-RESEARCH PAPER-

International Journal of Mining and Geo-Engineering

IJMGE

IJMGE 59-3 (2025) 229-235

DOI: 10.22059/IJMGE.2025.369905.595132

# Comparative analysis of support methods for TBM entrance walls

Mahdi Mohammadi [a], Rashid Hajivand Dastgerdi [b, *], Behzad shokati [c], Adriko Norman Burua[d] and Dariush Mohammadi [a]

[a] *Faculty of Mining Engineering, Amir kabir University of Technology, Tehran, Iran.*

[b] *Faculty of Geo-Data Science, Geodesy, and Environmental Engineering, AGH UST, Krakow, Poland.*

[c] *Faculty of Civil Engineering, Yildiz Technical University, Istanbul, Turkey.*

[d] *Faculty of Civil Engineering, Southwest Jiaotong University, Sichuan, China.*

Article History:

Received: 20 December 2023.

Accepted: 20 May 2025.

**ABSTRACT**

The excavation and construction of underground stations are essential elements of modern urban infrastructure. This research article delves into the critical aspect of station construction within underground transportation systems, focusing specifically on stabilizing entrance walls of a metro station, particularly for Tunnel Boring Machine (TBM) entrances. The study conducts a comparative analysis between two support systems: the plastic concrete piles method and its combination with soil nailing, evaluating their efficacy in the context of TBM entrances. Employing both 2D and 3D Finite Element Modelling (FEM), the research investigates various soil constitutive models, including the Hardening Soil and Hardening Soil with Small Strain models. The findings emphasize the combined approach of utilizing plastic concrete piles with soil nailing as being more advantageous, demonstrating superior displacement control. Additionally, the comparison of modelling approaches indicates that the utilization of 3D modelling with the Hardening Soil with Small Strain model is recommended for numerical analysis of deep excavations near sensitive properties due to its ability to predict realistic ground movement distributions.

**Keywords:** *Excavation, Finite element method, Support techniques, Soil constitutive models.*

## 1. Introduction

The continuous advancements in technology have revolutionized the feasibility of excavating underground spaces across diverse geological conditions. These subterranean structures, integral to modern society's infrastructure, play a pivotal role in various applications, notably in the construction of metro lines and public transportation systems, involving the creation of tunnels and stations. These structures, predominantly situated in urban areas and fragile geological formations, pose intricate challenges due to their sensitivity to stability concerns. Consequently, understanding their behavior during construction becomes imperative. To stabilize Tunnel Boring Machine (TBM) entry and exit portals within metro stations, various techniques are employed, including freezing the ground, injection operations, implementing plastic concrete piles, fore-polling, and using soil placement at entry and exit points, among others.

Numerous studies have extensively utilized the Finite Element Method (FEM) modelling approach to analyze underground structures. For instance, in 2009, F. Xuan et al. employed Plaxis software to investigate constitutive models such as HSS, HS, and MC in excavation cases, with findings favoring the HSS model's closer alignment with reality [1]. Additionally, researchers like Lim et al. and Wei-dong recommended specific soil constitutive models, emphasizing their accuracy in predicting ground movement and stress-strain characteristics during deep excavations [2, 3]. Farzi et al. proposed rigid support systems as the most effective approach for stabilizing urban deep excavations, considering construction, structural, and economic conditions [4]. A.M. Hassan's 2019 study extensively investigated wall movement, surface settlements, and their impact on adjacent structures during deep trench excavation in the Chicago subway renovation project, utilizing the Hardening Soil model via a 3D FEM analysis [5]. Similarly, Nematollahi et al., in 2022, validated soil-structure interactions for urban tunneling, emphasizing the effectiveness of Plastic Hardening over linear elasticity for non-symmetric load conditions induced by retaining walls [6].

This research article delves into the stabilization of entrance walls for metro stations, specifically those used by TBMs. The study compares the effectiveness of two stabilization methods: employing plastic concrete piles solely versus combining them with soil nailing at TBM entry points. Using both 2D and 3D Finite Element Modelling (FEM), the research explores various soil constitutive models, including the Hardening Soil and Hardening Soil with Small Strain models.

## 2. Case study

The B7 metro line station is situated in the southeastern region of Tehran. Due to its relatively shallow depth and the potential for temporary traffic diversion, as well as the aim to minimize costs and implementation difficulties, the cut and cover method with a vertical wall was selected for the station's construction. During the construction of this station, elements of the support structure were integrated as part of the main structure, ensuring structural integrity and stability. The stratigraphy of the B7 station comprises four distinct layers. Starting from the surface and reaching a depth of approximately 2 meters, there is a layer of backfill. From a depth of 2 to 15 meters, a clayey sand layer with gravel is encountered (SC/CL). The layer between 15- and 30-

* Corresponding author: *Tel./Fax:* +48 452374789 , *E-mail address:* : Dastgerd@agh.edu.pl (R. Hajivand Dastgerdi).

meters' depth also consists of clayey sand with gravel, where the clay content may vary (SC/CL). Beyond a depth of 30 meters, the subsurface material transitions to gravelly clay with sand (GC/SC). The water table lies at a depth of 40 meters. The profile of subsurface materials was obtained through the examination of logs from two wells and three boreholes, in addition to the results of field and laboratory tests. The geotechnical parameters for each soil layer are presented in Table 1, providing valuable insights for the analysis and design of the station's foundation and support systems.

