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Prediction of Ground Movements under the Effect of Circular Tunnel Anchoring - Algiers Metro Case Study

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Abstract*— Assessing the impact of tunnels in urban environments is indeed a complex problem, and traditional empirical methods can often be insufficient to provide accurate estimates of the ground movement induced by tunnel excavation. This is mainly due to the many factors involved, including soil geology, structure geometry. To predict ground movement (horizontal displacements and surface settlements), engineers often use advanced numerical modeling techniques that take into account soil characteristics, tunnel geometry and other relevant parameters. These models can be used to estimate ground movement at various depths and distances from the tunnel, which is essential for designing appropriate mitigation and monitoring measures. In addition, real-time monitoring techniques are often used during and after construction to detect ground movement and take corrective action if necessary. The study presented in this article deals with an important analysis of the results obtained from the 2D numerical modeling of the tunnel of the Algiers metro extension project, more precisely the section between the E-El Harach Center, Bab Ezzouar, and Algiers International Airport. The objective of the modeling is to evaluate the surface settlements and horizontal displacements in the vicinity of the tunnel.

***Index Terms*— Horizontal Displacements, Numerical Simulations, Tunnel Excavation, Surface Settlements**

I. INTRODUCTION

The ground mass where a tunnel is located will deform as a result of tunneling. The primary feature of these deformations are troughs, which are irregular but concentrated subsidence located somewhat above the ground [1].

Subsidence phenomena are particularly sensitive in cities, affecting all components of the urban fabric: buildings, engineering structures, roads, networks, etc, [2]. At depth, there may be other structures in the zone of influence of the tunnel under construction. In other words, the construction of twin tunnels [3] in which the second tunnel interacts with the first, galleries and collectors, etc.

The excavation of the tunnel for the extension of the Algiers metro system E-El Harach Centre-Bab Ezzouar-Algiers International Airport can cause surface settlements, the numerical modeling of which is the subject of this study. The settlement analysis and horizontal displacements for the different tunnel construction phases were carried out using the PLAXIS software.

After a review of the problems posed by surface settlements in urban areas and the modeling methods (in 2D) proposed in the literature,[4] we present the geometric model of the tunnel, the modeling and the analysis of the results in terms of horizontal displacements and surface settlements for the different phases of tunnel construction.

II. SURFACE SETTLEMENT DURING TUNNEL EXCAVATION

The amplitude of horizontal deformations or settlements depends on the mechanical properties of the soil, surface surcharges, hydraulic conditions, and excavation and support methods that affect surface settlement [5, 6].

In fact, tunnel design requires the ability to decide on the feasibility of construction by one method or another [7], to estimate the settlements or other movements caused in the host massif by tunnel excavation, especially in the final phase under seismic excitation [8], and to provide the final structure with sufficient strength [9, 10].

Considerable effort has been devoted to studying surface movements during tunnel excavation, modeling them, and compiling feedback from experience [11, 12].

III. MECHANISMS AND RISKS OF INSTABILITY

In the case of deep or shallow tunnels, the displacements propagated in the massif during the tunnel excavation phase cause settlements [13, 14] and horizontal displacements at the surface [15]. Horizontal displacements tend to follow the front and change direction as it advances.

Therefore, surface subsidence depends on the state and behavior of the overlying ground as well as on the ground in which the tunnel is excavated [16]. The geometry of shallow tunnels, whose diameter is not negligible compared to their depth, reduces the transverse and longitudinal vaulting effects that occur naturally in deep massifs.

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This increases the risk of instability and the amplitude of displacement. For this reason, in deformable, low-strength terrains, supports are installed and closed as soon as possible, as close to the face as possible, or even before the face (pre-support) [2], to avoid instability that would be dangerous for site personnel and detrimental to the structure before the final pavement is built. On the other hand, in urban areas, it is also important to limit surface settlement to acceptable values, which may require appropriate adaptation of the underpinning and careful construction.

