid development of China's transportation infrastructure construction, shallow-buried tunnel sections passing beneath existing surface buildings under complex geological conditions have become a growing occurrence. Stratum deformation caused by tunnel construction is highly likely to jeopardize the structural safety of surface buildings, which poses a serious threat to the residents' lives and properties, and also hampers project progress. As a typical case of such complex working conditions, the Banzhulin Tunnel of Xubi Railway, has a high reference value for an in-depth investigation of its relevant laws and response strategies, and can provide key technical support and practical examples for subsequent similar projects.

2 Engineering Background Analysis

2.1 Overview of Banzhulin Tunnel

The Banzhulin Tunnel is a single-line tunnel with a total length of 12,780 meters, of which the section D2K230+910~D2K231+185, is a shallow-buried section with a

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length of 270 meters. The buried depth of the tunnel ranges from 10 to 20 meters, with the minimum distance being approximately 8.9 meters.

2.2 Complex Geological Conditions

The shallow-buried section passes through the Quaternary slope-pluvial deposits, eluvial-slope deposits, as well as Cambrian dolomites and fault fragmentation zone, with the main lithology being pulverized clay, gravel soil and dolomite. There is one fold and one fault in the area, where the rock mass is fractured, joints and fissures are well-developed, groundwater is abundant and has a good hydraulic connection with surface water. The elastic modulus of pulverized clay is 100MPa, and the internal friction angle is only 5°, resulting in poor soil stability; the gravel soil has loose particles, weak cohesion, which is easy to be disintegrated when exposed to water; the joints and fissures of dolomite create the conditions for the groundwater seepage, which increase the difficulty of the construction. The longitudinal section and the layout plan of the shallow-buried section of the tunnel is shown in Figure 1 and Figure 2.

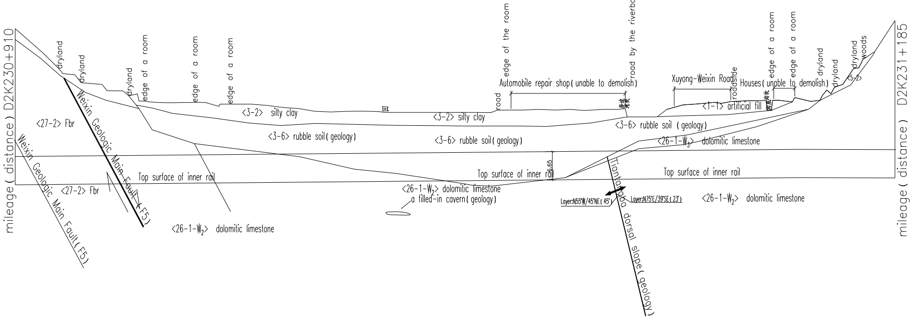

Fig. 1. Longitudinal section of the shallow-buried section of the tunnel

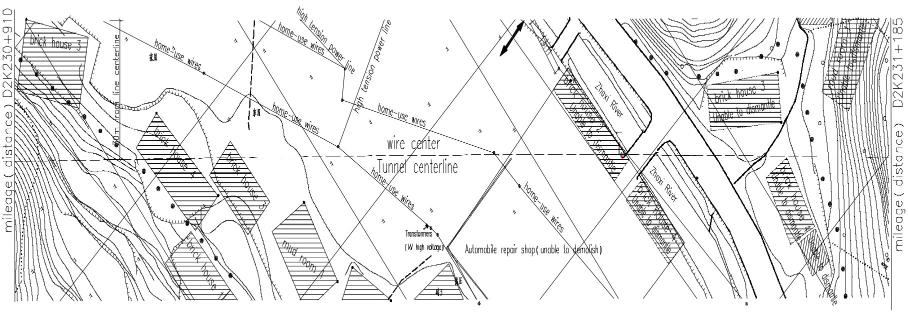

Fig. 2. Layout Plan of the shallow-buried section of the tunnel (underneath buildings)

2.3 Variety of Houses in the Surrounding Area

There are 14 houses within 30 meters on both sides of the line centerline in the shallow-buried section, including masonry, brick-concrete and frame structures. The picture of the buildings are shown in Figure 3, and the survey statistics of demolished buildings is shown in Table 1. Most masonry houses were built in the early years with shallow foundations, suffering from wall cracking, foundation settlement and limited load-bearing capacity; although the brick-concrete structures have been improved, the integrity and stability are poor in the face of construction disturbances; the frame structures are relatively stable, but the beam-column nodes are prone to safety hazards if the ground settlement exceeds the allowable value. The construction materials of these buildings include stone, brick and concrete, with varying degrees of newness and aging.

