OPEN ACCESS
The Journal of Engineering and Exact Sciences – jCEC, Vol. 10 N. 04 (2024)
journal homepage: https://periodicos.ufv.br/jcec
eISSN: 2527-1075
ISSN: 2446-9416

Shallow tunneling's impact on surface settlements

Article Info:
Article history: Received 2024-02-02 / Accepted 2024-05-13 / Available online 2024-05-13
doi: 10.18540/jcecvl10iss4pp18591

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Abstract
The research described in this paper deals with the impact of shallow tunneling on surface settlements in urban areas. The study focuses on carrying out a numerical analysis and a parametric geotechnical study to investigate the effects of tunnel excavation on the surface ground, particularly with regard to distortion and potential damage to structures above the tunnel. To carry out the study, the researcher used a finite element method (FEM) software package called Plaxis. This software is commonly used for geotechnical analysis and allows simulating and analyzing the subsurface conditions in Algiers underground in the context of excavating a shallow tunnel. The New Austrian Tunnelling Method (NATM) excavation method was chosen for the study. The results of the numerical analysis are presented in terms of displacements. The results indicate that ground flow has a significant influence on ground movement, probably contributing to surface settlement. However, the effect of tunnel excavation on the lowering of the water table and Young's modulus (a measure of soil stiffness) is relatively small in comparison. The research provides valuable information on the potential impacts of shallow tunneling in urban areas and the factors that play a crucial role in determining the extent of ground movement and surface settlement. By using numerical analysis and conducting a parametric geotechnical study, and gives valuable insights into the potential impacts of shallow tunnelling in urban areas and the factors that play a crucial role in determining the extent of ground movements and surface settlements. By using numerical analysis and conducting a geotechnical parametric study, and contributes to a better understanding of the behavior of the ground during tunnelling operations in Algiers. The findings can be helpful in designing future tunnelling projects to mitigate potential risks to structures and infrastructure located above the tunnels.
Keywords: Tunnel, FEM, NATM, Young modulus, Plane strain.

1. Introduction

Since any building constructed in this area is vulnerable to damage, it is essential to minimize settlements using suitable excavation techniques. To reduce the likelihood of structural damage, it is crucial to consider the following elements: excavation techniques and selecting an excavation method that will reduce settlements in the crucial zone and allow for effective ground movement management. Putting in place a reliable monitoring system to continually track settlements and ground movements during and after tunnel construction. Managing groundwater levels appropriately during construction, to prevent excessive uplift and settlement, doing a thorough geotechnical investigation to understand the behavior of the soil, and using suitable design solutions to limit settlements.

Building tunnels is commonly required as a result of crossing issues brought on by the growth of the road, highway, and rail networks. Urban density also necessitates the construction of underground transportation networks, such as subway and road systems. The construction of these structures presents several significant challenges, including the need to ensure both short- and long-term wall strength through the appropriate selection of support and lining (Orestes *et al*., 2003; Miwa *et al*., 2005). Ocak and Seker (2013) noted the rising urban infrastructure demands have increased the emphasis on shallow soft ground tunneling methods, especially in metro constructions. Hasanipanah *et al*. (2016) developed a hybrid model of artificial neural network (ANN) optimized by particle swarm optimization (PSO) for predicting maximum surface settlement (MSS) in subway and tunnel excavations, demonstrating higher accuracy compared to ANN results using 143 data sets from Iran. The results showed higher accuracy in predicting MSS compared to ANN results. Moghaddasi *et al*. (2018) observed that urbanization and population growth have increased the necessity for subway tunnels, leading to challenges like poor ground conditions and surface settlement risks. They introduced an ICA-ANN hybrid model using 143 datasets from the Karaj subway project in Iran. This hybrid model surpassed traditional regression models, demonstrating greater accuracy in predicting Maximum Surface Settlement (MSS) and offering a more dependable solution compared to standalone ANN and multiple regression (MR) models.

Chen *et al*. (2019) examines the efficiency and feasibility of six machine learning algorithms (back-propagation neural network, wavelet neural network, general regression neural network, extreme learning machine, support vector machine, and random forest) in predicting tunneling-induced settlement. Field data sets from four tunnel sections were used to build models. Results showed ML algorithms have great potential, with GRNN and RF algorithms showing the best performance. In recent work, Gang *et al*. (2023) reviews 677 articles on ground settlement induced by tunnelling in urban areas, focusing on empirical, analytical, numerical, and artificial intelligence methods. It introduces the application of AI in tunnelling-induced ground deformation and clarifies the challenges of ground displacement prediction by machine learning, suggesting future research directions.