### *2.1. Excavation support system*

Wall stability is addressed through two distinct methods for the transverse walls: (1) a combination of plastic concrete piles with nails, and (2) the sole use of plastic concrete piles. The stabilization approach for the longitudinal walls focuses on the precise implementation of nails with specific dimensions and properties. Furthermore, a 15 cm thick layer of shotcrete has been applied to reinforce both the transverse and longitudinal walls, enhancing their overall stability.

#### *2.1.1. Longitudinal walls*

Additionally, a nailing technique has been employed for the longitudinal walls, utilizing 12-meter-long nails with a diameter of 28 mm for the upper section and 9-meter-long nails with a diameter of 32 mm for the lower section. The transverse distances between the nails have been established at 2 meters for the upper section and 1.25 meters for the lower section, thereby ensuring comprehensive reinforcement across the entire structure.

#### *2.1.2. Transverse walls*

**a) Plastic concrete piles and nailing system**

In accordance with the station plan, plastic concrete piles with a diameter of 80 cm and a length of 24 meters have been strategically positioned before excavation, as depicted in Figure 2. These piles are arranged in five rows, with a center-to-center distance of 60 cm. The overlapping arrangement of the piles creates a rectangular space measuring 3.2 m by 10.3 m, with the depth of 24 m. The upper section of the wall incorporates 12-meter-long nails, arranged in three complete rows with a horizontal distance of 2 meters and a vertical spacing of 1.7 meters as illustrated in the figure below. It is important to note that nailing has not been implemented at the entrance of the TBM.

**b) Plastic concrete pile system**

In this particular method, only plastic concrete piles are implemented at the back of transverse walls. As depicted in Figure 3, which illustrates the corresponding plan, the transverse wall is fortified with trapezoidally arranged plastic concrete piles. These piles possess a diameter of 80 cm and are positioned at a center-to-center distance of 60 cm.

## 3. Numerical modelling

To analyze the excavation behavior of the B7 station accurately, we employed the Finite Element Method (FEM). FEM is a specialized numerical technique widely used in geotechnical engineering, notably successful in modelling soil nailing phenomena [7]. The FEM analysis utilized Plaxis 2D and 3D software, renowned tools in geotechnical engineering. To ensure model reliability and accuracy, meticulous attention was dedicated to meshing and selecting an appropriate constitutive model representing the complex behavior of soil layers surrounding the station excavation [7]. For a comprehensive comparison of modelling results, two distinct behavioral models for soil layers were considered: the hardening soil behavioral model (HS) and the hardening soil behavioral model with small strains (HSS). Table 2 displays the construction phases used to simulate two distinct stabilizing methods.

