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Shallow urban tunnelling method in complex geological conditions; case study: Naghsh-e-Jahan station-line 2 metro of Esfahan

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ABSTRACT: The paper investigates a case study of metro station construction in urban areas using the New Austrian Tunnelling Method - Shallow Tunnelling Method (NATM-STM). Naghsh-e-Jahan metro station, located on Line 2 of the Esfahan metro, was constructed using an underground approach and a combined method that included the NATM with STM, with low overburden in the upper part of the platform level and supported lateral piles in the lower part of the platform level. The choice of the underground construction method was due to the requirements imposed by the location of the station in the historic fabric of Esfahan, which has a high sensitivity to settlement, and the high groundwater level that rules out systematic dewatering. This article systematically shows the potential use of combined methods and the application of STM in the construction of urban shallow underground spaces, despite the complex geological and geotechnical conditions. The findings of the study can be used for future tunnelling projects under the same conditions.

1 INTRODUCTION

Tunnelling and metro systems play a vital role in modern urban infrastructure, particularly in densely populated cities where surface transportation options are limited. As urban areas expand and encounter increasing population density, the demand for underground transportation networks has risen significantly (Cui et al., 2017). The evolution of tunnelling techniques underwent a major transformation in the mid-20th century with the introduction of the new Austrian tunnelling method (NATM), which became widely adopted due to its flexibility under various geological conditions. However, debates exist regarding its applicability in soft ground. In response to challenges posed by soft ground, the Institution of Civil Engineers (ICE) introduced the concept of sprayed concrete lining (SCL) (ICE, 1996). Soft soils present unique challenges that may not align with conventional NATM theories; thus, the development of SCL aimed to address these issues and offer a more effective solution for tunnelling in such geological conditions. Continuous monitoring and control during the use of SCL in soft ground are essential to ensure tunnel safety (Brown, 1981).

Subsequently, the shallow tunnelling method (STM) emerged as a valuable technique for tunnel construction at shallow depths, particularly in densely populated urban areas with soft ground conditions (Moghbeli et al. 2025b). Key characteristics of STM include shallow overburden (requiring careful control of surface ground movements), the sensitivity of soft soils to deformation and instability, and the need to minimize surface movements to protect infrastructures (Moghbeli et al. 2025c). The development of pre-reinforcement techniques has significantly enhanced the stability and safety of shallow tunnels in challenging geological environments. Drawing from successful experiences with NATM and adapting them to shallow tunnelling conditions, engineers can continue to improve the efficiency and effectiveness of STM projects (Cui et al., 2017, Moghbeli et al. 2025a). Fang et al. (2012) showed the effectiveness of STM for tunnelling in soft ground with shallow depth. Amiri and Dehghan (2022) reported that STM significantly reduced surface settlement compared to the pile and rib method (PRM), with a maximum settlement of approximately 6 cm. According to Liu et al. (2022), STM is commonly applied to shallow tunnels in soft soils in China, particularly in metro projects. Zhang et al. (2020) proposed a complex construction plan for shallow urban tunnels in silty soils, a case study in Fuzhou, Fujian Province.

The present paper investigates a case study (Naghsh-e-Jahan station-line 2 metro of Esfahan) of underground metro station construction in urban areas using the NATM-STM. It provides a detailed analysis of the design of an underground station, including construction method, structural design, and architecture, in complex geotechnical and geological conditions in the historic fabric of Esfahan city.

2 PROJECT DESCRIPTION

2.1 Project characteristics and geological settings

The project's alignment depth at this station is 17.10 meters below the ground surface, with an overburden of approximately 8 meters. The central core structure of the station, designed at a depth of 16.4 meters below the ground level, has a length of 105 meters and comprises a single level (the station platform). This core includes the ticket hall and side structures extending over a length of 65 meters. A connecting gallery, linking the side structures, is located at a depth of approximately 11.40 meters and extends about 20 meters in length. The general layout of the station, including the central core and its side structures, is presented in Figure 1.

