Numerical Modeling of Soil Improvement for Construction of Tunnels Using Forepole Presupport

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***Abstract*—Generally, 2D plane strain numerical simulation is employed for analysis of a NATM[1] tunnel construction in practice. Using forepole presuport technique, a soil region at the top of the tunnel has been improved and tunnel section can be advanced safe and with a lower risk condition; However, as forepole elements cannot be modeled by plane strain structural elements, a soil region with high strength parameters is considered on the top of the tunnel which is representative of the soil improved by forepole elements. To calibrate the parameters for the improved soil region on the top of the tunnel, a simple beam supported at the two ends is supposed and subjected to an increasing distributed load by Plaxis and then increase of load capacity and stiffness of the improved beam (beam with forpole elements) in respect to the soil beam are achieved. After calibration of the improved soil, two different analyses of tunnel construction have been performed. Consequently, it is concluded that forepole reduces the displacement; however, it has not sensible effects on reduction of mobilized forces in the initial lining of the tunnel.**

***Index Terms*—shallow tunnel, NATM, numerical modeling, forepole**

I. Introduction

In recent years, due to growing demands, underground structures such as tunnels have become increasingly common in metropolises. The main concerns of tunnel construction in populous regions are the excavation instability and ground settlement which may lead to distress beneath surface structures' foundation and appear cracks in urban facilities and adjacent buildings. The New Austrian Tunneling Method (NATM) is a method in which shotcrete is applied to the surface of the tunnel and the surrounding rock or soil becomes integrated into the support structure. Extreme care is taken during excavation and immediate application of support media prevent unnecessary loosening of media. These tunnels use rounded tunnel shapes to prevent stress concentrations in corners where most failure mechanisms start; and also utilize thin linings to minimize bending moment. Observation of tunnel behavior during construction is an important part of NATM which is important especially in urban areas. This optimizes working procedures and support requirements. Many countries have adopted this method as the primary method of construction. Therefore, this method is selected in this research. Some researchers have applied 2D and 3D numerical models for the analysis of NATM tunnels under static conditions [1]-[3]. On the other hand, Construction of shallow tunnels is one of the major challenges in urban areas. Construction of the tunnel with low soil overburden may result in undesirable settlements of ground surface or urban facilities. Moreover, stability of a tunnel due to propagation of soil failure surface from tunnel into the surface should be noticed. Consequently, to secure the safety of the tunnels and utilities above the tunnel, the deformations induced by tunnel constructed by NATM must be minimized in order to avoid damage of buildings and utilities. In order to achieve this goal, the load-carrying capacity of soil surrounding the tunnel may be improved by means of ground improvement techniques such as jet grouting and forepoles. Some researchers have investigated the effects of jet grouted support to reduce the surface settlements in urban tunneling [4]. Forepoles are load bearing pipes placed at the face and ahead of it on the top of the crown of a tunnel injected with cement grout. Using this pre-support technique, a soil region at the top of the tunnel has been improved and tunnel section can be advanced safe and with a lower risk condition. This method has been used for construction of shallow tunnels in different tunneling projects of Iran [5], [6].

Generally, 2D plane strain numerical simulation is employed for analysis of a NATM tunnel construction in practice. However, as forepole elements cannot be modeled by plane strain structural elements, a soil region with high strength parameters is considered on the top of the tunnel which is representative of the soil improved by forepole elements. Calibration of the soil parameters of the improved soil is a concern which should be studied. For this purpose, a simple model including both forepole and natural soil elements is subjected to simple beam loading for calibration of the improved soil parameters. After determining the parameters of the improved soil model, analysis of a tunnel section with and without pre-support of forepoles have been performed by plane strain model, and the results have been compared.

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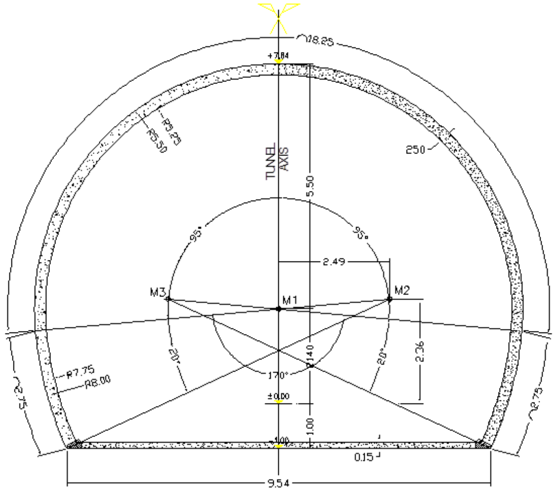


Figure 1. Cross section of the tunnel.