Complexity is increased in these projects by managing hydraulic phenomena in the presence of aquifers and controlling surface movements, which occur mainly when structures are erected near other urban structures or at shallow depths (Wang *et al*., 2019; Sun *et al*., 2020; Benbo *et al*., 2024). Because of these many obstacles, building must be done with an integrated strategy and close attention to detail (Pourtaghi *et al*., 2012). Underground constructions that are completely embedded in a rock or soil mass, need to have their entire extent precisely geotechnically characterized. In their design, four types of calculation tools are frequently used: numerical methods like finite differences (Zhang *et al*., 2021) and finite elements (Huang *et al*., 2015; Zhao *et al*., 2017), semi-empirical methods (Chen *et al*., 2019; Su *et al*., 2022), analytical methods (Park, 2004, Zhang *et al*., 2017; Su *et al*., 2022). Each of these tools offers distinct advantages and limitations, and their combined application allows for a more thorough understanding and assessment of the geotechnical aspects of subterranean constructions. The Finite Element Method

(FEM) has established itself as the industry standard for modeling the behavior of subterranean structures throughout the last 20 years. Semi-empirical approaches are frequently taken into consideration as a means of estimating settlements, although numerical methods are already well established. Analytical methods are employed to provide orders of magnitude or validate the outcomes of complicated models (Gang *et al*., 2023). Surface settlements, deformations at soil-structure interfaces, stresses assumed by the support, and hydraulic impacts brought on by the works may all be examined using calculation methods (Vasiliki *et al*., 2023; Zhu *et al*., 2021) on numerical techniques applied to underground structures. More recently, Fan Wang *et al*. (2024) in the prediction of subsurface settlement induced by shield tunnelling in sandy cobble stratum.

This work investigates a numerical examination of the effects of shallow tunnel excavation on a multistory building directly above the tunnel axis, including geotechnical characterization. The planar deformation finite element method-based Plaxis simulation software is the foundation of the employed technique. The Algiers metro is used as a specific environment to apply the study. The excavation was done using the NMA which is the deconfinement procedure.

2. Modelling of algiers underground railways

2.1 Formulation and Discretization in 2D Tunnel Modeling using Finite Element Method

In two-dimensional modeling, we assume a plane transverse to the tunnel axis. The convergence-confinement method (Panet, 1995) is widely used for 2D tunnel modeling. We consider the gradual convergence of the ground in front of and behind the tunnel section by a "relaxation" of the stresses applied by the excavated zone on the remaining ground.

In the Finite Element Method (FEM), the equilibrium of a drained solid under nonlinear static loading can be represented using the principle of virtual powers (Boulon, 2004; Brinkgreve *et al*., 2002). This principle allows us to describe the equilibrium of the solid within the domain Ω, regardless of its behavior law (material constitutive model) "Equation (1)".

$$\int_{\Omega} {}^{T}\dot{\varepsilon}\left(\sigma_n-\sigma_{n-1}\right)d\Omega=\int_{\Omega} {}^{T}\dot{u}^{*}\left(f_n-f_{n-1}\right)d\Omega+\int_{\Omega} {}^{T}\dot{u}^{*}\left(t_n-t_{n-1}\right)d\Omega \qquad (1)$$

The virtual power principle gives the matrix equation corresponding to the discretised problem “Equation (2)”:

$$\sum_e \int_e {}^{T}B_e \int_{\Delta tn} D_e \,.\, \dot{\varepsilon}_e . dt . d\Omega = \sum_e \int_e {}^{T}H_e \left(f_n - f_{n-1}\right) + \sum_e \int_{e \in \Gamma\sigma} {}^{T}H_e \left(\bar{t}_n - \bar{t}_{n-1}\right) d\Gamma$$
(2)

Where u* virtual kinematic permissible displacement for load step n with u real displacement vector (small displacements), $\dot{u}^*$ virtual velocity vector, σ pseudo vector stress (real), ε pseudo vector strain (real)

$\dot{\varepsilon}^*$ virtual pseudo vector deformation rate (virtual), f volume forces vector, t stress vector or surface forces on the Γσ part of the Γ boundary of Ω (stress boundary conditions), ${}^{T}X$ transposed of the matrix X.

