Soil Nailing For Radial Reinforcement of NATM Tunnels

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Abstract: Due to the rapid growth in urban development in most major cities, and space limitations the demand for tunnels construction for various purposes (utilities, and transportation systems) is increasing. These tunnels are constructed at shallow depths mostly, for accessibility, serviceability and economy reasons. Since the ground at shallow depth consists of either soft soils or weak rocks, shallow tunnels are usually exposed to the occurrence of excessive settlement. In such areas, settlements induced by the tunnelling excavation may cause serious damage even collapses to nearby structures. Shallow tunnels are usually constructed by either TBM or conventional tunneling methods such as the New Austrian Tunneling Method (NATM). Accordingly, maintaining the tunnel stability has the highest priority since the instability issues may cause a loosening of the ground leading to a complete tunnel collapse. Therefore, the focusing of this paper is to control displacements in NATM tunnels, by using soil nailing system as a radial reinforcement technique. A series of 3D and 2D finite element analyses were conducted to investigate the deformation of NATM tunnel excavation under different conditions of face subdivision and excavation step length. Accordingly, the critical case for the 3D analysis was determined to be used in addition to 2D model for studying the displacement control by soil nailing technique as a radial reinforcement. Hence, 3D and 2D finite element analyses established for simulating the contribution of soil nailing in assisting NATM tunnels stability and controlling displacements. A wide range of system parameters were considered by varying reinforcement (diameter, density, length…etc.). Using the relationships between the displacements (vertical, horizontal) and the soil nailing system parameters, the effect of the reinforcement on displacement control in NATM tunnels was investigated. A new construction technique was developed and checked to increase the efficiency of the system.

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1. Introduction

The concept of in situ soil reinforcement by tensile inclusion is relatively old, where people in ancient cultures used sticks and branches for reinforcing mud houses and other religious structures [1]. The origin of soil nailing developed in the early 1960s, from the support systems used for underground excavations in rock referred to as the New Austrian Tunneling Method (NATM). This tunneling method consists of the installation of steel reinforcement (e.g., rock bolts) followed by reinforced shotcrete applications. This concept of combining steel reinforcement and shotcrete has also been used to the stabilization of rock slopes since the early 1960s [2].

The soil nailing system improves the stability of the soil mass though the mobilization of tension in the soil nails [2] [3] [4]. The tensile forces in the soil nail reinforce the ground by directly supporting some of the applied shear and by increasing the normal stresses in the soil at the potential failure surface. The tensile forces are developed in the soil nails by the frictional interaction between the soil nails and the ground and as well as the reaction provided by soil nail head/facing (If any).

NATM, also known as Sequential Excavation Method (SEM), describes a popular method of modern tunnel design and construction. This technique first gained attention in the 1960s based on the work of Ladislaus von Rabcewicz, Leopold Müller and Franz Pacher between 1957 and 1965 in Austria [5]. The name NATM was intended to distinguish it from the old Austrian tunnelling approach. The fundamental difference between this new method of tunneling, as opposed to earlier methods, comes from the economic advantages made available by taking advantage of the inherent geological strength available in the surrounding rock mass to stabilize the tunnel, but old conventional tunnelling methods considered the rock mass surrounding the tunnel only as a loading member.

The world-wide data show that NATM tunnels, especially in soft ground in urban areas, may, when they collapse, result in major consequences not just to those working in the tunnel but to members of the public, the infrastructure and the built environment [6]. Therefore tunneling at shallow depths in difficult ground conditions, maintaining the stability has the highest priority since the instability of the tunnel causes a loosening of the ground and may thereby lead to a complete tunnel collapse. Even in rock tunneling, there are many occasions where tunnels are excavated through thick, highly sheared and altered fault zones. Therefore, in NATM the control of displacements is essential, which will be discussed in the present work by using soil-nailing techniques. Soil nailing techniques, are usually used for stabilizing the soil mass during excavation. Soil nailing can be used for both face and radial reinforcement. The most popular use for soil nailing is face stabilization in tunnels. This is due to its ability to control of both face and surface displacements. In this paper, the main focus is to investigate the displacements control in NATM tunnels, by using soil nailing system following radial reinforcement technique.

2. NATM Analysis Section

The proposed tunnel cross section, Figure 1, was considered to be suitable for double track metro; its geometry was chosen to coincide with soil profile which leads to stresses optimization [7].

The cover depth of the tunnel, soil layers, and the mechanical soil parameters used in the analysis are shown in Figure 2. The tunnel was simulated to be excavated in a deep clayey layer lies above a sand layer, and a fill layer located at the surface, with no existence of ground water.

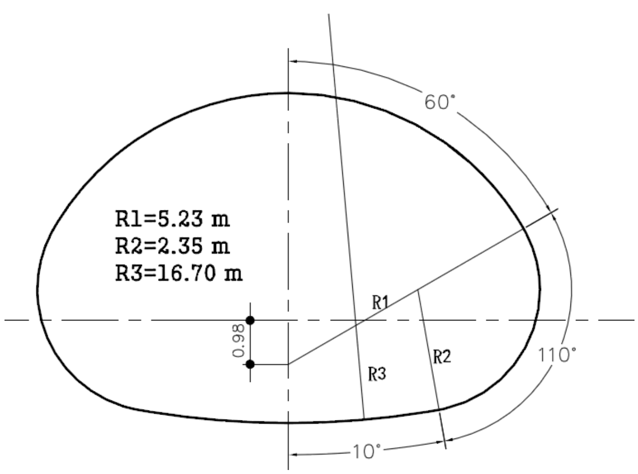

Figure 1. The NATM tunnel cross section

3. 3D and 2D Analyses for the NATM Tunnel Section

3D Numerical models were used in order to check the excavation face subdivisions, excavation sequence, and unsupported length and to predict the effect of these parameters on the surface and crown settlement. Then a 2D model was used to compare the results within the 3D models. From the previous analyses, the critical case that causes excessive deformation was obtained, and used in the study of displacement control by soil nailing technique for radial reinforcement. The analyses of the models were performed using FINAL package [8].

