Integrating Geotechnical Engineering and Finite Element Analysis in Urban Tunnel Construction: Case Study of Zhongshan Road Station on Hohhot Metro Line 2

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Abstract. The expansion of Metro Line 2 with the addition of Zhongshan Road Station in Hohhot presents a paradigm of urban engineering that merges infrastructure growth with the conservation of extant utility systems. This study examines the station's construction, located at a critical junction, which includes a novel straight-wall arch tunnel in close proximity to essential gas pipelines. The core of this paper explores the geotechnical challenges, the application of advanced construction techniques, and particularly the strategic use of grouting for soil stabilization. The employment of Midas GTS NX (2020) for finite element numerical simulation analysis facilitated a thorough investigation of soil dynamics and the interaction with gas pipelines, utilizing the Mohr-Coulomb model. This research also evaluates the impact of different grouting reinforcement approaches on pipeline settlement through a series of controlled simulations. The results demonstrate the significance of grouting methods and their scope in reducing pipeline settlement, where full-section grouting is most effective, but semi-section grouting within a 2.0 m range provides a viable, resource-efficient alternative. The findings of this study offer practical guidance for urban tunnel construction near sensitive infrastructure and emphasize adaptable grouting techniques to ensure the integrity of new and existing structures.

Keywords: Urban Engineering, Tunnel Construction, Zhongshan Road Station.

1 Introduction

The expansion of Zhongshan Road Station on Metro Line 2 in Hohhot exemplifies the intricate balance required in urban engineering between infrastructure development and the preservation of existing utilities[1]. Located at a key intersection, the station incorporates an advanced straight-wall arch tunnel design that intersects with a vital gas pipeline network. This paper examines the challenges faced during the station's construction, emphasizing the role of detailed geotechnical analysis, cutting-edge construction methods, and strategic soil stabilization techniques[2]. Central to the project's suc-

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cess was the application of grouting to reinforce the soil structure and mitigate settlement risks[3], alongside a bilateral roadway tunneling method that upheld structural integrity and minimized urban disturbance.

Employing Midas GTS NX (2020), the project utilized finite element numerical simulation to analyze soil behavior and pipeline interactions under stress, guided by the Mohr-Coulomb model. This approach provided a predictive insight for devising safety control strategies. The study also explores the impact of different grouting reinforcement techniques on pipeline settlement through controlled numerical simulations[4]. The results indicate that grouting significantly affects pipeline settlement, with full-section grouting being most effective, although resource-heavy, while semi-section grouting offers a resource-efficient alternative without compromising on effectiveness.

2 Project Synopsis

The Zhongshan Road Station on Metro Line 2 in Hohhot is positioned on the southern side of Xilingol South Road's junction with Zhongshan East Road[6]. The station features an underground passage and an open pit for entry and exit no. 2, depicted in Figure 1. This passageway utilizes a straight-wall arch design, spanning a length of 16.40 meters, segmented into a standard and an extension section. The construction employed a bilateral roadway technique, with primary supports made from steel wire frames, reinforcement mesh, and 35 cm thick C25 shotcrete[7], followed by a 60 cm thick C35 reinforced concrete for the secondary lining[8]. Directly above the subterranean passage lies a cast iron gas pipeline, 30 cm in diameter and 3 cm thick, buried 2.17 meters deep and situated 2.7 meters vertically from the tunnel’s main support[9].

2.1 Geotechnical Context

Per the geotechnical assessment, the subterranean strata of the station’s entrance and exit comprise organic fill, rounded gravel, chalk, and a sand and gravel mixture, while the area around the gas pipeline primarily contains common fill. The soil is characterized by its loosely-packed nature, high permeability, and limited self-supporting capacity.

2.2 Construction Methodology

2.2.1 Soil Stabilization Technique:

For the soft soil layer above the vault of the No. 2 entrance and exit, excessive grouting was employed to reinforce it, extending 2.0 meters above the excavation profile. Grouting tubes were positioned at angles adjusted to the situational pipeline requirements. The initial grouting was 12 meters in length, with 10 meters for excavation and 2 meters reserved for the sealing of the bedrock. A barrier was created prior to grouting, utilizing C25 shotcrete 300 mm in thickness, reinforced with a grid. A double-layer steel wire mesh of 6.5 mm in diameter with a 150 mm bar spacing was anchored to steel rods, with HRB400 grade steel bars of 22 mm diameter and 1.5 m length, spaced

500 mm apart. The grouting pipes, arranged in a staggered pattern, had three rows with each diversion pipe being 2 meters long and the pipes having a diameter and wall thickness of 32 mm and 3.25 mm, respectively. The grouting used a cement and waterglass mixture, influencing a radius of 0.8 m, with a grouting velocity of 3050 L/min and a pressure of 0.81.5 MPa[5].