The space is discretised into elements with nodes in common or in their own right, the unknowns of the loading stage are:

- On the one hand, the nodal displacement field at the end of step n (main unknowns)
- The stress paths during loading step n (unknowns linked to the main unknowns).

To calculate these unknowns, we discretise the displacement velocity field element by element ue, is real field and ue* virtual field on element e.

$$\dot{u}_e = H_e \cdot \dot{U} \qquad (3)$$

$$\dot{u}_e^* = H_e \cdot \dot{U}^*$$
(4)

Where He is a local interpolation matrix, $\dot{U}$, $\dot{U}^*$ real (respectively virtual) nodal displacement rate.

Assuming the size of the loading step, we can substitute $\dot{U}$ its can be substituted for its approximate finite difference expression: $(U_n – U_n\text{-}1) / \Delta t_n$

Un nodal displacement field at the end of step n (unknown)

Un-1 nodal displacement field at the end of step n-1 (known)

Δtn time interval corresponding to loading step n

De is the matrix representing the local (non-linear) behavior law within the element e

$$\dot{\sigma}_e = D_e \cdot \dot{\varepsilon}_e \quad (5)$$

The virtual power principle gives the matrix equation corresponding to the discretised problem “Equation (6),”

$$\sum_e \int_e {}^{T}B_e \int_{\Delta tn} D_e \,.\, \dot{\varepsilon}_e . dt . d\Omega = \sum_e \int_e {}^{T}H_e \,(f_n - f_{n-1}) + \sum_e \int_{e \in \Gamma\sigma} {}^{T}H_e \,(\bar{t}_n - \bar{t}_{n-1}) d\Gamma \quad (6)$$

Where Σe is a summation on the elements

dt : time increment during step n

∫e : integral on the element e

The second member of the preceding matrix equation represents the variation in the nodal forces equivalent to the external forces (in accordance with the chosen interpolation element).

So, for step n:

$$\sum_e \int_e {}^{T}B_e \int_{\Delta tn} D_e . \dot{\varepsilon}_e . dt . d\Omega \Big/ \Delta t_n = F_n - F_{n-1} \quad (7)$$

Given the above approximate expression for U, equation (x) becomes:

$$\sum_e \int_e {}^{T}B_e \int_{\Delta tn} D_e . B_e . dt . d\Omega \left(U_n - U_{n-1}\right) / \Delta t_n = F_n - F_{n-1} \quad (8)$$

FEM shows extra surface integrals in the case of two solids (soil and foundation, for example), using special (interface) elements in which the relative displacement between the two solids replaces the role provided by the solids' deformations. "Interface" behavior is involved in these elements.

2.3 Geometrical assumptions and geotechnics

This calculation section was chosen within the Hamma/Garden of Tests section, towards PK 5.100-5.200. This particular section consists entirely of compact marls (EMA, 2003). The geometric description of the structure is depicted in Figure 1. The tables 1., 2., and 3 show the characteristics of the soil layers that make up the massif and the characteristics of the materials used in the construction of the tunnel.

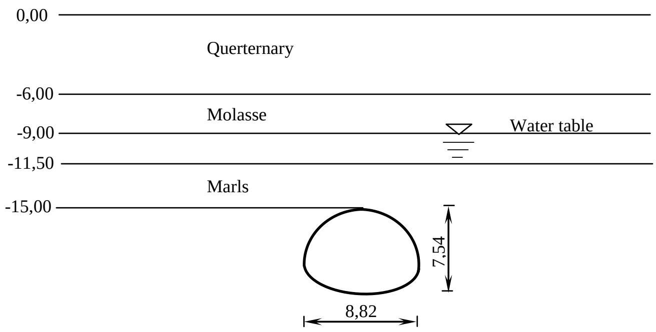

Figure 1 - Cross section of tunnel.

TABLE 1. Geotechnical characteristics of soils

Soil type	γ_d (kN/m³)	γ_{sat} (kN/m³)	E_0 (MPa)	E_∞ (MPa)	ν /	K_0 ()	Cu (kPa)	φ_u (°)	C' (kPa)	φ' (°)
Quaternary	19	22	120	100	0.25	0.54	30	27.5	10	27.5
Molasse	17	20.5	120	100	0.25	0.46	5	32.5	0	32.5
Marls	22	24	500	350	0.30	0.50	250	30.0	150	30.0

TABLE 2. Soils permeability and interfaces stiffness

Soil type	k_h (m/s)	k_v (m/s)	Interfaces stiffness R_i
Quaternary	$1{,}5.10^{-4}$	$1{,}5.10^{-4}$	1
Molasse	5.10^{-5}	5.10^{-5}	1
Marls	$8{,}6.10^{-9}$	$8{,}6.10^{-9}$	1