IV. NUMERICAL MODEL OF THE PROPOSED TUNNEL SYSTEM

A. Geometric model

Numerical calculations were performed using the two-dimensional (2D) finite element software Plaxis [17, 18] to evaluate the influence of tunnel anchored depth on horizontal displacements and settlements at the model surface [19].

The schematic diagram of the investigated model is shown in figure 1, where the geometry consists of a circular tunnel with a diameter (D=9.30m).

Only the tunnel anchorage depths (Table 1) and the lateral distance from the vertical center of the tunnel (dx) are considered as variable parameters in the present study (Figure 1).

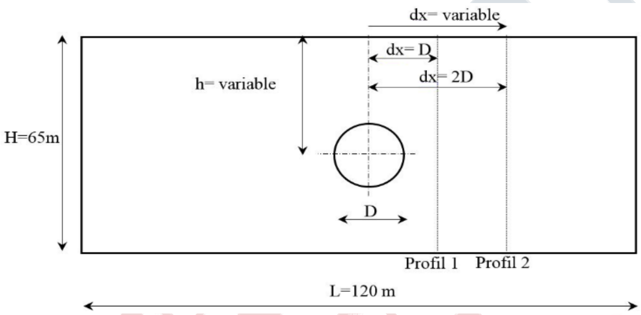

Fig. 1. Geometric study model.

Table. 1. Different study cases according to anchorage depth.

Case studies	Tunnel depth h(m)
First case (h=3D)	27.9
Second case (h=4D)	37.2
Third case (h=5D)	46.5

B. Constitutive Model and Boundary Conditions

In the PLAXIS program, a 2-D plane deformation model was used for the soil modeling, taking into account the Mohr-Coulomb model for the soils used [20] and plate-like elements for the modeling of the tunnel segment.

Triangular elements with 15 nodes were used to simulate soil behavior. To generate standard boundary conditions for seismic loading, a combination of absorbing boundaries and prescribed displacements were generated and assigned to the model.

The geometric model consists of a rectangular domain 120 m wide and 65 m deep to place the lateral boundaries far enough away, as shown in figure 2.

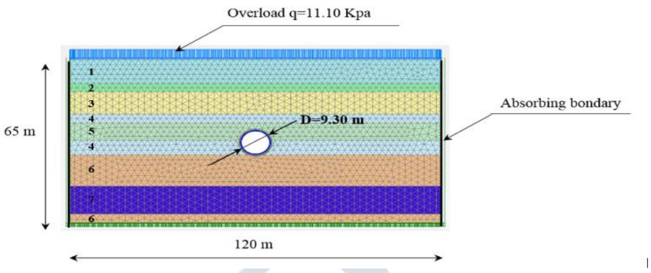

Fig. 2. Typical PLAXIS model with boundary conditions

The geological formations along the bored tunnel consist of clay and mixtures of clay-sand and clay-marl, with seven main layers considered. The mechanical parameters of the different soil layers are summarized in table 2.

Table. 2. Soil layer property values used in the numerical simulation.

	No of layer	Dry density (kN/m3)	Satureted density (kN/m3)	Elasticity Modul E (kN/m2) 10^4	Cohesion C (kN/m3)
Backfill (Ba)	1	17	20	1.00	0
Silty clay with little sand (SCLS)	2	17	20	3.05	31
Clayey silty sands with presence of sandstone (CSSS)	3	18	21	5.4	10
Marly clay with yellowish to grayish marl (MCYGM)	4	17	21	0.38	40
Silty clayey sands with pebbles (SCSP)	5	18	21	7.7	31
Fine, medium to coarse, yellowish sand with sandstone fragments (FMYS)	6	18.5	21	15.6	10
Marly clay with greenish to grayish marl (MCGGM)	7	17	21	0.50	41

C. Structural parameters

The reinforced concrete elements that form part of the tunnel segments were modeled in PLAXIS 2D using plate-type elements, according to the project specifications and the requirements of the applicable standards, particularly in terms of load-bearing capacity and deformability.

These structural elements have a linear elastic behavior. Table 3 shows the characteristics of the elements used in the calculation model.

