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Numerical Simulation of the Segmental Tunnels Performance in the Swelling Rocks

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Abstract

In this research, the performance of tunnels with segmental lining in swelling rocks have been studied. In this regard, the way segments are arranged in relation to each other, how the segments are connected along the longitudinal and circumferential lines of the tunnel, and the extent of creating the excavation wall, the effect of the thickness of the segment and the lining system, the effect of the depth of the tunnel and other details are studied. In this regard from the FLAC 3D software was used for numerical modeling. Among the important results obtained in this research, the displacements of the tunnel after applying the boundary conditions and modeling the segments and taking into account all the elements and the phenomenon of creep and surrounding stones with accurate values as the average initial displacement around the tunnel at the specified points are 4.63 mm, this displacement continues the upward trend with a steep slope for a week and increases up to 6.49 mm, and after a week, the increasing rhythm decreases and reaches 6.92 on average in 50 days, and this trend increases again. After 400 days, it reached the value of 9.85 and then the increasing rhythm decreased again, so that after 11 years, the average displacement reaches the value of 11.09, and after this period of time, the displacement of the tunnel becomes very insignificant.

Keywords: segmental lining, swelling rocks, tunnel, numerical simulation

1-Introduction

The construction of today's tunnels, especially urban tunnels, is often done by mechanized drilling systems (TBM) [1] which is done together with the implementation of the segmental lining system (precast concrete panels) which has many static advantages. The segments are placed next to each other like puzzle pieces and form a ring. This rim is connected to the adjacent rims and forms integrated parts and strengthens the tunnel wall. The design of the segments is based on the amount of static and dynamic loads imposed on them during the operation period. The static loads that include the overhead on the tunnel depend on the depth of the tunnel and the type of ground. This means that different soil and rocks impose different loads on the segments. In most rocks with different geotechnical conditions and in granular soils, the load on the tunnel lining does not change much over time, but in clay soils and some rocks of clay origin, the swelling property there is acceptance. In this type of ground, the change in the shape of the swelling rock mass, both in the short term and in the long term, causes a change in the distribution of stresses around the tunnel. This will cause additional pressure on the segmental cover, which should be considered in the designs. In general, many details affect the performance of segmental coatings, which must be properly known, modeled, and studied. These details include how the segments are arranged in relation to each other, how the segments are connected in the longitudinal and peripheral direction of the tunnel, and the creation of the space behind the segments and the excavation wall that faces the injection pressure. The effect of the factors mentioned above on the performance of these segments in swelling rocks should be studied. Phenomenon of squeezing

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is one of the common problems of drilling in all inappropriate geotechnical areas, including swelling rocks and squeezing host rocks, in which the mass of these rocks with inappropriate geotechnical characteristics moves radially inward, which leads to a reduction in the size of the drilling section. Rocks with such characteristics in the dimension of time cause creeping phenomenon and phenomenon of squeezing in the tunnel sections, all these phenomena are applied in the software in 3D and according to the resulting analysis, the exact model of the maintenance system is selected. In the current research, these phenomena have been modeled with segmental maintenance system and mechanized drilling method in such unsuitable environmental conditions. For all the parameters, the analysis was done through FLAC 3D [2] software in three dimensions and if necessary, RocLab software was used to calculate the parameters more accurately, and finally the results were presented numerically. The main goal of the current research is to study the effect of time in the tunnel passing through the swelling rocks and with the segmental lining system. In this regard, different parameters with different values will be considered to distinguish each of the behavioral dimensions and the effectiveness of each parameter, to provide us with accurate and reliable results for each behavioral section.

