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Effects of different processes of tunneling on displacements soil using 3D Finite Element Method

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Abstract

The excavation process of tunnels induces stresses and deformation in the surrounding soil. The method of excavation is one of the major problems related to the safety of the operators and the ground stability during the construction of underground works. So, it is necessary to choose an ideal method to minimize the displacements and stresses induced by tunneling.

The main aim of this study is to simulate numerically the effect of different processes of tunneling on ground displacements, the settlements at surface soil and the internal efforts induced in the lining tunnel; in order to select the best process of excavation, which gives us a less effects on displacements generated by tunneling, thus, ensuring the stability and the solidity of the underground constructions. In addition, this study allows us to control and to predict the diverse movements generated by tunneling (displacements, settlements, efforts internes) exclusively for the shallow tunnel nearby to the underground constructions in the urban site. This modeling will be done by employing five different processes for tunnel excavation using the NATM (New Austrian Tunneling Method) method.

The first process, the modeling of the excavation tunnel, is done almost in the same way as in reality; the partial face excavation, with seven slices, made by the excavation. The second process, by partial face excavation, is divided into eleven slices, next, we used the partial face excavation by nine slices, and then in thirteen slices. Finally, the dig is made by full-face excavation.

The paper contributes to the prediction of the response of the soil environment to tunnel excavation using the NATM method and to minimize the diverse movements generated by tunneling. The appropriately chosen methodology confirms that displacements and subsidence are strongly influenced by the tunneling method. The three-dimensional Finite Elements Method using Plaxis3D program has been applied in the numerical simulation. The study resulted in the recommendation of a process that minimizes the effect of excavation on subsidence and ground displacement for a particular Setiha tunnel.

Key words: tunnel, excavation, process, finite element analyses, Plaxis3D

1 Introduction

The nature of the excavation work being undertaken will affect the selection of an excavation method and safe system for this work. Deep excavations are usually employed in urban development projects and the works are carried to construct underground infrastructures such as deep basements, subways, and service tunnels. The execution of underground structures has always been of major risk concern, as intense ground movements and displacements of the settlement at surface soil are induced during the excavation process [1, 2, 3, 4, 5]. Also, they cause severe damage to the neighboring structures. The performance of excavation is affected by various factors, including the local ground conditions, the structural support systems, the construction processes, and the technique of excavation. The finite element analysis is generally used to model deep excavation construction processes. In urban areas, there are many situations where the tunnels facilities are proposed to be constructed adjacent to an old building. There are many types of execution techniques and methods developed for the construction of tunnels, and there are different processes of the excavation tunnel, where the researchers and engineers have given significant attention to the responses of soils due to the tunnel excavation method. Inadequate tunnel method construction or inadequate scenario can cause damage to the adjacent structure, more or less significant, depending on the process of drilling adopted. The tunneling operations lead to changes in the stresses, movements, and displacements of the surrounding soil. The study of the crossing tunnel under the mount of Setiha (tunnel zone) (Figure 1) appears in the setting of the modernization of the National Road n° 43. For the realization of this study, where the geotechnical stability and the soil/structure interaction dress a fundamental role, we chose the PLAXIS 3D software.

2 Tunnel project characteristics

The location of the object of the study is located in the region of Mount Atlas, in the middle of the summits of Koudiet Es Sous and Koudiet Bous En Nar (Figure 1). It is situated at about 20 km in the Southwest of Skikda city and at about 50 km to the Northeast of Constantine town. The total length of the tunnel at about 935 meters, it constitutes a single gallery, which will fit two ways.



Figure 1: Trace of the tunnel retrieved from Google Earth

3 Tunnel model calculation

The transversal section type (Figure 2) expected will guarantee the insertion of a road platform with a total width of about 7.60 m and will assure a 5.0 m height along this width. In the central zone, an additional area above this height permits the installation of the ventilation system inside the tunnel.

The top of the tunnel is 24.50 m below the surface of the soil. The tunnel has a height of 7.5 m and a width of 10.20 m; the tunnel lining with a thickness lining of 25 cm consists of a cement B 25 layer, which includes the steel reticulate HEB160 /0.75.

Figure 3 presents the geometry of elements following with the calculation model representative in the road kilometer point [KP 0+400], using the PLAXIS3D program. This model aims to value the geotechnical and structural tunnel behavior in the zone where the cover is reducing and where the tunnel crown crosses a clayey layer that seems to correspond to a faille (fragment of rocks).

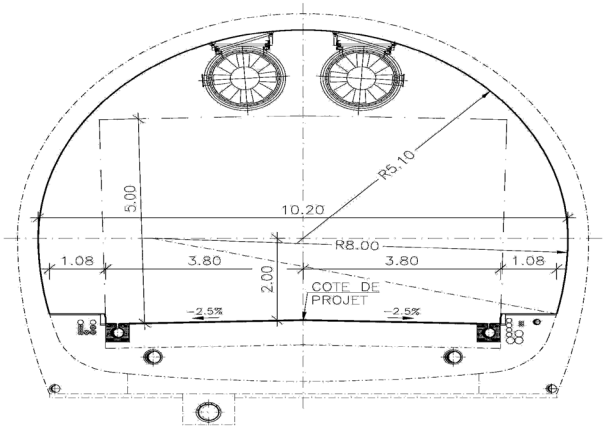


Figure 2: Transverse section type of tunnel

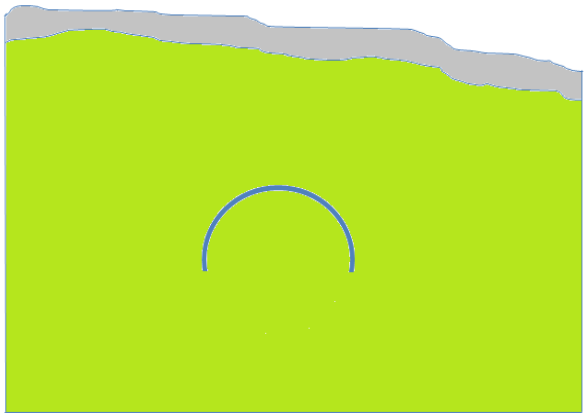


Figure 3: Geometry of model at KP 0+400

3.1 Soil horizons

Concerning the soil horizons (rubble, clay) these were simulated using the constituent model of Mohr-Coulomb. The parameters associated with these horizons were defined carefully with regards to the results of SPR tests (Standard Penetration Test) or the nature of the horizons. Besides, the clayey layer associated with a possible faille (fragment) close to the portal is also simulated with this constituent model. The parameters are given in Table 1.