Due to disputes over demolition, some houses can't be demolished. Given the shallow burial depth of the tunnel, the adverse geology during construction is prone to cause soil deformation and collapse, which will easily affect the surface houses and threaten their safety. Therefore, the construction of the shallow-buried section of the Banzhulin Tunnel is confronted with tremendous challenges, and it is necessary to formulate scientific construction programs and take effective safety measures to ensure the smooth progress of the project and the safety of the surrounding environment.

Fig. 3. Shallow-buried section of the tunnel underpassing buildings

Table 1. Survey Statistics of Demolished Buildings in the Shallow Buried Section of Banzhulin Tunnel

Serial No.	Affiliated unit	Distance to centerline (m)		Building Evaluation			Building area	Progress of demolition
				Building materials			Measured on site (floor-m2)	
		L	R	Foundation	Walls	Roof		
1	Villagers' houses	18		stone	brick	roof tile	3-613	O
2	Villagers' houses	2		stone	brick	Tile	4-836	O
3	Villagers' houses		14	stone	brick	concrete	1-280	O

4	Villagers' houses		27	stone	brick	Tile	4-907	N
5	Villagers' houses		14	stone	brick	concrete	1-345	O
6	Villagers' houses		5	stone	brick	Tile	2-336	O
7	Villagers' houses		18	stone	brick	Tile	3-378	N
8	Villagers' houses		18	stone	brick	Tile	3-606	N
9	Automo-bile ork-shop		18	stone	brick	Tile	1-2885.8	N
10	Villagers' houses	6		stone	brick	Tile	3-627	N
11	Villagers' houses		6	stone	brick	Tile	4-514	N
12	Villagers' houses		17	stone	brick	concrete	1-85	N
13	Villagers' houses	28		stone	brick	concrete	2-90	N
14	Villagers' houses	10		stone	brick	concrete	1-253	N
Note: O stands for demolition completed, N stands for no demolition possible.								

3 Impacts of Tunnel Shallow-Buried Section Construction on Surface Building Structures

3.1 Internal Mechanism

3.1.1 Root Cause of Ground Deformation. Tunnel construction breaks the stress balance of the soil mass, and surrounding rock convergence triggers stratum loss. Meanwhile, the construction affects the groundwater level, alters soil properties and reduces the bearing capacity.

3.1.2 Evolution of Structural Stress. Stratum deformation is transferred to the foundation of the houses, resulting in uneven foundation settlement, which may make the houses tilted or locally overhanging, leading to cracks in the houses and even overall structural instability. Especially masonry structures are more sensitive to foundation deformation.

3.2 Mechanical Mechanism

3.2.1 Changes in the Force of Houses. Tunnel construction makes the surrounding rock convergence, the stratum loss is transferred to the foundation of the houses, the uneven settlement of the foundation makes the walls easy to crack due to the additional bending moment, and the overall force of the houses is in a high-risk state. Masonry houses are brittle and shallow, and the walls are easy to crack and collapse; brick-concrete structures are under strong stratigraphic changes, and the stress concentration at the connection between the walls and floor slabs threatens the stability of the structure.

3.2.2 Surface Settlement and Structural Response. lateral settlement presents a normal distribution state with the tunnel centerline as the axis of symmetry, in which the settlement directly above is serious, the foundation of the house settles a lot, and the settlement slows down with the increase of the distance, but the house produces torsion to tilt due to the uneven force. Longitudinal settlement changes in stages, houses experience slight disturbance during advanced settlement phase, the settlement rate rises dramatically during construction and gradually slows down upon completion. If the residual settlement is not controlled, it will weaken the durability of the house.