2- Literature Review

Numerical analysis method and finite elements regarding tunnel modeling, we can refer to models such as Negro and Queiroz's modeling [3] and Muniz's modeling [4], which have a total of 63 scientific articles. About the tunnels, they presented a numerical method, most of them were investigated in two-dimensional form. For this reason and in the way of making these models more complete, three-dimensional models were also carried out, which also considered the mechanization of the drilling type, among which we can refer to Franzius and Pat's [5] research. Next, the three-dimensional modeling of the segmental lining system was done by Klappers [6] in a simplified form with four connections in the segmental plates. This modeling was investigated into two types, two-dimensional and three-dimensional, and the results of these two modeling's were compared with each other. The comparison results showed that the structural pressure values on the segments in both two-dimensional and three-dimensional types are very similar, but the results obtained from some values such as the bending moment show a slight difference between the two types. In 2008, three-dimensional modeling of the segmental lining system was done by Medina Rodriguez [7] using FLAC 3D software. In this modeling, the connection between the segments was done extensively and an integrated segmental system was created, and the results of this modeling also showed that the behavior of the segment is similar to that of shotcrete. Arnau and Molins [8] analyzed the effect of interaction between structurally adjacent rings in a tunnel with a segmental lining system for uniform longitudinal loading. In this direction, a three-dimensional modeling using the finite element method was investigated on a real sample. The new line number 9 of the Barcelona metro was modeled in the software. The application of modeling techniques allowed to study the interaction performance of nodes and the behavior of materials through simulation. The sensitivity of these analyzes changes depending on the influence of some parameters or the importance of some parameters. Such as the hardness of the ground and the real load and the remaining longitudinal force in the three-dimensional interaction of the structure. However, the interaction and performance of the ground and its structure were considered and modeled as a spring element in the radial, tangential and longitudinal direction. In addition to this, the influence of other aspects in tunnel construction, such as the buffer and drilling machine and structural loads (for example, the pressure of the drilling front and the pressure of the connection) are not mentioned. Joints in a tunnel lining have a great influence on the behavior of the tunnel. However, these effects have not been mentioned and have not been clarified. So far, no 3D modeling has been done to focus on these materials and analyze them. Finally, in completing all these modeling, Dias and his colleagues [9] carried out detailed modeling of tunnels with mechanized digging, with a segmental lining system (which is similar to the segmental modeling in the present research). Dias and his colleagues modeled the behavior of segment tunnels and the effect of segment connections in different dimensions and conditions. The numerical results obtained from this research showed a significant reduction of the bending moment with the increase of the connections of the segments and the effects of the bending moment on the placement method. Etisalat (line of connections) in the tunnel was also among the results of this research. The study of the hardness coefficient of the environment around the tunnel on the tunnel's resistance, the secondary pressures (tensions created after a short period of time) of the environment around the tunnel and its effects on the overall resistance of the tunnel were also analyzed by this research group. Following this research, Dias and his colleagues [9] performed three-dimensional modeling of segments with various connections in tunnels, and the results showed the potential effects of connections and the method of segment connections on the behavior of tunnels. According to Dias and his colleagues, the proper way to design the segment and choose the way to place the ring connections in the segment is the general aspects of the tunnel resistance. Dias and colleagues [10] then investigated the segmental tunnel with mechanized excavation under various ambient conditions. Three-dimensional drilling modeling (TBM) in the tunnel, modeling the behavior of the tunnel with mechanized drilling in various types of soft rocks was one of the other researches of Dias and his colleagues [10]. A review of the researches shows that so far no comprehensive study has been done regarding the performance of segmental tunnels focusing on the details of this type of tunnels. Therefore, this issue will be addressed in this research. A review of the researches shows that so far no comprehensive study has been done regarding the performance of segmental tunnels focusing on the details of this type of tunnels. Therefore, this issue will be addressed in this research. Regarding the phenomenon of swelling in tunnels, Wiesmann [11] conducted his research in a tunnel in Switzerland that was excavated by non-mechanized methods. Weismann's initial research was the beginning of expanding research on swelling rocks. Einstein [12], Grob [13] and Kovari [14] presented papers and simpler methods of swelling rocks in the tunnel, the main purpose of these papers was simply to prove the predictions presented by the researchers, which were based on experiments. And the modelings were obtained on the swelling stones. Anagnostou [15] investigates tunneling in swelling rocks. He stated that the presence of clay or minerals interacting with clay and its combination with water is necessary for the initiation of the swelling phenomenon in rocks and he considered the swelling rocks as an elastoplastic material and all the researches It advanced based on the elastoplastic behavior of the rocks around the tunnel. G. Anagnostou did his modeling according to Terzaghi's theories about tunnel behavior and according to his own theories. The results obtained were that the swelling of the rock continues to the area of the rock around the tunnel which has plastic properties and in the elastic area this property becomes much weaker and even at the border of these two areas, the rock behaves completely different from itself. it shows. Studying and investigating the behavior of rocks and the effects of time on their properties and behavior, which is mainly known under the general title of creep, has a special importance in rock mechanics and mining activities. With the passage of time and the gradual change of loads or pressures on the rock, for example, due to the flow of water, the stress or displacement changes. The geometrical condition of the loading area or the drilled structure changes due to the drilling progress. The deformation properties of the stone change due to weathering or water penetration, or the stone slowly reacts to changes in stress. Rock type, rock structure, rock integrity, rock life, tunnel excavation type, tunnel excavation angle, and underground structures have an impact on rock stability over time [16]. Convergence and ambient pressure in the tunnel lining system increases over time. These phenomena are due to the progress of the drilling front and time-dependent reactions in the surrounding environment of the tunnel. This time-dependent characteristic of the tunnel is mentioned in several articles under the title of creep phenomenon (considering one of the aspects Creep such as weathering, hydration, and deposition, etc.) have been researched. Kontogianni and his colleagues [17] analyzed two road tunnels in Greece and acknowledged that more than 50% of the total deformation of tunnels is due to the time-dependent nature of the environment around the tunnel. Creep in rocks has been researched by different people, among them the researches of Cristescu [18], studies of Ladanyi [19], and studies of Cristescu and Hansche [20] can be mentioned. Sulem et al [21] presented a closed solution to determine the displacement of tunnel walls and the peripheral pressure on the tunnel support system. In order to describe the time-dependent behavior of the rock around the tunnel, they have used an empirical function based on the Kelvin model. Considering that the Kelvin model is not able to describe the secondary region of the creep curve, for this reason Berger presented a behavioral model that is capable of modeling all aspects of creep (primary creep and secondary creep). In this context, the most specific modeling is related to Fahimifar and his colleagues [22] who modeled the creep phenomenon in their research and obtained the amount of tunnel deformation in different periods of time and the interaction of different parts of the tunnel in different time intervals and compared with each other. In Fahimifar's research, it is clearly seen that the passage of time has effects on the environment around the tunnel and its maintenance system, which shows the same time-dependent characteristics of the stone. The diagrams presented in this research also graphically and schematically represent the effect of time on tunnel elements. Fahimifar's modeling is close to the modeling of the present research. The design of the segments is calculated and carried out based on the amount of static and dynamic loads imposed on them during the operation period. The static loads that include the overburden on the tunnel depend on the depth of the tunnel and the type of ground.This means that different soil and rocks impose different loads on the segments. In most rocks with different geotechnical conditions and in granular soils, the load and overburden on the tunnel lining does not change much over time, but in clay soils and some stones of clay origin, it has the property of swelling and squeezing. In this type of field, the deformation of the swelling rock mass, both in the short term and in the long term, causes a change in the distribution of stresses and overburden around the tunnel. This will cause double pressure on the segment coverage that is considered in the modeling in this article. All these cases will put extra overburden on the tunnel section and segment coverage that is considered in the modeling in this article.