TABLE 3. Mechanical characteristics of lining

	Support line		Definitive support line	
	Short term	Long term	Short term	Long term
EA (kN/m	$2{,}45.10^{6}$	$2{,}45.10^{6}$	$1{,}2.10^{7}$	6.10^{6}
EI (kN.m²/m)	$7{,}82.10^{3}$	$7{,}82.10^{3}$	$2{,}5.10^{5}$	$1{,}25.10^{5}$

The geometric definition of the tunnel structure is 7.54 m height, with an internal opening of 8.82 m. The definitive support line is made up of a final B35 concrete lining that is 40 cm thick in the vault and 60 cm wide in the invert and a B25 shotcrete for support line that is 15 cm thick in the invert and 20 cm thick in the vault and pedestals where it is coupled with HEB120 hangers placed 1.5 m apart. To ascertain how tunneling and geotechnical factors affect surface settlements and vertical displacement at the top of the crown.

The model is confined to a half-space due to the symmetry along a vertical axis (Gesta, 2005). It extends laterally 80 meters from the work's axis and falls vertically 65 meters into the surface of the earth (Prat *et al*, 1995). The reference model includes 1561 triangular elements, 3299 nodes and 4683 stress points (Figure 2.). In accordance with the spirit of the NATM excavation method, the law chosen for the interaction between the temporary support and the ground is the perfect adherence. Elastoplasticity calculations were performed while maintaining an elastoplastic law with the Mohr-Coulomb failure criterion for the various soils and a linear elastic constitutive law for the support and lining. The horizontal fixities at the lateral limits (u=0) and the total fixities along the bottom (u=v=0) serve as the model's boundary conditions (Djenane, 2006)..

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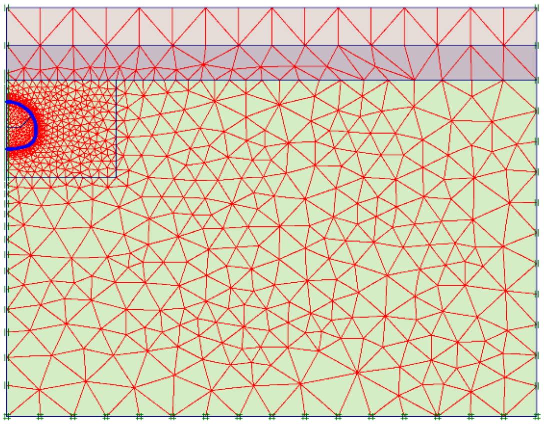

Figure 2 - Finite element mesh of the Algiers undergruond railways.

2.4 Phasing of calculations

The building project is divided into many discrete stages. The initial stress distribution in the soil is explained by the initialization of the geostatic stresses. Phase 1 involves tunnel excavation, which results in a deconfinement rate of β_1 ($\sum$M stage = 0.4). Phase 2 (Panet, 1995) and (Oreste, 2003) then entails the construction of support structures, which results in an additional rise in deconfinement from β_1 to β_2 ($\sum$M stage=0.6). The goal of phase three is to finish the deconfinement procedure ($\sum$M stage = 1). While installing the tunnel lining, the next phases, Phases 4 and 5, respectively, consider the long-term and short-term properties of the soils (Fine, 1998). The last stage concerns the installed lining's long-term qualities (Panet, 1979).

2.5 Understanding Settlement Prediction and Technique Method

The initial focus was predicting settlement, moving from an empirical approach to using 2D or 3D numerical simulation tools. At the same time, the problem of the impact of these movements on existing buildings has been the subject of developments aimed at proposing a clear relationship between the amplitude of the settlements and the damage they cause, taking into account the behaviour of the structure. Finally, the control of these movements also involves the use of soil treatment and reinforcement techniques, the effectiveness of which we are trying to predict

The many observations made over the last few decades have confirmed that, in the absence of structures or specific geotechnical conditions, the ground surface settlement can be described, as proposed by Peck (1969), by a Gaussian curve with the equation:

$$S = S_{max} \exp\left(-\frac{x^2}{2i}\right) \quad (9)$$

In this approach, the trough's volume is linked to the volume loss caused by tunnel excavation. Its width, represented by parameter i (distance from the centre to the inflection point of the trough), is determined by empirical rules and abacuses suggested by different authors (Figure 3). The Figure 4 show the settlement curves representing the calculated displacements and the Peck curves adjusted to the measurements auscultated in the field after the passage of the tunnel front, compared to the measured displacements, the calculated displacements are slightly underestimated.