3.3 Grouting to Improve the Stratum

The construction of the shallow-buried section of the tunnel has a complex impact on the housing structure, involving the evolution of structural stress caused by deformation of the stratum and the structural response under different settlement modes. Grouting is an effective measure to improve the stratum and reduce the impact. By filling pores and fissures, it enhances the cohesion and internal friction angle of the soil and improves the physical and mechanical properties. Grouting in different geological areas can reduce the stratum deformation, reduce the uneven settlement of the foundation of the house, guarantee the safety of the house structure, and ensure the smooth progress of tunnel construction.

4 Numerical Simulation Study Based on Midas GTS NX

4.1 Computational Conditions and Model Construction

1. The theory of“ stratum-structure ”is chosen, and Midas GTS NX program is used to accurately reflect the interaction between the stratum and the supporting structure in the tunnel excavation; the value of the load is taken into consideration of the constant load, the influence of the house and the safety coefficient; please refer to Table 2 for details.

Table 2. Load combinations

Load type		Load standard value	Load combination factor
Permanent load	Self-weight	Calculated by modeling	1.35
	Overburden pressure	Calculated by modeling	1.35
	Surface house weight	Calculated by modeling	1.35
	Floor Load	3kPa	1.35

2. The calculation range is 100 meters horizontally in each direction, and 50 meters in the vertical direction from the bottom of the tunnel (including 13 meters of burial depth), to avoid the boundary effect. Boundary conditions are set as X-displacement constraints at the left and right boundaries, Y-displacement fixed at the bottom boundary, and free boundary from the upper boundary to the ground; the Plane strain model is constructed based on the actual parameters and the layout of the houses, and the boundary effect is considered. See Figure 4 for details.

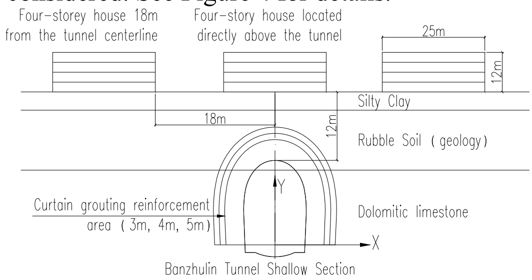

Fig. 4. Geometric model for numerical simulation of Banzhulin Tunnel

3. Referring to the geological survey report for the Banzhulin Tunnel[1] and Code for Design of Railway Tunnel[2], physical and mechanical parameters are assigned to the surrounding rock, lining and house structure, as shown in Table 3 below.

Table 3. Physical and mechanical indexes of surrounding rock and lining materials

Type	Surrounding rock type	Gravity γ (kN / m^3)	Modulus of elasticity Ec (GPa)	Poisson's ratio μ	Angle of internal friction ψ	Cohesion (kPa)
Type of surrounding rock	Pulverized clay	18	0.1	0.35	5°	8
	Gravel soil	21	1	0.35	38°	0
	Gravel soil (after grouting)	21	1	0.35	45°	25
	Dolomite	26	1	0.35	40°	200
Lining material	Secondary lining C35 reinforced concrete	25	32.2	0.2	——	——
	Initial support C25 concrete	25	23	0.2	——	——

4. In the simulation, plane elements are used for surrounding rock and primary support, and beam elements are used for houses, secondary lining and steel frames, so that the working state of each structure is truly reflected through reasonable selection of elements and parameter setting.

4.2 Simulated Working Condition Design

During the construction of the shallow-buried section of the Banzhulin Tunnel, in order to control the deformation impact of tunnel excavation on the surface houses directly above and near the underpass, considering of the surrounding rock, depth of burial, the connectivity of surface and underground and environmental protection requirements, the measure of advance curtain grouting for surrounding rock reinforcement was adopted; to investigate the inhibitory effect of different reinforcement ranges on the deformation of houses at various surface locations, a total of eight simulation conditions were carried out.

4.2.1 Program for Setting Working Conditions. For two representative houses at the shallow-buried section of Banzhulin Tunnel-directly above the tunnel and 18m from the center line, different reinforcing conditions were set up, such as no reinforcement, 3m, 4m, 5m curtain grouting and other different reinforcing scopes, which listed in Table 4 below. A multi-dimensional comparison system was constructed to deeply analyze the intrinsic connection between tunnel excavation and the deformation and force of the house structure, and to accurately quantify the influence weight of each factor on the safety of the house.