3-Materials and Methods

3.1. Materials

To model the desired lining system, the liner element is selected from the default structural elements of the software. Depending on the degree of freedom, the type of element can be entered in the next command. The mechanical behavior of the liner element is such that it can withstand bending loads. Also, in the shear direction, there is a possibility of frictional interaction between these two structural elements and the network. Also, in the normal direction of the liner structural element, it is able to withstand compressive and tensile forces. In Table 1 and Table 2, the characteristics of the rocks around the tunnel and the characteristics of the lining system are specified in detail.

Table 1
Characteristics of the rocks around the tunnel [24].

Mass per unit volume (kg/m3)	Volumetric modulus of elasticity (MPa)	Maxwell viscosity (MPa day)	Kelvin viscosity (MPa day)	Maxwell shaer modulus (MPa)	Kelvin shear modulus (MPa)
2600	1694	47897222.2	239486.1	3448.6	344.86

Table 2
Characteristics of the lining system [24] [9]

Poisson’s ratio	Radius (m)	Thickness (m)	density (Mass per unit of volume) of concrete (Kg/m3)	Modulus of elasticity (MPa)	Compressive strengths of concrete (MPa)
0.2	4	0.6	2600	16553.28	40

3.2. Methods

Creating the geometry of the model is the first step in modeling the desired structure in FLAC 3D software. In order to choose suitable dimensions for modeling, dimensional analysis has been done on the target model. Suitable dimensions for the tunnel are 5 to 10 times the radius of the tunnel. Therefore, according to the radius of 4 meters in the tunnel we are considering in this thesis, the dimensions of 160×80×160 were chosen first. In order to accurately control the results, twelve points of the model were selected, and in some cases we only use two important points to achieve the results faster. Of the twelve points whose coordinates are shown in Tables 3 and 4, two important points are the fourth point (the crown of the tunnel) on the plane of y=40 and its opposite point on the ground (tunnel floor) that was chosen as the 10th point. The coordinates of the points are listed in Tables 3 and 4, and their positions are shown schematically in Figure 1.

Table 3.
The around points analyzed of coordinates segmental lining system.

Points	Point 6	Point 5	Point 4	Point 3	Point 2	Point 1
Coordinates	(-3.46,40,2)	(-2,40,3.46)	(0, 4, 4)	(2,40,3.46)	(3.46,40,2)	(4, 40, 0)

Table 4.
The around points analyzed of coordinates segmental lining system.

Points	Point 12	Point 11	Point 10	Point 9	Point 8	Point 7
Coordinates	(3.46,40,-2)	(2,40,-3.46)	(4, 0, 40)	(-2,40,-3.46)	(-3.46,40,-2)	(-4, 40, 0)

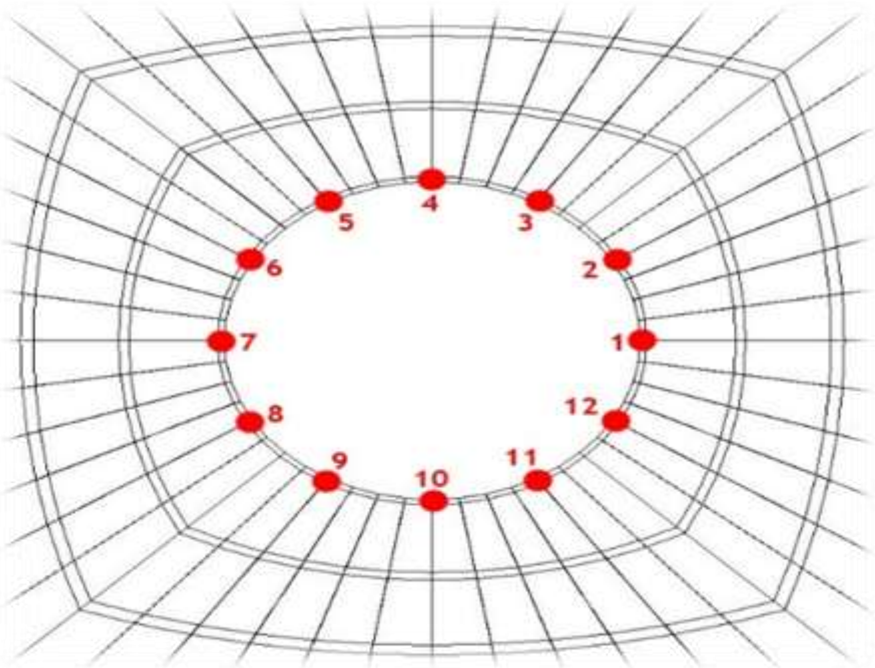

Fig.1. The location of the analyzed points around the lining system.