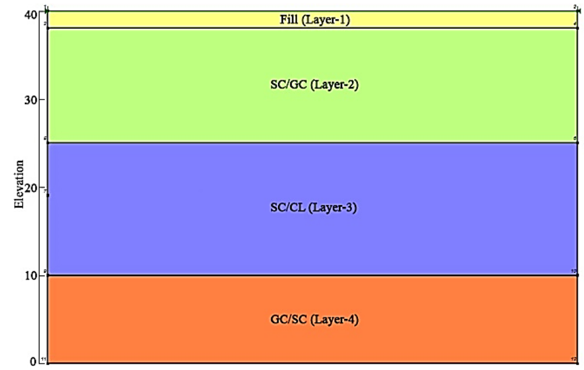



**Fig. 1.** Soil layers.

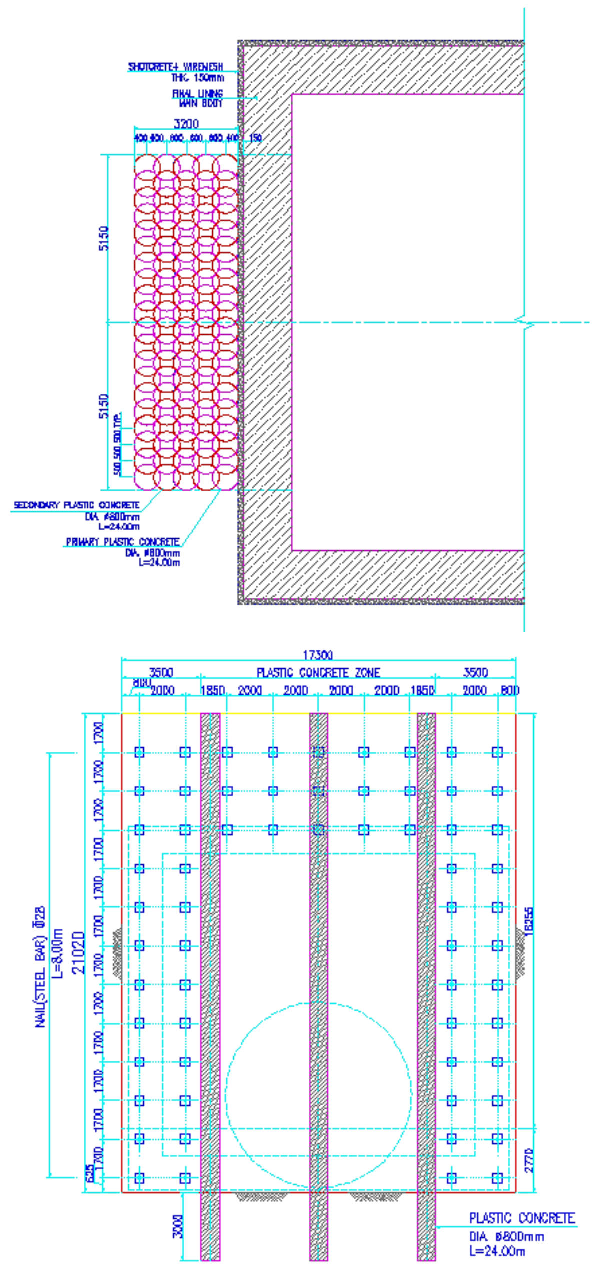



**Fig. 2.** Combined method details (plastic concrete piles and nailing).

**Table 1.** Geotechnical characteristics of soil layers.

| Layer | Depth (m) | $\gamma_d$ (KN/m³) | $\gamma$ (KN/m³) | $E_{50}^{ref}$ (KN/m²) | $E_{oed}^{ref}$ (KN/m²) | $E_{ur}^{ref}$ (KN/m²) | $c_{ref}$ (KN/m²) | $\varphi$(°) | $\gamma_{0.7}$ | $G_0^{ref}$ (KN/m²) | $K_0^{ref}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| L1 | 0 – 2 | 16.5 | 17.5 | 15000 | 15000 | 45000 | 10 | 20 | 0.0002 | 114000 | 0.658 |
| L2 | 2 – 15 | 17.65 | 19 | 45000 | 45000 | 135000 | 30 | 32 | 0.0002 | 192000 | 0.47 |
| L3 | 15 – 30 | 17.93 | 19.5 | 65000 | 65000 | 195000 | 35 | 35 | 0.0002 | 244000 | 0.426 |
| L4 | >30 | 18.92 | 20 | 90000 | 90000 | 270000 | 42 | 36 | 0.0002 | 309000 | 0.412 |

**Table 2.** Excavation and construction phases.

| Phase No. | Description | |
|---|---|---|
| | Plastic Concrete Piles with Nailing Method | Plastic Concrete Pile Method |
| Phase 1 | Application of traffic surface load | Application of traffic surface load |
| Phase 2 | Install the concrete plastic piles | Install the concrete plastic piles |
| Phase 3 | Excavate till depth 2 meters and install shotcrete | Excavate till depth 2 meters and install shotcrete |
| Phase 4 | Install row 1 of nails at depth 1.7 meters | Excavate till depth 4 meters and install shotcrete |
| Phase 5 | Excavate till depth 4 meters and install shotcrete | Excavate till depth 6 meters and install shotcrete |
| Phase 6 | Install row 2 of nails at depth 3.4 meters | Excavate till depth 8 meters and install shotcrete |
| Phase 7 | Excavate till depth 6 meters and install shotcrete | Excavate till depth 10 meters and install shotcrete |
| Phase 8 | Install row 2 of nails at depth 5.1 meters | Excavate till depth 12 meters and install shotcrete |
| Phase 9 | Excavate till depth 8 meters and install shotcrete | Excavate till depth 15 meters and install shotcrete |
| Phase 10 | Excavate till depth 10 meters and install shotcrete | Excavate till depth 18 meters and install shotcrete |
| Phase 11 | Excavate till depth 12 meters and install shotcrete | Excavate till depth 19.5 meters and install shotcrete |
| Phase 12 | Excavate till depth 15 meters and install shotcrete | Excavate till depth 21 meters and install shotcrete |
| Phase 13 | Excavate till depth 18 meters and install shotcrete | - |
| Phase 14 | Excavate till depth 19.5 meters and install shotcrete | - |
| Phase 15 | Excavate till depth 21 meters and install shotcrete | - |

