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Research Article

Comparative Assessment of Mohr-Coulomb and Hardening Soil Models for Deep Excavation Design in Stratified Soils: Insights from Numerical and Field Data

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Abstract:

This study presents a comprehensive numerical and experimental investigation into the performance of deep excavation support systems in stratified soil conditions. A real-world case study from the OuedSmar metro station in Algiers serves as the basis for evaluating the predictive capabilities of two widely used soil constitutive models: Mohr-Coulomb (MC) and Hardening Soil (HS). The excavation, supported by a diaphragm wall and multi-level anchoring system, was instrumented with inclinometers to capture high-resolution displacement data throughout construction. Finite element simulations were conducted using PLAXIS 3D, and model outputs were compared against field measurements to assess accuracy. Results indicate that the HS model consistently outperformed the MC model, accurately replicating wall deflection magnitudes, deformation profiles, and boundary conditions with errors below 12%, while the MC model significantly overestimated displacements and failed to capture observed behavior. The findings underscore the limitations of simplified constitutive models for serviceability limit state analysis and demonstrate the necessity of using advanced elastoplastic formulations like the HS model in deep urban excavations. This research contributes to improved model selection and calibration practices for safe, reliable, and cost-efficient geotechnical design.

1. Introduction

The accelerating expansion of urban infrastructure has created an unprecedented demand for deep excavations in densely populated metropolitan environments. Such subterranean works—ranging from metro stations to multi-level underground commercial facilities—necessitate robust, serviceable, and durable earth-retaining systems, including diaphragm walls, secant pile walls, and anchored retaining structures, to ensure global stability and to minimize adverse impacts on adjacent facilities. The inherent complexity of soil–structure interaction (SSI) in these settings requires advanced geotechnical numerical modeling approaches to accurately predict deformation mechanisms, optimize support system stiffness, and safeguard structural performance under heterogeneous geological and hydrogeological conditions.The accurate assessment of ground deformation and structural stability in deep excavations within stratified soil profiles hinges critically on the appropriate selection and calibration of soil constitutive models. Conventional models, such as the linear elastic-perfectly plastic Mohr-Coulomb (MC) model, have long been employed in routine geotechnical design due to their simplicity and relatively modest data requirements. However, a growing body of literature has highlighted significant limitations associated with the MC model in predicting ground behavior under complex loading andstratification conditions[1].

Consequently, more advanced constitutive frameworks, particularly the Hardening Soil (HS) model, have been developed to more accurately represent nonlinear stress-strain behavior, stress-dependent stiffness, and plasticity evolution in soils[2].Finite element (FE) tools such as PLAXIS are central to geotechnical modeling, enabling rigorous simulations of excavation processes. The choice of constitutive model is critical[3, 4] showed that the Mohr-Coulomb (MC) model often produces unrealistic displacement profiles, whereas the Hardening Soil (HS) model yields results much closer to field data. Case studies and laboratory work [5,6] further confirmed that HS parameters reproduce nonlinear soil behavior with high accuracy. Field monitoring [7] and project-based evaluations [8] also demonstrated that HS predictions align closely with inclinometer records, typically within a 15% margin of error. Collectively, these findings establish HS as the more reliable framework for serviceability limit state analysis in deep excavations.The stratified nature of urban soils, often comprising alternating layers of soft and stiff materials, further necessitates the use of constitutive models capable of reproducing stiffness degradation with depth and under cyclic loading. The HS model, by incorporating nonlinear elasticity, stress-dependent stiffness, and hardening plasticity, has been shown to effectively capture this complexity [3-6]. In contrast, the MC model's constant stiffness assumption leads to unrealistic settlement distributions, particularly near excavation walls and at soil–structure interfaces [7, 8].Recent comparative investigations have examined different constitutive frameworks, including Mohr-Coulomb (MC), Hardening Soil (HS), Hardening Soil Small-Strain (HSsmall), and Duncan–Chang models. Although MC remains simple and computationally efficient, it has been shown to overestimate displacements and settlements, making it unsuitable for serviceability limit state analyses [3], [5]. In contrast, elastoplastic formulations such as HS and HSsmall provide more reliable predictions of soil–structure interaction and stress–strain behavior [9-11].Three-dimensional studies further confirm these findings. For instance[12] demonstrated that HS accurately reproduces excavation-induced heave and wall deflections in layered soils, whereas MC significantly diverges from field measurements. Overall, advanced constitutive models, particularly HS and HSsmall, offer superior accuracy and are more appropriate for the design of deep urban excavations.Field-monitored excavation projects consistently confirm the superior accuracy of the Hardening Soil (HS) model. Studies show that the Mohr-Coulomb (MC) model often overestimates wall displacements, while HS predictions align closely with observed deformation profiles [3–5]. Recent evidence from coastal and urban basement projects further demonstrates that HS reliably captures excavation-induced deformations across varied geological conditions [12,13]. Its proven adaptability to different soil profiles and support systems makes HS the preferred framework for design optimization, whereas reliance on MC introduces risks of conservative and misleading predictions.This study aims to bridge this gap by providing a rigorous, measurement-based evaluationof MC and HS model predictions for a deep excavation in geologically heterogeneous, stratified soils, with direct implications for design safety, cost-efficiency, andriskmitigation in civil engineering practice.

