Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-105

ECSMGE 24
XVIII EUROPEAN CONFERENCE
ON SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING

Advanced numerical modelling using the Hardening Soil Small Strain material model for sensitive excavations adjacent to a metro station

Modélisation numérique avancée utilisant le Hardening Soil Small Strain pour des excavations sensibles adjacentes à une station de métro

C. Merino*, J. González
Ove Arup & Partners SAU, Madrid, Spain

A. Prados
Former Ove Arup & Partners SAU, Madrid, Spain

**carlos.merino@arup.com*

ABSTRACT: This study focuses on the advanced numerical modelling of retaining structures for deep excavations in urban areas using the Plaxis Hardening Soil model with small-strain stiffness (HSS). The main objective is to provide a safe and stable solution for deep excavations next to metro stations and tunnels. This model is utilized to simulate soil response and soil-structure interaction. The numerical results are validated and calibrated against field measurements to update models for additional accuracy and reliability. The advanced numerical modelling approach based on HSS material models can effectively predict the behaviour of the soil and retaining structures and provide valuable information for the design and construction of retaining structures for deep excavations in urban areas.

RÉSUMÉ: Cette étude se concentre sur la modélisation numérique avancée de structures de soutènement pour des excavations profondes dans les zones urbaines en utilisant le modèle HS Small Strain de Plaxis. L'objectif principal est de fournir une solution sûre et stable pour les excavations profondes à proximité des stations de métro et des tunnels. Le modèle HSS est utilisé pour simuler la réponse du sol et l'interaction sol-structure. Les résultats numériques sont ensuite validés et calibrés par rapport aux mesures sur le terrain pour mettre à jour les modèles pour plus de précision et de fiabilité. La modélisation numérique avancée basée sur le modèle HSS de Plaxis peut prédire efficacement le comportement du sol et des structures de soutènement et fournir des informations précieuses pour la conception et la construction de structures de soutènement pour des excavations profondes dans les zones urbaines.

Keywords: Metro; deep excavations; HSS (Hardening Soil model with small-strain stiffness); tunnel; sensitive infrastructure

1 INTRODUCTION

We present a deep basement excavated next to a metro station and tunnel, that had to remain operational and safe during all works. A detailed understanding of the soil behaviour was crucial for predicting ground movements, settlements, and potential impacts on nearby structures. This required the use of models that could accurately simulate the soil behaviour and predict ground movements and settlements. Finite element models were created to numerically simulate the expected soil response. The HS-Small Strain model (Benz, 2007) was used to simulate soil behaviour since these deep excavations typically involve small strains, especially in the early stages of the excavation process. This model was tailored to specific well known geological and soil conditions at the site in Madrid.

2 BACKGROUND

The proposed site is located in the vicinity of the centre of Madrid. It was occupied by an industrial building bounded by Dédalo Street to the south and Alcalá Street to the north. Adjacent to the plot (less than 1m in some areas) and along Alcalá Street, there is an existing metro station (Torre Arias Station –Line 5 Madrid Metro) was built in the 80s. The proposed building is 80m long and 74m wide, five storeys high above ground floor and has three basement levels below the street level.

Given the presence of Torre Arias metro station, contiguous bored pile retaining walls with diameters of 850mm, 650 mm and 450mm were required to support the ground and adjacent structures.

Temporary propping and ground anchors were required in some areas during construction to support the retaining wall prior to construction of the permanent basement structure (Figure 1).

Wall thicknesses and construction details of Torre Arias station were undocumented. To avoid damage or distress to the underground station and to confirm the validity of the proposed design, it was necessary to undertake intrusive investigations inside the station to determine material and construction details of the metro structures. The investigations included core drilling to confirm wall thicknesses (and strength) at several different station facilities, core drilling in the crown and shoulders of the tunnel and CCTV survey of the drains and ventilation shafts to establish more detailed information adjacent to the piling works. As part of the characterization campaign, concrete cylinders for compression testing were taken to determine the compressive strength of the concrete used in construction in the 80s.

Given the proximity of adjacent structures it was necessary to assure a high overall stiffness for the pile retaining wall, in order to reduce the overall lateral deformation, through anchors, berms with struts inclined to the ground on strip foundations, and diagonal steel struts specifically in the northeast corner of the plot (Figure 2).

Figure 1. Front view of the retaining wall during the construction works (©Arup).

A strategy for monitoring both pile retaining wall and adjacent metro infrastructures before, during and after construction works, was implemented to assess the influence of the excavation on the nearby infrastructures. The monitoring system comprised inclinometers in the embedded wall, convergence monitoring and tape extensometers for the tunnel and different station facilities.

3 GROUND CONDITIONS AND PARAMETERS

Having analysed the project details, the two most representative sections are shown on Figure 3. The natural stratigraphy comprised anthropic fill (R) overlying 'Facies Madrid' sediments, as follows in depth: sands and clayey sands '*Arenas de Miga*' (AM), overconsolidated sandy/silty clays '*Toscos Arenosos*' (TAR) and '*Toscos Arcillosos*' (TARC). The stratigraphic columns adopted in the calculations are shown in Table 1 and Table 2.