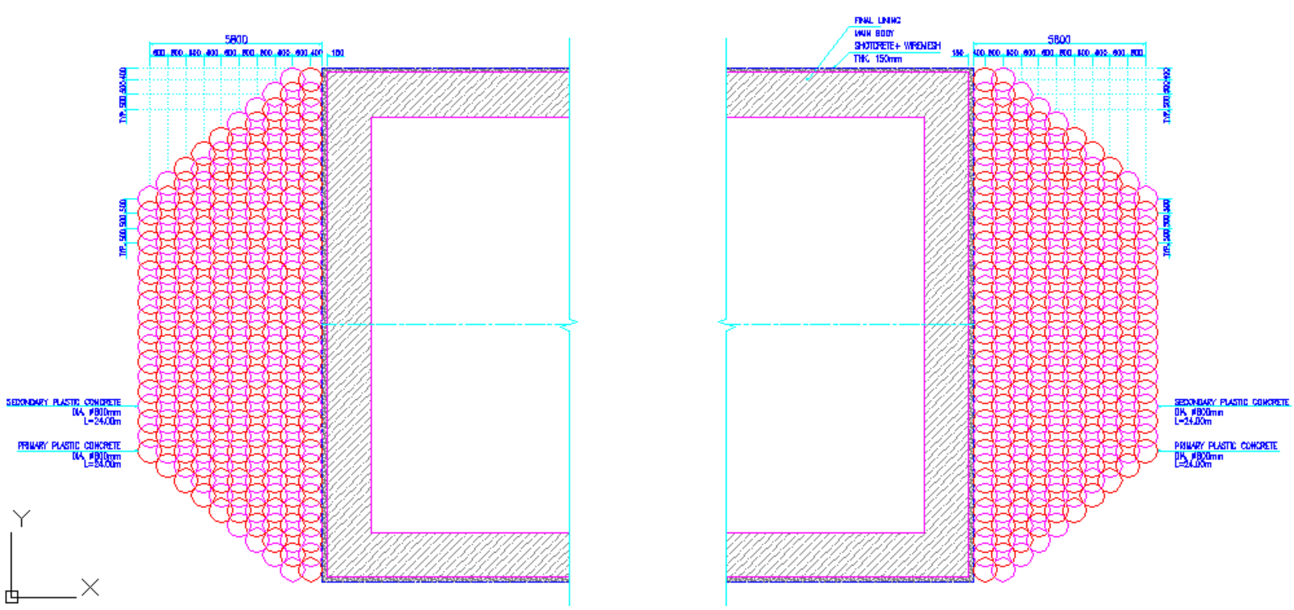



**Fig. 3.** Plastic concrete pile method pattern.

### *3.1. Boundary conditions and loadings*

Considering engineering experience, it is known that the effects of excavation can extend from the sides to approximately 3–4 times the depth of the excavation and from the depth to about 2-3 times the depth of the excavation [8]. Based on these insights and incorporating trial and error during the modelling process, the size of the model has been determined. Consequently, the influence of excavation at the model's borders has been reduced to less than 5% of the maximum displacement. The dimensions of the 2D models are thus set at 46*90 meters, while the 3D models have dimensions of 39*60*40 meters. By carefully determining the ideal dimensions of the models, this study seeks to reduce the impact of boundary effects and effectively depict the behavior of the station structure during excavation. This methodology strengthens the credibility and accuracy of the analysis outcomes. In the 2D models, the right and left boundaries are fixed in the X direction, and the model's bottom is fixed in both the X and Y directions. The top surface is left unrestricted to allow movement. Conversely, the 3D models have fixed boundaries along all edges in both the X and Y directions. Furthermore, the bottom of the 3D model is constrained in the X, Y, and Z directions. Similar to the 2D models, the top surface of the 3D model is unrestricted, enabling movement in all three dimensions. To consider gravitational effects, body forces in the models are applied using the standard acceleration due to gravity, typically set at 9.8 m/s². Additionally, for simulating embankments and surface traffic loads, the 2D and 3D models employ a surface load of 1 ton/m². The underground water level is situated at a depth of 40 meters; however, its presence does not impact the modelling results.

### 3.2. 2D and 3D model

In order to expedite the calculation process, a simplifying assumption has been implemented: that the soil nailing in the 2D model is treated as a plane strain problem, assuming that the behavior is primarily confined within the plane of analysis. Figure 4 illustrates the 2D finite element model FEM employed to simulate the longitudinal wall of the station. The model incorporates structural elements, such as soil nails and shotcrete. Table 3 provides comprehensive mechanical and geometrical details of the utilized nails. Additionally, Tables 4 and 5 present the detailed properties of shotcrete and concrete piles, respectively.

**Table 3.** Properties of the Nails.

| Type | Diameter (mm) | $E(\frac{kN}{m^2})$ | Axial Skin Resistance (KN/m) | Spacing (m) |
|---|---|---|---|---|
| 1 | 28 | 30000000 | 300 | 2 |
| 2 | 32 | 30000000 | 250 | 1.25 |

**Table 4.** Concrete pile properties.

| $\gamma(\frac{kN}{m^3})$ | $E(\frac{kN}{m^2})$ | $\nu$ |
|---|---|---|
| 25 | 25,000,000 | 0.2 |

**Table 5.** Shotcrete properties.

| Thickness (m) | $\gamma(\frac{kN}{m^3})$ | $E(\frac{kN}{m^2})$ | $\nu$ |
|---|---|---|---|
| 0.15 | 25 | 21,000,000 | 0.2 |