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Table. 3. Characteristics of flat elements for tunnel segment simulation.

Characteristics	EA (kN/m)	EI (kN.m²/m)	Poisson's ratio □
values	$1.71\ 10^7$	$2.89\ 10^5$	0.2

D. Phases of numerical modeling

The different phases followed in the numerical modeling with the Plaxis software, in order to reproduce the different stages of the tunnel construction process, are as follows

Phase I: Generation of the initial stress state (application of the K_0 method).

Phase III : Tunnel excavation (TE).

Phase IV: Installation of tunnel segments (ITS).

Phase V: Dynamic loading (DL).

E. Dynamic parameters

The earthquake that occurred on May 21, 2003, in Zemmouri, 70 km east of Algiers, had a dynamic effect on the surrounding ground and the tunnel. Its intensity was 6.8, its length was 27.675s, and its greatest acceleration was 556.79cm/s² (Figure 3).

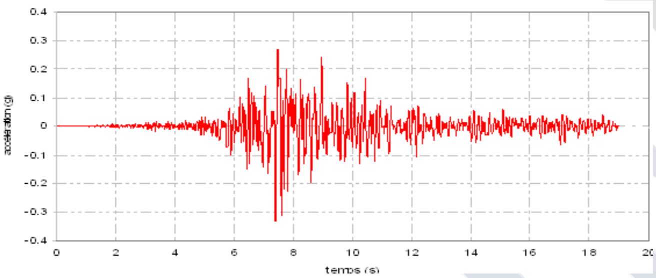

Fig. 3. Accelerogram of the Boumerdes earthquake (2003)

The seismic load is modeled in Plaxis by a horizontal displacement imposed on the base of the model, which follows the evolution of the Boumerdes earthquake [21].

V. STATE OF INDUCED HORIZONTAL DISPLACEMENTS IN THE GROUND IN PROXIMITY TO THE TUNNEL CAVITY

Figure 4 shows numerical simulation results of lateral movements on the right side of the tunnel after excavating and installing segments. The results are shown at distances dx=D and dx=2D from the tunnel's vertical axis. Upon initial observation, the curves display a nearly identical shape, which can be classified into three distinct zones: above the key, around the horizontal axis of the tunnel, and below the invert.

- Above the key, the horizontal displacement converges towards the maximum values at the model surface obtained after simulation.
- Around the horizontal axis of the tunnel, the soil between the key and the invert is displaced by the confining pressure, and continues to be pushed outwards (positive values) and inwards (negative values).
- Below the invert, the ground stabilizes or horizontal displacements tend toward zero at the base of the model (the lower limit of the model is recessed).