Segments are modeled in a rotational manner in such a way that each ring rotates 30 degrees compared to its previous ring. Each rim consists of 6 segments. The radius of the tunnel was 4 meters, so the lining system was also modeled with a radius of 4 meters to the inner wall of the tunnel (Figures 2 and 3).

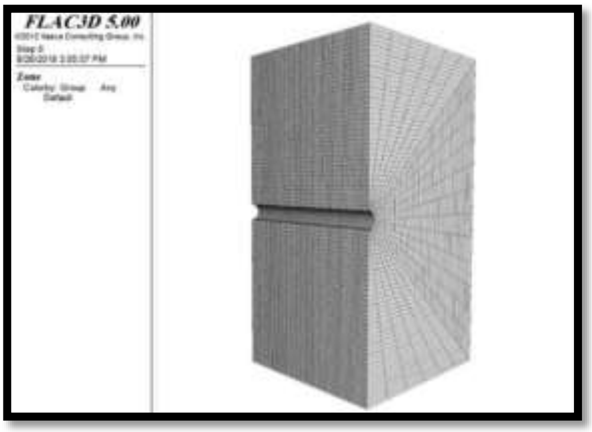

Fig.2. Half geometry modeled in FLAC 3D software.

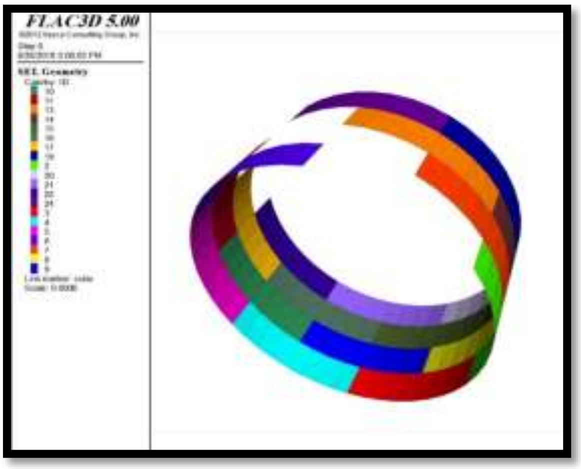

Fig.3. Displaying the segments and era of each loop compared to the previous loop in FLAC 3D software.

In this research, Berger's viscoelastic behavior model is used and the assumptions of this model in FLAC 3D software are such that the creep criterion in Berger's model is a combination of Maxwell's and Kelvin's behavior model and its stress-strain behavior is fully elastic, which is Considering the characteristics of this project, it is the most suitable behavioral model (Figure 6). After constructing the network and determining the behavioral model and material properties, boundary conditions should be applied in the model (Figure 4). In a numerical model, the boundary conditions include the values of field variables such as displacement, stress, velocity, pore pressure, etc., which must be defined at the boundaries of a numerical grid. Model boundaries can be classified into two categories: real and virtual. True boundaries are the boundaries that actually exist around the physical object to be modeled. For example, the wall of the tunnel or the surface of the ground are considered a real boundary. While external boundaries do not exist externally and are defined only to enclose the zones of a model. Virtual boundaries can be used to reduce the volume of calculations. For example, for a logical modeling of a tunnel, the dimensions of the model on the sides of the roof and floor of the model vary from 5 to 10 times the radius of the tunnel.

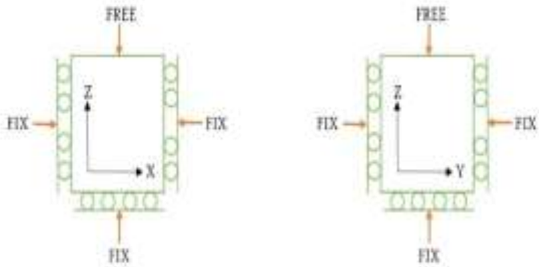

Fig.4. Applying boundary conditions [1].

In all civil engineering and mining projects, before any drilling or construction operations, the state of tension is in place. In FLAC software, this situation is possible by setting the initial conditions. For a uniform rock or soil layer that has a free surface, the vertical stresses are usually equal to gρz. In this thesis, the target model is made with dimensions of 160x80x160. The movement of all model nodes on its sides in the horizontal direction and in the X-Z and Y-Z planes (y=80, y=-80) (x=80, x=-80) is restrained. The nodes in the bottom of the model (z=-80) are restrained in the vertical direction. The current model consists of 186,705 nodal points and 184,320 zones. System stability calculations are done and according to the diagram, after achieving stability, the analysis steps are continued (Figure 5).

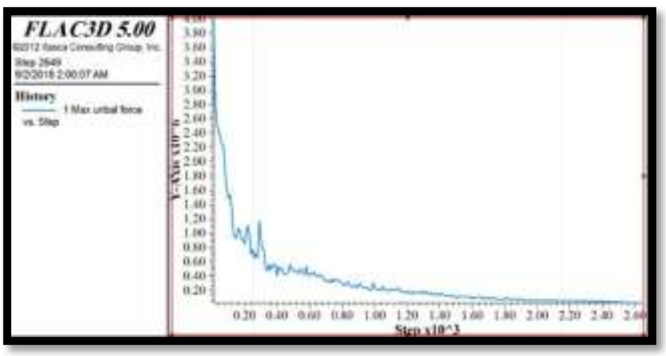

Fig.5. Unbalanced forces diagram of the constructed model.