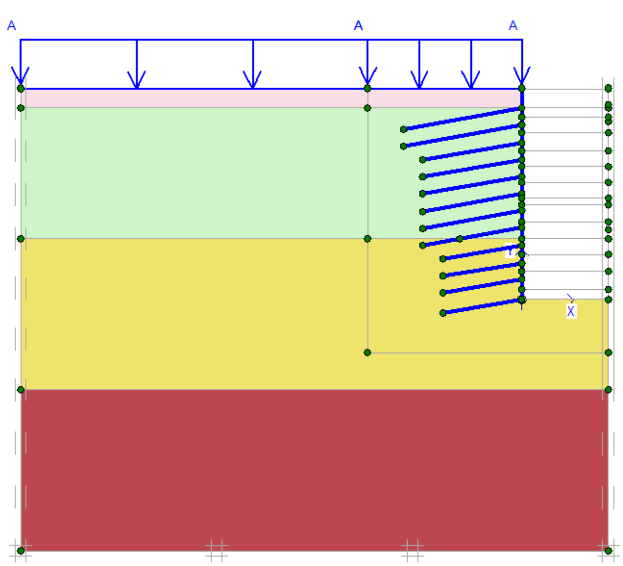


**Fig. 4.** 2D model of the longitudinal wall.

Figures 5 and 6 illustrate the 2D models of the transverse wall, representing two distinct approaches: one involving plastic concrete piles combined with nails, and the other using only plastic concrete piles.

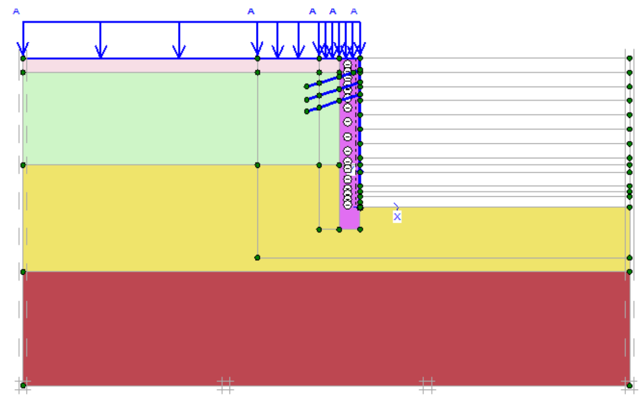


**Fig. 5.** 2D Model: transverse walls with combined nailing and plastic concrete pile method.

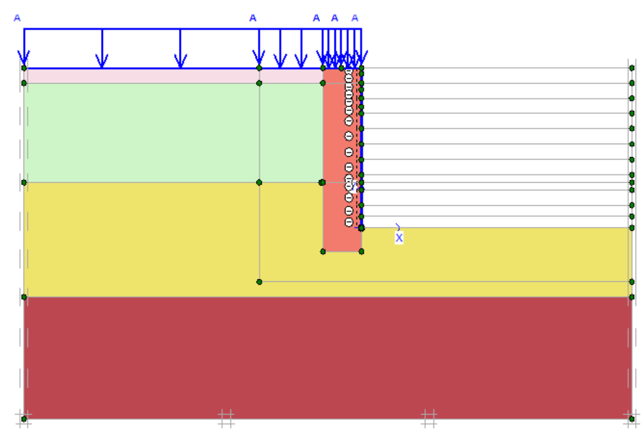
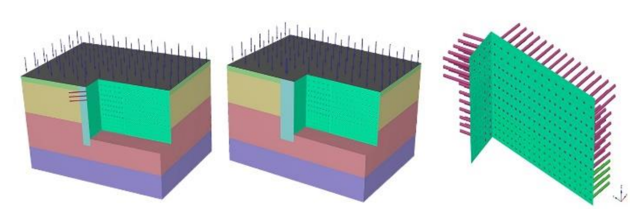


**Fig. 6.** 2D Model: transverse wall using the plastic concrete pile method.

In the 2D models, we considered a uniform traffic load and omitted the consideration of surface load due to the absence of surface structures. Additionally, due to the station's symmetry, only one side of the station was modeled.

Figure 7 displays constructed 3D models representing two support methods. Each model covers half of the station's length, allowing the analysis of both longitudinal and transverse walls. Due to symmetry in two planes, our simulation only covers one quarter of a full 3D model. In all models, the fully overlapping piles are treated as a unified homogeneous area in both 2D and 3D models.



(a) (b) (c)

**Fig. 7.** (a) 3D model depicting the combined method of soil nailing and plastic concrete piles. (b) 3D model showcasing the plastic concrete piles method. (c) Configuration of nails in the transverse and longitudinal walls for the combined method of nailing and plastic concrete piles.

## 4. Results and discussion

### 4.1. Safety Factors

In Figure 8, the safety factors for all modelling scenarios are depicted. In the 2D models, it is evident that the transverse walls exhibit a lower safety factor compared to the longitudinal wall. Similarly, in the 3D model where safety factors for both walls are calculated, it is observed that the minimum safety factor pertains to the transverse walls. This aligns with the findings from the 2D model, where the longitudinal wall demonstrated a higher safety factor. It is important to note that the design of the transverse walls is structured to ensure that the safety factor never falls below 1.35, as recommended for soil nail walls [9].