Table 1: Mechanical and geotechnical characteristics of soils in the PLAXIS3D program for the Mohr-Coulomb Model.

Soil	Unit weight (kN/m^3)	Friction angle Φ	Cohesion (MPa)	Elastic modulus (MPa)	Poisson ratio ν
rubble	18	35	10	50	0,3
Faille (clay)	22	35	30	50	0,3

The tunnel is constructed in a homogeneous soil, with a linear elastic model for the tunnel

lining. The Mohr Coulomb model is adopted for simulating the plastic behavior of soil under static conditions.

NOTE: No hydrostatic pressure has been considered because we planned the installation of the drainage devices during the excavation. Therefore, the phreatic level does not have any influence on tunnel behavior.

3.2 Properties of the tunnel lining

Table 2 presents the properties of tunnel lining "Plate" considered for the calculation of the excavation phase, simulating the lining support (incorporating or not of the metallic hangers) through a linear elastic behavior.

Table 2: Tunnel lining parameters as inputted in the PLAXIS3D program

	Description	EA (x10^3) kN/m	EI kN/m^2	ν
Lining tunnel	Shotcrete 25 cm+ Steel	6520	35380	0.15

4 Numerical simulation of the tunnel (ATM Method)

All calculations are founded on the choice of the triangular elements to a 15-node triangle. An elastic-plastic law governs the behavior of soil and the tunnel where the criteria of Mohr-Coulomb has been adopted. For the tunnel, an elastic linear behavior has been adopted. The boundary conditions are taken into account while blocking the horizontal displacement and the two displacements - horizontal and vertical - for the lower limit of the model. The mesh is refined to the region of the tunnel. The Setiha tunnel will be constructed according to the ATM method. All works will be performed in the same technique as the installation of the components of the support system. The excavation is made in stages for the Crown, Bench, and Invert [6].
In this analysis, the cross-section of the tunnel type is selected (NAT Method) (Figure 4). The top of the tunnel is 24, and 50 m below the surface of the soil. The surrounding ground tunnel constitutes two different layers. The modeled domain was 80 m in length, 40 m in width, and 50 m in depth.

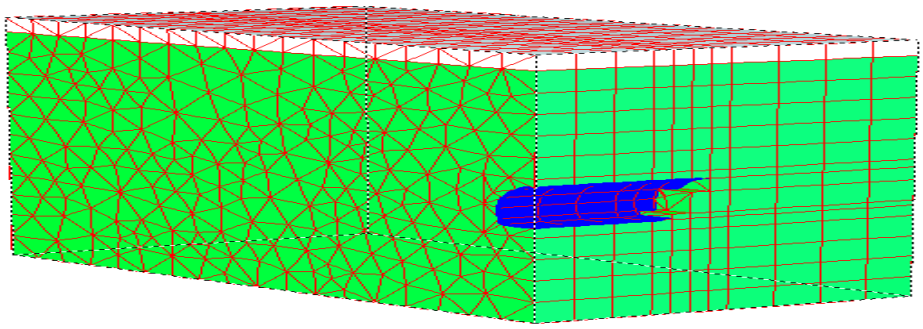


Figure 4: 3D Finite element mesh of NATM Tunnel project (symmetrical model)

5 Numerical simulation procedure of the tunnel

The effect of different processes of tunneling on movements of the soil is assessed in terms of the global displacements and the internal forces that build up in the lining during tunnel excavation. The three-dimensional Finite Element Method using the Plaxis3D program has been applied in the numerical simulation. The soil is described through Mohr-Coulomb behavior. i:

- The partial face excavation
- The full-face excavation

Five processes are tested: Each process includes several slices. Every slice is 2m (excavation step).

5.1 Partial face excavation (Processes n°: 1, 2, 3, 4)

The modeling of the calculation phases is done almost in the same manner as in reality, the excavation is made by partial face excavation, and it is performed according to the first, second, third, and fourth process, as shown in the following Figures (5, 6, 7, and 8).

