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Comparison of Mohr-Coulomb and Hardening Soil Models' Numerical Estimation of Ground Surface Settlement Caused by Tunneling

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ABSTRACT: Due to in depth tunnel excavation, tensions in the soil are eased, causing elastic and plastic deformations in the area of tunnel and leading to surface settlement at the ground level. Currently, along with the use of numerical methods in analysis and design of engineering projects, it is known that this method has used extensively in the analysis of problems related to geotechnical engineering and tunneling. Selection of the appropriate parameters and soil model can have a significant impact on the results of numerical analysis. The Mohr-Coulomb elastic-plastic model (MC) is one of the most widely used models, used in cases evaluating the hardness of materials, independent of the surface tension. If the Mohr-Coulomb used for numerical modeling of tunnel where in-depth tunneling excavation is involved and where an increase in maximum ground surface settlement and decrease in the reliability of stability of tunnels can be seen, which may not be appropriate in some conditions. The more appropriate model should be used to solve this problem, one that can model the hardness of materials based on changes in the level of stress. In this study, the maximum ground surface settlement due to tunnel excavation, obtained from Mohr- Coulomb model was compared with those of Hardening Soil (HS) Model results. Therefore, the ground surface settlement because of an assumption tunnel in different depths was analyzed with Mohr-Coulomb and Hardening Soil models by using PLAXIS 2D. As a result of the analyzes, it is observed that as the depth of the tunnel increases, the settlements on the ground surface decrease according to Mohr-Coulomb and approach the real values.

Keywords: Finite Element Method, Material models, PLAXIS, Surface settlement, Tunneling

Tünel Kazısından Dolayı Zemin Yüzeyindeki Oturmaların Mohr-Coulomb ve Pekleşen Zemin Modelleriyle Nümerik Tahminlerinin Karşılaştırılması

ÖZET: Zemin içinde yapılan tünel kazısı nedeniyle, zemindeki gerilmeler boşalarak kazı alanında elastik ve plastik deformasyonlara yol açmakta ve zemin yüzeyinde oturmalar meydana gelmektedir. Günümüzde, mühendislik projelerinin tasarım ve analizinde sayısal yöntemlerin kullanımı ile birlikte, Geoteknik mühendisliği ve tünel ile ilgili problemlerin çözümünde bu yöntemin yaygın bir şekilde kullanıldığına tanıklık etmekteyiz. Uygun parametrelerin ve zemin modelinin seçilmesi, nümerik analiz sonuçlarını üzerinde önemli etkiye sahiptir. Mohr-Coulomb (MC) elasto-plastik model malzemelerin sertliğinin yüzey gerilmelerden bağımsız olarak tanımlandığı durumlarda kullanılan en yaygın zemin davranış modellerinden biridir. Tünel modellemelerinde Mohr-Coulomb kullanılması halinde, kazı derinliği arttıkça zemin yüzeyindeki oturmaların gerçek değerlerden fazla çıktığı ve güvenilirliğin azaldığı görülmektedir. Bu problemin çözümü için, gerilme düzeyindeki değişikliklere bağlı olarak malzemelerin sertliğini modelleyebilen daha uygun bir davranış modeli kullanılmalıdır. Bu çalışmada, tünel kazısından dolayı Mohr-Coulomb modelinden elde edilen maksimum zemin yüzey oturmaları Pekleşen Zemin modeli (HS) ile karşılaştırılmıştır. Bu nedenle, varsayılan farklı derinliklerdeki bir tünelden dolayı zemin yüzeyinde oluşacak oturmalar PLAXIS kullanılarak Mohr-Coulomb ve Pekleşen Zemin malzeme modelleriyle analiz edilmiştir. Yapılan analizler sonucunda, Pekleşen Zemin modelinde tünelin derinliği arttıkça zemin yüzeyindeki oturmaların Mohr-Coulomb'a göre azaldığı ve gerçek değerlere daha yaklaştığı görülmektedir.