Table 1. Stratigraphic column of section S3.

Soil unit	Top elevation (masl)	Bottom elevation (masl)	Thickness (m)
R	652.00	648.50	3.50
AM	648.50	640.40	8.10
TAR	640.40	634.80	5.60
TARC	634.80	To depth	-

Table 2. Stratigraphic column of section S6.

Soil unit	Top elevation (masl)	Bottom elevation (masl)	Thickness (m)
R	651.00	645.30	5.70
AM	645.30	639.60	5.70
TAR	639.60	634.20	5.40
TARC	634.20	To depth	-

A detailed ground investigation was carried out to derive representative geotechnical parameters for the soil units indicated above. They are shown in Table 3:

Table 3. Geotechnical parameters adopted.

Unit	R	AM	TAR	TARC
Model	MC	HSS	HSS	HSS
γ (kN/m^3)	19	20	20	20
c' (kPa)	0	10	20	50
Φ' (°)	28	34	32.5	29
E_{50}^{ref}/E' (MPa)	10	90	100	120
υ_{ur}/υ	0.35	0.20	0.20	0.20
G_o^{ref} (MPa)	-	661.3	976	976
$\gamma_{0.7}$	-	6E-05	6E-05	6E-05

Figure 2. Front view of the strutting system (©Arup).

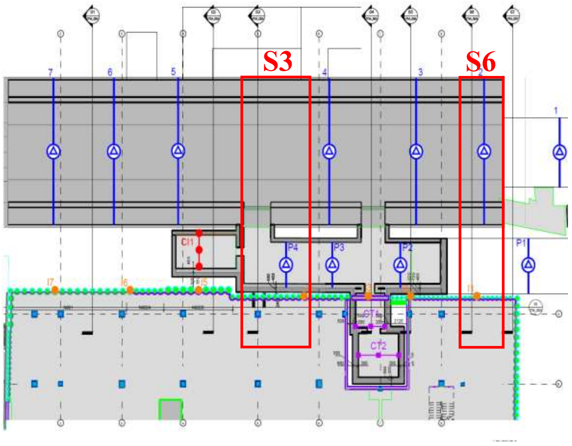

Figure 3. Plaxis 2D sections and inclinometer locations.

4 NUMERICAL ANALYSIS

The piled wall structure and its supporting elements (temporary strand anchors, strutting system at the northern east excavation corner), along with the nearby underground structures, were modelled with Plaxis 2D under plane-strain conditions.

Prior to starting the construction of the piled wall, it was essential to obtain the initial stresses acting on the ground. For that purpose, the construction sequence of the existing nearby tunnel and its galleries were simulated and, later, the displacements were set to zero. The construction sequence and overall geometric properties of the tunnel lining were provided by the asset owner.

The HSS model was calibrated using downhole geophysics for small strains and presuremeter tests for larger strains, alongside comparison to published literature on Madrid soils. The free-length of the cable anchors and its bond length (i.e. grout body) were modeled with node-to-node anchor and embedded beam row elements, respectively. For modelling the steel lattice beam elements of the strutting system and the concrete slab floors of the projected building were used fixed-end anchor elements. The geometry of the temporary anchors and prestress load are included in Table 4.

Table 4. Temporary anchors geometry.

Elev. (masl)	Free length (m)	Bond length (m)	$L_{spacing}$ (m)
648.50	17.0	8.5	1.60

A detailed staged analysis was defined considering up to 14 phases including intermediate excavation phases, installation of ground anchors/strutting system, berms, localised excavation for foundations and final support from basement concrete slabs. This allowed monitoring to be checked during all stages of the works.

Figure 4 compares the displacements predicted at sections 3 and 6 with the measurements taken in-situ by the nearest inclinometers (I1 and I4 respectively), once the final excavation level was reached and concrete slab floors built, along with the removal of supporting structures (earth berm, strutting system and temporary anchors). As shown above, there is a tight correspondence between predictions and measurements in section S6. However, differences of up to 10mm were observed in section S3, suggesting that the anchors did not behave as initially expected.

Constant monitoring of the wall displacements allowed for immediately warning of these unexpected displacements during one of the excavation phases. A more intensive anchor testing campaign was proposed to determine the causes. The tests revealed that some anchors had lost a significant portion of the applied prestressed load in spite of following standard BS EN 1537:2013 procedures. Further investigations revealed the existence of backfill material in this area that had not been identified during the geotechnical survey. To address this issue, the free anchor length was reduced from 17m to 9m, the spacing between anchors was reduced to 0.80m and the prestressed load was reduced.