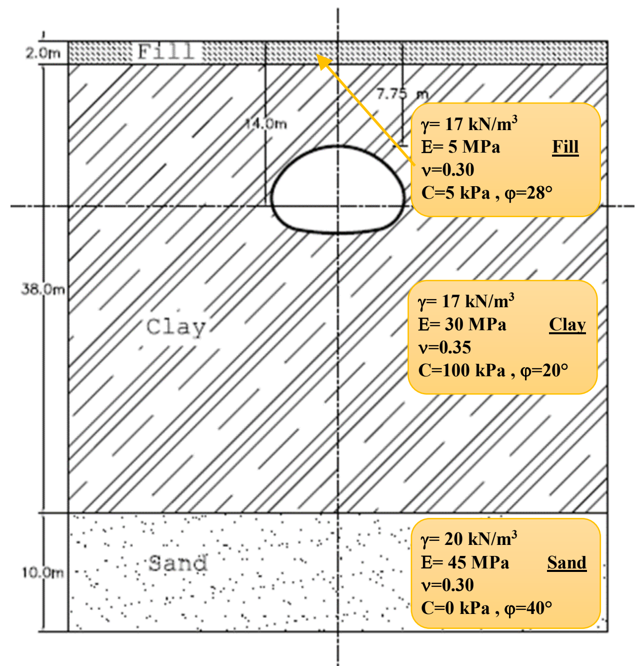

Figure 2. Tunnel cover depth, soil layers and soil parameters.

3.1 Geometrical Parameters

The 3D analyses were performed for three cases of face subdivisions, excavation sequence, and unsupported length as follows:

I. **(Case a)** The excavated cross section was divided into two parts, top heading and invert. The unsupported length was assumed to be 3 m as shown in Figure 3.

II. **(Case b)** The excavated cross section was divided into two parts, top heading and invert. The unsupported length was assumed to be 6 m.

III. **(Case c)** The excavated cross section was simulated to be excavated in full face. The unsupported length was assumed to be 3 m.

The 2D analysis was performed for the cross section divided into two parts, top heading and invert (Case a, and Case b).

3.2 3D Modeling

A 3D finite element analysis was developed using FINAL package [8] in order to study the behavior of the excavation process for the different three cases mentioned earlier.

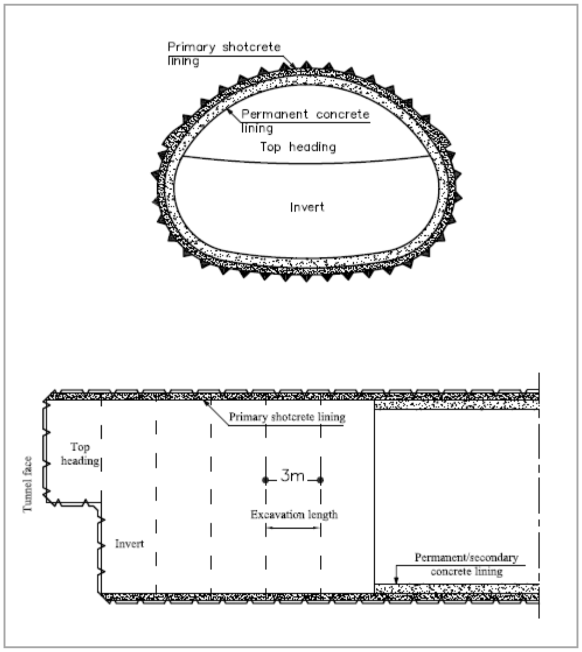

Figure 3. Top heading and invert subdivision with 3m unsupported length.

The ground was discretized using IPQS element, which is a type of Isoperimetric Quadratic Solid elements with 20-nodes. Each node has 3 transitional degrees of freedom u, v, w [8]. An eight-node shell element with 6 degrees of freedom (3 transitional and 3 rotational) for each node was selected to model the concrete linings. The shell element is capable to model the axial force and bending moment induced in the tunnel lining.

In order to minimize the required computational time, it is preferable to minimize the model size and the number of elements involved within acceptable limits. Since a symmetrical plane could be easily identified at the centerline of the tunnel, only half of the cross section was simulated.

In the analysis, the soil was assumed elasto-plastic material following the Mohr–Coulomb failure criterion, while the constitutive model used for the tunnel linings is an isotropic linear elastic model [8].

Simulation of the actual process for the excavation of the previous NATM tunnel included the following steps:

1. Establish of initial geostatic conditions.
2. Applying of surface loads.
3. Stress elimination for excavation elements, then removing of these elements.
4. Activation/placement of initial lining.
5. Activation/placement of final lining.

The step 5 is not applied until the steps 3 and 4 repeated for all subdivision parts of the excavation face.

3.3 2D Modeling

A 2D finite element analysis was developed using FINAL package [8] in order to study the behavior of the excavation process for the NATM tunnel as follows:

The ground was discretized using LST element, which is a type of 6-node Linear Varying Strain Triangular element. Each node has 2 transitional degrees of freedom u, v [8]. A curved boundary beam elements (Beam6) with 3 degrees of freedom (2 transitional and 1 rotational) for each node was selected to model the concrete linings.