Anahtar kelimeler: Malzeme modelleri, PLAXIS, Sonlu Elemanlar Metodu, Tünel, Yüzey oturması

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INTRODUCTION

Due to urbanization and population growth in recent decades, the topic of efficient use of urban spaces, including underground space, has been frequently discussed (Chakeri et al., 2013). Underground space applications include development of urban infrastructure, transportation, water supply lines, and so on (Salimi et al., 2013). Ground surface settlement caused by tunnel excavation, especially in urban areas, has special significance. The process of these settlements differs according to the depth of excavation in different areas, increasing or decreasing depending on the depth of excavating (Melis et al., 2002; Chakeri et al., 2013; Papastamos et al., 2015). Notably, when excavation exceeds a certain depth, ground surface settlement will decrease (Boscardin and Cording, 1989; Guglielmetti et al., 2008). In order to prevent damage to surface structures and existing buildings due to tunnel excavation, a correct and reliable estimate of ground surface settlement is necessary (Fasihnikoutalab et al., 2012). A variety of different methods are provided to estimate ground surface settlement due to tunneling. These methods have been categorized into three groups: experimental, analytical and numerical methods. The experimental and analytical methods are only useable in specific geological conditions, for in some geological conditions they are not reliable (Franzius, 2002). Thanks to advancements in computer science and, accordingly, the development of advanced models for introduction of materials, numerical methods command a high acceptance rate among designers.

According to measurements in place, analytical and empirical relations, the geometry of circles settlement, and the general pattern of movement of the ground surface due to tunneling is such that, after the increase in excavation depth, the settlement of the ground surface is low and the trough forms a wider depression. That is, by reducing the depth of tunnel excavation, the settlement of the ground surface increases, and the shape of the trough grows narrower (Chou and Bobet, 2002). Most empirically functional relationships are based on studies by Peck (Peck, 1969), which are expressed in the equation 1.

$$S_v = S_{max} e^{-\frac{x^2}{2i^2}} \tag{1}$$

According to Peck, the trough settlement shape in a cross section is approximated with acceptable accuracy by a normal distribution curve (curve of Gauss), and the maximum settlement coincides with the axis of the tunnel at ground level (Figure 1).

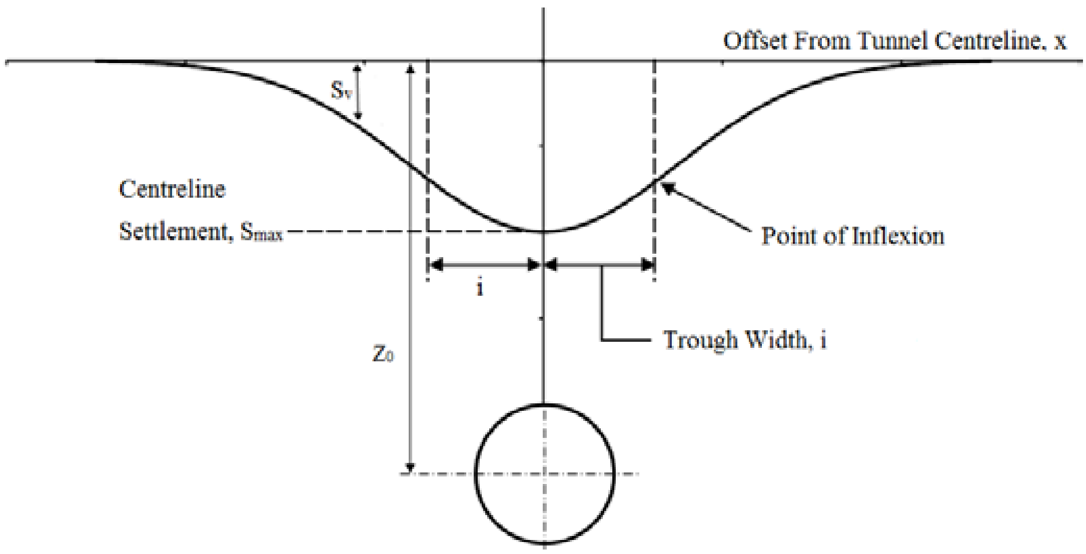

Figure 1. Ground surface settlement trough induced by a single tunnel (Ma et al., 2014)