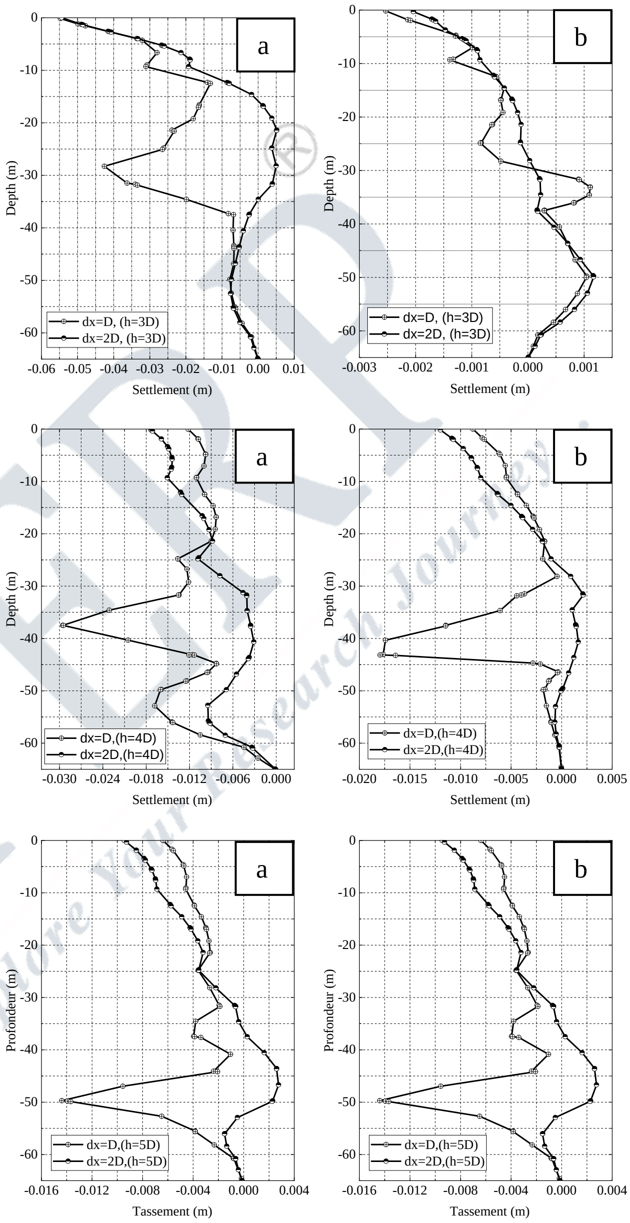

Fig. 4. Horizontal displacements in the vicinity of the tunnel (a)- Tunnel Excavation phase, (b)-Installation of tunnel segment phase

Two cases can be highlighted in the evolution of the lateral displacements along the vertical profiles located at distances dx=D and dx=2D from the vertical center of the tunnel:

1- During the tunnel excavation phase, the soil surrounding the tunnel converges towards the maximum value on its horizontal axis in the vicinity of the tunnel for both profiles (dx=D and dx=2D). However, this convergence is not observed for the zones above and below the tunnel.

2- During the tunnel segment installation phase, ground movement is intensified near the horizontal axis of the tunnel, while the ground is pushed back in the vicinity of the tunnel due to the ovalization of the tunnel segment.

The figure 5 below illustrate the horizontal displacement evolution in the ground surrounding the tunnel, as a function of the anchorage depth (h) and profile position (dx=D and dx=2D) under seismic excitation, through the results obtained we can note that's:

- The seismic load induces displacements that result in axial deformations on the model's surface and in the ground surrounding the tunnel. These axial deformations lead to ground compression around the horizontal axis.
- The values for maximum axial displacement are highest at the ground surface and in the soil above the tunnel key, at a depth of 5 to 10 meters.

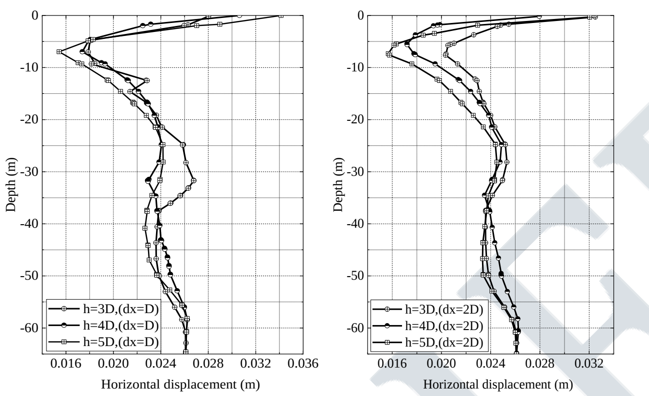

Fig. 5. Horizontal displacements in the vicinity of the tunnel under seismic excitation at dx=D and dx=2D.

Figure 6 shows the maximum surface displacements for all cases, including excavation, installation, and seismic conditions.