Table 4. Details of simulated working condition settings

Location of the house	Scope of reinforcement			
	No reinforcement	3m curtain grouting	4m curtain grouting	5m curtain grouting
directly above the tunnel	Working Condition1	Working Condition 2	Working Condition 3	Working Condition 4
18m from centerline	Working Condition 5	Working Condition 6	Working Condition 7	Working Condition 8

4.2.2 Calculation Process. The simulation process is rigorous and scientific, aiming to deeply study the role of advance curtain grouting on the safety of housing structure.

1. Carry out the in-situstress calculation to accurately obtain the stress distribution of the stratum in its natural state;

2. Activate the house and floor loads to truly reproduce the actual condition of the house acting on the stratum, so that the simulation is more consistent with the surrounding stress environment during tunnel excavation;

3. According to different curtain grouting reinforcement range, adjust the parameters of surrounding rock elements in the corresponding areas, so as to simulate the effect of advance grouting reinforcement;

4. Passivate the elements of excavation range, activate the elements of primary support and steel frame at the same time, simulating the tunnel excavation and support process .Pay close attention to the deformation of the surrounding rock and the structural response of the house, and obtain the key data through numerical calculation.

4.3 Analysis of Simulation Results

Analyze the impact of tunnel excavation on building structures at different locations and the reinforcement effect of advance curtain grouting.

4.3.1 Deformation Analysis of Houses Directly above the Tunnel.

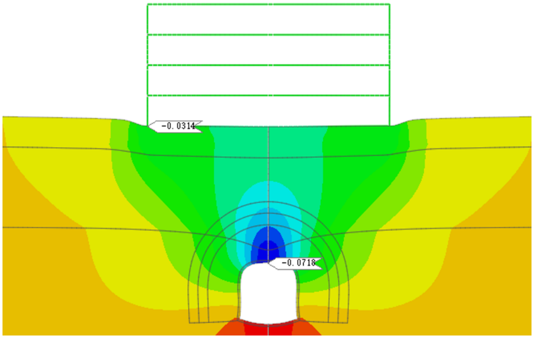

Fig. 5. Grouting extent and house settlement curve (without reinforcement)

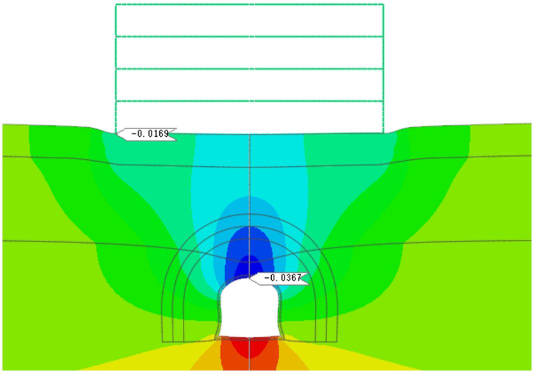

Fig. 6. Grouting extent and house settlement curve (3m of grouting)

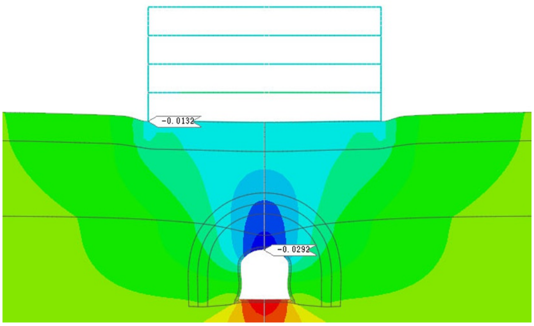

Fig. 7. Grouting range and house settlement curve (4m of grouting)