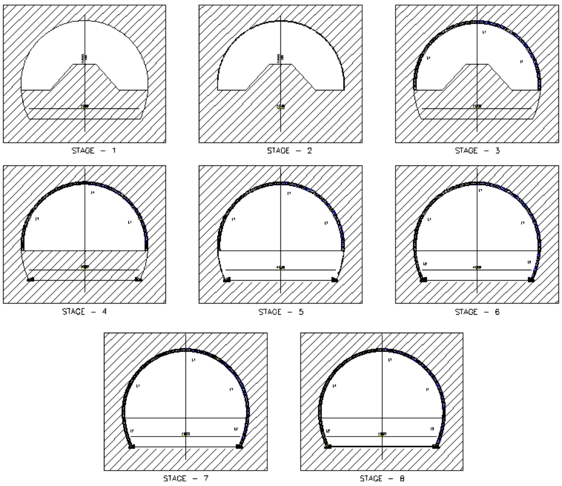


Figure 2. Construction sequences of the tunnel.

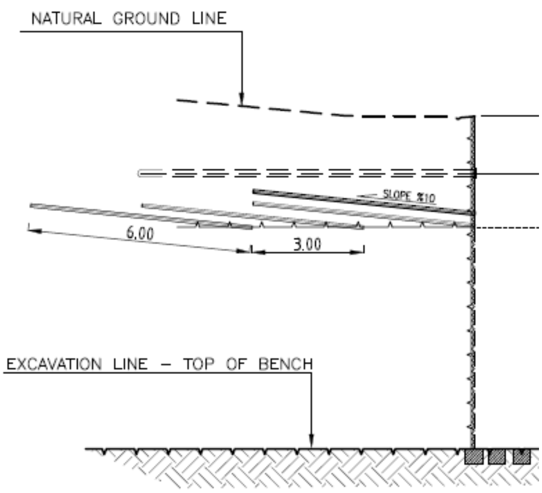


Figure 3. Longitudinal profile of a tunnel with forepoles.

II. Tunnel Section

1.5 lane tunnel with width of 9.54m and height of 8.84m has been selected for analysis. Cross section of the tunnel and related construction stages are brought in Fig. 1 and Fig. 2 respectively. This method begins with partial excavation of the top heading to 1 m length followed by installation of lattice girders and application of shotcrete on the face of the excavation. Next, bench is excavated.

After excavation and support of 1 to 3m of top heading, forepole elements of 6m in length are installed ahead of it and above the tunnel. Fig. 3 shows the schematic longitudinal profile of a tunnel with forepole elements.

III. Numerical Modeling

This section describes 2D analysis of the tunnel section and loading a composite beam using PLAXIS computer software which has built-in features for modelling soil-structure interaction and stages of the construction [7]. The structure and the surrounding soil are modeled together simultaneously. Staged excavation and lining sequence has been incorporated in the model based on the conceptual construction procedure following establishment of the initial stress condition. The tunnel initial lining is statically loaded. The loads are computed by the software directly from the soil-structure interaction based on the material properties for the soil layers.

A. Soil Model

In the present study, soil model namely HS-model (Hardening soil model) is employed for the numerical simulations. It should be noted that 2m filling material are considered using MC-model (Mohr-Coulomb). Soil model parameters are brought in Table I.