The soil was assumed elasto-plastic material following the Mohr–Coulomb failure criterion, while the constitutive model used for the tunnel linings is an isotropic linear elastic model [8].

For the simulation of the excavation sequences and shotcrete installation, the 2D plane strain finite element model was employed with the following different loading cases:

1. Establish of initial geostatic conditions.
2. Applying of surface loads.
3. Each part of excavation subdivision was simulated in two steps using the stiffness reduction method [9].
   - In the first step, the stiffness of the soil in the excavated part was reduced by a factor accompanied with stress redistribution at the tunneling periphery.
   - In the second step, the excavated part was removed and the initial lining was activated in its fresh state accompanied with a stress elimination of the excavated soil.
4. Activation/placement of final lining.

3.4 Results and Comparison

It is seen from Figure 4 below that the zone of significant movements extended laterally from the tunnel face, forming a narrow 'chimney' propagating almost vertically from the tunnel crown up to the ground surface.

A comparison between the 3D and 2D analyses values is illustrated in Figure 5. It is seen from this figure that the vertical settlement for 3D analysis case b Figure 4 exceeds the values for 3D analysis cases a, c and there is a convergence in the results between cases a, c. Hence, the excavation step length (unsupported length) is found to have more effect on the vertical displacement than the excavation face subdivision. Also, as expected, vertical displacement for 2D model exceeds the values for all 3D analyses cases due to the approximation in the 2D numerical modeling.

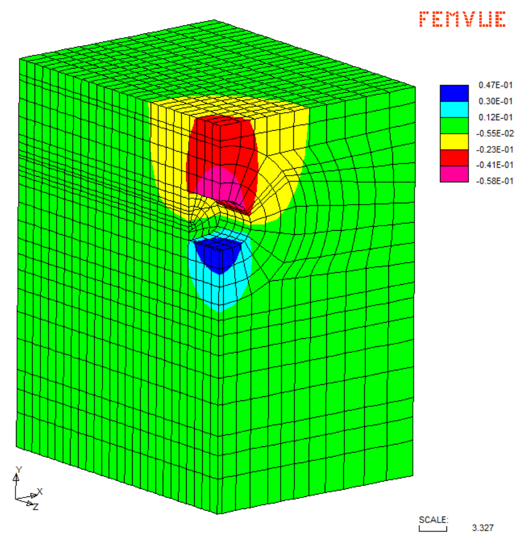

Figure 4. 3D analysis case (b) -Vertical deformation (m).

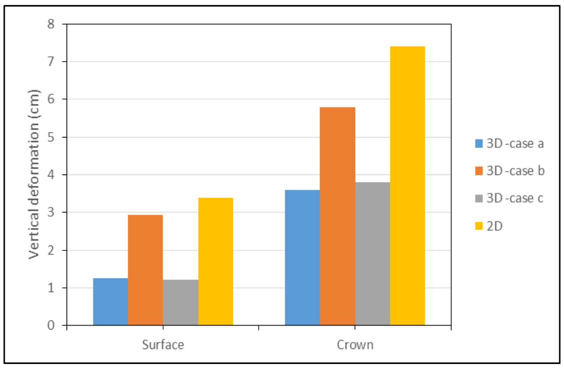

Figure 5. Comparison between vertical deformation of 3D & 2D analyses.

Accordingly, the critical case for the 3D analysis is case b (Top heading and invert subdivision with 6m unsupported length); therefore, it is used in addition to 2D model for studying the displacement control by soil nailing technique for radial reinforcement.

4. Soil Nailing for NATM Tunnels

To investigate the deformation behavior of NATM tunnels reinforced with soil nailing system as a radial support a series of 3D and 2D finite element analyses were conducted. The modeling process in addition to what mentioned above are summarized in the following:

4.1 Assumptions of the Idealization for Excavation Procedures

The following assumptions were used in the idealization of the tunnelling simulation:

1. The boundary effect was considered negligible, hence the excavation step no. 1 used to study the soil nailing effect on the stability of the tunnel face.
2. The nails were considered to be installed wished-in-place (i.e., the nails are placed at the desired location without drilling the hole and applying the grouting material).

4.2 Modeling of Nails

The nails were modeled using BOLT element, which is a type of 4-node (2 basics and 2 virtual) for 2D and 3D analyses. Each node has two transitional degrees of freedom u, v [8]. The bolt element is capable to model the axial force induced in the soil nails and can account for the grout contribution around the nail. In the analysis, the constitutive model used for the soil nailing is an isotropic linear elastic model.

4.3 Model Parameters

The parameters of the drill and grout soil nails with steel solid section that were used in the finite element analysis are summarized in Table 1.

Table 1. Parameters of the soil nailing bars (Steel solid bars).

	Young's modulus	Poisson's ratio	Yield stress	Compressive strength
Soil nailing	210 GPa	0.30	500 Mpa	-
Grout	3.86 GPa	-	-	80 MPa

4.4 Nails Distribution and Lengths

Location of the soil nails shall be chosen to govern the area of excessive vertical deformations. Hence by referring to the plotted vertical deformations around the tunnel in Figure 4, it is seen from this figure that the excessive vertical settlement located around the tunnel crown down up to the end of the top heading part. Accordingly, the schematic radial distribution for soil nails Figure 6 was used to enhance the stability of the tunnel to control the vertical displacements. 29 nails (with approximate density D= 1.13 nail/m) were used to cover the tunnel perimeter have been intensified at top heading part especially around the crown point. Soil nails of 7.0 m length were used throughout the analysis with inclination angle perpendicular to the tangent. The effect of the nail length and inclination angle will be investigated in the following.