2. Constitutive models overview

The selection of an appropriate constitutive model plays a decisive role in finite element analysis of geotechnical problems, as it governs how soil stress-strain behavior is represented. This process has a direct impact on the calculated forces, displacements, and overall performance of the soil-structure system. In this study, two widely used models are employed to evaluate diaphragm wall behavior: the Mohr-Coulomb (MC) model, a simple linear elastic-perfectly plastic model, and the Hardening Soil (HS) model, a more advanced nonlinear elastoplastic model[14].

A. Mohr-Coulomb (MC) Model

In the elastic range, the Mohr-Coulomb model assumes linear soil behavior defined by constant Young's modulus (E) and Poisson's ratio (ν). Once yielding occurs, plastic deformation continues at constant stress, with no strain hardening. The failure envelope is defined by cohesion (c) and internal friction angle (φ), while dilatancy angle (ψ) accounts for volumetric changes during shear. This model uses only five basic parameters—(E, ν, c, φ, ψ)—which are easily obtained from standard lab tests (e.g., triaxial, direct shear). Its main advantages are simplicity, computation, and sufficient accuracy for ultimate limit state analyses focused on failure[15]. However, the model assumes constant stiffness, failing to capture real soil behavior where stiffness increases with confining pressure. This leads to inaccurate deformation predictions, especially for surface settlements, wall deflections, and base heave during unloading phases of deep excavations.

B. Hardening Soil (HS) Model

The Hardening Soil (HS) model was developed to overcome the limitations of the Mohr-Coulomb model in simulating stress-dependent soil behavior,

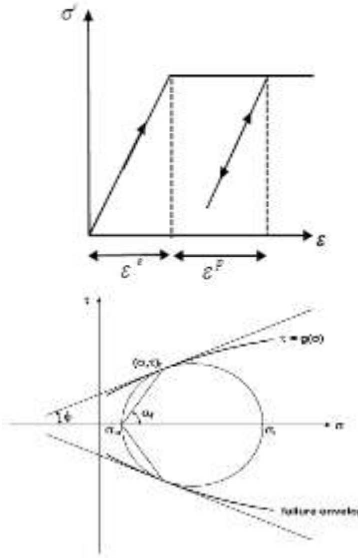

Figure 1. *(a) Schematic illustration of the basic concept of an elastic perfectly plastic model, and (b) Mohr diagram with associated failure envelopes[15].*

particularly in applications such as deep excavations and embankments. As an advanced elasto-plastic constitutive model, HS incorporates nonlinearity in stiffness, defined by stress-dependent moduli governed by a power-law relationship. It utilizes a hyperbolic stress-strain formulation to capture soil response even at small strain levels and distinguishes between loading and unloading stiffness, a critical improvement for modeling excavation-induced stress relief[14].

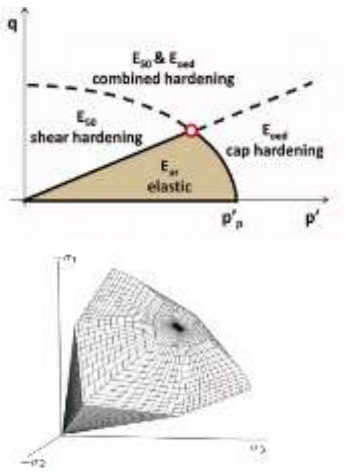

Figure 2. *(a) Schematic representation of the dual yield surfaces in the Hardening Soil (HS) model, and (b) three-dimensional visualization of the HS model's yield surfaces[14].*

In addition to standard strength parameters (cohesion, friction angle, and dilatancy angle), the model requires stiffness parameters from triaxial and oedometer tests (E_{50}, E_{oed}, E_{ur}), as well as a stress-dependency exponent (m) and a Poisson's ratio for unloading. The inclusion of shear and cap hardening mechanisms allows the model to simulate irreversible strains under deviatoric and volumetric loading, respectively[2].