$$V_s = \sqrt{2\pi}.i.S_{max} \quad (10)$$

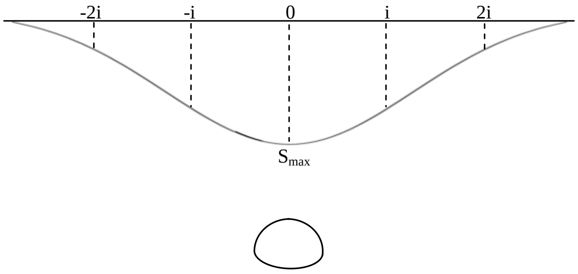

Figure 3 - Peck's curve of settlements ground surface.

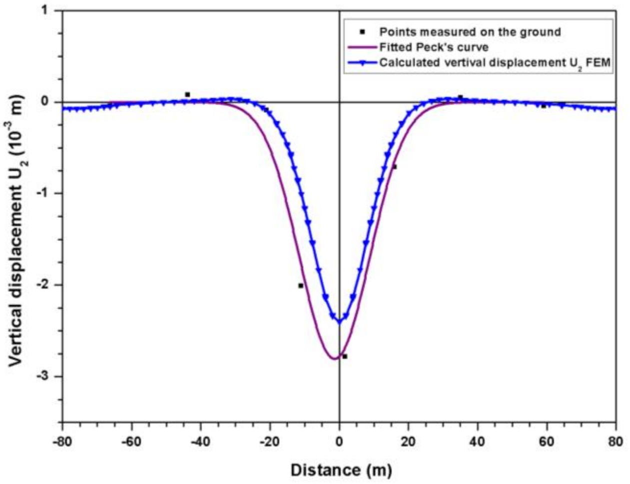

Figure 4 - Calculated and measured responses of ground surface settlements.

3. Results and discussions

3.2 Parametric Study

From the information given, parametric research was carried out on a reference model of six nodes to examine the impact of several geotechnical factors (φ, E, ν), groundwater flow, and depth on settlements. Due to the high amount of marl cohesion, it was discovered that the cohesion parameter c had no discernible effect on settlements. However, other parameters, like flow, groundwater depth, Poisson's ratio (ν), angle of internal friction (φ) and Young's modulus (E), showed significant effects on surface settlements and vertical displacement above the tunnel crown. The findings indicate that the Quaternary layer was raised during tunnel construction, with a vertical displacement along the tunnel axis ranging from 20 to 50 meters.

Influence of water table level: In metro projects, monitoring groundwater levels before, during and after construction operations is very important. The characteristics of massive hydraulic permeability of the soil must also be known for a better analysis of groundwater-related problems during and after construction work. Consolidation is a type of water-soil interaction in which the slow release of pore pressure causes additional displacements in the soil. This behaviour involves two mechanical effects. Firstly, changes in pore pressure lead to changes in effective stress, which affects the response of the solid. A reduction in effective stress can induce plastic deformation. Secondly, water in a zone responds to changes in volume by modifying its pore volume, mechanical by a change in pore pressure.

Figures 5 (a) and (b) shows the influence on displacements both in the vertical mass of the tunnel key and on surface settlements. We vary the water table level, considering a drawdown and a 5m rise in the water table level compared with the initial case considered for the reference profile. In that case, we observe an appreciable soil uplift between 20 m and 50 m abscissas. The drawdown of the water table induced by tunnel construction or pumping operations causes excessive surface settlements, which can damage surface structures such as roads and buildings. Figures 6 (a) and (b) illustrate the effect of flow on surface settlement. A significant increase in vertical displacements can be observed at the crown of the tunnel exceeding 150%, and a change in the shape of the settlement curve.