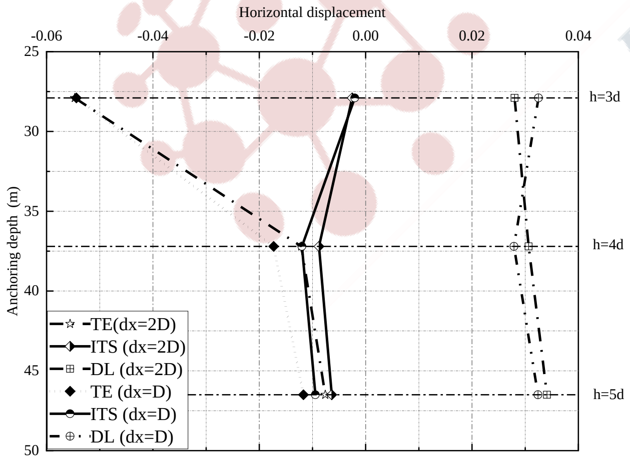

Fig. 6. Evolution of maximum settlement as a function anchor depth at dx=D and dx=2D

The results show that the tunnel excavation phase produced the maximum horizontal displacement for an anchoring depth of h=3D at distances dx=D (-56.96 mm) and dx=2D (-54.657 mm) from the vertical axis of the tunnel during both the excavation and segment installation phases.

Under seismic excitation, the maximum horizontal displacements were obtained for an anchoring depth of h=3D, with a maximum of 32.5 mm for dx=D and 1.65 mm for dx=2D, when moving away from the vertical center of the tunnel.

VI. SURFACE SETTLEMENT STATE

Figures 7 and 8 displays the final settlement troughs for the three study cases. All settlement points have stabilized, with the maximum settlement occurring around the vertical axis of the tunnel. The appropriate dimensions for the geometric model are evident, with vertical boundaries away from the center of the tunnel resulting in surface settlement values approaching zero confirmed by Yuan [22] and Leca [23].

The settlement troughs are wider and exhibit greater settlement after tunnel excavation, while troughs obtained after segment installation are narrower and exhibit less settlement. This difference may be attributed to the tunnel's anchored depth and the installation of the segments, which help to reduce settlement.

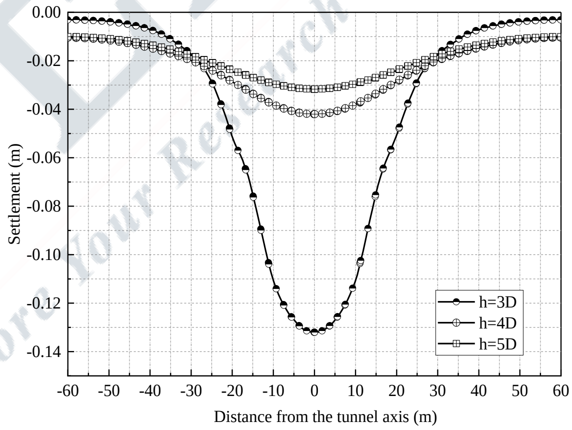

Fig. 7. Surface settlement at different anchor depth (Excavation phase)

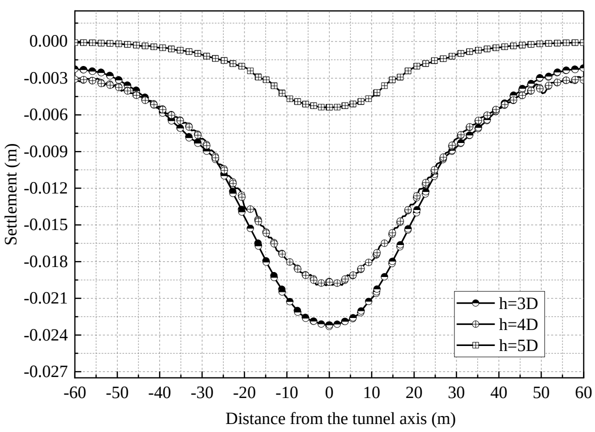

Fig. 8. Surface settlement at different anchor depth

(Segment installation phase)

Figures 7 and 8 confirms that excavation started to affect surface settlements for an inking depth of h=3D, with values of 132.03 mm and 5.38 mm for the tunnel excavation and installation phases, respectively.

The settlements decreased as the inking depth increased, measuring 41.98 mm and 31.72 mm for h=4D and h=5D, respectively.