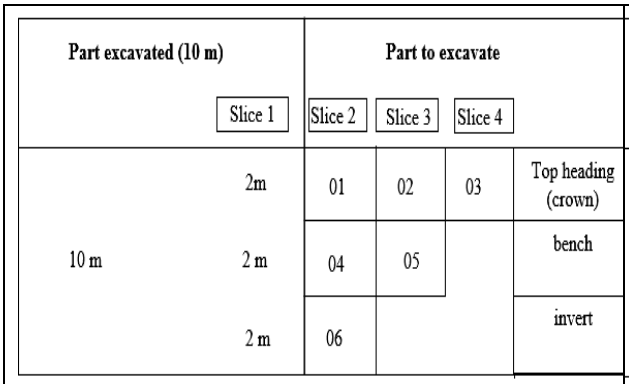


Fig.5 Excavation phases from the First process

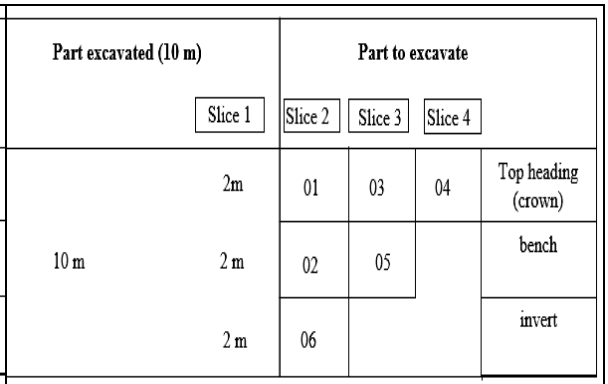


Fig.6 Excavation phases from the Second process

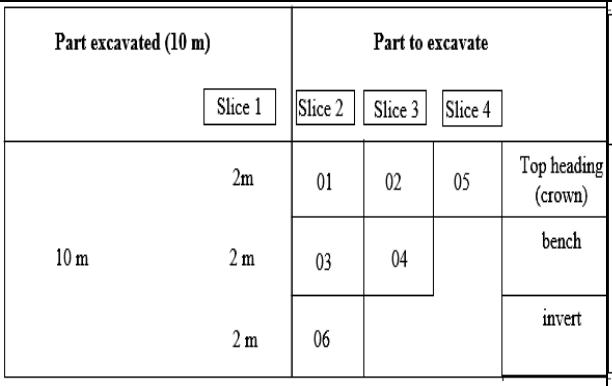


Fig.7 Excavation phases from the Third process

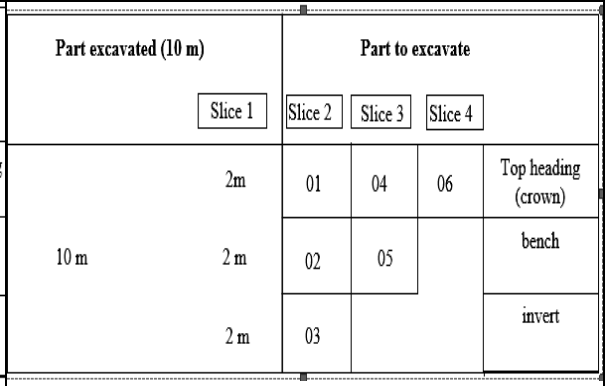


Fig.8 Excavation phases from the Fourth process

5.2 Full section excavation (Fifth process)

The modeling of the calculation phases is made through full-face excavation, by total section, and it is performed according to the fifth process, as shown in Figure 9.

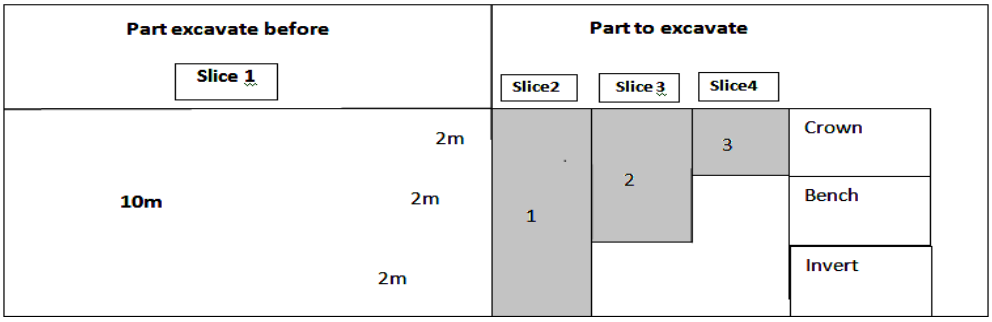


Figure 9: Excavation phases from the Fifth process

6 Results and discussion

The study reveals a significant effect of the order of the tunnel cutting sections on the subsidence on the free soil surface, accepting five different processes.
The aim is to simulate numerically the effects of different processes of tunneling on movements/displacements, and settlement of surface soil, also the convergence and the internal efforts induced in the tunnel lining. The excavation is made through slices for the calotte, stross (crown), and invert, the step of advancement is equal to 2 m. It has been modeled in two phases for each component (excavation - shotcrete).

6.1 Prediction of the vertical displacement of the soil /settlement

Loganathan et al. [7, 8] studied the analytical predictions of tunneling-induced ground movements. The vertical and the horizontal displacements, and the settlement induced by the tunnel excavation following the five distinguished processes are displayed in Figure 10.

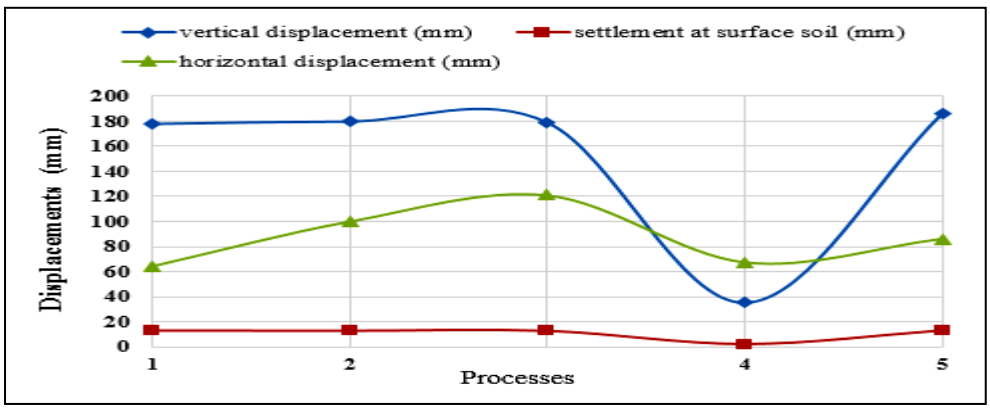


Figure 10: Displacements following the different processes

Figure 10 presents the settlement profiles at the free soil surface, also the vertical and horizontal displacements of soil, due to the excavation of the tunnel, using different processes of tunneling. It is registered that the excavation of the tunnel by the partial face section according to the fourth process gives lower results in terms of displacements (vertical /horizontal) and the settlement at surface soil. The first process offers a minimum value for the horizontal displacement compared to the vertical displacement.
According to these profiles, we can conclude that displacements and subsidence are strongly influenced by the tunneling excavation method (process).
The comparison of the results shows that the process n°4 minimizes the effect of excavation on settlement and ground displacement.

6.2 Effects of different processes on the vertical displacement of the frontal section

In this part, the vertical displacements (subsidence) of the first plan (frontal section of tunnel excavation) are analyzed for different processes of excavation.