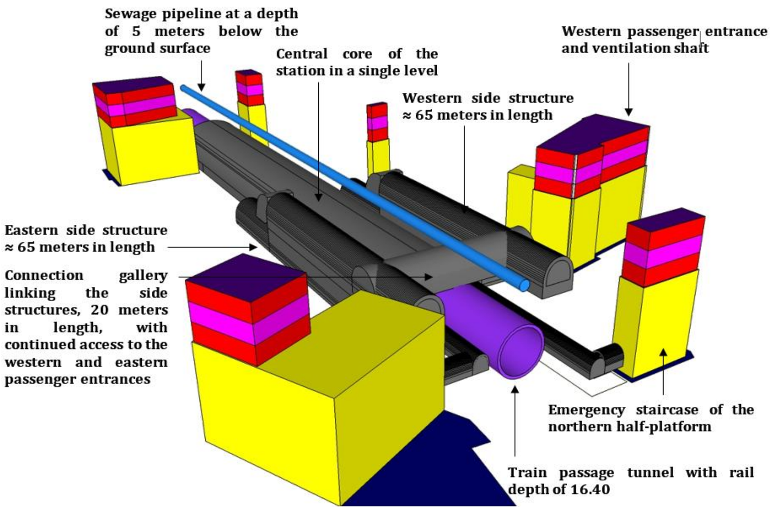

Figure 1. General layout of the Naghsh-e-Jahan station-line 2 metro of Esfahan.

The construction method used for this station is a combination of NATM and STM. Excavation was carried out in two main parts, upper and lower, each subdivided into three drifts (two side drifts and one central drift). The cross-sectional area of the NATM segment is approximately 100 square meters, while the total excavation cross-sectional area of the station is 180 square meters. The internal height of the excavation section is 12 meters, and the width is 17 meters. A cross-sectional view of the station, showing the excavation subdivisions considering the geological layout, is presented in Figure 2.

Table 1-A presents the physical and mechanical properties of the project site. The first major challenge of the project is the relatively shallow overburden of the tunnel compared to the ground surface, which increases the risk of ground settlement sensitivity. The second challenge arises from the station's location at an intersection surrounded by deteriorating urban infrastructure and historically significant cultural buildings. Additionally, the presence of the Zayandeh Rood River,

which flows through the central area of Isfahan, results in a high groundwater level. The station is constructed in clayey soil with coarse-grained interlayers, exhibiting hydrodynamic characteristics such as high transmissivity and permeability coefficients. Consequently, dewatering and pumping operations have not been effective in lowering the groundwater level. The main geological and physical challenges of the project are summarized in Table 1-B.

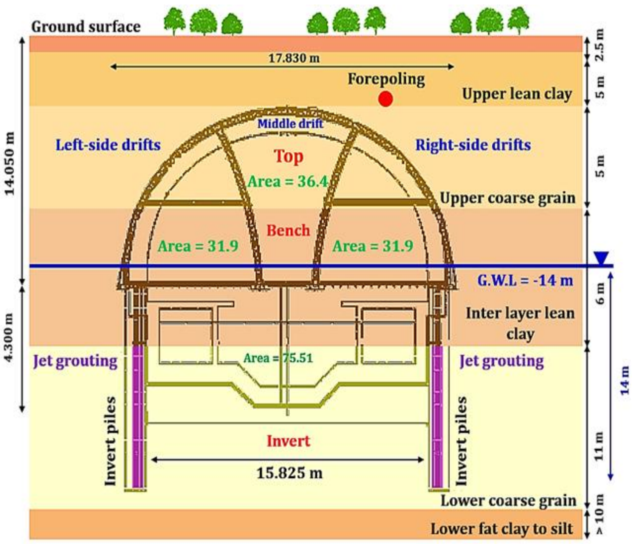

Figure 2. Schematic design of the Naghsh-e-Jahan station-line 2 metro of Esfahan, considering the geological layout (Moghbeli et al. 2025d).

Table 1. (a) Key characteristics of the project, (b) Main challenges of the project.