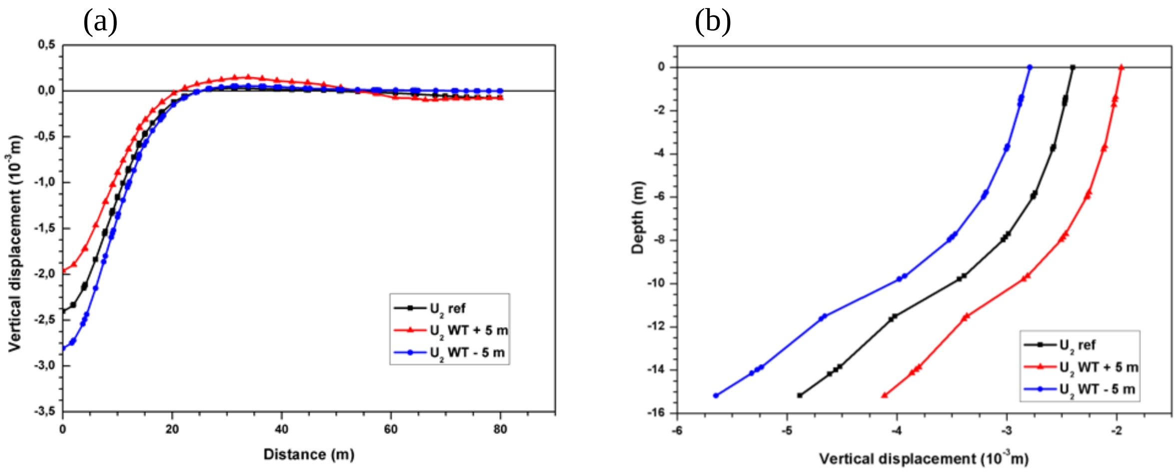

Figure 5 - (a) Influence of the water table level on surface settlements, (b) influence of the water table level on the vertical displacements at the plumb of the centerline of tunnel.

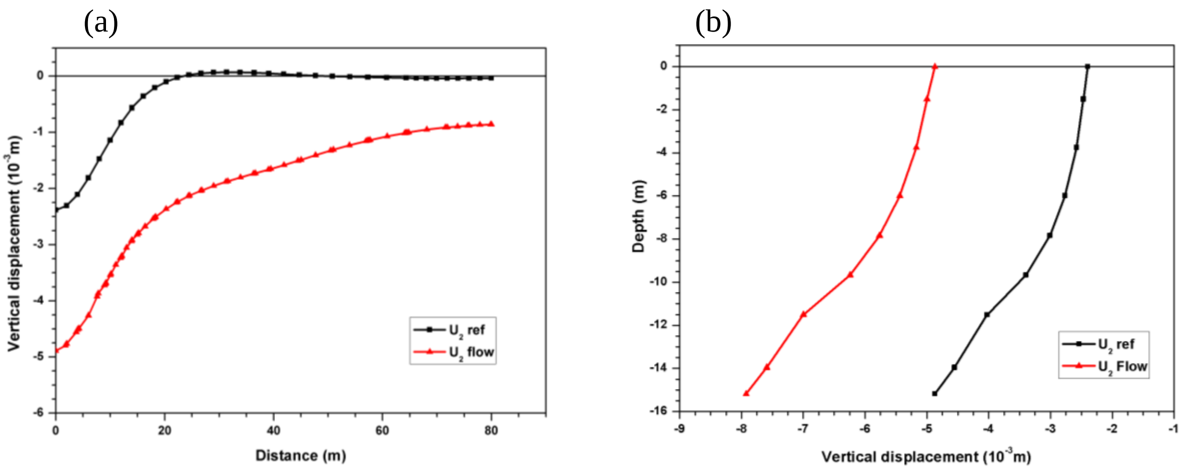

Figure 6 - (a) Influence of the flow on the surface settlements, (b) Influence of the flow on the vertical displacements at the plumb of the centerline of tunnel.

<u>Influence of Poisson ratio</u>: The reference model used in this parametric study is the model dealt with in Section 2, with the geotechnical characteristics of the different components of the soil mass, the hydraulic parameters varied which shows the variation of the settlements at the surface and vertically from the centre of the tunnel as a function of the horizontal distance for the poison coefficient ν (figure 7 a and b). The curves obtained from the numerical calculations are similar in all cases, but the difference lies in the values of the maximum settlement Smax of the settlement surfece ground, which is wider for the value of (ν). The curves obtained from the numerical calculations show that the evolution of the settlement basin is similar for all cases, but the difference lies in the values of the maximum settlement Smax of the settlement basin, which is slightly wider for the value (ν+0.1). There was an uplift between abscissas 20 and 40 m for the case (ν - 0.1). The angle of friction is a determinant of soil resistance.