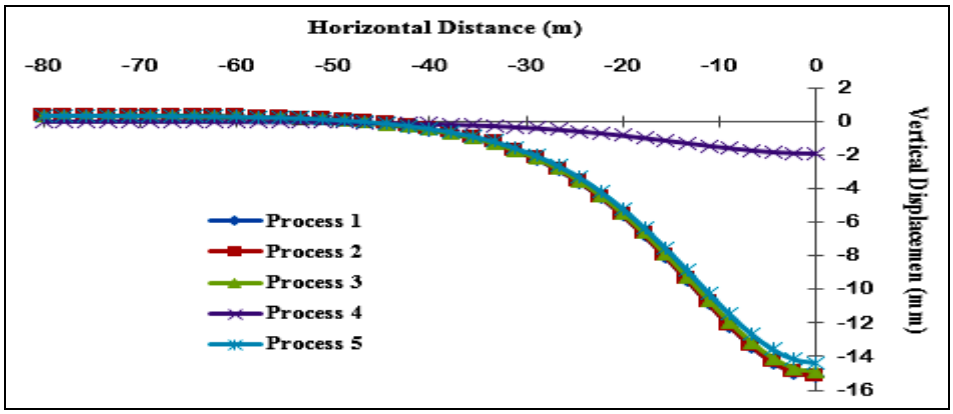


Figure 11: Vertical displacement following the different processes in the tunnel's front section

Figure 11 presents the vertical displacements at the front section of the tunnel corresponding to each excavation process without considering the displacements of the previous phases. Figure 11 shows that each method of excavation (process) generates a vertical displacement relative to the horizontal distance from the starting profile. The settlements engendered in this profile by the fourth process are lower compared to the other processes, therefore this process is selected (n°4), leading to the reduction of the settlement in the front section.

6.3 Effect of the elevation of different parts of the tunnel on the ground movement and settlement

Thayanan [9] and Dong et al. [10] investigated the effects of the construction sequence and the cover depth on the crossing-tunnel interaction. The tunnel is excavated in different parts (for example, crown, bench, and invert), where successive parts are executed at a certain distance after the previous part. After the excavation of the separated parts, the tunnel contour is secured by the temporary lining of the tunnel. The effect of elevation of each part of the tunnel's excavation on the settlement of the surface soil and the ground displacements is investigated and the influence of each excavated part (crown, bench, and invert) on the

response of the soil is observed. The stability of the soil was investigated in four variants. The full tunnel height was 7.5m. (1) The first variant: The elevation of each part to be excavated (crown, bench, and invert) is equal to *H*/3 (2.5m, 2.5m, 2.5m) respectively, as shown in Figure 12.

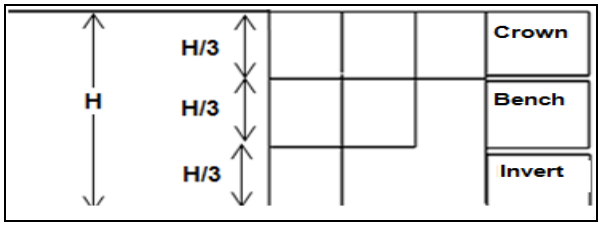


Figure 12: The first variant of the tunnel excavation

(2) Second variant: The elevation of each tunnel part (crown, bench, and invert) is equal to *H*/4, *H*/4, and *H*/2 respectively, as shown in Figure 13.

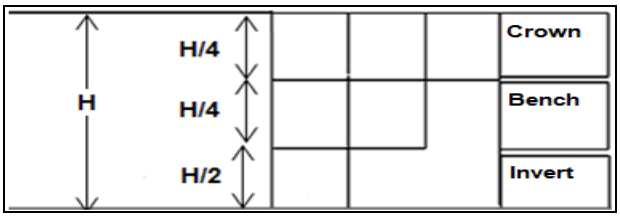


Figure 13: The second variant of the tunnel excavation

(3) The third variant: The elevation of each tunnel part (crown, bench, and invert) is equal to *H*/2, *H*/4, and *H*/4 respectively, as shown in Figure 14.

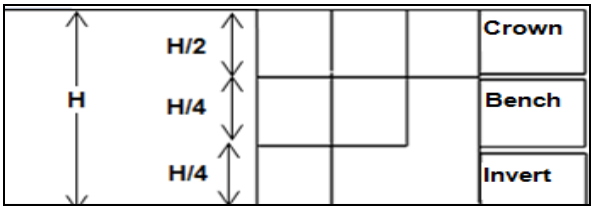


Figure 14: The third variant of the tunnel excavation

(4) The fourth variant: The elevation of each tunnel part (crown, bench, and invert) is equal to *H*/4, *H*/2, and *H*/4 respectively, as shown in Figure 15.

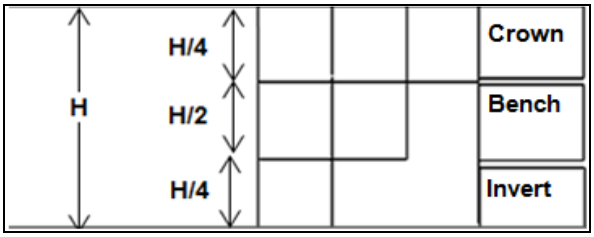


Figure 15: The fourth variant of the tunnel excavation

The effects of the elevation of the different parts (crown, bench, and invert) of the tunnel to be excavated on subsidence and ground displacement, according to different variants are displayed in Figure 16.