3. Methodology and numerical modeling

A.case studyproject description

Thestation ofOuedSmar is strategically located in an open area adjacent to the Bab EzzouarUniversity in the city of Algiers[16]. The chosen site assures that no existing structures or urban infrastructure will be directly impacted by the construction operations. Notably, a tiny creek is located to the north of the project site, with its flow rate depending on seasonal and rainfall changes. This hydrological feature demands careful study throughout both the design and construction stages, especially with regard to drainage and soil stability.

B. Soil Stratigraphy and Geotechnical Characterization

A clear understanding of subsurface conditions is crucial for geotechnical analysis. The site comprises four distinct layers—engineered backfill, silty clay-sands, marly clay, and silty clayey sand with pebbles—each defined by specific strength and stiffness parameters. These characteristics, summarized below, were derived from in situ and laboratory investigations.

C. Station Description

The station structure measures 130 meters in length, 20.5 meters in width, and extends to a depth of 30.7 meters. It is stabilized by means of a diaphragm wall structure, formed by 120 reinforced concrete segments.The excavation support system consists of a reinforced diaphragm wall coupled with a multi-level anchoring system designed to ensure stability of the surrounding soil. The diaphragm wall reaches a depth of 47.0 meters and has a thickness of 1.2 meters.To enhance its bending resistance and counteract lateral earth pressures, metallic HEB600 profiles (buttons) are embedded at strategic depths within the wall.The anchoring system comprises several rows of pre-stressed tie rods installed at depths ranging from 27 to 33 meters, efficiently transferring loads to deeper, more competent soil layers

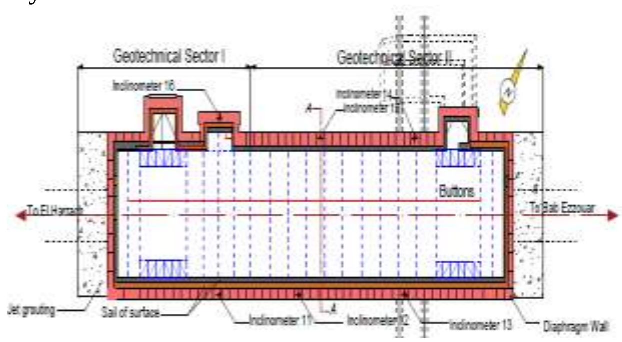

Figure 3. *Plan View and Layout of the Inclinometers*

D. Monitoring Sections and Instrumentation

Inclinometer monitoring, conducted in accordance with standard NF P 94–156, was employed to assess real-time geotechnical performance during excavation. Installed along the retaining wall, the system records vertical and horizontal displacements, enabling detailed profiling of wall deformation and providing critical insights into soil–structure interaction behavior.

E. Field Measurement Methodology

During construction, inclinometer casings were installed within the excavation chamber to monitor lateral displacements. Readings were recorded at 0.5 m intervals along each casing, enabling the reconstruction of detailed displacement profiles. To minimize systematic errors, measurements were taken in two opposing runs—top-to-bottom and bottom-to-top—and discrepancies exceeding acceptable limits were corrected accordingly. The base of each borehole, assumed to remain unaffected by excavation activities, was adopted as a stable reference point. The inclinometer data were then used to assess the deformation behavior of the retaining wall throughout successive excavation stages. The resulting displacement profiles (Figure 3) provided valuable insights into wall movement patterns in relation to excavation depth, soil stratification, and construction sequence, thereby supporting the evaluation of design assumptions and compliance with geotechnical safety criteria. It should be noted that the raw monitoring data supporting these findings are documented within internal project reports