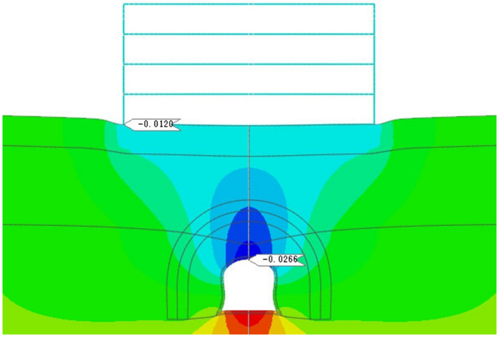

Fig. 8. Grouting range and house settlement curve(5m of grouting)

When the house is directly above the tunnel, under the unreinforced condition, tunnel excavation makes the vault settlement 7.18cm, the house settlement 3.14cm, as shown in Figure 5, the house foundation sinks, the wall cracks, the beam-column node is damaged, and the structure is on the verge of failure. With the reinforcement scope of advance curtain grouting expanded from 3m to 5m, the tunnel vault settlement decreases to 3.67cm, 2.92cm, 2.66cm, the house settlement drops to 1.69cm, 1.32cm, 1.20cm, which is shown in Figure 6~8, the settlement of house foundation is controlled, the structural stability is significantly improved.

4.3.2 Structural Deformation Analysis of Houses 18m from the Centerline. When the house is 18m from the tunnel center line , under the unreinforced condition, tunnel excavation makes the vault settlement 6.80cm, the house close to the tunnel side settlement 0.86cm, the far side 0.005cm, as shown in Figure 9, the near side of the foundation sinking to the house tilting, floor cracks, beams and columns uneven stress, leading to the risk of local instability. With the reinforcement scope of advance curtain grouting expanded from 3m to 5m, the tunnel vault settlement decreases to 3.15cm, 2.50cm and 2.24cm, the house settlement drops to 0.46cm, 0.34cm and 0.29cm, the cracks are closed, and the structure restores stability3.15cm, 2.50 cm, 2.24 cm, the settlement of the house decreased to 0.46 cm, 0.34 cm, 0.29 cm, which is shown in Figure 10~12. This rectifies the building tilt, closes the cracks and restores the structural stability.

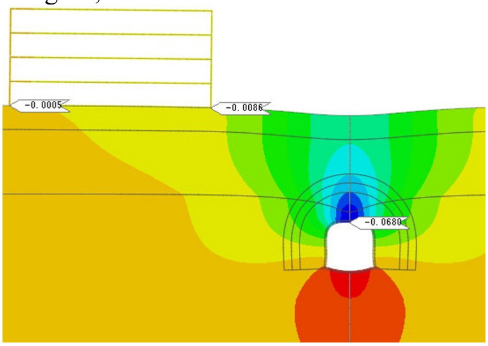

Fig. 9. Grouting extent and house settlement curve (no reinforcement)

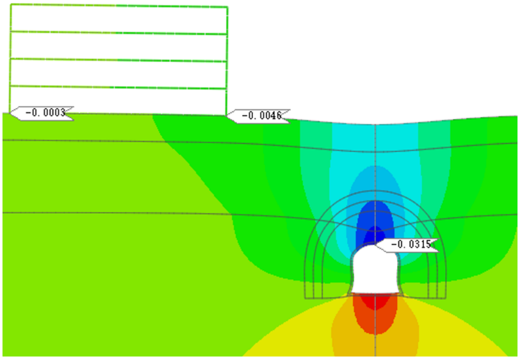

Fig. 10. Grouting extent and house settlement curve (3m of grouting)

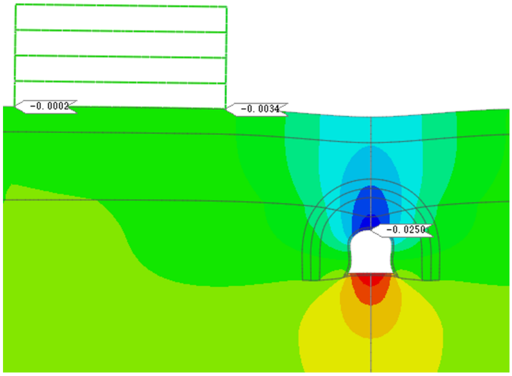

Fig. 11. Grouting range and house settlement curve (4m of grouting)