TABLE I. Parameters of Soil Layers

The properties of the filling material (Mohr- Coulomb)	
$\phi = 30$ °	Internal friction angle
c = 0.1 Kg cm^{-2}	Cohesion
γ= 1.80 gr cm^{-3}	Natural density
$\nu = 0.3$	Poisson ratio
E = 400 kg cm^{-2}	stiffness
The properties of the sub surface (Hardening soil)	
$\phi_{cu} = 34$ °	Internal friction angle (CU)
c=0.35 Kg cm^{-2}	Cohesion(CU)
γ= 1.90 gr cm^{-3}	Natural density
$\nu = 0.2$	Poisson ratio of unloading/reloading
650 kg cm^{-2}	Secant deformation modulus
0.27	Power of stress level of stiffness

B. Numerical Model for Calibration of the Improved Soil Parameters

To calibrate the parameters for the improved soil region on the top of the tunnel, a simple beam supported at the two ends is supposed and subjected to distributed force. Analysis has conducted for the beam model with and without forepole elements. It should be noted that properties of forepole elements (stiffness and strength) should be divided by the spacing between nails (0.5m in this study) to average the effect in 3D over the distance between forepoles for plane-strain simplification. Fig. 4 shows the simple beam model. Also, vertical displacements of the model are brought in Fig. 5. To calibrate the parameters for the improved soil region on the top of the tunnel, the simple beam is supposed and subjected to an increasing distributed load and then increase of load capacity and stiffness of the beam due to installation of forepoles are achieved.

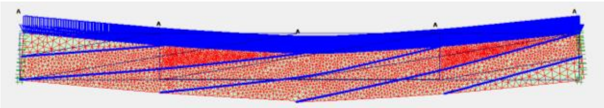


Figure 4. Simple beam model for the improved soil.

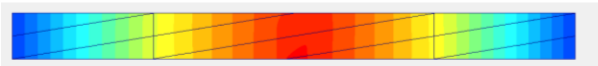


Figure 5. Vertical displacements of simple beam model with forepole.

Fig. 6 shows the diagrams of applying load versus midpoint vertical displacements of the beam for two different scenarios (with and without forepole elements). Higher loading capacity and higher initial stiffness in the beam model with forepole elements are observed in respect to the model without any forepole elements.

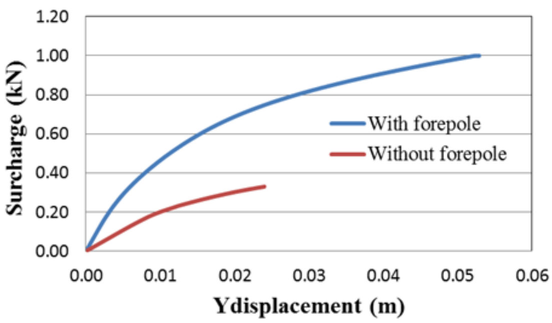


Figure 6. Applying distributed load versus midpoint vertical displacement.

Using the ratios of strengths and initial stiffness for the beam model, increased cohesion and increased young's modulus for the improved region above the tunnel can be estimated as follows:

$$\frac{c'}{c} = 3 \tag{1}$$

$$\frac{E'}{E} = 3.15 \tag{2}$$

In which c' and c are the soil cohesion and updated cohesion of improved soil for analysis of tunnel section, and E' and E are the soil Young modulus and updated Young modulus of improved soil for analysis of tunnel section.

In fact, using the results of the mentioned analyses the bearing capacity of forepole elements in longitudinal direction of tunnel is considered.

C. Numerical Model of Tunnel Construction with and without Forpole

After calibration of the improved soil, two different analyses of tunnel construction have been performed (with and without forepole elements), and the results have been compared with each other. Fig. 7 shows the 2D plane strain model of tunnel construction.