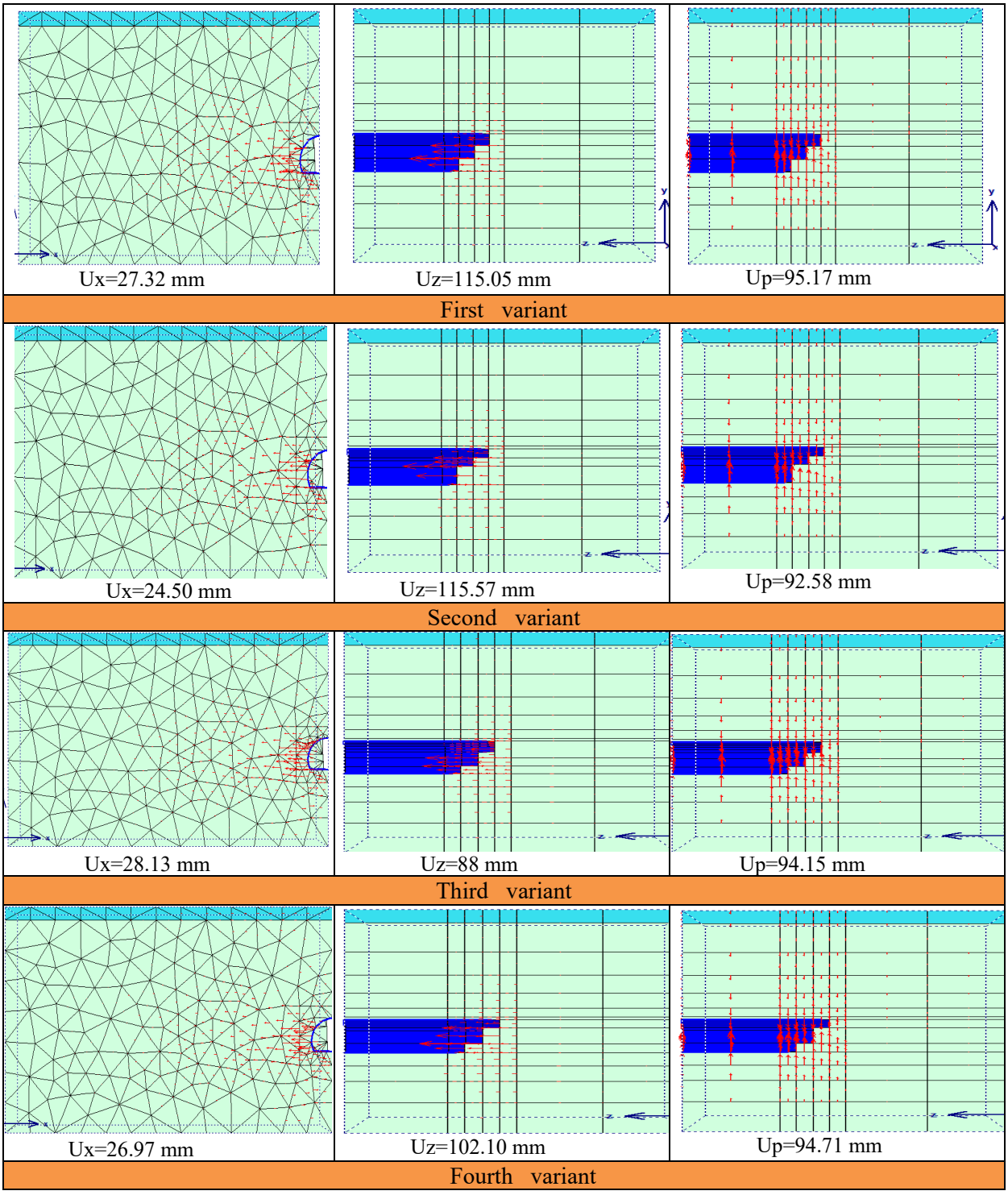


Figure 16: Results obtained for different variants

Figure 17 shows the settlement profiles relative to the horizontal distance for each variant.

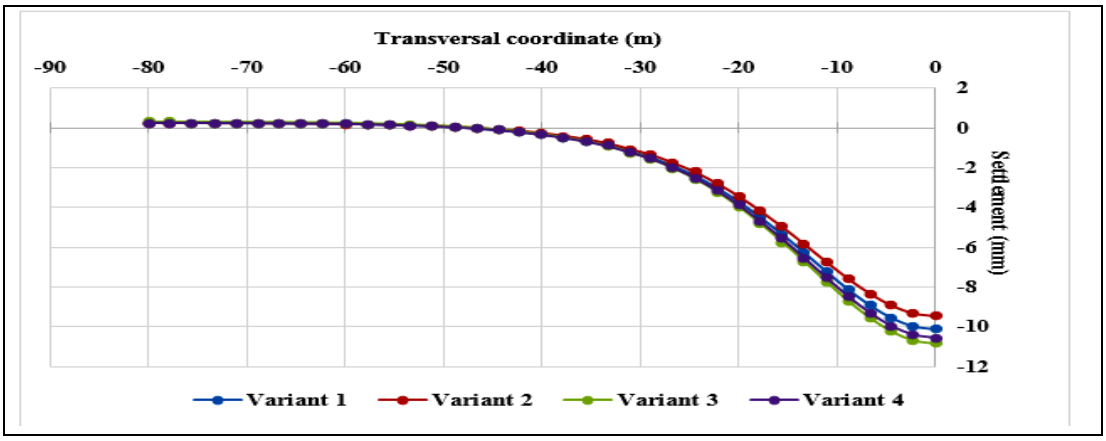


Figure 17: Settlements values at soil surface following the different variants

The results show that the maximum value of the settlement appears on the level of the vertical axis of the tunnel for each variant and then decreases to zero.
It can be seen from Figure 17 that the numerically calculated settlement values at the soil surface in the transverse section for diverse variants (considering only the vertical displacement of the last phase) are almost similar; where the maximum values are between 9.5 mm and 10.8 mm but slightly decreasing for the second variant (-9.5 mm).
So, the excavation by adopting the second variant gives lower results compared to other variants.