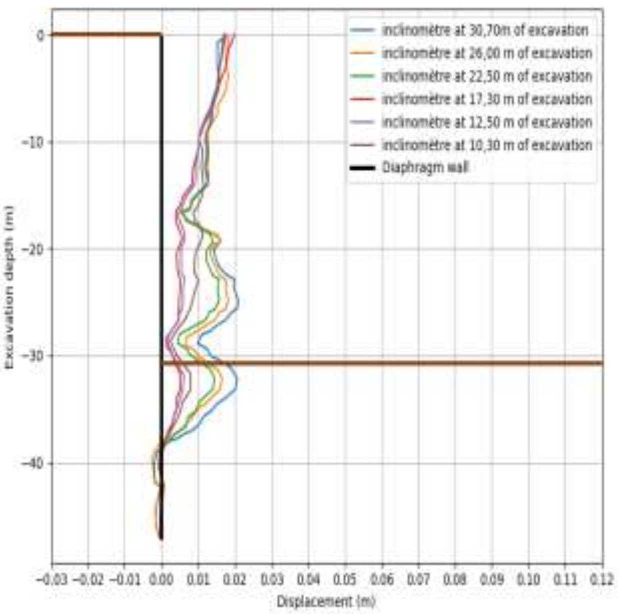

***Figure* 4.** *Inclinometer 15 Wall Displacement Measurements*

4. Numerical model and simulation results

Numerical simulations were performed using PLAXIS 3D, a finite element software tailored for geotechnical applications. The model domain spans 150 m in the horizontal (X) direction and 24 m horizontal (Y-axis) to capture excavation-induced ground deformations.

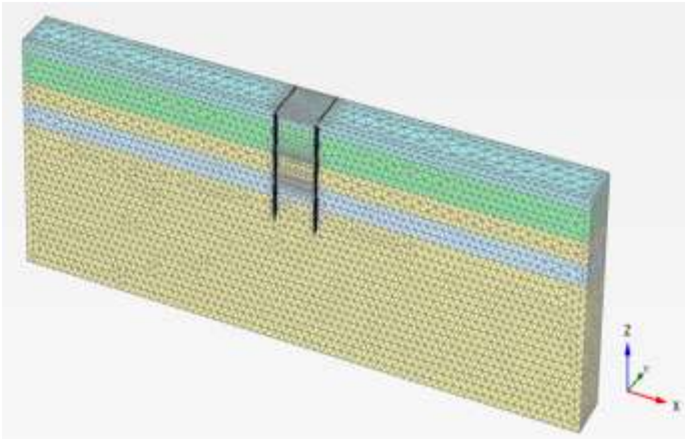

Figure 7. *Overview of the Adopted Numerical*

A. Calculation Sequence

The numerical model replicates the actual construction sequence to accurately simulate the staged excavation process and corresponding structural interventions.

B. Simulation Outcomes

Between phases 06 and 12, which correspond to the installation of the stability stiffeners, a notable reduction in lateral displacement contours is observed. This trend continues through phase 13 with the addition of the final level of stiffeners and the initial anchor installation, further decreasing displacement magnitudes. In the final stages, once all structural elements are in place, displacement values stabilize, and the maximum displacement contours are concentrated in the vicinity of the anchors.

C. Evaluation of Numerical Results Against Field Measurements

Excavation was performed in sequential phases involving diaphragm wall construction, excavation stages, and staged activation of structural supports (metallic buttons and tie rods). Wall displacements were monitored throughout, down to the final depth of −30.70 m. Field measurements were then compared with predictions from the Mohr-Coulomb and Hardening Soil models, enabling a quantitative assessment of their accuracy in stratified soil conditions.