After making the model and reaching the initial balance in the modeling, step by step drilling and installation of the lining system will begin. Due to the use of the TBM drilling machine in practice, the drilling modeling operation in this article is selected as a gradual drilling method. The drilling steps in each stage are selected as 1 meter and as wide as one ring of the lining system. . In each step, first 1 meter of gradual drilling is done, and then the lining pressure of the drilling front and the slurry pressure are introduced into the drilling chamber. To calculate the pressure of the drilling front, the method used in the study of Dias et al. At the stage of installing the lining or covering system in the tunnel, the lining system used in this project is concrete segments. In the Figure 6, the schematic of the behavioral model and the characteristics of the segments and the host rocks are presented in detail.

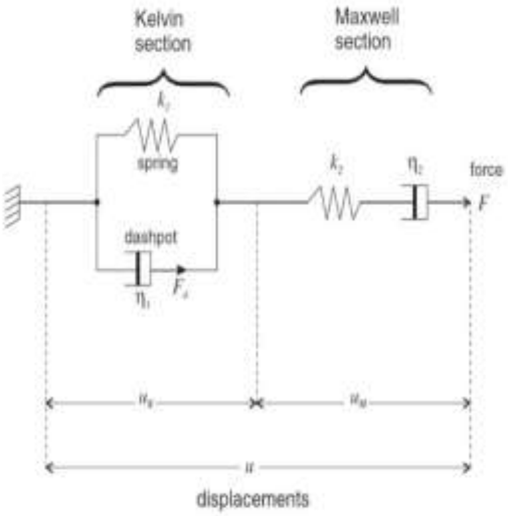

Fig.6. Schematic of Berger's behavioral model with definition of variables.

3.3. Verification

In order to ensure the correctness of calculations and the correctness of modeling, Dias et al.'s and Fahimifar et al.'s studies were modeled in Berger's viscoelastic model under hydrostatic pressure conditions and similar results were obtained. The results presented in the modeling include the displacement of the existing tunnel lining system in the measurement section and the displacement of the lining system considering the time dimension. By comparing the results, it can be seen that in the case where shotcrete is used as a lining system, the difference between 0 and 5% and the results in the case where segmented cover is used as a lining system is between 10 and 15%. The main article is different (Figure 7).

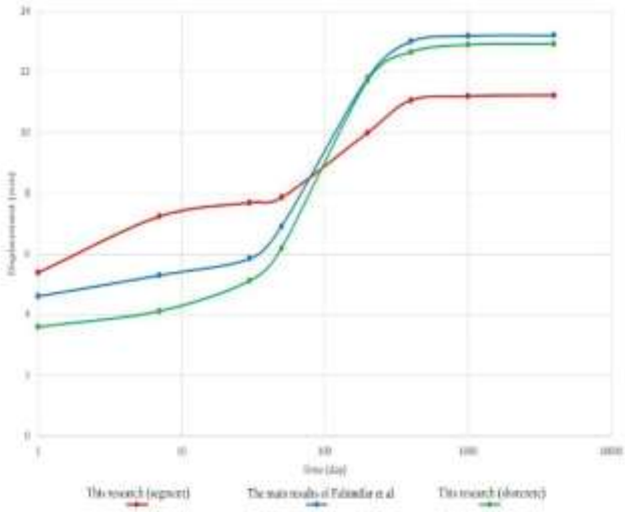

Fig.7. Comparison diagram of lining system displacement in shotcrete and segment mode with main results [24].

The reason for the difference in the shotcrete mode with the original results can only be seen in the change of the size of the meshes or other possible errors. In Figure 8, the amount of difference between these two results is drawn in the time period of 4000 days.

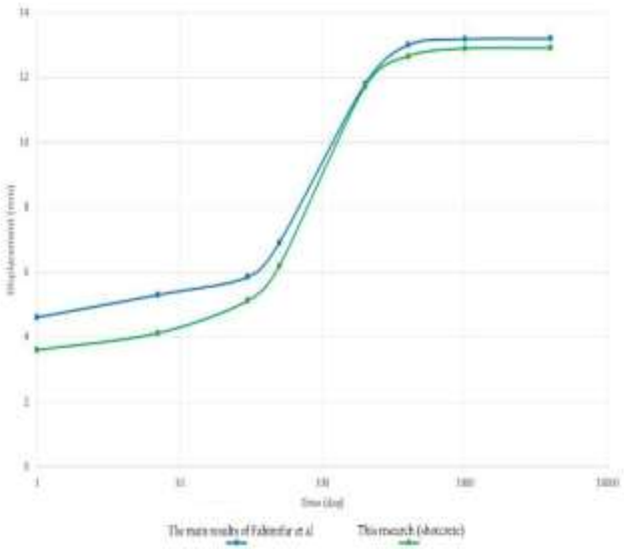

Fig.8. Comparison diagram of the displacement of the lining system in shotcrete mode with the main results [24].

The reason for the difference between the results in the segmented mode and the main results is due to the different lining system, which itself is an influencing factor in the amount of displacement, and the different size of the meshes (Figure 9).