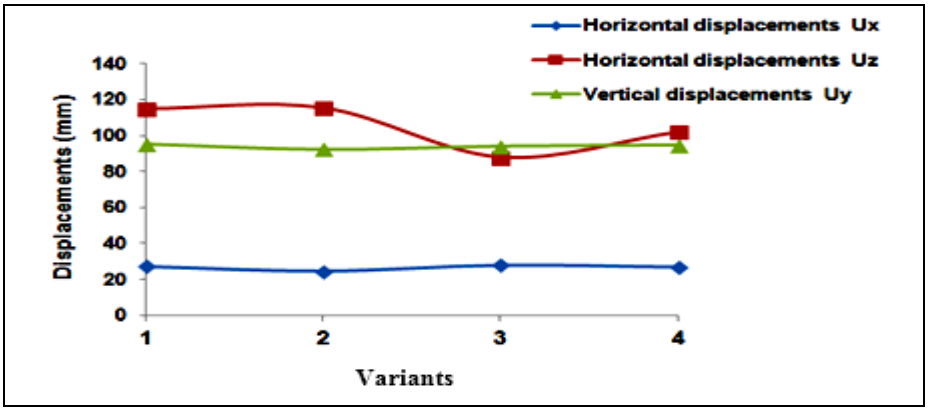


Figure 18: Soil displacement values according to different variants

Figure 18 presents the displacements (horizontal U_x, horizontal U_z, and vertical U_p) relative to each variant. The results illustrate that the minimum horizontal displacement U_x, and the vertical displacements U_p emerge for the second variant. On the other hand, it can be noticed that the minimum horizontal displacement U_z (in the longitudinal direction) appears for the third variant.
Hence, the movements of the soil occur due to the change of the soil rigidity because of the

weakening of the excavation surroundings. This is an important factor in the movement of the ground.
Therefore, for the lower effect on the settlement and displacement of the soil, we propose, in this case, excavating the tunnel in accordance with the second variant. This case is explained per the quantities of excavation soil. The excavation of the tunnel shall be done in little quantities so to the soil is not destabilized (crown = *H*/4; bench = *H*/4, then invert *H*/2).

6.4 Effect of the order of parts of tunnel excavation on the settlement and movements of the soil

To analyze the effect of the order of the excavation of tunnel parts (typical construction stage procedure) on the settlement of the surface soil, we use several configurations of excavation.
The tunnel is simulated numerically using the section-divided method. In this case, it is required to use a three-dimensional model (3D).
Eight (8) configurations of the construction sequence are tested and shown in Figure 19.