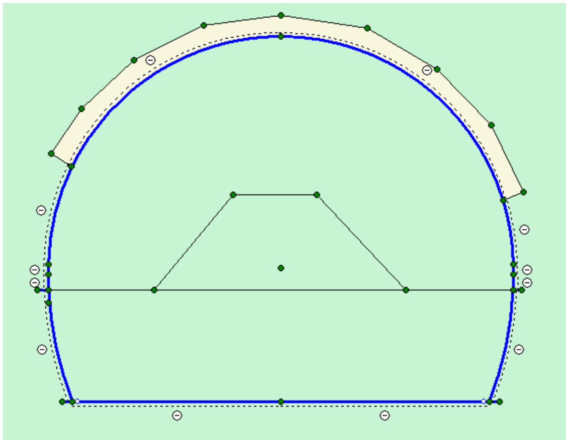
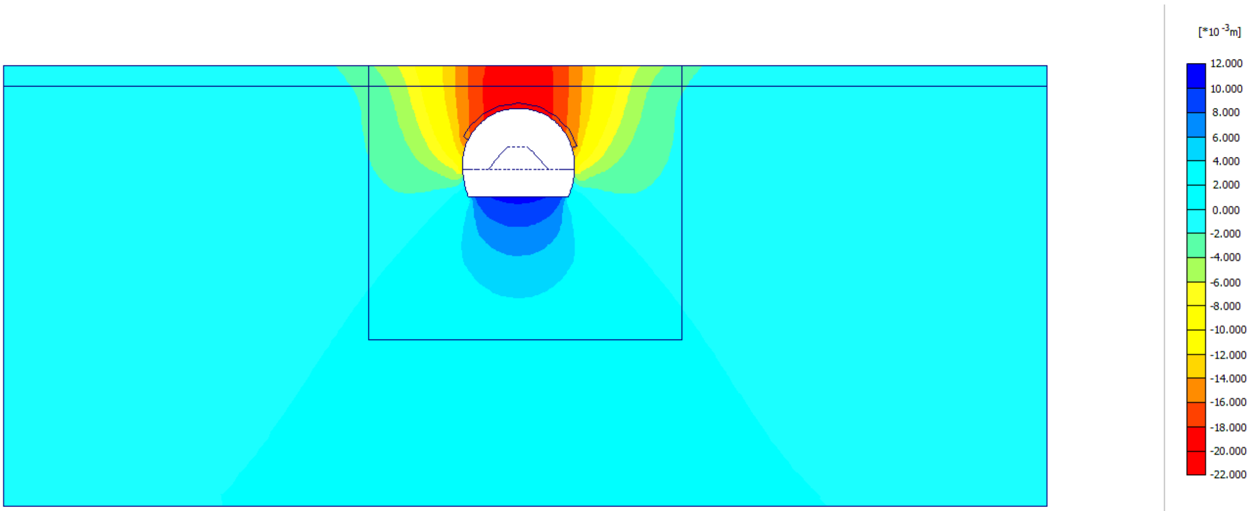
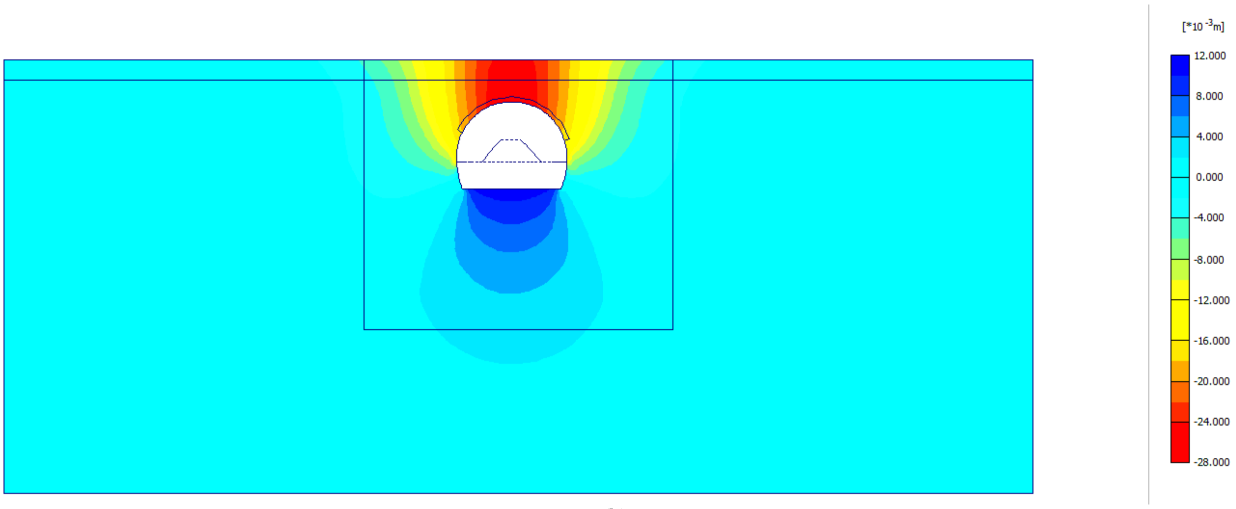


Figure 7. Model of 1.5 lane tunnel.