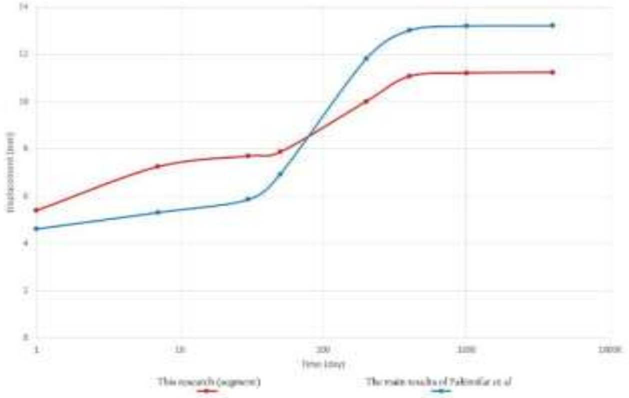

Fig.9. Comparison diagram of the displacement of the lining system in segment mode with the main results [24].

4. Results

First, the initial movements, the first day, the first week, the first month, 50 days, 200 days, 400 days, 1000 days, and finally 4000 days are examined separately, and then their differences are compared in the general diagram (Figure 10).

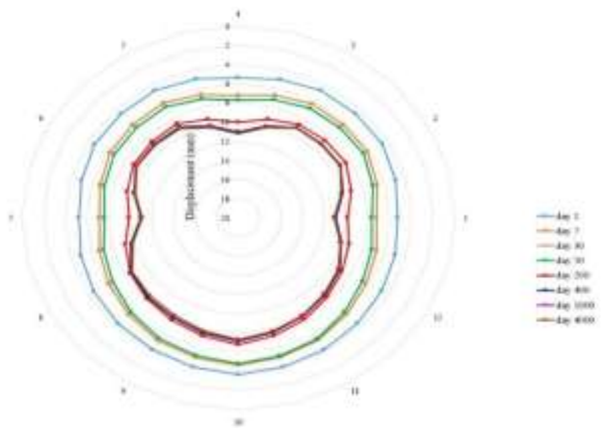

Fig.10. Detailed movements around the tunnel in the time dimension.

According to Figure 10 and Table 5, The average initial displacements in this diagram is 4.63 mm, which reaches 5 mm in the crown of the tunnel and 4.12 mm in the bottom of the tunnel. The average displacements after one day are 4.47 mm, which is 5.2 mm in the crown of the tunnel and 4.17 mm in the bottom of the tunnel. In the continuation of the investigations, according to Figure 10 and Table 5, it is clear that the displacement of the tunnel continues at a slow pace after a week. After a month has passed, the amount of movement is still moving at a slow and steady pace compared to the previous days. In the continuation of the investigation process, it is clear that the displacement rate continues with its previous rhythm after 50 days. After 50 days, when the rate of displacement continued with a constant rhythm, the rate of displacement took on a sharp rhythm and the rate of displacement increased relatively. The increasing trend with a steep slope after the passage of about a year has now reached an increasing trend with a very low and negligible rhythm. The tunnel reached an equilibrium state after 400 days and is now in equilibrium after 1000 days after a very small increase in displacement. After the passage of 4000 days, the changes in the displacement of the tunnel are practically zero and there are no noticeable changes in the displacement of the lining system. In general and according to Figure 10 and Table 5, The differences between the average initial displacements and the total average displacements after 4000 days is 7 mm.

Table 5.
The exact amount of displacement of the lining system in certain time intervals

Time progress (day)	Displacement in the floor (mm)	Displacement in crown (mm)	Average displacement (mm)
Initial	4.12	5	4.63
1	4.17	5.2	4.47
7	5.23	7.22	6.49
30	6.51	7.72	6.78
50	6.73	7.91	6.92
200	6.18	10.2	8.09
400	8.02	11.06	9.85
1000	8.25	11.2	10.88
4000	8.66	11.39	11.09

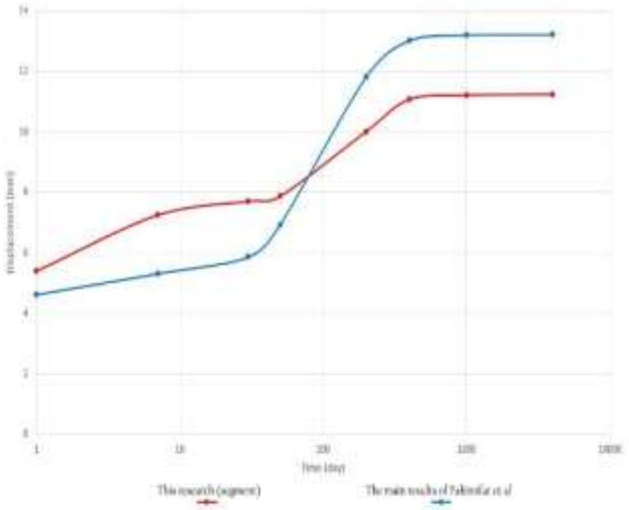

Fig.11. Initial displacement and displacement after 4000 days.

4.1.The Effect of Excavation Depth on Tunnel Displacement

The tunnel has been modeled under the same conditions (according to the specifications of the tunnel presented in the previous section) at depths of 40, 80, 160 and 240 meters and the results are that with the increase in the depth of the tunnel, the amount of displacement and the characteristics depending on the time of swelling stones increases (Figure12).