The installation of the tunnel segments significantly affected the settlement, which became more concentrated around the tunnel's vertical axis after the installation of the tunnel segments. On the other hand, the values obtained during the tunnel excavation phase are more significant than those obtained during the installation of the tunnel segments phase, with a decay rate of 95.92%, 44.47%, and 38.11% for the anchored depths h=3D, h=4D, and h=5D, respectively.

VII. TENDENCIES OF THE SETTLEMENT IN THE VICINITY OF THE TUNNEL

A. Tunnel excavation and segment installation phase

Figures 9 and 10 displays the development of settlements on profiles located at distances dx=D and dx=2D during the tunnel excavation and segment installation phase.

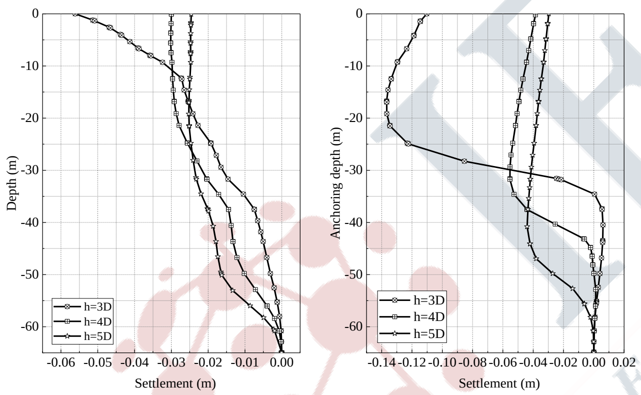

Fig. 9. Depth settlements for profiles dx=D (tunnel Excavation phase)

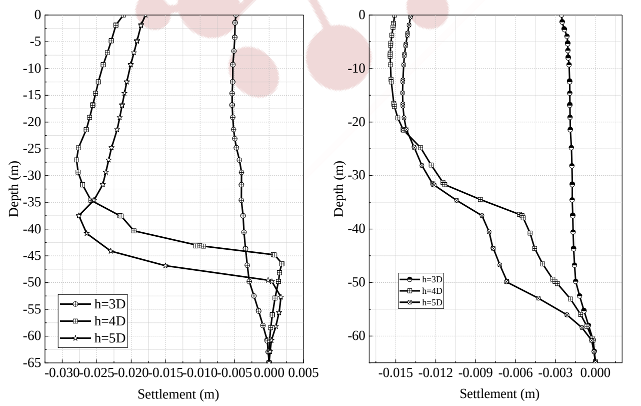

Fig. 10. Depth settlements for profiles dx=2D (installation phase)

During the tunnel excavation phase, settlements at the model surface increase with anchoring depths of h=3D, h=4D, and h=5D, reaching 29.66 mm, 38.51 mm, and 197.4 mm, respectively.

During the installation of the tunnel segments, a reduction in settlement at the surface of the model was observed. The reduction percentages were 83.82%, 53.52%, and 89.31%, depending on the depth of anchorage.

B. Dynamic loading (earthquake)

Figure 11 display the settlements at profiles dx=D and dx=2D obtained under seismic excitation. The settlements are concentrated on the horizontal axis of the tunnel. Stability in terms of settlements is achieved because settlements at the model surface are less significant than in other construction phases.

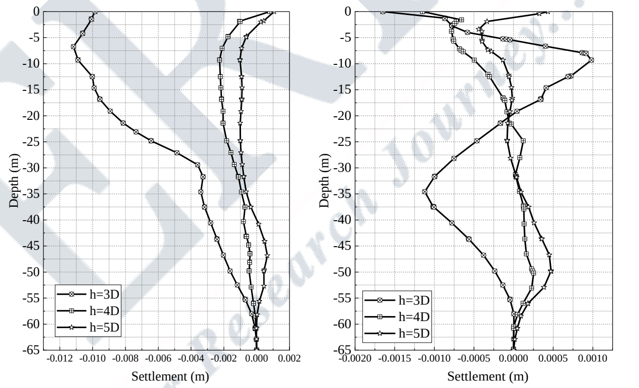

Fig. 11. Settlement Evolution during Seismic Excitation Phase at dx=2D

C. Evolution of maximum settlement versus anchor depth

The maximum surface settlement for all the cases considered, excavation phase, installation and under earthquake conditions is illustrated in figure 12, for the various tunnel anchorage depths.