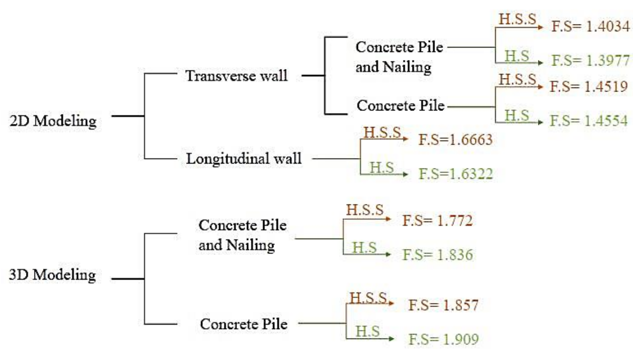


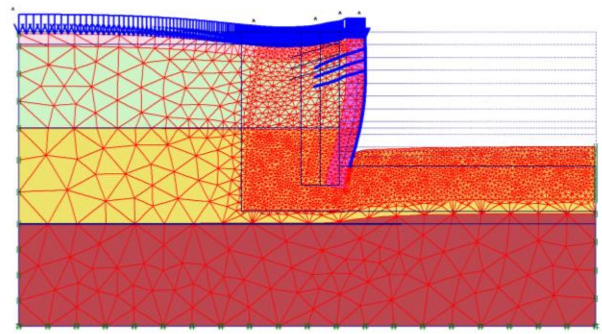

**Fig. 8.** Safety factor values for 2D and 3D models with HS and HSS soil behavior.

### 4.2. Deformations

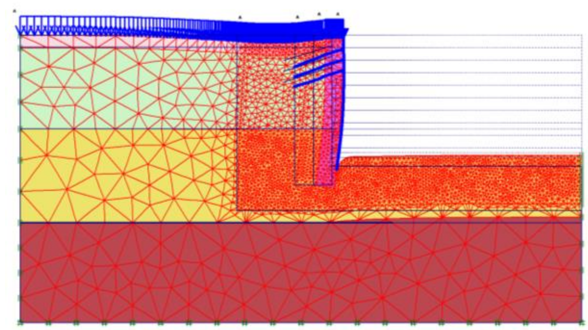
From the analysis of the 2D models and the visual depiction of the deformed meshes, it is evident that the maximum horizontal displacement of the transverse wall in the excavation occurs at the ground level (refer to Figure 9). By incorporating an additional depth of 2 meters for the plastic concrete piles at the excavation's base, the horizontal displacements in the deeper levels of the transverse wall are notably reduced. In the combined method, the presence of three rows of nails in the upper part of the excavation serves as a barrier, effectively halting the movement of the soil wedge behind the wall. Consequently, the combined method proves superior to the plastic concrete method in terms of preventing displacements. Furthermore, it is evident that the HSS model calculates less deformation than the HS model, aligning with findings from other researchers.

Figure 10 portrays the settlement curves of the longitudinal wall, where settlement measurements were taken behind and perpendicular to the wall. The comparison reveals that three-dimensional models utilizing the HSS soil behavior model display lower settlement than those employing the HS behavior model. While there exists a slight disparity in the settlement curves, it becomes apparent that the method of support for the transverse wall minimally has negligible influences on the settlement magnitude behind the longitudinal wall. Notably, the settlement curves obtained for various stabilization methods exhibit a similar trend. Examining the settlement curves of the longitudinal wall, it is apparent that the settlement remains relatively consistent up to a distance of approximately 11 meters from the wall. This consistent settlement behavior can be directly attributed to the presence of nails within this specific area.

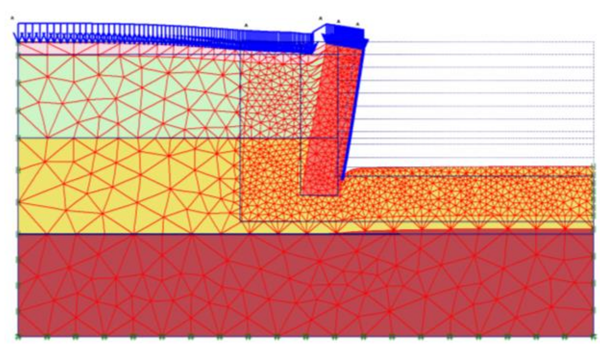
In Figure 11, the settlement curves derived from the two-dimensional modelling of the longitudinal wall are depicted. The graph demonstrates that the two-dimensional model utilizing the HSS soil behavior displays a notably lower settlement magnitude compared to the model employing the HS soil behavior. The maximum settlements obtained from the two-dimensional modelling, using the HSS and HS soil behavior models, are 24.68 mm and 33.56 mm, respectively.



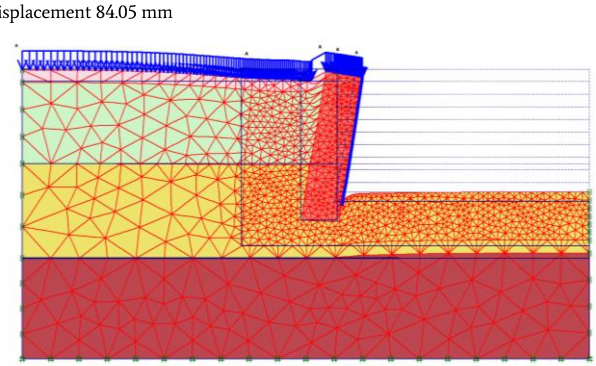
(a). Combined method of plastic concrete piles and nailing with HS behavioral model. Extreme total displacement 43.07 mm;



(b). Combined method of plastic concrete piles and nailing with HSS behavioral model. Extreme total displacement 20.42 mm



(c). Method of plastic concrete piles with HSS behavioral model. Extreme total displacement 84.05 mm



(d). Method of plastic concrete piles with HSS behavioral model. Extreme total displacement 83.62 mm.