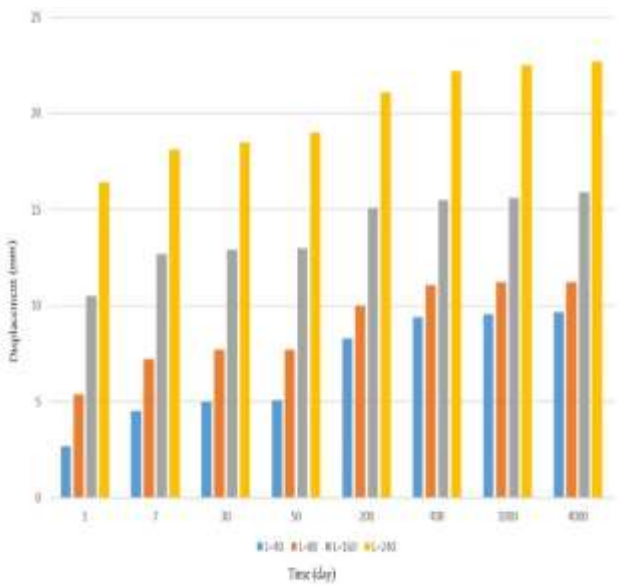

Fig.12. Comparison of displacement in different drilling depths considering the time dimension.

According to Figure12, it is clear that in all displacement days, as the depth of the tunnel increases, the displacement of the tunnel increases in the environment with swelling rocks, and at greater depths, this displacement reaches its maximum value.

4.2. The Effect of Segment Characteristics on Tunnel Displacement

To distinguish the effect of segment thickness on tunnel displacement, modeling with segments with thicknesses of 40, 60 and 80 cm was analyzed, and the results indicate a direct effect of segment thickness on the overall tunnel displacement (Figure13).

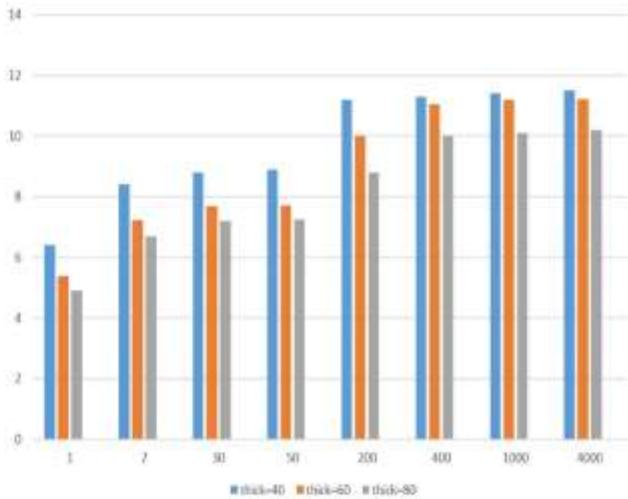

Fig.13. Bar graph comparing displacement in different thicknesses of the lining system.

According to Figure 13, it is clear that the thickness of the lining system has an effect on the overall displacement of the tunnel and the amount of displacement of the lining system itself. As the thickness of the cover layer of the storage system increases, the amount of displacement decreases.

4.3. Effect of Shotcrete Lining System on Tunnel Displacement

Shotcrete as a lining system is one of the common methods in tunnel consolidation. In this research, in order to better touch the difference between lining systems, shotcrete was also used as a lining system and was analyzed. All the characteristics of shotcrete were considered according to the characteristics of the segmented lining system in order to better compare the difference in displacement.

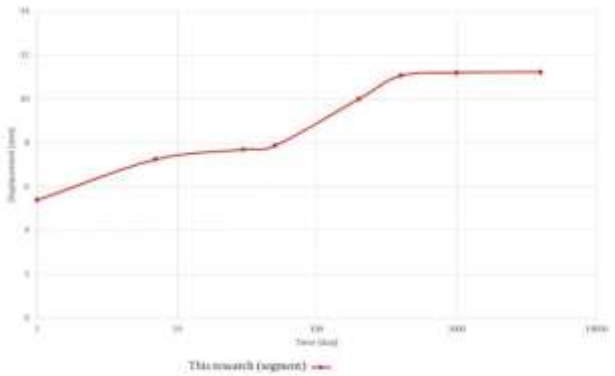

Fig.14. Displacement of segmental lining system.

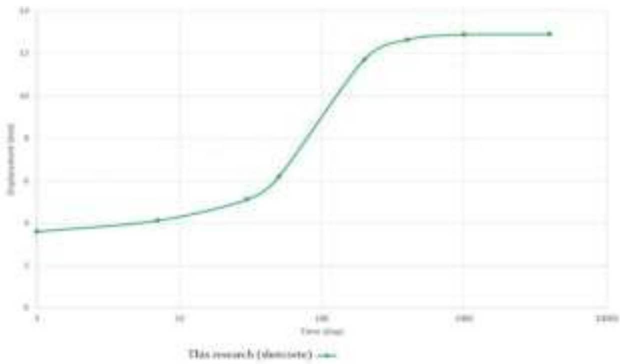

Fig.15. Displacement of shotcrete lining system.