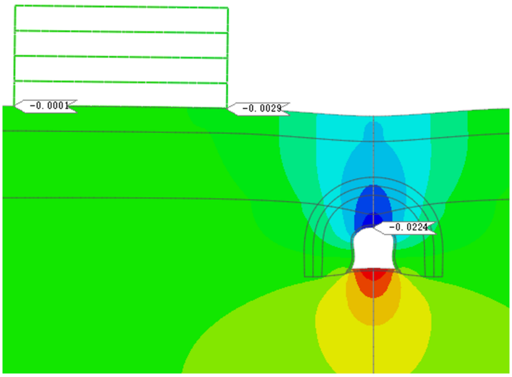

Fig. 12. Grouting range and house settlement curve (5m of grouting)

4.3.3 Summary of Simulation Results. The simulation results show that the maximum vertical deformation induced by tunnel excavation occurs at the vault, and the surface settlement does not exceed that at the vault. Advance curtain grouting can effectively reduce the surface settlement of houses, with a more significant effect as the reinforcement scope increases; tunnel excavation exerts the most prominent impact on the houses directly above the tunnel, and the impact on the houses more than 43 meters from the center line is negligible. The specific settlement variation trend is shown in Figure 13 below, from which the variation laws of tunnel vault and the house settlement under different reinforcement scopes can be clearly observed.

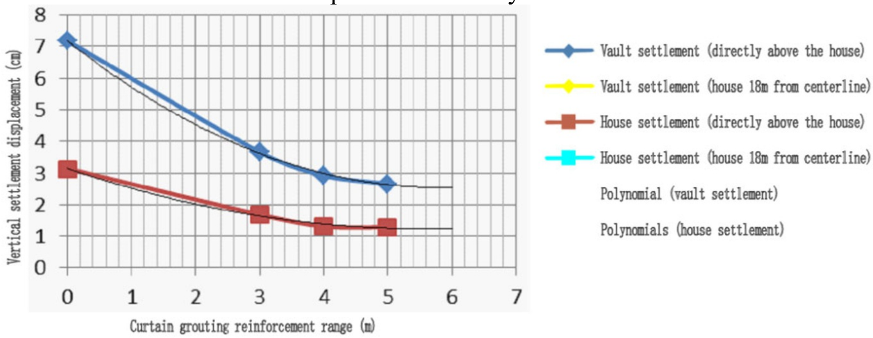

Fig. 13. Correlation diagram of grouting scope and vertical settlement displacement of the houses

In this simulation, the parameters of surrounding rock reinforced by curtain grouting are for reference only. For engineering application, the simulation results shall be reasonably revised by combining on-site geological conditions, construction technologies and monitoring data to provide a reliable basis for decision-making.

4.4 Analysis of Surface Settlement Control Standards

4.4.1 Settlement Control Indicators in Relevant Specifications and Standards. Different industry codes and specifications stipulate varying standards for surface settlement control. Technical Specification for Monitoring Measurement of Railway Tunnels (Q/CR 9218) [3] requires that "when tunneling through weak strata, no cracks shall be induced in the ground surface or structures, and surface settlement shall be controlled within the range of -10mm to +30mm." Section 9.2.3 of Code for Monitoring Measurement of Urban Rail Transit Engineering (GB 50911) [4]states: " Control values for surface settlement monitoring of mine-driven tunnels (Class I sections): 20-30 mm." Technical Code for Monitoring Measurement of Subway Engineering (DB11T490) [5]stipulates that the cumulative control value for ground settlement deformation monitoring shall be ≤20-40 mm. The Code for Design of Building Foundations (GB50007) [6], from the perspective of building foundations, permits surface settlement not exceeding 20mm to ensure structural safety for general buildings within this settlement range.

4.4.2 Determination of Surface Settlement Control Standards of the Banzhulin Tunnel. In railway construction, surface settlement control standards vary across regions and lines due to differing geological conditions, train operating speeds, and track structure types. Subway projects are often located in densely populated urban areas with high pedestrian traffic, necessitating extremely stringent surface settlement control.