Part A		Part B	
Parameters	Descriptions	Challenges/Limitations	Descriptions
Tunnel length	105 m	Congestion and traffic	Yes
Excavation method	NATM-STM	Uncompacted and fine-grained soil	Yes
Tunnel diameter	12 m	Sensitive railway tracks	No
Overburden	8 m	High groundwater level	Yes
Overburden/diameter ratio	0.66	Historical buildings	Yes
Geological unit	Clayey soil with coarse-grained interlayers	Sensitive and deteriorated infrastructures	Yes

2.2 Engineering geological and geotechnical investigation

The Naghsh-e-Jahan station-line 2 metro of Esfahan project is situated within the Qm sedimentary unit. Engineering geological and geotechnical specifications were defined using pre-construction laboratory testing and in-situ field investigations, as well as sampling during station construction. Table 2 presents the geotechnical properties of materials along the project alignment, which were utilized in the design phase of the construction.

Table 2. Geotechnical characteristics of materials along the project.

Geotechnical factors	Unit	Man fill	Upper lean clay	Upper coarse-grained	Inter-layer lean clay	Lower coarse-grained	Lower fat clay to silt
Depth	m	0-2.5	2.5-7.5	7.5-12.6	12.6-18	18-29	29-40
Elastic modulus	Kg/cm^2	100	170	270	156	330	140
Poisson	-	0.3	0.35	0.3	0.35	0.3	0.35
Friction angle	degree	15	26.7	36.5	29	34.3	26.7
Cohesion	Kg/cm^2	0.1	0.25	0.06	0.24	0.04	0.24

Wet density	gr/cm^3	2.05	1.98	2.07	2.01	2.08	1.85
Dry density	gr/cm^3	2.0	1.9	2.05	1.95	2.1	1.81
Permeability	cm/s	-	$1.0*10^{-6}$	$1.0*10^{-4}$	$5.36*10^{-6}$	$2.6*10^{-4}$	$1.0*10^{-6}$

2 PROPOSED TUNNELLING METHOD

The Naghsh-e Jahan Station is constructed underground, on a single level, using a combined NATM-STM method along with braced piling. The choice of an underground construction method was necessitated by the proximity of deteriorated and historical buildings, which made surface-level construction operations unfeasible. Moreover, due to the high groundwater level, the station was designed and constructed as a single-level structure to reduce exposure to groundwater-related challenges. Access to the station's central core was designed through a shaft approximately 9 by 18 meters in size, extending to the platform level, along with an access gallery at the platform elevation. Excavation of the upper part of the platform (divided into three sections: two side drifts and one central drift) was carried out using the NATM technique, while the lower part was executed using braced piling. The upper structure of the station's central core consists of 35 cm-thick shotcretes, reinforced with mesh and rebar. To ensure structural integrity, the design calculations were based on the early-cured age compressive strength of shotcrete (160 kg/cm²). In the lower part of the platform, piles with a diameter of 0.9 meters and a spacing of 2.5 meters were used. The construction stages associated with the application of the combined NATM-STM with braced piling method for this station are presented in Figure 3.