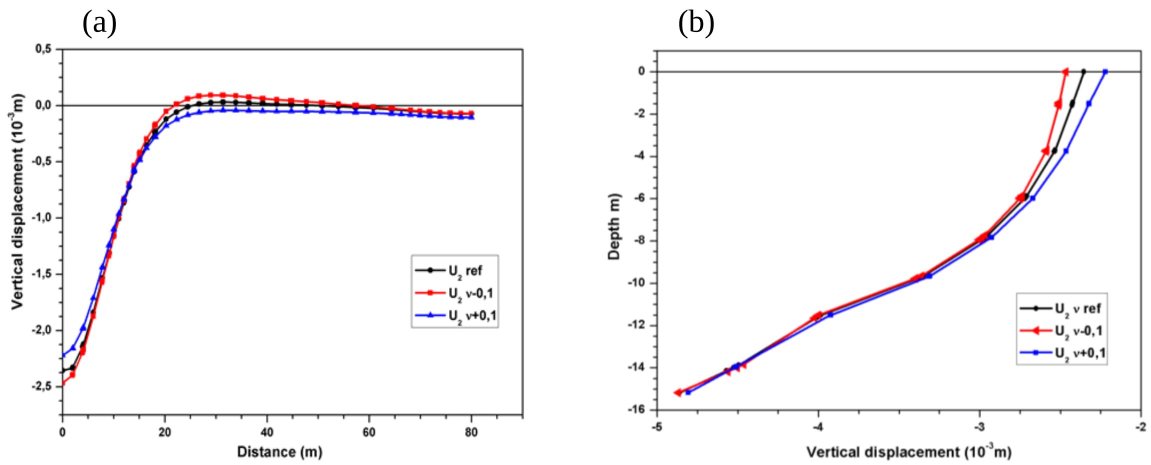

Figure 7 - (a) Influence of Poisson ratio on surface settlements (b) influence of the poison coefficient on the vertical displacements at the plumb of the centerline of tunnel.

Effect of the angle of soil friction: The Figure 8 (a) shows a comparison of the surface displacement values calculated for each case. The shape of the surface settlements is the same, with a slight shift in the maximum value and a slight increase of a few tenths of a millimeter with an increase in the angle of friction, this is observed for the first 10 meters, which are fields close to the axis of the tunnel. However, for the case (φ - 5°), although the curves merge for the remaining values and the settlement values are the same, a slight increase is observed between the abscissas of 25 m and 40 m. The vertical displacements calculated perpendicular to the tunnel axis for different values of φ are shown in Figure 8 (b). The curves are parallel and the difference between the displacements is maintained over the whole depth for the different values of φ. It is clear that a variation in the friction angle of 5° causes identical subsequent displacements over the whole depth, since tgφ is related to the stress σ in the Mohr-Coulomb law. The modulus E is related to the elastic part of the displacement.

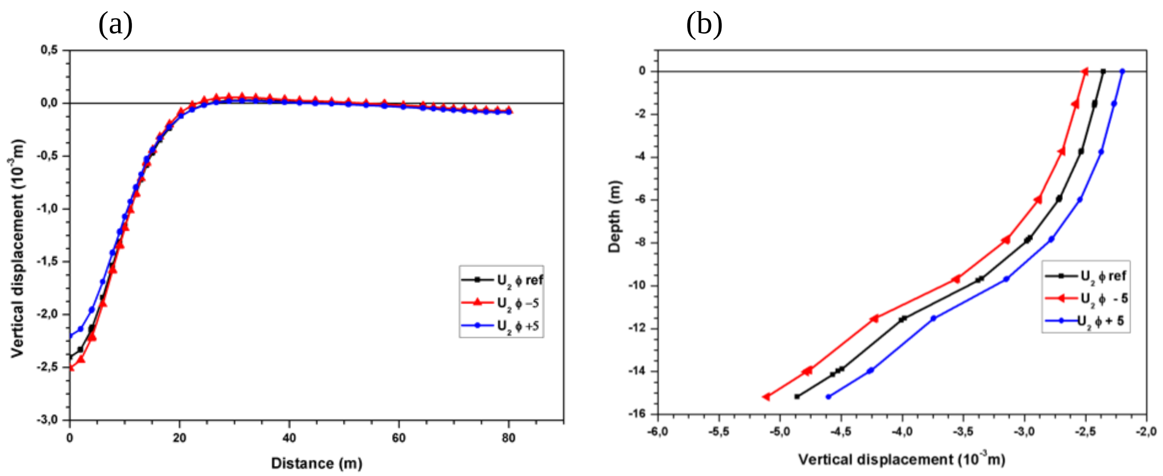

Figure 8 - (a) Influence of friction angle on surface settlements (b) influence of the friction angle on the vertical displacements at the plumb of the centerline of tunnel.