4.5 3D Numerical Simulation for the Tunnel Excavation with Radial Reinforcement

The same 3D and 2D simulation of the actual process for the tunnel excavation that mentioned earlier were used to simulate the actual process for the tunnel excavation with radial reinforcement. The only modifications on these steps was the activation of soil nails during the excavation process.

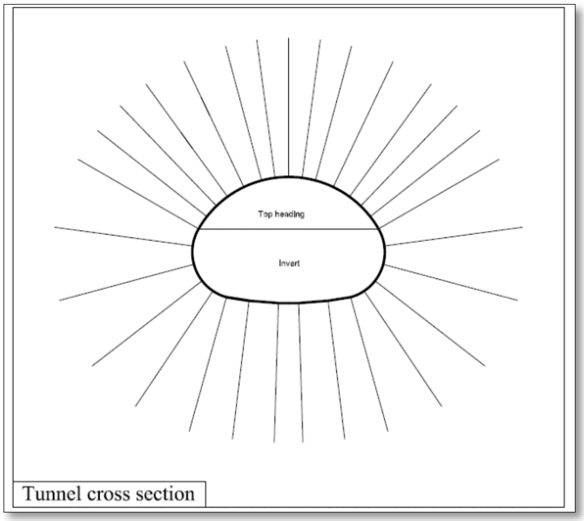

Figure 6. Soil Nails radial distribution.

5. Computed Results

The 3D and 2D finite element models mentioned above were used to study the behavior of the radial reinforced tunnel with 45mm steel solid bars, under expected loads during different stages of tunnel construction. The obtained numerical results will be discussed in the following:

Figure 7 shows the vertical settlement plots around the tunnel. For the unreinforced case the significant movements extended laterally from the tunnel face, forming a bowl shaped pattern with the maximum values for settlement occurring immediately above the tunnel face (top Crown Point). This settlement extended from the tunnel crown up to the ground surface. As for the reinforced case, the significant vertical settlement was reduced, as much as by 33.78% for 2D model and 36% for 3D model with a good agreement between the two models. The results presented above clearly demonstrate that the soil nailing as a radial reinforcement technique can be used as a positive measure for limiting/controlling the ground surface settlement for tunnels in urban areas.

Figure 8 shows the plots of plastic zones around the tunnel face for 3D finite element models. The plastic zone for the unreinforced case covers the whole face area and extend to 1.5 m approximately ahead of the face. For the reinforced case, a limited effect was observed except for the parts where reinforcement are crossing and due to stabilization of soil mass above tunnel face the plastic zone for the excavated parts was decreased little bit. This illustrates the ability of the soil nailing as radial reinforcement to reduce to some extent the development of plastic zone around the tunnel face.

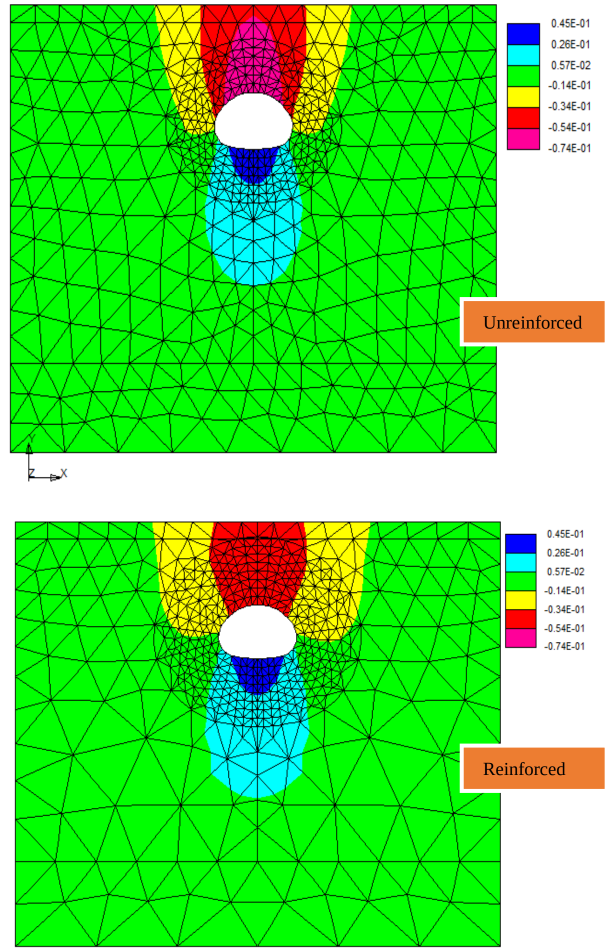

Figure 7. 2D Tunnel vertical displacements.

By referring to the above-mentioned results, it is seen that the effect of soil nailing, as a radial reinforcement to control displacements in NATM tunnels is limited to some extent. This may be a direct consequence of lack of effectiveness of soil nailing system as radial reinforcement in deformation control in NATM tunnels. To have more effectiveness of soil nails; it should tie the soil active zone to the passive zone, Figure 9, to achieve the internal stability of the system. This does not exist in NATM tunnels where the settlement extended laterally from the tunnel face up to the ground surface. Accordingly, the soil nailing almost lies in active zone along the whole length, which reduces their contribution in assisting tunnel stability and deformation control.