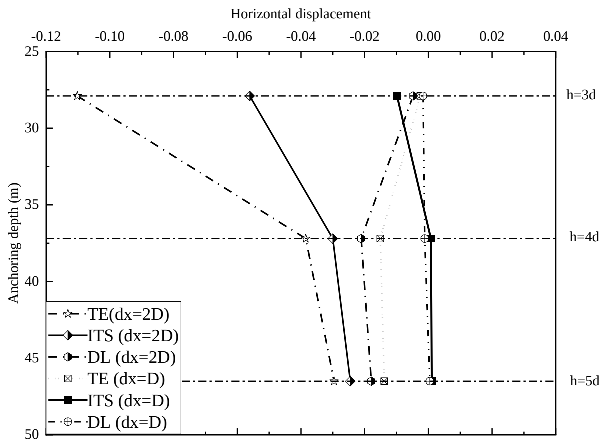

Fig. 12. Evolution of maximum settlement as a function

anchor depth at dx=D and dx=2D.

The settlement values indicate that the excavation phase for an anchoring depth of h=3D at distance dx=D resulted in the highest settlements, reaching a value of 56.96 mm. Under seismic excitation, the maximum settlements were obtained for an anchoring depth of h=4D, with a maximum settlement of 32.5 mm for dx=2D, as we move away from the vertical center of the tunnel.

VIII. CONCLUSION

The study aims to provide information on the behavior of the soil around the tunnel and at the surface under various conditions, such as excavation, installation and seismic activity.

A 2D numerical modeling technique is used to simulate the behavior of the surrounding soil. This modeling approach enables a detailed examination of horizontal settlements and displacements.

By examining the results, we can graphically compare how maximum surface settlement varies with different tunnel anchorage depths under each condition. This comparison can help to understand the influence of anchoring depth on surface settlement, and to determine the optimum design parameters for minimizing the effects of settlement during tunnel construction and operation.

Numerical modelling results show that the application of segments plays a very important role in tunnel stability. It is concluded that the closer the excavation zone is approached, the greater the settlements during all phases of the project, particularly during the excavation phase, which is considered to be the phase in which the ground is most disturbed, with maximum surface settlements reaching 132.03, 41.98 and 31.72 mm for anchoring depths of h=3D, h=4D and h=5D respectively.

The tunnel excavation crosses important urban areas. Understanding the behavior of the soil around the tunnel and assessing surface settlement in this context is crucial to ensuring the safety and stability of the surrounding infrastructure and minimizing potential disturbance during tunnel construction and operation.

REFERENCES

[1] P. Lunardi, The dynamics of tunnel advance, Design and Construction of Tunnels: Analysis of controlled deformation in rocks and soils (ADECO-RS), (2008) 3-13.

[2] A. Athanasopoulo, A. Bezuijen, W. Bogusz, D. Bournas, M. Brandtner, A. Breunese, U. Burbaum, S. Dimova, R. Frank, H. Ganz, Standardisation needs for the design of underground structures, European Commission-JRC Technical Reports, (2019).

[3] T. Do Ngoc, K.D. Van, V.P. Van, Q.N. Van, Prediction of surface settlement due to twin tunnel construction in soft ground of Hanoi metro line 03, GEOMATE Journal, 22 (2022) 66-72.

[4] A. Amorosi, D. Boldini, Numerical modelling of the transverse dynamic behaviour of circular tunnels in clayey soils, Soil Dynamics and Earthquake Engineering, 29 (2009) 1059-1072.

[5] A. Ansari, K. Rao, A. Jain, Seismic analysis of shallow tunnels in soil medium, in: Stability of Slopes and Underground Excavations: Proceedings of Indian Geotechnical Conference 2020 Volume 3, Springer, 2022, pp. 343-352.