Effect of the Young's modulus: The data analysis presented in Figures 9 (a) and (b) highlights a significant correlation between Young's modulus E and settlement at the tunnel axis. When Young's modulus decreases, there is a notable increase in settlement. This observation underscores the importance of material strength in maintaining the stability of underground structures.

Specifically, a decrease in Young's modulus leads to more significant deformation of the soil around the tunnel axis. This increased deformation can be attributed to the material's reduced ability to resist applied forces, resulting in greater flexibility and susceptibility to settlement.

However, it is worth noting that despite this increase in settlement, the uplift at the ground surface remains relatively insignificant compared to other parameters studied. This finding suggests that while settlement may be more pronounced near the tunnel axis with a decrease in Young's modulus, the effects on the surface are limited. This can be attributed to various factors such as tunnel depth, geological characteristics of the soil, and stress distribution within the surrounding structure.

Ultimately, this analysis highlights the importance of considering the Young's modulus in the design and construction of tunnels, mainly to ensure the long-term stability of underground infrastructure.

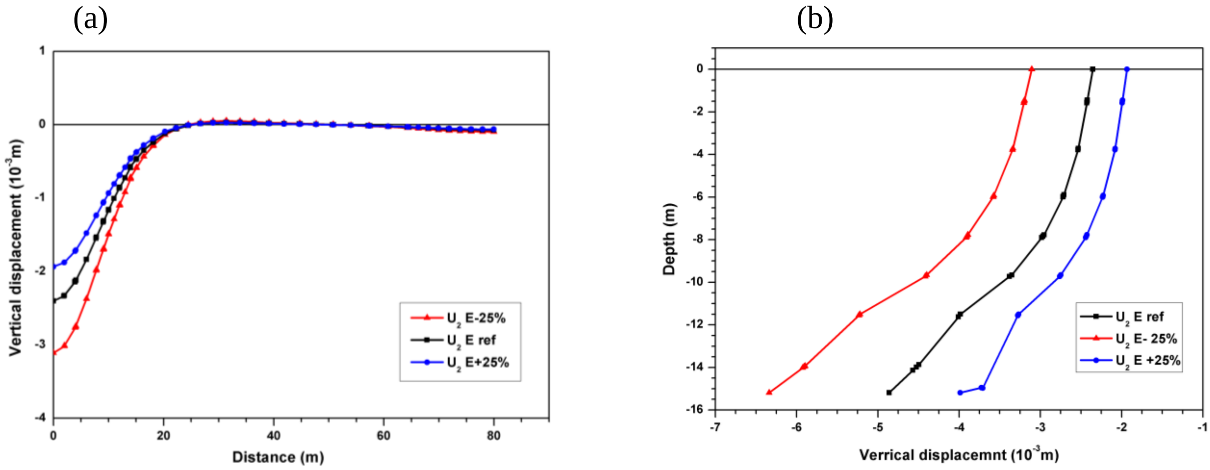

Figure 9 - (a) Influence of Young modulus E on surface settlements (b) Influence of the Young modulus on the vertical displacements at the plumb of the centerline of tunnel.

4. Conclusions

Although imperfect, the model computation for an actual project is described in the paper as a viable approach. The main objective of the research is to assess how different geotechnical characteristics affect surface settlements. It was discovered that Young's modulus, water table level, and flow greatly influenced the settlements. Furthermore, the article proposes that additional factors, including interface characteristics, liner stiffness, and parameter combinations, might be adjusted to evaluate their impact. In this work, the authors stress the need to utilize sophisticated constitutive models. These models can offer more realistic depictions of the material's behavior and aid in improving knowledge of the substance's reaction. The paper's parametric research is highly significant as it offsets the constraints and uncertainties related to in-situ geotechnical investigation. It should be emphasized that the study does not discuss how tunneling affects the superstructure. The authors advise utilizing a three-dimensional model to investigate the effects of the working face's advancement to improve the analysis further. This would shed light on how tunneling operations impact buildings above ground. Overall, the work uses a parametric study to offer a realistic method and emphasizes the significance of considering various geotechnical characteristics and sophisticated constitutive models to comprehend the behavior of the studied system. The authors also recommend future paths for developing the study to incorporate, via the use of three-dimensional models, the effect of tunneling on the superstructure.

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