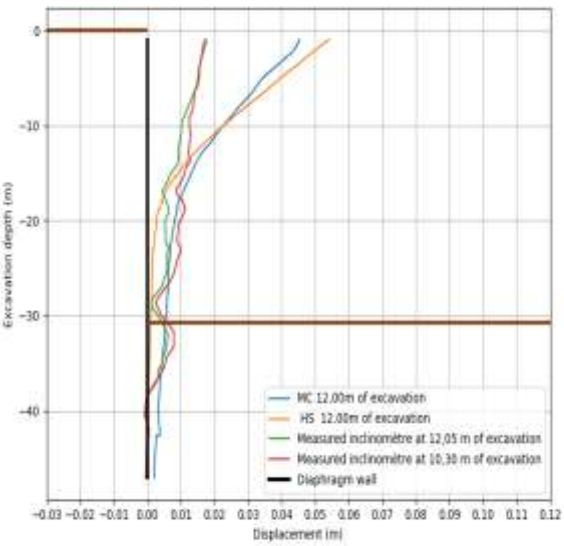

***Figure 8.** Measured X-Direction Movements at Excavation Phase 6*

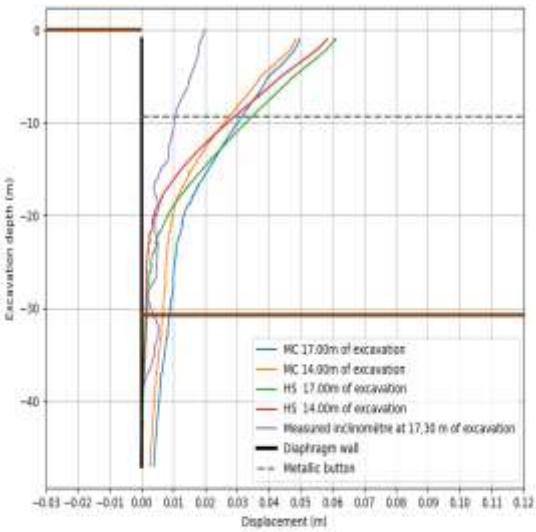

***Figure 9.** Measured X-Axis Displacements at Excavation Phases 7 and 9*

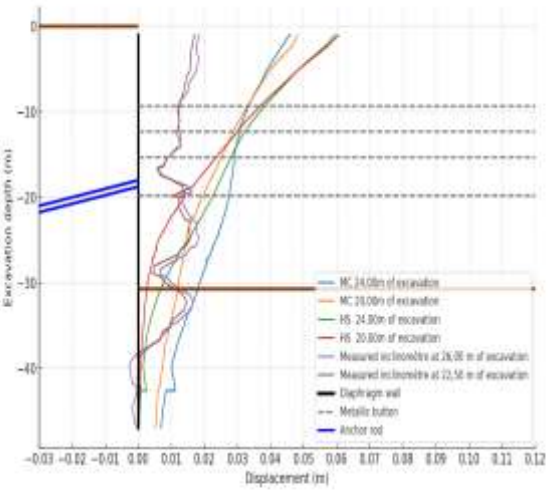

***Figure 10**. Measured X-Axis Displacements at Excavation Phases 10 and 13*

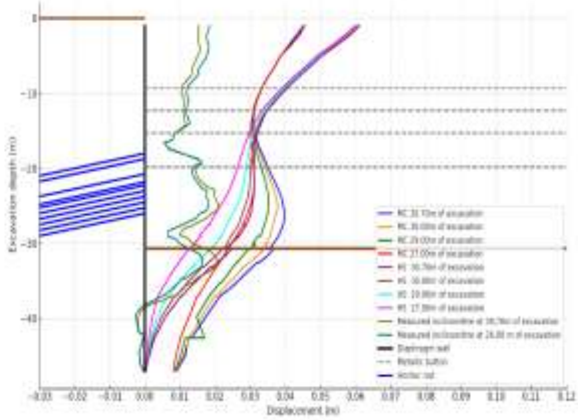

***Figure 11.** Measured X-Axis Displacements at Excavation Phases 14 and 20*

5. Results and discussion

A rigorous comparative assessment was conducted between the advanced Hardening Soil (HS) constitutive model and the conventional Mohr-Coulomb (MC) model for the deep excavation works at the OuedSmar metro station, with model predictions validated against high-resolution inclinometer measurements. The inclinometer data serve as the reference ground truth, enabling a direct evaluation of each model's ability to reproduce the observed wall deformation behaviour under staged excavation.At the final excavation stage (depth ≈ 30.7 m), field monitoring recorded a maximum lateral deflection of 18.5 mm at approximately − 22.0 m depth, exhibiting a characteristic bulging profile typical of multi-propped retaining walls, with the wall toe behaving as a near-fixed boundary (displacement ≈ 0.1 mm). The HS model reproduced these observations with remarkable fidelity, predicting a maximum deflection of 18.8 mm at –22.25 m (1.6% deviation), accurately replicating both the deformation shape and the fixed toe condition. Conversely, the MC model produced significant discrepancies: it overestimated the maximum deflection by approximately 145% (45.4 mm), misplaced the peak displacement at a much shallower depth (–11.68 m), and predicted an unrealistic inward displacement of the wall toe (17.7 mm), which is inconsistent with the measured fixed-base response.This pattern of divergence was consistent across earlier excavation stages (e.g., depths of 17.3 m and 12.5 m). The HS model consistently maintained close agreement with field measurements, with deviations not exceeding ±12%, while the MC model persistently overpredicted displacements by over 100% at all stages and misrepresented the deformation mechanism as a cantilever-type response rather than the observed propped-wall behaviour.From a geotechnical perspective, these discrepancies are rooted in the fundamental assumptions of each constitutive model. The HS model incorporates stress-dependent stiffness, with modulus values increasing with depth due to confining pressure effects, thereby capturing the natural stiffening of deeper soils. It also distinguishes between initial loading stiffness (E_{50}) and the higher unloading–reloading stiffness (E_ur), which is particularly relevant in excavation scenarios where soil behind the wall undergoes predominant unloading. This formulation enables accurate simulation