[6] J. Su, Y. Wang, X. Niu, S. Sha, J. Yu, Prediction of ground surface settlement by shield tunneling using XGBoost and Bayesian Optimization, Engineering Applications of Artificial Intelligence, 114 (2022) 105020.

[7] D. Peila, A theoretical study of reinforcement influence on the stability of a tunnel face, Geotechnical & Geological Engineering, 12 (1994) 145-168.

[8] R. Huang, J.X. Zhu, X.J. Zhu, Z.M. Liu, Analysis of Ground Settlement during Shield Tunnel Construction in Soft Soil, Soil Mechanics and Foundation Engineering, 60 (2023) 134-140.

[9] M.J. Lebas, Performance measurement and performance management, International journal of production economics, 41 (1995) 23-35.

[10] S. JIANG, Y. ZHU, Q. LI, H. ZHOU, H.-l. TU, F.-j. YANG, Dynamic prediction and influence factors analysis of ground surface settlement during tunnel excavation, Rock and Soil Mechanics, 43 (2022) 195-204.

[11] E. Cording, W. Hansmire, LES DEPLACEMENTS AUTOUR DU TUNNEL EN TERRAIN TENDRE, Tunn Ouvrages Souterr, (1977).

[12] R. Rowe, K. Lo, G. Kack, A method of estimating surface settlement above tunnels constructed in soft ground, Canadian geotechnical journal, 20 (1983) 11-22.

[13] Q. Di, P. Li, M. Zhang, X. Cui, Investigation of progressive settlement of sandy cobble strata for shield tunnels with different burial depths, Engineering Failure Analysis, 141 (2022) 106708.

[14] Y.-S. Fang, C.-T. Wu, S.-F. Chen, C. Liu, An estimation of subsurface settlement due to shield tunneling, Tunnelling and underground space technology, 44 (2014) 121-129.

[15] L. Mu, P. Zhang, Z. Shi, M. Zhu, Z. Gu, Predicting longitudinal tunnel deformation due to deep excavation-induced ground movement, Tunnelling and Underground Space Technology, 131 (2023) 104793.

[16] P. Lunardi, Design and construction of tunnels: Analysis of Controlled Deformations in Rock and Soils (ADECO-RS), Springer Science & Business Media, 2008.

[17] R. Brinkgreve, S. Kumarswamy, W. Swolfs, D. Waterman, A. Chesaru, P. Bonnier, PLAXIS 2016, PLAXIS bv, the Netherlands, (2016).

[18] T. Li, W. Gong, X. Yang, Stability analysis of a non-circular tunnel face in soils characterized by modified Mohr-Coulomb yield criterion, Tunnelling and Underground Space Technology, 109 (2021) 103785.

[19] Q. Xu, Y. Zhu, S. Lei, H. Fan, D. Wang, K. Ma, Z. Fang, A Simplified 3D Theoretical Model for Calculating the Surface Settlement Induced by Tunnel Undercrossing Excavation, International Journal of Geomechanics, 23 (2023) 04023185.

[20] W.H. Baker, R.J. Krizek, Mohr-Coulomb strength theory for anisotropic soils, Journal of the Soil Mechanics and Foundations Division, 96 (1970) 269-292.

[21] F. Meziani, K. Amar, S. Gabi, Evolution of Soil Settlements under a Rockfill Dam Based on Potential Earthquake Harmfulness (PEH)'Case of Boumerdes Earthquake, Algeria

2003', International Journal of Engineering Research in Africa, 42 (2019) 109-121,https://doi.org/110.4028/www.scientific.net/JERA.4042.4109.

[22] C. Yuan, M. Zhang, S. Ji, J. Li, L. Jin, Analysis of factors influencing surface settlement during shield construction of a double-line tunnel in a mudstone area, Scientific Reports, 12 (2022) 22606.

[23] E. Leca, B. New, Settlements induced by tunneling in soft ground, Tunnelling and Underground Space Technology, 22 (2007) 119-149.

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