The shallow-buried section of the Ban Zhu Lin Tunnel passes beneath commercial land and surface structures. Conventional demolition methods are impractical (due to extremely high costs and cumbersome procedures), and there is insufficient space for temporary relocation of production sites and personnel. To ensure the structural safety of surface structures and maintain normal production and living order during the tunnel's safe and orderly passage through the shallow-buried section, while preventing safety incidents and secondary disasters, and achieving an optimized balance between construction and surrounding environmental safety, this study adopts the most stringent settlement control standard permitted by regulations: 20mm.

Due to the commercial land use designation of the shallow-buried section and difficulties in temporary demolition, conventional construction methods involving surface operations—such as cut-and-cover, top-down construction, surface consolidation (or dewatering) combined with tunnel excavation—cannot be employed. All operations must be conducted within the tunnel bore. Additionally, the rock mass in the shallow-buried section is highly fractured and water-bearing. Conventional in-tunnel measures such as advance large pipe arches and advance peripheral grouting cannot effectively control water ingress or consolidate the rock mass. It is challenging to limit surface settlement to no more than 20mm. Construction risks within the tunnel and third-party risks outside the tunnel are high, and risk control is difficult. Advance curtain grouting enables the early establishment of a full-section enclosed reinforcement ring, achieving comprehensive coverage of critical areas above and on both sides of the tunnel that impact the safety of structures. This forms an integrated and effective protection system combining “waterproofing-reinforcement-settlement control.” Supplemented by other advance support measures, it satisfies the requirements for “zero disturbance” and settlement control in sensitive areas while ensuring controllable risks for both in-tunnel construction and third-party activities outside the tunnel.

4.5 Grouting Parameters for the Shallow-buried Section of the Banzhulin Tunnel

Analysis indicates that a 3-meter grouting reinforcement ring can effectively control settlement, meeting the surface settlement control standard of no more than 20 mm, regardless of whether buildings are directly above the tunnel or 18 meters from the centerline.

Based on geological surveys and groundwater monitoring results for the shallow-buried section of the Ban Zhu Lin Tunnel, advance curtain grouting (forward-advancing segmental grouting) will be implemented for the section passing beneath buildings. using single-liquid cement grout (water-cement ratio 0.8-1:1). Based on engineering analogies and field tests, the grouting parameters were determined as: 3m beyond the excavation contour line, grout diffusion radius ≥1.2m, and final grouting pressure of

2MPa. The representative cross-section of curtain grouting is illustrated in Figure 14. During construction, a monitoring system for tunnel support stability and surface structure settlement will be established to ensure continuous and timely closure of the grouting rings, thereby reducing safety risks.

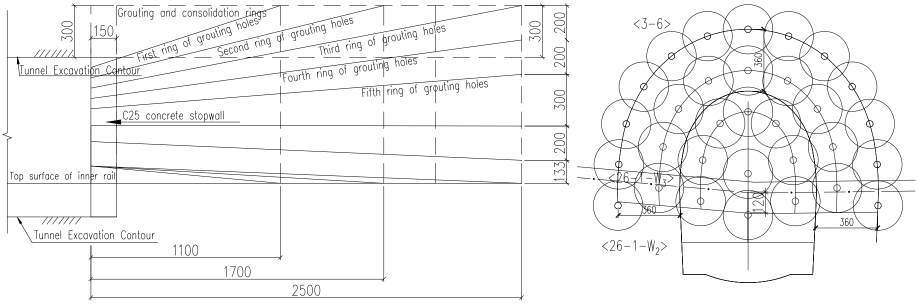

Fig. 14. Representative cross-section of curtain grouting

5 Conclusion

This study thoroughly explores the influence mechanism of tunnel construction on building structures, and establishes a comprehensive engineering risk early warning and prevention system covering the root causes of stratum deformation to the laws of ground surface settlement. Through Midas GTS NX simulation, the remarkable effect of curtain grouting in settlement control is clearly presented, the collaborative optimization mode of reinforcement scope, grouting materials and pressure parameters is defined, and mechanical performance parameters are extracted according to the ground surface settlement control criteria, thus providing technical support for similar projects.

Looking ahead, in order to better cope with the challenges of tunnel construction, it is necessary to strengthen the geological investigation with advanced technologies, strictly control construction based on real-time monitoring, explore the innovative technologies, and promote the harmonious development of the engineering projects and all parties.

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