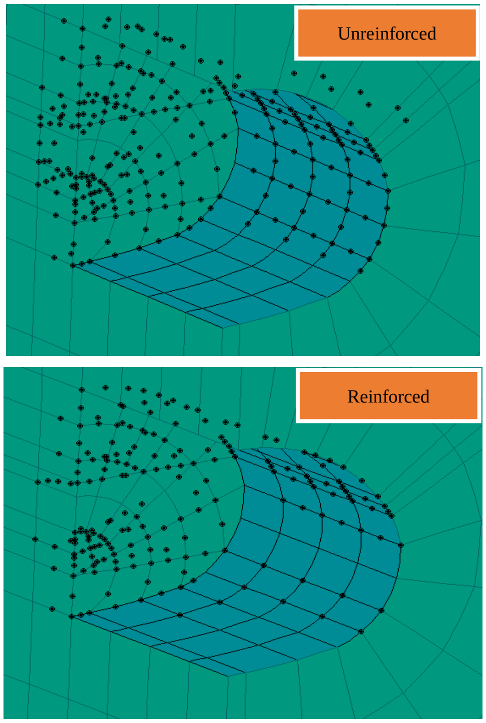

Figure 8. Plastic zones around tunnel face.

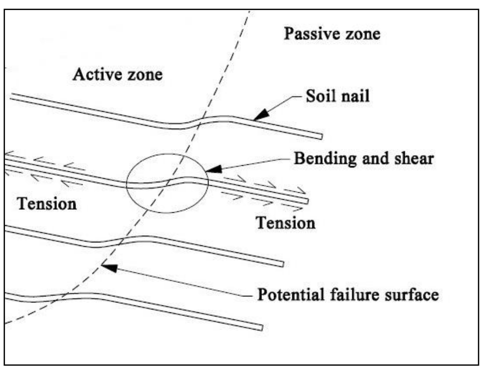

Figure 9. Active and passive zones model of a Soil nailing System

6. Parametric Study

The 3D and 2D finite element models followed above were used in a parametric study to identify the effect of different parameters of soil nailing (diameter, density, length, inclination angle and distance between nails rows) on the contribution of the soil nailing system as a radial reinforcement on assisting NATM tunnel stability. These critical soil nails parameters were determined from a relationship between the maximum displacements at crown and surface for each reinforcement parameter.

6.1 Effect of Nails Diameters

A Series of 2D finite element models with 20, 32, 45, 64 and 89 mm diameters of steel solid bars nails with 7m length and inclination angle perpendicular to the tangent, were used to study the effect of soil nails diameter on displacements control. Figure 10 shows the relationships between the resulted vertical surface and crown settlement for the above-mentioned soil nails diameters within reference to the case without reinforcement. It is seen from this figure a slight reduction in the displacement with the increase in soil nails diameters, that's due to the ability of stiffer nails of attracting more load with improving in soil shear strength. The effect of nails diameters does not appear clearly, due to limited contribution of soil nailing in assisting NATM tunnels stabilization that caused by the extension of the active zone around the whole length of nails.

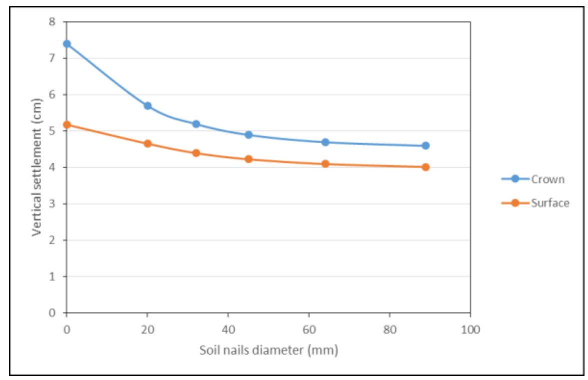

Figure 10. Relationship between vertical settlement and nails diameters.

6.2 Effect of Nails Numbers

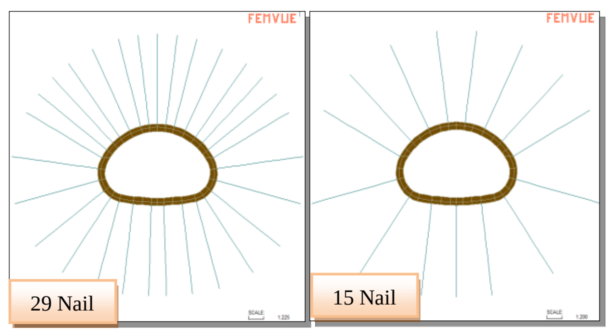

Figure 11. Soil Nails numbers and distribution.

To study the effect of soil nails numbers and distribution on displacements control in NATM tunnels, a series of 2D finite element models were generated for 45 mm diameter steel solid bars nails with 7m length and inclination angle perpendicular to the tangent. Two different no. 15, and 29 soil nails were used Figure 11.

Figure 12 shows the relationships between the simulated vertical surface and crown settlement for the above-mentioned soil nails numbers, with reference to the case without reinforcement. It is seen from this figure a slight reduction in the displacement with the increase in soil nails numbers. The effect of nails numbers and distribution did not appear clearly, due to limited contribution of soil nailing in assisting NATM tunnels stabilization that caused by the extension of the active zone around the whole length of nails.