Also, the frequency of the inclinometer readings was increased. Thereby, the displacements could be properly controlled to meet the requirements imposed by the metro station asset owner and the building construction was safely completed. Figure 5 and

Figure 6 show the sections in the final Plaxis model, before starting the building's construction.

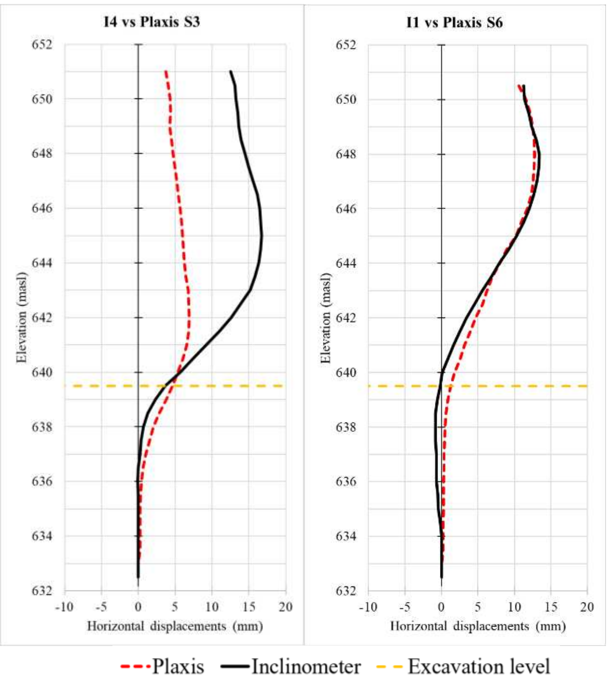

Figure 4. Horizontal displacements. Piled wall.

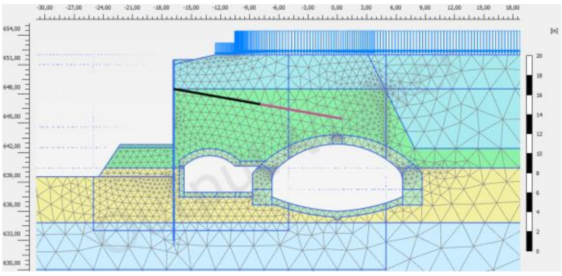

Figure 5. Plaxis Section 3 (anchor, earth berm).

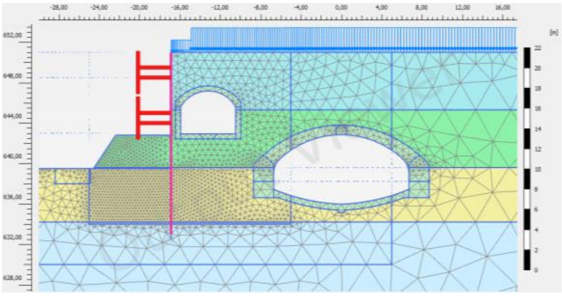

Figure 6. Plaxis Section 6 (strutting system, earth berm).

5 SUMMARY AND CONCLUSIONS

Using advanced constitutive models such as the Plaxis HS Small Strain model to simulate soil response and soil-structure interaction was essential to accurately assess potential impacts on a nearby sensitive metro station infrastructure. Overall, the numerical models allowed for a comprehensive understanding of soil behavior and its implications on adjacent structures. It facilitated effective design, risk mitigation, and optimized construction methods to ensure the safety and stability of both the excavation and nearby sensitive infrastructure. Another advantage was that the finite element models integrated both geotechnical and structural analysis, providing a holistic understanding of the interaction between the excavation, the soil, and nearby structures. This helped in making in-formed design decisions.

A detailed monitoring scheme alongside the use of numerical models was incorporated to enhance the safety and success of construction project. It enabled a proactive and responsive approach, allowing for timely adjustments and mitigations based on real-time data and observations such as:

- Real-Time performance evaluation
- Early detection of issues
- Validation of analytical models
- Calibration of design assumptions
- Confirmation of safety measures
- Record and benchmark for future projects
- Digital data-driven decision making
- Record of compliance verification

Finally, this case study showed it is crucial not only to accurately characterize the ground around the retaining structures but also at the anchor locations. In congested urban areas or near critical infrastructure these locations may vary considerably and end up being distant from the retaining structures. Unexpected displacements can compromise the excavation and safety of nearby structures unless a strict monitoring scheme is implemented, with suitable remedial measures that have been incorporated previously into the design as part of the decisionmaking process.

ACKNOWLEDGEMENTS

The authors are grateful to Metro de Madrid, S.A. for their active involvement during both design and construction phase. We would also like to give thanks to other collaborators involved in the project.

REFERENCES

Benz T. (2007). Small-strain stiffness of soils and its numerical consequences. *Ph.D. Thesis, University of Stuttgart.*

Oteo Mazo C. and Rodriguez Ortiz JM. (1997). Subsidence and monitoring in the Madrid Subway Network. *Revista de Obras Públicas Nº3.369. October 1997.*