of soil arching effects, whereby lateral earth pressures are redistributed toward the support system, reducing wall loads and displacements.In contrast, the MC model assumes a constant Young's modulus for an entire soil layer, typically selected conservatively to reflect weaker near-surface conditions. This uniform stiffness assumption inherently underestimates the rigidity of deeper strata, leading to exaggerated displacement predictions. Furthermore, the MC formulation does not differentiate between loading and unloading stiffness, thereby failing to capture the stiffness recovery during stress reversal. Its inability to model arching effects results in a simplified lateral pressure distribution (triangular or trapezoidal), producing higher bending moments and unrealistic deformation patterns.A quantitative synthesis reinforces these findings: at excavation depths of 30.7 m, 17.3 m, and 12.5 m, the HS model exhibited errors of +1.6%, –3.6%, and –11.9% respectively, compared with +145%, +130%, and +117% for the MC model. These results conclusively demonstrate that the HS model offers superior predictive capability for serviceability limit state (SLS) analysis, delivering realistic deformation magnitudes, shapes, and boundary condition responses. While the MC model remains applicable for preliminary design and ultimate limit state (ULS) verification—where conservative estimates of internal forces may be acceptable—it is unsuitable for accurate displacement predictions. For final design stages and impact assessments on adjacent structures, the adoption of the HS model, or an equivalently advanced constitutive framework, is essential to ensure both technical reliability and economic efficiency.

***Figure** 5. Overview of the Oued Smar Station Site*

***Table 1.** Soil layers properties*

Geotechnical Layer	AveragePenetrationDepths (m)	Unit weight of unsaturated γ_h (kN/m³)	Unit weight of saturated soil γd (kN/m³)	Effective Internal Friction Angle φ' (°)	Reference effective cohesion c' (kPa)	DrainedDeformationModulus E' (MPa)	Coefficient K_0
Backfill (Re)	0.0 – 5.0	20	17	20°	0	10	0,6
Siltyclay – sands (Qs)	5.0 – 18.0	21	17	25°	25	50	0,5
Marly clay (QM)	> 18.0	21	17	22°	35	90	0,6
Silty clayey sand with pebbles (QMsg)	27.50 – 37.00	21	17	25°	25	50	0,6

Table 2. *Additional parameters for the hardening soil (HS) model*

Property	Diaphragm Wall	Buttons
Density (kN/m³)	25	78
Thickness (m)	1.2	-
Type	/	HEB600
Poisson's Ratio	0.2	0.3
DeformationModulus (GPa)	33	210

Table 3. *Characteristics of structural elements*

Geotechnical horizon	Depth [m]	E_{50}^{ref} [kN/m²]	E_{oed}^{ref} [kN/m²]	E_{ur}^{ref} [kN/m²]	m
Backfill (Re)	0.0 – 5.0	10000	10000	30000	0.5
Silty clay–sands (Qs)	5.0– 18.0	50000	50000	150000	0.7
Marly clay (QM)	> 18.0	90000	90000	270000	0.8
Silty clayey sand with presence of pebbles (QMsg)	27.50–37.00	50000	50000	150000	0.7