**Fig. 9.** Total displacements of the 2D models of the transverse wall for the implemented methods with HS and HSS behavioral model. (Displacement scaled up 50 times)

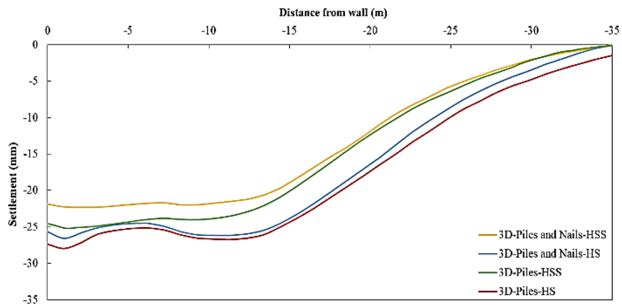



**Fig. 10.** Settlements behind the longitudinal wall in 3D models.

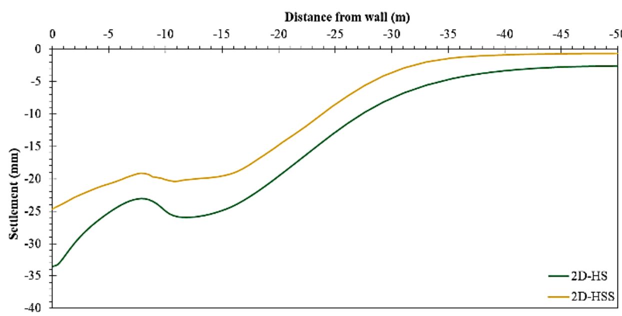



**Fig. 11.** Settlements behind the longitudinal wall in 2D models.

The settlement curves obtained from both the three-dimensional and two-dimensional models, employing the combined support method of piles and nailing for the transverse wall, are illustrated in Figure 12. In this method, plastic concrete piles are placed up to a distance of 3 meters from the wall, while nails are present up to a distance of 7.82 meters from the wall. Accordingly, settlement remains relatively constant up to a distance of 3 meters from the wall across all models. Beyond this distance, there is an increase in settlement up to a distance of 10 meters. The rate of settlement increase within this range is lower in the three-dimensional models compared to the two-dimensional models. A comparison between the two-dimensional and three-dimensional models reveals that the settlement values in the two-dimensional models surpass those in the corresponding three-dimensional models. Furthermore, it is noteworthy that the settlement profile range in the two-dimensional models is greater than that in the three-dimensional models. Additionally, it is observed that models utilizing the HSS soil constitutive model exhibit less settlement compared to those employing the HS soil constitutive model.

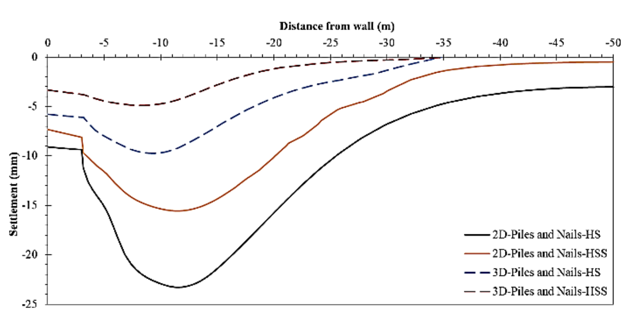



**Fig. 12.** Settlement behind the transverse wall using 2D and 3D modelling with the pile and nail method, employing HSS and HS soil behavior models.

Figure 13 displays settlement curves derived from both two-dimensional and three-dimensional modelling using the plastic concrete piles support method. The figure illustrates a distinct alteration in surface settlement values occurring roughly 6 meters away from the transverse wall. This phenomenon arises when the pile groups begin to exhibit a tendency towards toppling movement, directed toward the excavation area. Intriguingly, this change is more pronounced in the two-dimensional models than in the three-dimensional models. Given the increased movements observed in these models compared to the previous support method, both the HS and HSS models yield similar outcomes. It is important to note that the HSS model typically demonstrates its superiority when dealing with smaller displacements.

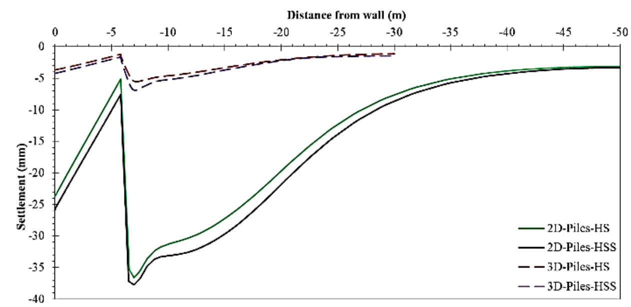



**Fig. 13.** Settlements behind the transverse wall in 2D and 3D models employing the plastic concrete pile method with HS and HSS behavioral models.

Table 6 presents the maximum ground settlements behind the longitudinal and transverse walls for all 14 models.