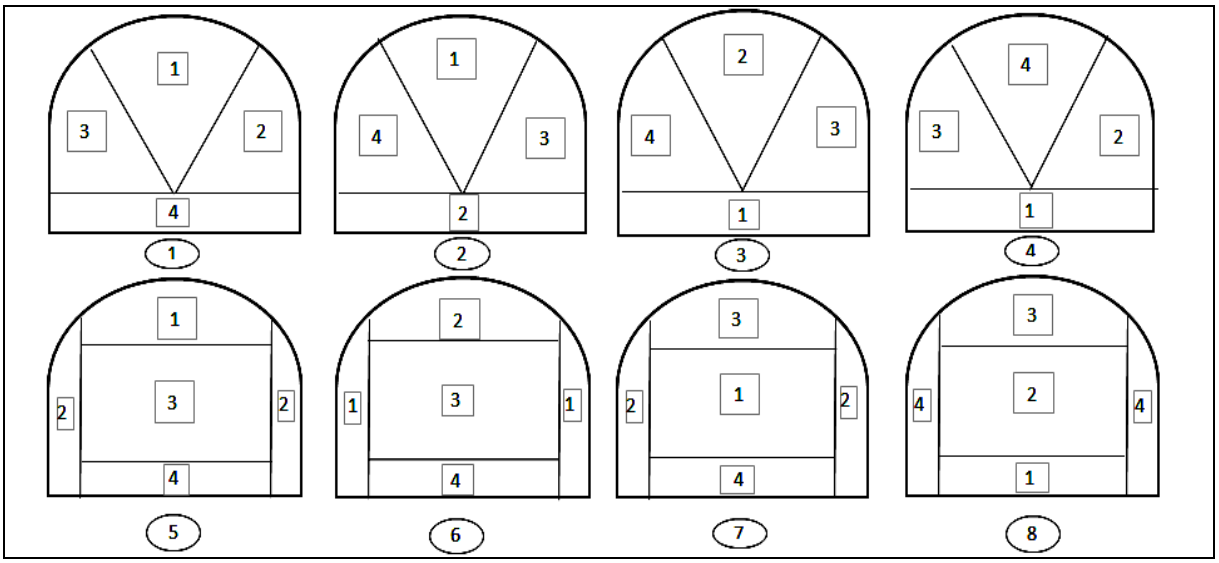
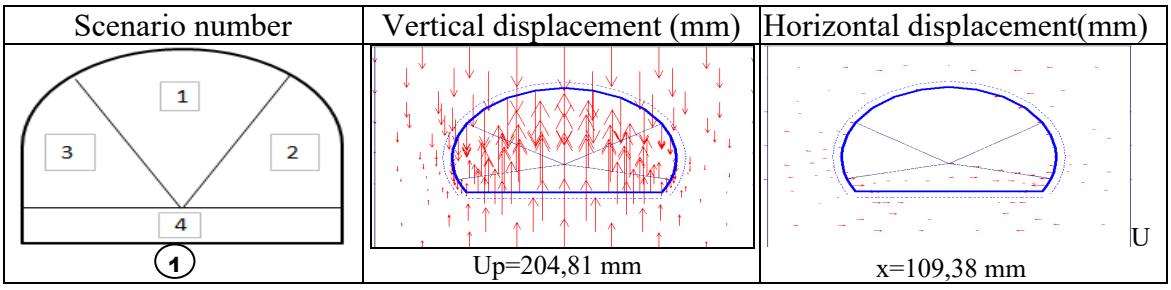
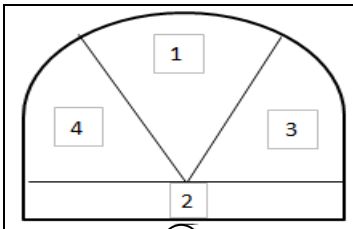
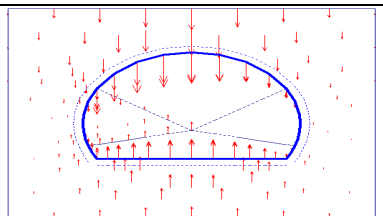
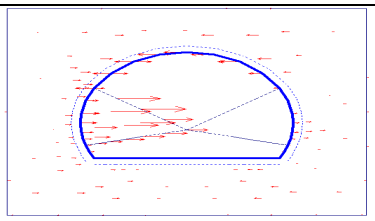
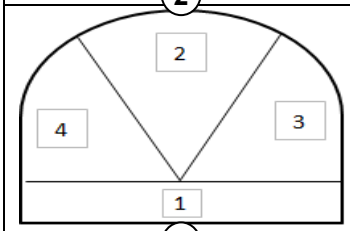
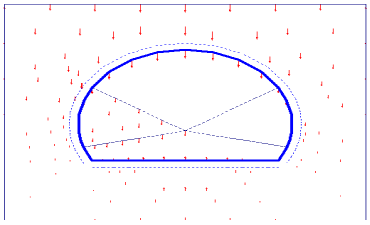
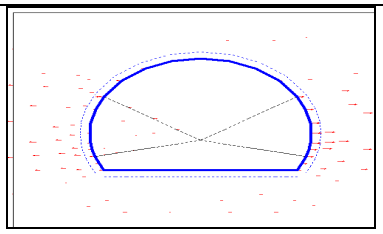
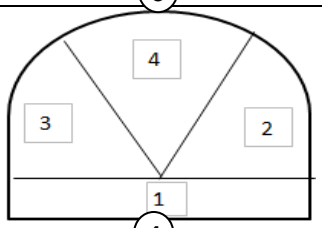
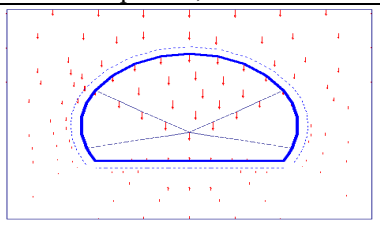
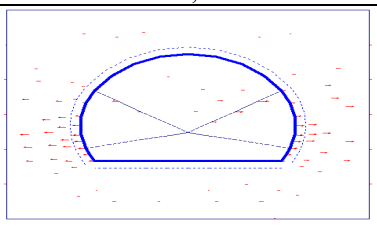
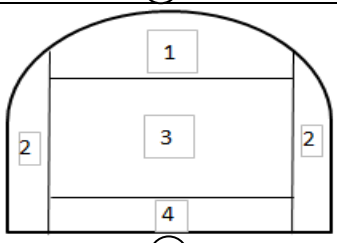
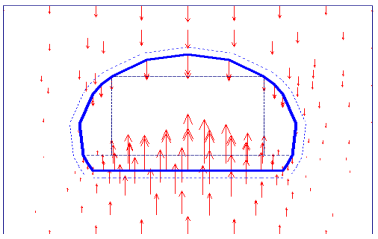
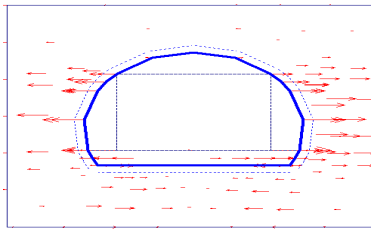
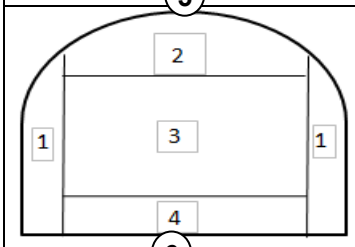
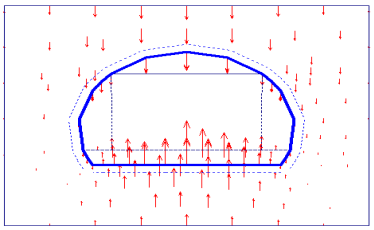
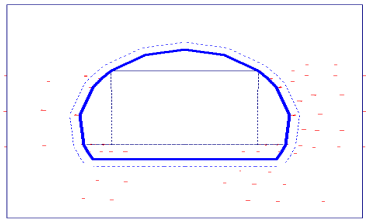
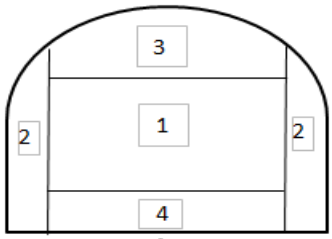
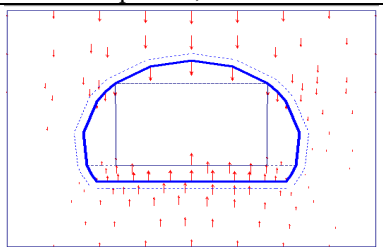
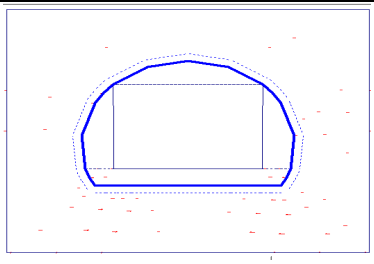


Figure 19: Eight configurations in the cross-section view (typical construction stage procedure)

The results obtained through this numerical study for the eight configurations of the construction sequence are summarized in Figure 20.



 2	 Up=265,83 mm	 Ux=119,28 mm
 3	 Up= 275,35 mm	 Ux= 69,05 mm
 4	 Up= 276,42 mm	 Ux= 67,32mm
 5	 Up= 111,34 mm	 Ux= 42,42mm
 6	 Up= 130,01 mm	 Ux= 162,96 mm
 7	 Up= 276,84 mm	 Ux= 182,75 mm