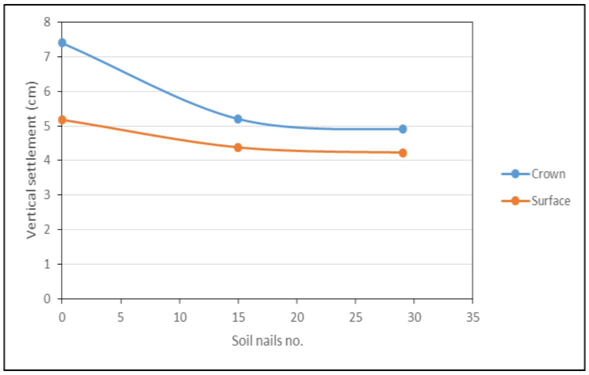

Figure 12. Relationship between vertical settlement and nails no.

6.3 Effect of Soil Nails Lengths

To study the effect of soil nails lengths on displacements control in NATM tunnels, a series of 2D models were generated for 45 mm diameter steel solid bars nails with inclination angle perpendicular to the tangent. 29-soil nails models were used with different lengths (3, 4, 6, 7, and 8m).

Figure 13 shows the relationships between the simulated vertical surface and crown settlement for the above-mentioned soil nails lengths, with reference to the case without reinforcement. It is seen from this figure a slight reduction in the displacement with the increase in soil nail lengths. Where longest nails can reach a more stable soil parts (more effective passive zone) but this effect does not appear clearly, due to limited contribution of soil nailing in assisting NATM tunnels stabilization that caused by the extension of the active zone around the whole length of nails.

6.4 Effect of Soil Nails Inclination Angles

To study the effect of soil nails inclination angles on displacements control in NATM tunnels. A series of 2D finite element models were established for 45 mm diameter steel solid bars nails with 7m length and different inclination angles (-5°, 0°, 5°, 10°, 15°, and 20°). Where the angles were assumed to be as following Figure 14:

1. Equal zero when soil nails are perpendicular to the tangent.

2. Negative when the nails inclination is orientated from perpendicular case towards the tunnel centerline (area of MAX deformation).

3. Positive when the nails inclination is orientated from perpendicular case away from the tunnel centerline (area of MAX deformation).

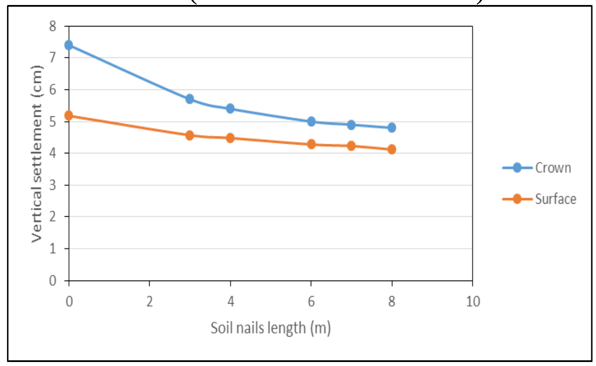

Figure 13. Relationship between vertical settlement and nails length.

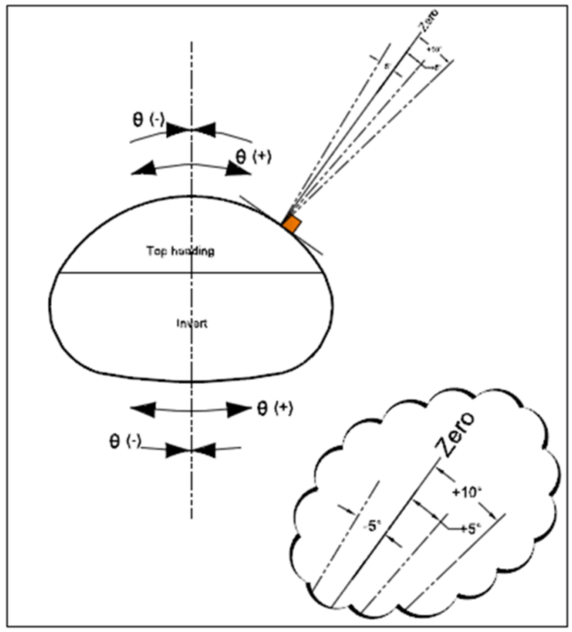

Figure 14. Positive and negative positions for soil nails inclination angle.

Figure 15 shows the relationships between the simulated vertical surface and crown settlement for the above-mentioned soil nails inclination angles. It is seen from this figure a slight reduction in the displacement when soil nails are orientated away from the tunnel centerline (area of MAX deformation). While a slight increase in the displacement was observed when soil nails are orientated towards the tunnel centerline (area of MAX deformation). The nails when orientated away from tunnel centerline, it located in a stiffer soil, where the passive zone can be more effective and restrain the nails from being pulled out. Hence, mobilization of instability forces and increasing on the soil nails contribution on displacements control in NATM tunnels can be achieved.

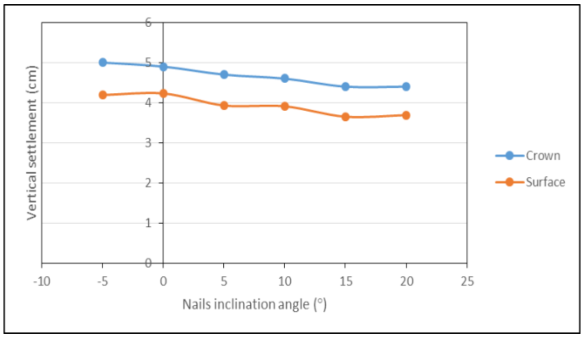

Figure 15. Relationship between vertical settlement and nails inclination angle.