In equation (1), "S_v" is the amount of ground surface settlement at a point of "x" distance from the axis of the tunnel; "S_{max}" is the maximum ground surface settlement at "x = 0"; and "i" is the horizontal distance from the tunnel centerline to the point of inflection on the ground surface settlement, estimated according to the depth of the tunnel and the soil type. The value of "S_{max}" is calculated from equation (2) (O'Reilly and New, 1982).

$$S_{max} = 0.313 \frac{V_l D^2}{k Z_0} \tag{2}$$

In this equation, "V_l" is the parameter of volume loos which is determined based on the procedure of tunneling; "D" is the diameter of tunnel; "k" is a dimensionless trough width parameter and "Z_0" is the depth of the tunnel. Further studies have been conducted by other researchers and are in line with the conclusions of the Pack reports (Attewell and Farmer, 1974; Attewell and Woodman, 1982; O'Reilly and New, 1982).

The general form of relationship "i" is set as "i = kZ_0". According to this relationship, with increasing insertion depth of the tunnel, when the value of "i" increases, according to equation (1), the amount of ground surface settlement is reduced and, thus, the width of the trough settlement increases. Therefore, it is necessary to determine the optimal depth of tunnel excavation based on the amount of settlement in the preliminary design of the track and the depth of the tunnel insertion.

Numerical modeling of the tunneling with simple models has proven inaccurate due to the lack of ability to properly simulate the phenomenon of unloading and the lack of distinction between the hardships of initial loading and unloading/reloading; thus, the pattern of movement of the ground and settlement values have been incorrectly and illogically expressed (Schanz et al., 1999; Boháč et al., 2002). The process of excavating a tunnel in the ground is such that, along with the excavating, the fulcrum portion of the soil will be removed. In other words, the weight of excavated soil is like a body force downward, which disappears after the tunnel is created. Consequently, when excavating and removing a body force downward on the floor of the tunnel is equivalent to adding a body force upwards, which leads to the creation of high-scurry on the floor of the tunnel (Corp, 2002). This conclusion is justified according to Newton›s Third Law and the principle of action and interaction. Of course, on the run, high-scurry on the floor of the tunnels, especially at shallow depths, due to low side pressure results in only a small amount of pressure. In numerical modeling, especially with simple linear models, such as linear elastic and the Mohr-Coulomb models, the rate of high-scurry is expected to be higher than that found in reality. Thus, using simple models causes a change in the expected pattern of movement and the subsequent change of ground surface settlement (Leca et al., 2007). In this paper the performance of numerical modeling in the estimation of ground movement patterns caused by excavating a hypothetical tunnel at various depths was modeled with Mohr-Coulomb and advanced Hardening Soil models using PLAXIS 2D, and a comparison was made between the general trend of ground surface settlement and high-scurry on the floor of the tunnel.

Features of the Mohr-Coulomb model

In the discussion of numerical modeling, it will be determined that the model and corresponding input parameters have critical effects on the results of analysis. In fact, models suggest a mathematical description of the mechanical behavior of materials, which affect important aspects of material behavior. The Mohr-Coulomb model is a perfect linear elastic-plastic model requiring five input parameters to express the stress-strain behavior. Among models, this model, because of the simplicity of formulation as well as the lesser data input determined by simple tests, has more applications than other models. With this model, problems such as the bearing capacity of soil or slope stability can easily have designed. In contrast, this model has fundamental flaw with respect to analyzing deformation problems such as tunneling and excavation (Obrzud, 2010). One of the weaknesses of this model on issues related to excavating has to do with the constant of stiffness and lack of distinction between initial loading and unloading/loading of materials, especially in soil. The difference between prediction of the stiffness in this model and that of actual tests such as triaxial and consolidation on a sample of soil is shown in Figure (2). In this figure, it is seen that there is a considerable difference between the actual behavior of material and that predicted by the Mohr-Coulomb model.