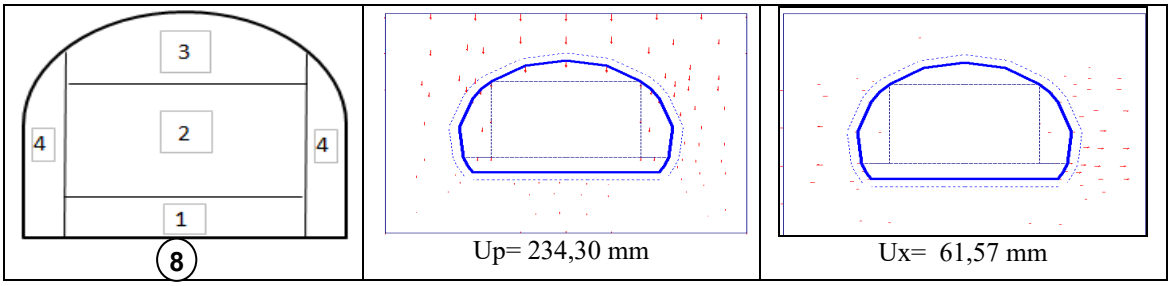


Figure 20: Results of the analysis for different construction sequences

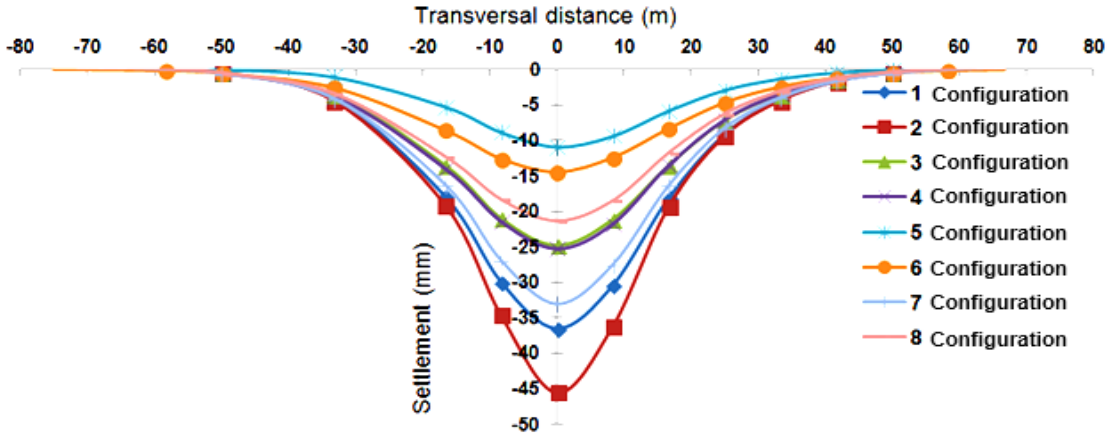


Figure 21: The settlement of the soil surface relative to the horizontal distance for different configurations

Figure 21 shows the distribution of settlement at the soil surface relative to the horizontal distance for different configurations of the construction sequence.

As illustrated in this Figure, the minimum settlement value mainly occurs at the fifth configuration. Maximum settlements occur at the second configuration. Due to the destabilization of the soil at the zone of influence differentiated by the lines that project 45° from the tunnel spring line (tunnel crown), the stability of the surroundings will be weakened. This is an important factor in the settlement of the soil surface.

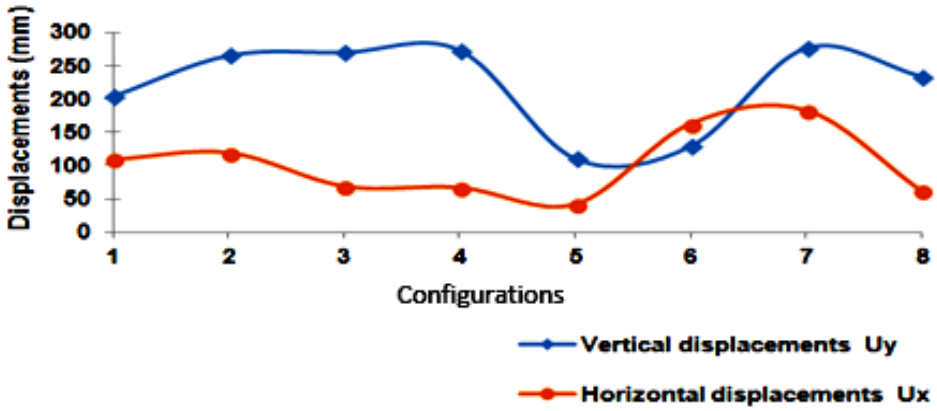


Figure 22: Soil displacement values according to the different configurations of the construction sequences

Figure 22 presents the values of different displacements (horizontal U_x, and vertical U_p) relative to the construction sequence.
Analysis results demonstrate that the minimum horizontal displacements and the vertical displacements appear at the fifth construction sequence.
The same goes for the settlement, where the minimum value appears at the fifth construction sequence.
Regarding different configurations of the construction sequences, we propose to excavate our tunnel in accordance with the fifth construction sequence and to minimize the effects (fewer impact) of tunneling on displacements and subsidence.

7 Conclusion

In this research, numerical modeling of the effect of different tunneling processes on movements and displacements of soil was presented, based on the three-dimensional Finite Element Method using the Plaxis3D program.
The modelling of the effects of the different tunneling processes was performed using the NRTM method on ground displacements and settlements of the soil surface. The modeling has been applied to a specific tunnel in Setiha to propose how to minimize the diverse movements generated by tunneling.
The following conclusions can be drawn from this numerical study:
- The procedures of construction affect the settlement, displacement, and internal efforts in the tunnel lining.
- The displacements and settlements engendered by tunneling using the partial-face excavation method are less important than the displacements and settlements obtained using the full-face excavation method. The difference between the results obtained using the two methods is mainly due to an augmentation of the number of open segments in the tunnel front. Therefore, the drilling using the partial-face excavation minimizes the effect on subsidence and ground displacement, thus we sufficiently ensure the stability of the tunnel front.
- This study reveals a significant effect of the order of the tunnel cutting sections on the subsidence of the free soil surface, accepting five different processes.
- Regarding the process of the excavation, there are five processes tested, four (4) with partial-face excavation, and one (1) with full-face excavation. The effect of the process of the excavation on the settlement and displacements shows that the fourth process is the best, with minimum values regarding the displacements and settlement predicting more stability of the ground.
- Regarding the effect of elevation of different parts of the tunnel (crown, bench, and invert) on the movement and settlement, there are four variants established. The effect of elevation of different parts of the tunnel shows that the second variant is the best (has less impact).
- Regarding the effect of the order of the tunnel excavation parts on the settlement and the movement of the soil illustrates that the fifth configuration of the construction sequence is the best of the eight configurations tested (less effect).
- The study resulted in the recommendation of a process/variant of excavation that minimizes the effect of excavation on subsidence and ground displacement. The conclusions are applicable to the practice of underground structures.

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