6.5 Effect of Soil Nails Distribution along the Tunnel (Distance between Nails Rows).

To study the effect of soil nails distribution along the tunnel on displacements control in NATM tunnels, a series of 3D models were generated for 45 mm diameter steel solid bars nails with 7m length and inclination angle perpendicular to the tangent. Where the spacing between nails rows (S) was taken as follows:

1. 0.25 EL (Excavation Length) = 1.5 m.
2. 0.5 EL = 3 m.
3. EL = 6 m.

Figure 16 shows the relationships between the simulated vertical surface and crown settlement for the above-mentioned spaces between nails rows. It is seen from this figure a reduction in the displacement with the decrease in spaces between nails rows along the tunnel. As more rows of soil nails are capable of making a discrete ground behaves as if it is a continuum one. Hence, the ground becomes stiffer, and the displacements were decreased. Accordingly, the spacing between nails rows shall be kept a minimum in a range equal to 25%-50% of the excavation step length.

7. Pre-Installation Technique

The risk of tunnel collapse is high immediately after excavation at the tunnel face. Soil nailing as radial reinforcement in NATM tunnel is usually installed after/during excavation, where a considerable deformation has occurred. It is not possible to use these supports as a means of preventing deformation before or immediately after the excavation. Furthermore, additional ground disruption caused by the installation of supports is unavoidable [10]. To overcome such problems, soil nails may be driven into the ground from the surface before excavation, trying to achieve mechanical advantages enhancing the deformation control of the ground and preserving the arching of the ground without additional ground disruption caused by the installation of the nails.

Figure 17 shows the pre-installation technique of soil nails which were driven from the surface before excavation. The nails were 45 mm diameter steel solid bars nails with a maximum length 20m for some nails. The inclination angle perpendicular to the tangent was used for nails located at top heading part and inclination angle up to 35° from the perpendicular to the tangent for nails located at the invert part for installation simplicity.

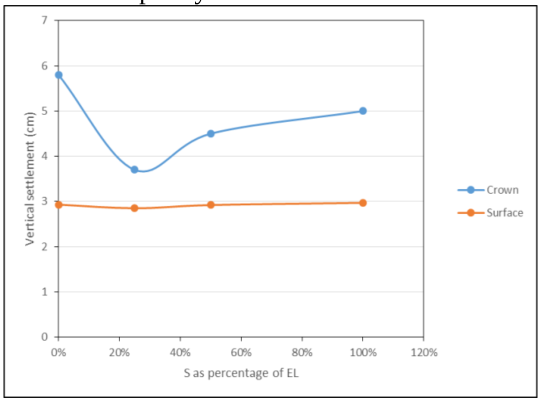

Figure 16. Relationship between vertical settlement and distance between nails rows along the tunnel.

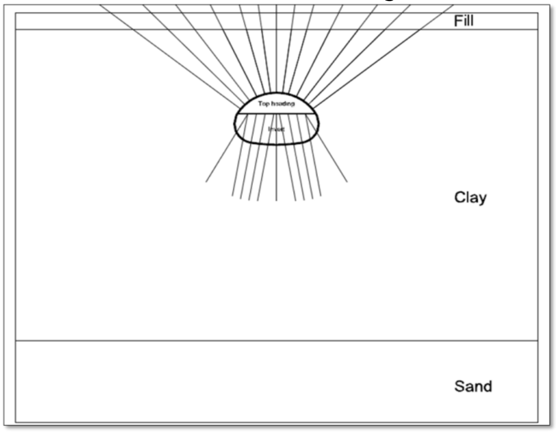

Figure 17. Pre-installation technique for soil nails.

Figure 18 shows the results of the two-dimensional numerical analysis. It is seen from this figure that the pre-installation technique reduces the ground deformation by approximately 53%, while it was 34% for the post-installation technique. D.H. Seo et al. [10] conducted a three-dimensional numerical analysis for pre-installation technique for soil nailing; the results obtained were verified by field application. These results showed a reduction in the ground deformation by approximately 50%, which in a good agreement with the obtained results in this study where the reduction value is 53%. Hence, the used 2D finite element model could capture the main principles and features of the soil nail as pre-radial support. Thus, it can be concluded that this technique not only reduces the risk of collapse in tunnel excavation at the face, but also it can reduce surface settlement and improve the stability of the tunnel face during excavation of shallow tunnels in soft ground.

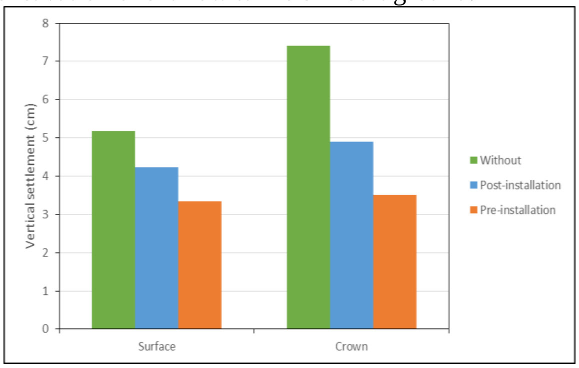

Figure 18. Vertical settlement for different soil nails installation techniques.

8. Pre-Installation Technique with Support

To have Soil nailing system as an effective measure in achieving stability; it shall tie the soil active zone to the passive zone, which are separated by the potential failure surface to achieve the internal stability of the system. This does not exist in NATM tunnels where the settlement extended laterally from the tunnel face, forming a bowl shaped pattern and extended from the tunnel crown up to the ground surface. Therefore, a new technique was developed trying to create a passive zone (support) for achieving the internal stability of the system and increasing the contribution of soil nailing system on deformation control in NATM tunnels accordingly. The new technique depends on using pre-installed soil nails, which are connected to a very stiff supporting system, located at the surface. The supporting system bases shall be located as far as possible from the area which affected by tunnel excavation to prevent any possibly ground disruption Figure 19.