### *4.3. Axial force in nails*

The arrangement of nails employed in the combined pile and nail method for stabilizing the transverse wall is depicted in Figure 14. Table 7 presents the maximum axial force values for the three rows of nails implemented using the combined method on the transverse wall across all models.

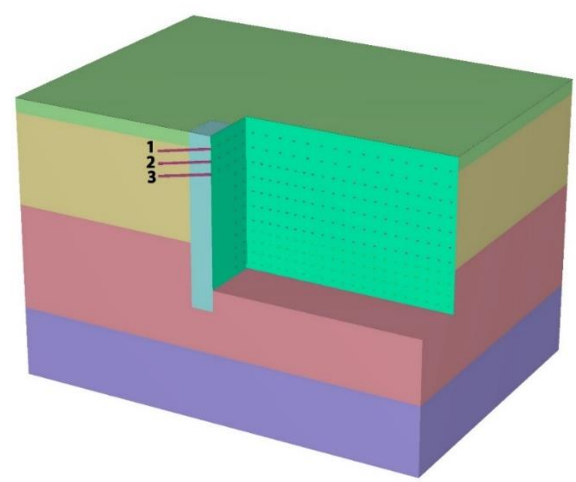



**Fig. 14.** Location of nails implemented in the combined method to support the transverse wall.

According to the results, the axial force in the analyzed nails is lower in the three-dimensional modelling compared to the two-dimensional modelling. This discrepancy arises due to the assumption of plane strain modelling in the 2D models. In reality and within the 3D modelling, the longitudinal walls provide support to the transverse wall, restraining its movement towards the excavation area. In this scenario, the transverse wall behaves akin to a beam subjected to uniform loading (lateral earth pressure) and is supported on both sides (by the longitudinal wall and the ground). Conversely, in the 2D models employing plane strain assumptions, the transverse wall acts more like a vertical pile experiencing lateral uniform pressure (lateral earth pressure).

**Table 6.** Maximum value of the ground settlement for all created models.

<table>
<tr><th rowspan="4">Soil Behavioral model</th><th colspan="7">Maximum ground Settlement (mm)</th></tr>
<tr><th colspan="3">2D</th><th colspan="4">3D</th></tr>
<tr><th rowspan="2">Longitudinal Wall</th><th colspan="2">Transverse Wall</th><th colspan="2">Longitudinal Wall</th><th colspan="2">Transverse Wall</th></tr>
<tr><th>Concrete Pile and Nailing</th><th>Concrete Pile</th><th>Concrete Pile and Nailing</th><th>Concrete Pile</th><th>Concrete Pile and Nailing</th><th>Concrete Pile</th></tr>
<tr><td>HS</td><td>33.56</td><td>23.28</td><td>36.57</td><td>28.16</td><td>27.95</td><td>9.76</td><td>5.32</td></tr>
<tr><td>HSS</td><td>24.68</td><td>15.56</td><td>37.72</td><td>22.31</td><td>25.19</td><td>4.88</td><td>6.63</td></tr>
</table>

**Table 7.** Comparison of maximum axial forces induced in each nail across all models using the combined support method.

| Nail No. | Axial Force (kN) | | | |
|---|---|---|---|---|
| | 2D | | 3D | |
| | HS | HSS | HS | HSS |
| 1 | 161.84 | 183.69 | 97.88 | 48.36 |
| 2 | 108.78 | 113.26 | 95 | 57.51 |
| 3 | 159.34 | 119 | 128.2 | 74.53 |

## 5. Conclusions

The conclusion of the present study can be summarized as follows:

1- In 3D models using both support methods—plastic concrete piles with nailing and plain plastic concrete piles—the safety factor is usually higher compared to 2D models. This happens because the 3D model can simulate a perpendicular wall that supports the transverse wall, preventing it from moving towards the excavation area. However, in 2D models, the transverse wall behaves like a long wall without this necessary support, which reduces its stability. Using 2D modelling with a plane strain assumption is not advisable for simulating a transverse wall, especially in metro excavations where these walls typically have short lengths.

2- The HSS soil behavior model exhibits reduced displacement compared to the HS model owing to its heightened stiffness at lower strains. However, in instances of substantial deformations, distinguishing between the HSS and HS models becomes less evident. HSS demonstrates exceptional performance in scenarios characterized by minimal deformations, showcasing its superiority under such conditions. In excavations with significant dimensions and displacements, both the HSS and HS soil behavior models demonstrate a high level of congruence in their results. Considering the shorter computational time required for modelling using the HS soil behavior compared to the HSS soil behavior, the former may be preferred for 3D modelling of expansive metro station excavations with substantial dimensions and displacements.

3- High deformations in 2D modelling lead to higher forces in structural elements like nails compared to 3D modelling, making designs more expensive. 3D modelling consistently provides more accurate results than 2D modelling due to its ability to avoid simplifications, ensuring better precision in analyses.

4- During the construction of the TBM entrance portal for the station, opting for plastic concrete piles with nailing to support the transverse wall proves to be advantageous. This approach offers easier implementation and greater control over displacements, resulting in superior outcomes compared to using only plastic concrete piles.

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