As can be seen in Fig. 7, the improved soil has been modeled by a region above the crown of the tunnel with updated parameters (as calculated in previous section).



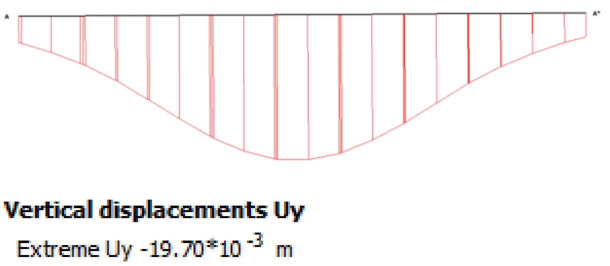
(a)



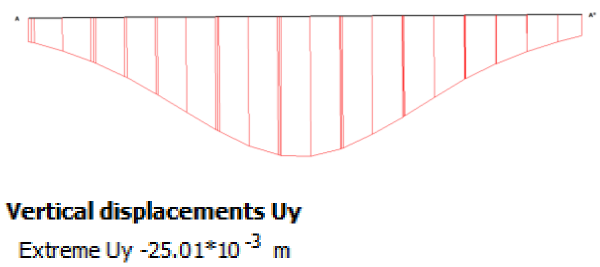
(b)

Figure 8. Vertical displacement of tunnel section: (a) with forepole, (b) without forepole.

Consequently, it is concluded that forepole reduces the maximum displacement from 30mm to 22mm and maximum surface settlement from 25mm to 19mm as shown in Fig. 8 and Fig. 9. In spite of the effect of forepole in reduction of displacement, it has not sensible effect in reduction of mobilized forced in the tunnel lining (Fig. 10).

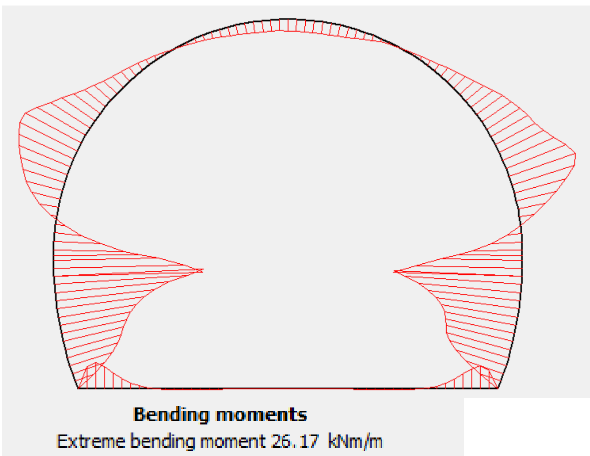


(a)

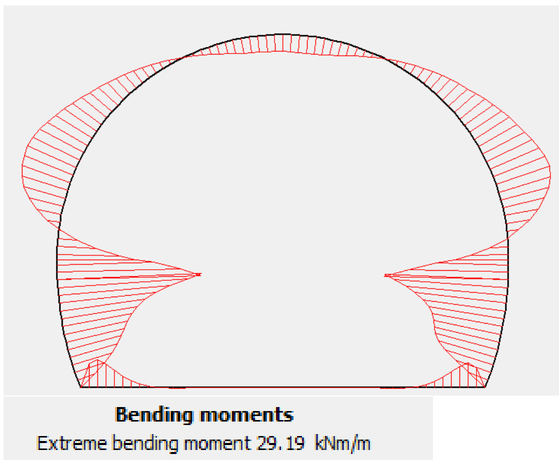


(b)

Figure 9. Profile of surface settlement: (a) with forepole, (b) without forepole.



(a)



(b)

Figure 10. Bending moment: (a) with forepole, (b) without forepole.

IV. Conclusion

A simple beam model is proposed which can evaluate the effect of forepole elements in longitudinal direction of tunnel. Higher loading capacity and higher initial stiffness in the beam model with forepole elements are observed in respect to the model without any forepole elements. After calibration of the parameters of the soil region improved by forepole elements by the proposed beam model, the effects of forepole on the reduction of the vertical displacements due to tunnel construction of shallow tunnel are evaluated. It was found that forepole before excavation can reduce the displacement and surface settlement sensibly; However, It has not sensible effects in reduction of mobilized forces in the tunnel lining.

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