Figure 19 shows a 2D model for pre-installation technique of soil nails which were driven from the surface before excavation. The nails were 45 mm diameter steel solid bars with a maximum length 20m for some nails. The inclination angle perpendicular to the tangent was used for nails located at top heading and inclination angle up to 35° from the perpendicular to the tangent for nails located at invert part for installation simplicity. The support system at the surface was modeled by fixing displacements at the end of the nails to zero.

From the results and comparisons in Figures 20 and 21, of the two-dimensional numerical analysis, it can be noticed that the pre-installation technique with supports significantly reduces the ground deformation by approximately 93%, while it was 53% for pre-installation technique without supports and 34% for the post-installation technique. Accordingly, the pre-installation technique with supports can be effectively used as a positive means for controlling the ground settlement ahead of face during NATM at shallow depths.

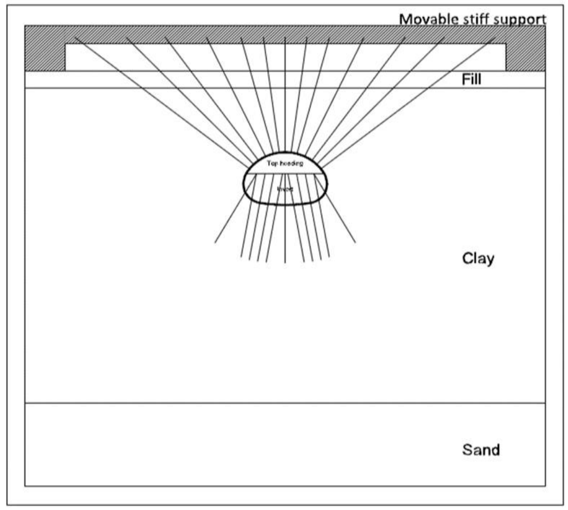

Figure 19. Pre-installation technique with support for soil nails.

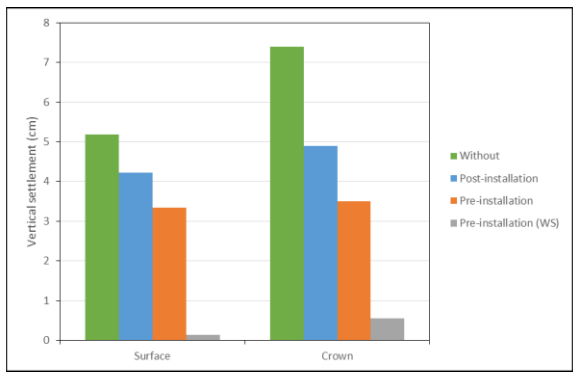

Figure 20. Vertical settlement for different soil nails installation techniques.

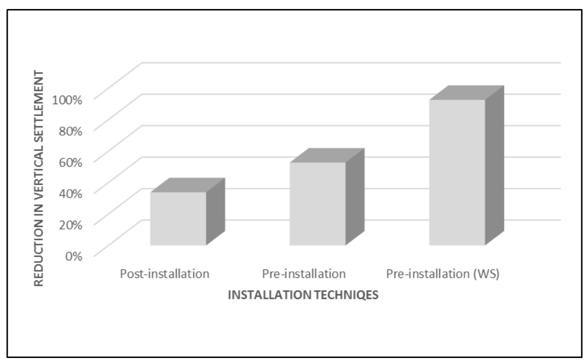

Figure 21. Percentages of reduction in vertical displacement for different soil nails installation techniques

The significant reduction, achieved is affected by the assumption that the supporting system is stiff enough to support the expected loads without any movements/deflections. Hence, any deflection will occured for the supporting system, the reduction in settlement will be decreased accordingly.

9. Conclusions

To investigate the deformation behavior of NATM tunnels reinforced with soil nailing system as a radial support, a series of 3D and 2D finite element analyses models were conducted. 2D finite-element analysis models were conducted to convert the soil nailing as radial reinforcement from being a post-supporting technique to a pre-technique, in addition, a development of a supporting system for the pre-installation technique was conducted to improve the efficiency of the soil nailing system. Based on the analyses results, the following conclusions can be drawn:

1. The soil nailing as a radial reinforcement technique can be used as a positive measure for limiting/controlling the surface settlement for tunnels in urban areas. In addition to reduce the development of plastic zones around the tunnel face.
2. The contribution of soil nailing as a radial reinforcement to control displacement in NATM tunnels is affected by the settlement pattern extended laterally from the tunnel face up to the ground surface.
3. The parametric study has been shown that one or more of the following can mobilize a greater effect of the reinforcement:
   - Increasing nails rigidity, numbers, and lengths.
   - Orientating the nails away from the tunnel centerline (area of maximum deformation).
   - Decreasing the distance between nails rows, where it shall be kept a minimum in a range equal to 25%-50% of the excavation step length.
4. The effect of soil nailing parameters does not appear clearly, due to the limited contribution of the soil nailing in assisting NATM tunnels stabilization that caused by the extension of the active zone around the whole length of the nails.
5. Adding a rigid support to the pre-installation technique proved to significantly reduce the ground deformation by approximately 93%, while it was 53% for pre-installation technique without supports and 34% for the post-installation technique. The significant reduction which was achieved is affected by the assumption that the supporting system is stiff enough to support the expected loads without any movements/deflections. It should be noted that any possible deflection that may occurs for the supporting system, will result in a reduction in system efficiency.

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