2.2.2 Tunneling Approach:

The straight-wall arch tunnel construction proceeded via a bilateral roadway method, with the initial phase involving lead grouting and the opening of the first guide hole, followed by the sequential excavation of six pilot tunnels. The secondary lining construction commenced post the diaphragm walls removal. The upper sections of Pilot Tunnel 1 saw the installation of steel mesh, arches, sidewalls, and diaphragm wall girders, followed by the placement of lock-foot anchors and shotcreting. The excavation of Pilot Tunnel 2 and subsequent chambers was performed with proper shoring, maintaining a minimum longitudinal step distance of 6 m between subsequent chambers. After constructing the main arch support and a temporary elevated arch, chamber 5 was excavated, succeeded by chamber 6, followed by the construction of the bottom secondary liner. Upon partial removal of the temporary diaphragm wall, the superstructure for the secondary liner was erected, leading to the complete removal of the temporary diaphragm wall.

3 Finite Element Numerical Simulation Analysis

3.1 Numerical Modeling

A three-dimensional numerical model with the dimensions 100 m in length, 20 m in width, and 50 m in depth is presented in Figure 1. For the simulation, the finite element software Midas GTS NX (2020) was employed. The soil behavior was represented using the Mohr-Coulomb failure criterion, which closely aligns with the actual material properties observed in the project. The soil matrix, the tunnel infrastructure, and the gas pipeline were each constructed using three-dimensional solid elements. For the main tunnel supports and the intermediate diaphragm walls, two-dimensional slab elements were utilized. To prevent horizontal movement, the lateral boundaries of the model were defined as displacement boundaries, while the upper boundary was set as a free boundary to restrict vertical movement only.

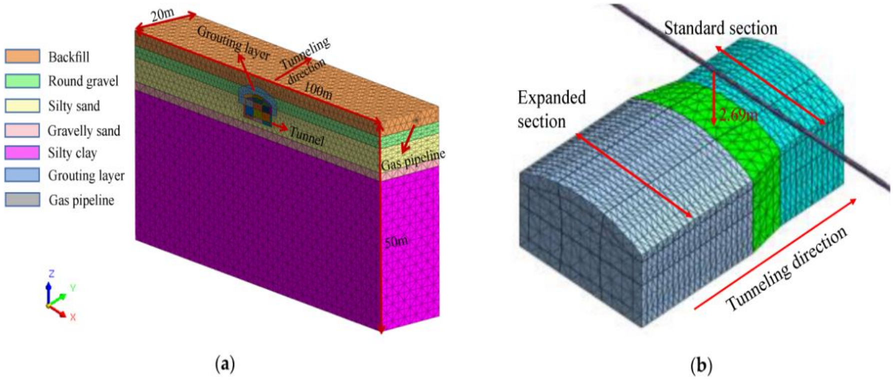

Fig. 1. Three-dimensional numerical model. (a) Overall structure; (b) relative position of tunnel and gas pipeline.

3.2 Numerical Simulation Scheme

In constructing straight-wall arch tunnels, the use of the double-side drift method for the close-proximity intersection with underground gas pipelines introduces heightened risk factors. This study employs the controlled variable approach to conduct a numerical simulation analysis across nine distinct working conditions. These conditions reflect variations in the grouting reinforcement area's design and extent, as well as the tunnel excavation stages. The objective is to explore the impact of various safety control strategies on the deformation of pipelines during the construction of new straight-wall arch tunnels that traverse existing subterranean gas lines. The specific numerical simulation configurations are detailed in Table 1, with Scheme 1 serving as the baseline safety control scenario against which the other conditions are measured. Schemes 1–3 focus on examining the effects of three disparate grouting reinforcement zones on pipeline deformation. Meanwhile, Schemes 1 and 4–6 are designed to assess the impact of four divergent grouting reinforcement extents on pipeline deformation. Additionally, the effect of varying the tunnel excavation increments on pipeline deformation is analyzed in Schemes 1 and 7–9.

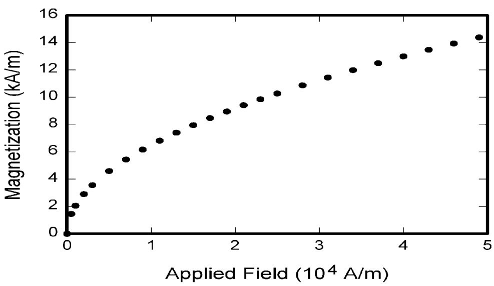

Fig. 2. Construction and geometrical dimensions of specimens.