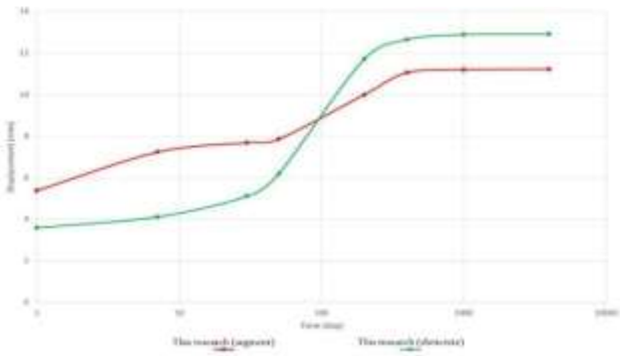

Fig.16. Comparison of displacement of segmental lining system with shotcrete.

4.4.Moving the Tunnel Crown and Floor

Due to the existence of double stresses and overheads, the crown of the tunnel showed the most displacement or so-called creep during the 4000 days of the model. The tunnel floor shows the least movement or creep during the 4000 days of the model. By comparing the diagram of displacement of the crown and the tunnel floor, which is presented in Figure 17, the difference between the amount of grouting in the tunnel crown and the tunnel floor can be understood. On average, between 2 and 4 mm difference in the amount of displacement of the crown and the floor of the tunnel is observed in the time dimension of 4000 days.

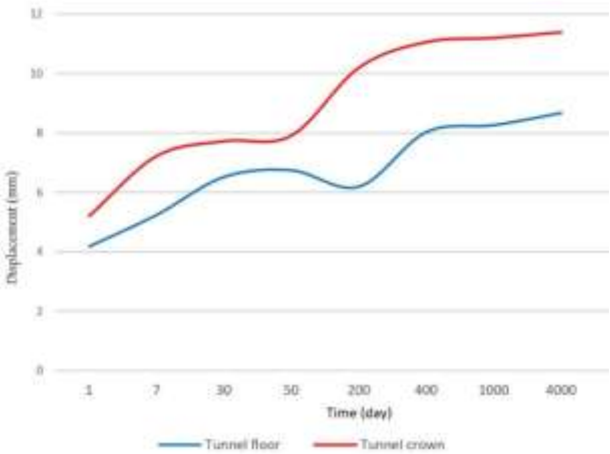

Fig.17. Comparison of tunnel crown and floor displacement.

4.5. Moving other Points of the Lining System

In addition to the floor and crown of the tunnel, all the points around the tunnel show displacement. In the diagram below, all the displacements of the specified points at the beginning of the research are presented in a diagram to be compared.

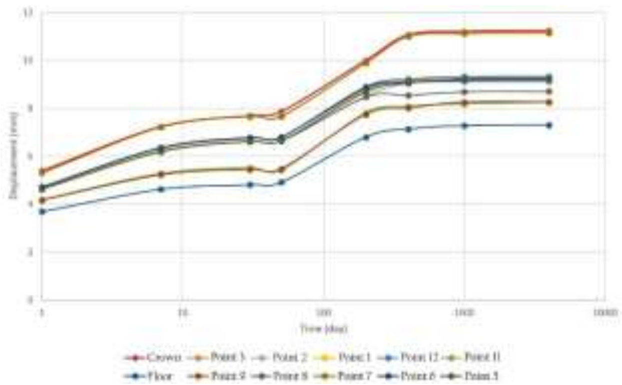

Fig.18. Comparison of the displacement of the tunnel crown and floor and other specified points around the lining system.

According to Figure 18, it is clear that the amount of all displacements is between the displacement of the tunnel crown and the tunnel floor. The left and right sides of the tunnel, which were numbered with points number 1 and 7, also show displacements close to the displacement of the crown.

5. Conclusion

Considering the importance of the time dimension in tunnels whose host rock has time-dependent properties, the necessity of studying changes and displacements in such tunnels is felt. In previous studies, the changes and displacements of these types of tunnels have been investigated using various methods, and the results show the significant impact of time on the existing tunnel, especially in certain time periods. Considering the number of influencing parameters in this process, in this research, it has been tried to examine each of the parameters separately, including the effect of the tunnel depth on the amount of creep and deformation of the tunnel, the amount of resistance of the maintenance system on He pointed out the phenomenon of creep and tunnel displacement and the effect of the variety of maintenance system on the tunnel displacement. In this research, the studies of Dias and his colleagues as well as the studies of Fahimifar and his colleagues were modeled in an integrated way, and all the influential parameters in both articles were applied in this modeling. And the influencing parameters were analyzed separately. Due to the fact that the influencing parameters were analyzed separately, the depth of tunnel excavation and the amount of soldiers and the tensions in the surroundings and on the surface of the ground strongly affect the displacement of the tunnel. The strength of the maintenance system, which can be specifically referred to as its thickness, affects the displacement of the tunnel in different time dimensions. The viscosity and shear modulus of the environment around the tunnel have a direct effect on the displacement of the tunnel and the stress distribution in them. The way of connections of the maintenance system affects the behavior of the tunnel and changes the behavior of the tunnel in different periods of time. The amount of displacement and deformation is different in different parts of the wall of the tunnel maintenance system, so that the maximum amount of displacement is obtained in the crown of the tunnel and the least amount of displacement is obtained in the bottom and bottom of the tunnel.

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