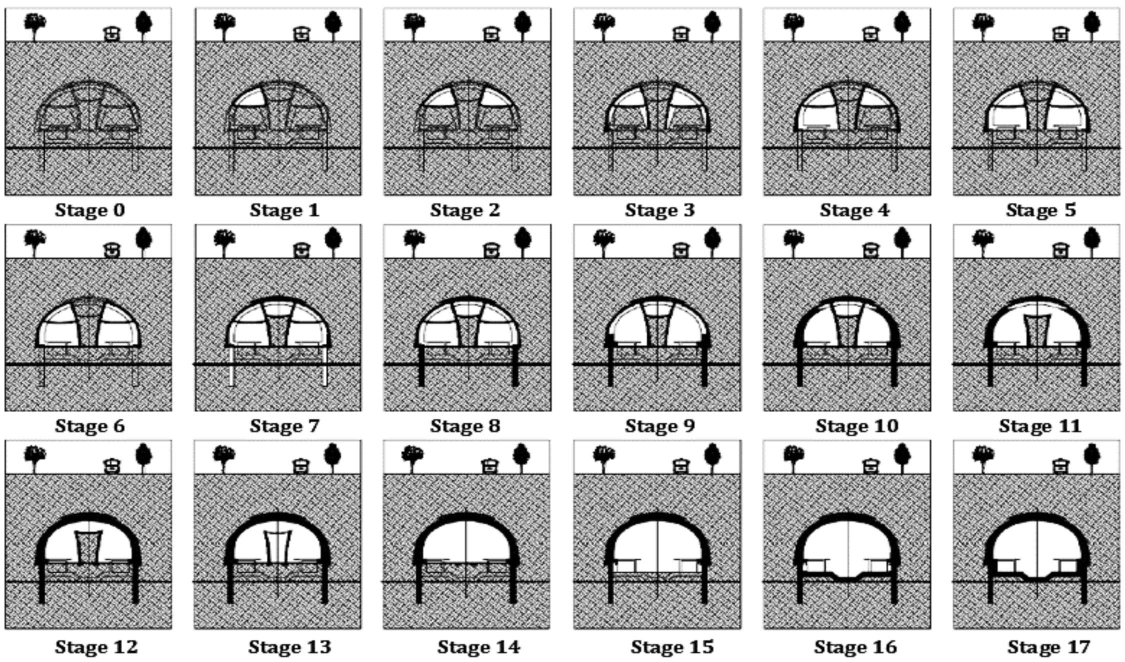

Figure 3. Step-by-step construction stages of the stations' central core using NATM-STM and braced piling methods.

It is worth noting that in the initial design, before the removal of the temporary central lattice girders, the use of a forepoling pre-reinforcement system was planned for the upper section. However, its implementation proved unsuitable due to the poor groutability of the upper soil layer above the crown. Consequently, a new construction approach was adopted, involving the installation of side arch walls (within the side drift zones) supported on a deep foundation system (the same lateral piles initially intended for the excavation beneath the platform), before the removal of the central temporary lattice girders. To achieve this, pile cap beams were first constructed atop the side piles. Then, the arch walls were executed from those beams, extending as far as feasible into the stable zones (Figure 4a). Following the construction of these walls, the upper portion of the central lattice girders was removed (Figure 4b), and the stabilizing side arch walls were connected by completing the remaining portion of the arched roof. Ultimately, the remaining parts of the central drift were removed (Figure 4c), and excavation of the lower section was carried out (Figure 4d), thereby completing the final profile of the station cross-section (Figure 4e).