Table 1. Numerical simulation scheme

Scheme	Grouting Reinforcement Form	Grouting Reinforcement Range (m)	Step Distances of Tunneling (m)
Scheme 1	Semi-section grouting	2.0	6.0
Scheme 2	Full-section grouting	2.0	6.0
Scheme 3	Without grouting	2.0	6.0
Scheme 4	Semi-section grouting	1.0	6.0
Scheme 5	Semi-section grouting	1.5	6.0
Scheme 6	Semi-section grouting	2.5	6.0
Scheme 7	Semi-section grouting	2.0	2.0
Scheme 8	Semi-section grouting	2.0	4.0
Scheme 9	Semi-section grouting	2.0	8.0

4 Numerical Simulation Outcomes

4.1 Grouting Reinforcement Variants

Settlement profiles of the gas pipeline under diverse grouting conditions are depicted in Fig. 2. The simulation results highlight the substantial influence of grouting type on pipeline settlement. Utilizing a full-section grouting approach minimizes the settlement, lateral shift, and spread of the gas pipeline's settlement trough. Specifically, full-section grouting results in a settlement of 11.06 mm, while semi-section grouting leads to a settlement of 18.23 mm, which is 39% greater. In the absence of grouting, the pipeline's settlement peaks at 26.17 mm. The disparity between Peck's formula adjusted values and simulation outcomes is at most 1.54 mm. Notably, maximum pipeline settlement tends to occur on the left of the tunnel's centerline, corresponding with the initial excavation of the left pilot tunnel.

The evolution of pipeline settlement under various grouting methods, illustrated in Figure 2, shows that grouting effectively mitigates pipeline settlement, with full-section grouting being more efficient than semi-section. Grouting fills voids, augments soil strength, and diminishes settlement caused by tunneling. The on-site semi-section grouting method controls pipeline settlement efficiently, offering a balance between resource expenditure and effectiveness, making it preferable for field implementation.

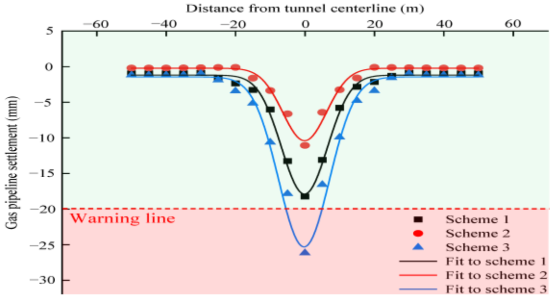

Fig. 3. Settlement trough curves of gas pipeline under different grouting reinforcement types.

4.2 Extent of Grouting Reinforcement

The range of semi-section grouting also influences pipeline settlement, as depicted in Fig. 3, with Fig 4 detailing the pipeline's settling trough parameters. Pipeline settlement and lateral shift decrease, and trough width increases with more extensive grouting. Extending the grouting range from 1.0 m to 2.0 m has a negligible effect on settlement, hovering around 20 mm, but expanding to 2.5 m reduces settlement to 12.41 mm, optimizing control effects. However, this wider grouting proximity increases trough width and potentially affects the pipeline due to the proximity of the grouting operation. Thus, a 2.0 m outward grouting range from the tunnel's perimeter was chosen as the optimal balance.

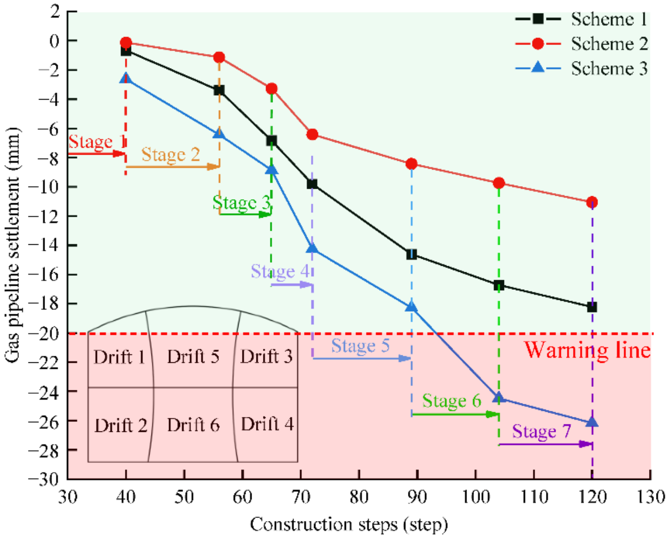

Fig. 4. The development of gas pipeline settlement.

5 Conclusion

The construction of Zhongshan Road Station on Hohhot's Metro Line 2, with its subterranean features near critical gas pipelines, posed significant engineering challenges. Success hinged on detailed geotechnical planning and robust construction techniques, notably grouting for soil stabilization, which proved crucial in preventing settlement and ensuring the tunnel's structural integrity. Utilizing Midas GTS NX (2020) for finite element numerical simulation and the Mohr-Coulomb model, the project accurately assessed the effects of grouting on pipeline deformation[10].

The study's results clearly show that grouting methods and scope considerably affect pipeline settlement. Full-section grouting was most effective in reducing settlement but was also resource-intensive. In contrast, semi-section grouting within a 2.0 m range offered a cost-effective and efficient solution, ideal for practical application. Extending grouting to 2.5 m optimized settlement reduction but at the expense of increased trough width, leading to the selection of a 2.0 m grouting range as the best compromise between effectiveness and safety.

In essence, this research advances tunneling practices near sensitive infrastructures and provides actionable guidelines for urban construction, emphasizing the strategic use of grouting. These insights are particularly valuable for future urban developments where existing utilities pose spatial challenges.

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