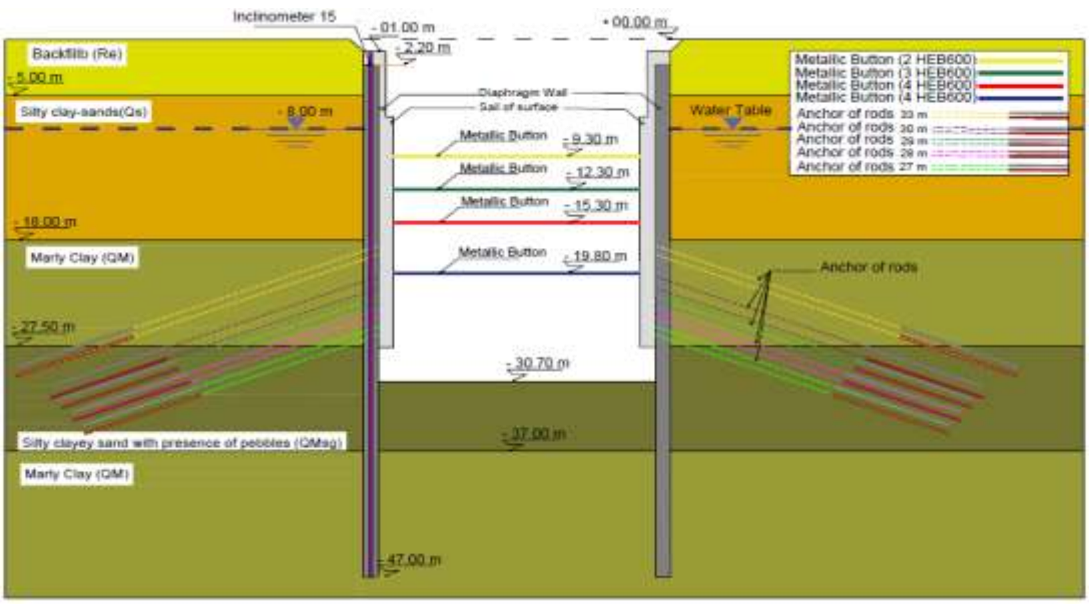

Figure 6. *Cross-section of the Oued Smar metro station showing anchorage elements (buttons and tie rods) and inclinometer placement.*

Table 4. Construction phases and sequences of the excavation

Phases	Construction sequences	Depth (m)		
		Excavation	Buttons	Tie rod
0	Initial phase			
1	Site preparation	-2.20		
2	Installation the Diaphragm Walls (e = 1.20 m)			
3	1st excavations	-5.00		
4	2nd excavations	-8.00		
5	3rd excavations	-12.00		
6	Activating the 1st level of the metal button (2HEB600)		-9.30	
7	4th excavations	-14.00		
8	5th excavations	-17.00		
9	Activating the 2ndlevel of metal button (3HEB600)		-12.30	
10	6th excavations	-20.00		
11	Activation the 3rdlevel of metal button (3HEB600)		-15.30	
12	7th excavations	-24.00		
13	Activation the 4th level of metal button(4HEB600) andActivation the 1st tie rod (33 m)		-19.80	-18.00
				-18.75
14	8th excavations	-27.00		
15	Activation the 2nd tie rod(30 m ; 29 m)			−20.75
				−21.80
				−22.25
				−23.00
16	9th excavations	-29.00		
17	Activation the 3rd tie rod(28 m)			−23.75
				−24.50
18	10th excavations	-30.00		
19	Activation the 4th tie rod(27 m)			−25.25
				−26.00
20	Final excavation	-30.70		

6. Conclusions

This study presents a comprehensive evaluation of numerical modeling approaches for deep excavation support systems in stratified soils, focusing on a real-world case from the OuedSmar metro station in Algiers. Field measurements obtained via high-precision inclinometer monitoring were used to validate the predictions of the Mohr-Coulomb and Hardening Soil constitutive models implemented in PLAXIS 3D. The comparative analysis clearly demonstrates the superior performance of the Hardening Soil model in replicating observed wall displacements, deformation profiles, and boundary condition behavior, particularly under staged excavation sequences and complex soil stratigraphy.

While the Mohr-Coulomb model offers computational simplicity, it significantly overpredicts displacements and misrepresents wall behavior due to its assumption of constant stiffness and inability to account for unloading–reloading effects or stress-dependent stiffness. In contrast, the Hardening Soil model accurately captures nonlinearity, stiffness degradation, and stress-path dependency, yielding displacement predictions with errors consistently below 12%.

The findings highlight the importance of adopting advanced constitutive models for serviceability limit state design in urban deep excavation projects. The integration of field-monitored data into numerical validation further reinforces the necessity of model calibration for reliable and cost-effective geotechnical engineering practice. Future research should continue to investigate soil-structure interaction mechanisms under more varied geological and hydrological conditions, as well as explore the potential of small-strain and time-dependent constitutive models.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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- **Data availability statement:** The raw monitoring data supporting the conclusions of this study are contained in confidential project reports and cannot be shared publicly. Processed datasets used for analysis are available from the corresponding author upon reasonable request.

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