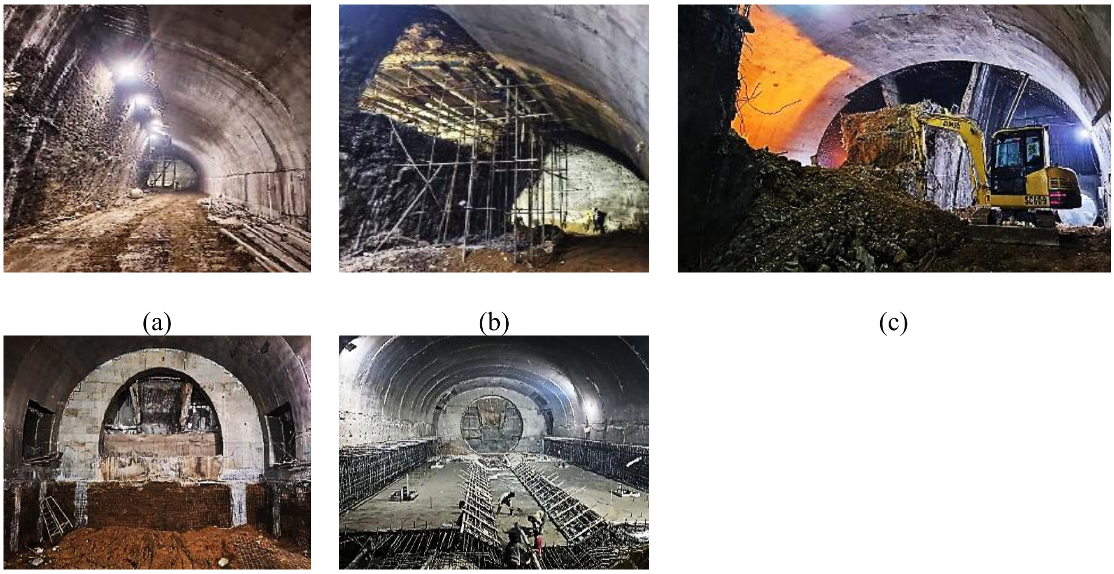

Figure 4. The construction sequence in the southern section of Naghsh-e Jahan Station, (a) construction of side arch walls, (b) removal of the lattice girder in the central drift, (c) complete removal of the central drift, (d) excavation of the lower section, (e) completion of the central core cross-section through foundation construction.

3 MONITORING

Instrumentation and monitoring systems were used concurrently with the construction activities as a mandatory requirement for the execution of underground spaces in urban environments. A total of 288 instruments were employed in the project, including 8 deep settlement gauges, 100 ground surface settlement gauges, 60 building settlement gauges, 14 convergence measurement sections, 42 crack meters, and 64 surveying targets. Among the approximately 100 ground surface settlement gauges and 60 building settlement gauges installed within the station area, the maximum recorded ground surface settlement reached 109.4 millimeters at ground settlement gauge G02-E, while the maximum building settlement reached 43 millimeters at building settlement gauge SW206.

According to the monitoring results, the excavation sequence of the upper section of the central core in a portion of the station was modified. Assuming the intersection point between the access ramp and the central core as the boundary between the northern and southern sections of the station, the instrumentation data indicated that the settlement values in the northern section were consistent with predictions, whereas in the southern section, the observed settlements exceeded the values anticipated by the design calculations.

Since the additional surface settlement in the southern section occurred after the excavation and stabilization of the side drifts and before the removal of the central drift, continuing construction stages—including completion of the central drift and removal of the temporary lattice girders—would have led to excessive surface settlement beyond the permissible limits and posed a risk of damage to the adjacent deteriorated structures within the excavation's impact zone. Therefore, a change in the construction method and implementation of additional settlement control measures became necessary.

An example of ground surface settlement measurements in the southern section of the station is presented in Figure 5. As seen in the graph, on 4 October 2023, corresponding to the completion of the side drift removals, the ground surface settlement reached approximately 8 centimeters. Subsequently, the side arch walls were constructed, and the temporary central lattice girders were removed. As a result, the ground settlement increased by only 0.5 millimeters up to 4 June 2024, indicating the effectiveness of the side arch walls in controlling surface settlement following the completion of the upper section excavation of the station core. Following this phase, excavation of the lower section of the station platform was carried out and completed by 4 December 2024. This phase resulted in an additional settlement of only 1.5 centimeters, confirming overall settlement control throughout the station construction.

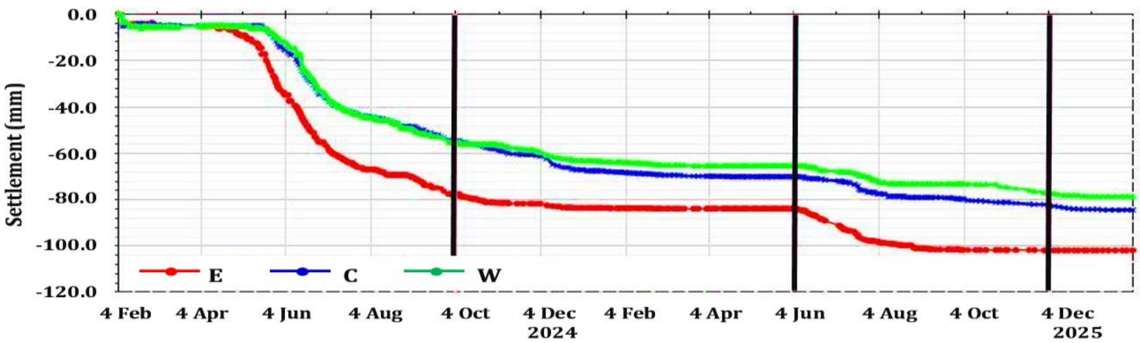

Figure 5. Monitoring results obtained from the three-point settlement gauge G06 in the southern section of Naghsh-e Jahan Station.

4 NUMERICAL MODELLING

A two-dimensional model of the central core of Naghsh-e Jahan Station was developed using Plaxis 2D v21 before construction, including soil–structure interaction. This model was subsequently updated using data obtained from instrumentation and monitoring during construction. Ground surface settlement was controlled throughout all construction stages, and the maximum settlement in the upper section constructed using the NATM-STM was recorded at various stages, as illustrated in Figures 6 to 9. According to the results, the maximum surface settlement increased from approximately 7.6 cm (following the removal of side drifts) to about 10.2 cm after the full completion of the cross-section. This corresponds closely with the monitored data obtained during construction, demonstrating a strong agreement between the numerical model and field observations.

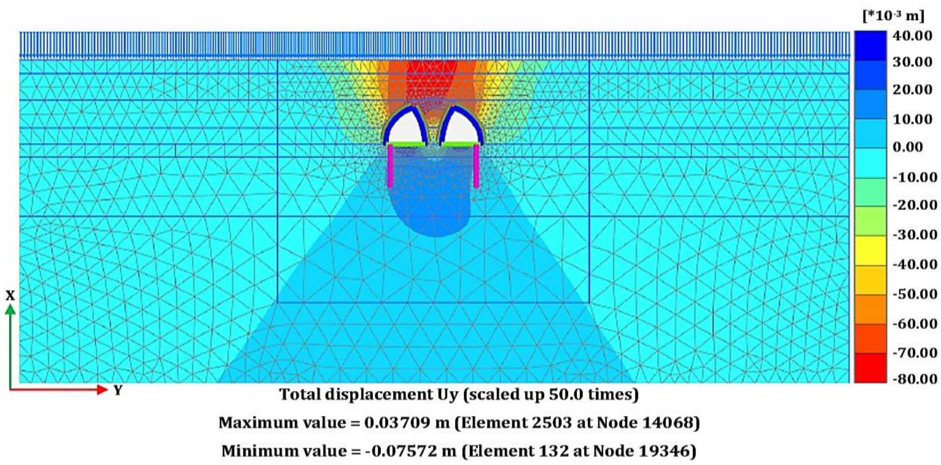

Figure 6. Settlement of Naghsh-e Jahan station after the removal of the side drifts based on the results of 2D modelling with Plaxis.

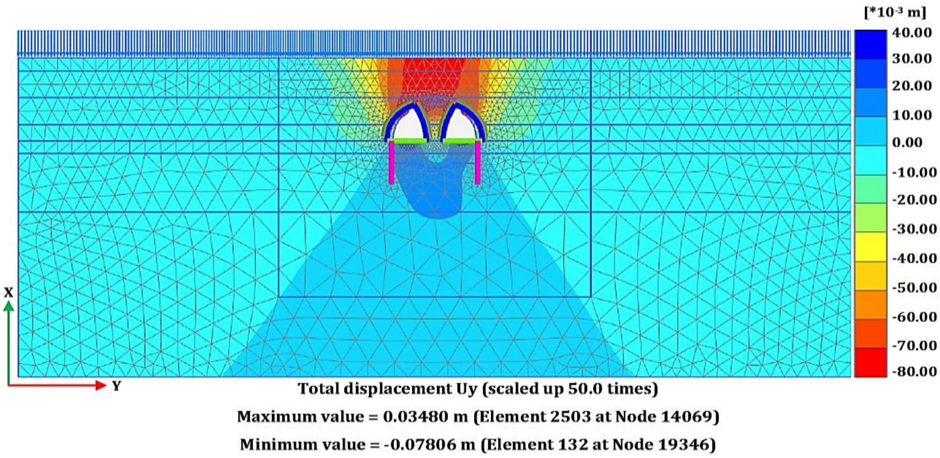

Figure 7. Settlement of Naghsh-e Jahan station after the construction of the arch walls based on the results of 2D modelling with Plaxis.

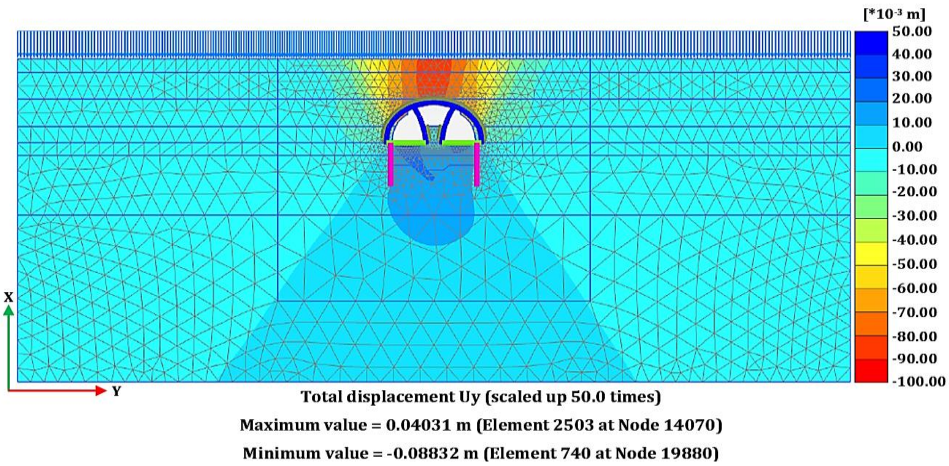

Figure 8. Settlement of Naghsh-e Jahan station after the removal of the upper part of the central drift based on the results of 2D modelling with Plaxis.

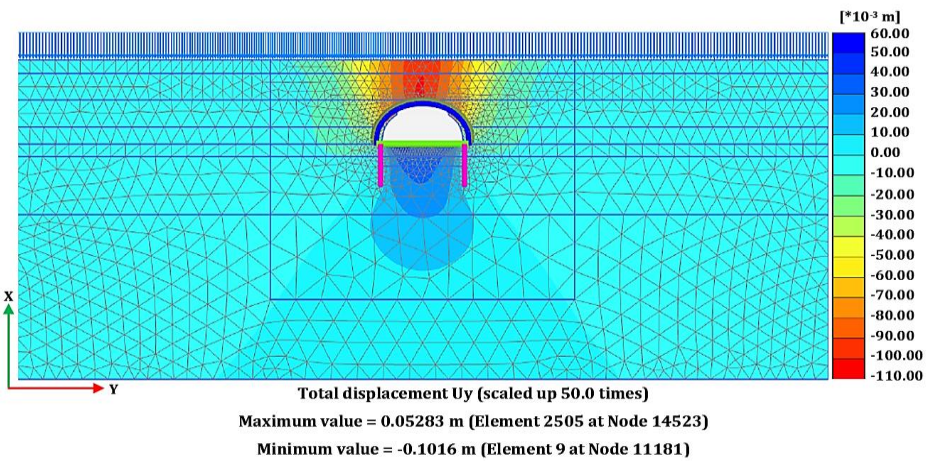

Figure 9. Settlement of Naghsh-e Jahan station after the complete removal of the central drift and connection of the arch walls based on the results of 2D modelling with Plaxis.

5 CONCLUSIONS

This paper examines the construction approach of the Naghsh-e Jahan metro station in Isfahan, utilizing the NATM-STM method in urban areas. This study presents the overall station layout, geometric design, challenges encountered during the design and construction phases, and proposed solutions to overcome these obstacles in the project. The successful construction of such metro stations, particularly those located near significant historical landmarks, existing infrastructure, or below the groundwater table, necessitates the application of the NATM-STM method alongside precise monitoring. The case study detailed in this paper shows how the geometric design of such stations is critical to their successful implementation in complex urban environments. By highlighting the strategic application of NATM-STM techniques in this project, the paper aims to provide a comprehensive understanding of the method's effectiveness in both theoretical and practical contexts. The outcomes emphasize the importance of adapting design approaches to specific geological and environmental conditions. The insights gained from this project offer guidance for future projects in similar geotechnical settings, illustrating the capability of NATM-STM to address complex construction challenges effectively.

6 ACKNOWLEDGMENT

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