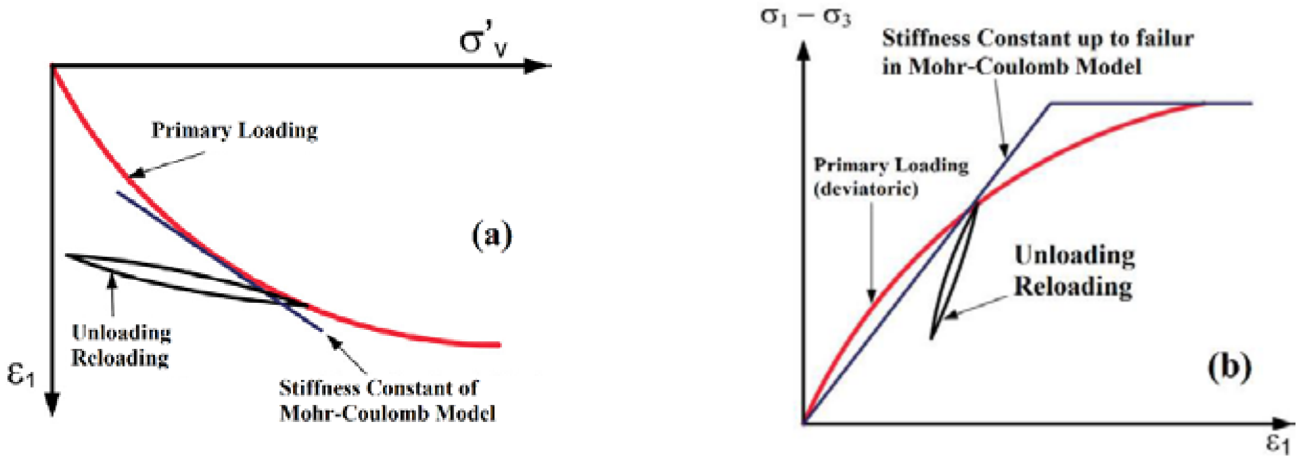

Figure 2. Typical schematic results from compression tests. (a) one-dimensional (b) triaxial (Schweiger, 2008)

Features of Hardening Soil model

Advanced models, despite representing important behavioral aspects of materials and having fewer parameters and simpler equations, are acceptable to most designers. One of these models is the Hardening Soil model. The Hardening Soil model was established in 1999 by (Schanz et al., 1999) in the framework of the theory of elasticity. In this model, the strains (elastic and plastic) are calculated based on the hardness of the surface tension and this hardness is different for the initial loading and unloading/loading (Obrzud, 2010). In this model, the behavior of material is nonlinear before the break, and after defeating, behavior is determined based on Mohr-Coulomb strength parameters (cohesion and angle of internal friction). The overall behavior of the stress-strain, along with a variety of stiffness parameters is shown in Figure 3.

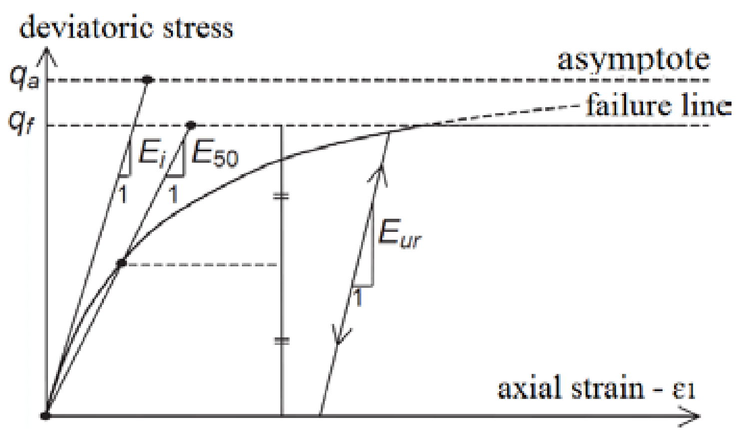

Figure 3. Hyperbolic stress-strain relationship used in Hardening Soil model (Obrzud, 2010)

Three types of stiffness have been defined in this model: loading stiffness , based on the results of triaxial pressure test; unloading stiffness , based on the results of triaxial unloading pressure test; and stiffness loading , based on the results of a one-dimensional consolidation test. The approximate relationship between the hardness parameters is suggested by and for most soil materials (Obrzud, 2010; Brinkgreve and Al-Khoury, 2016). In this paper, the performance of this model compared to the Mohr-Coulomb model in tunneling projects and ground motion pattern prediction is investigated.

MATERIALS and METHOD

Plane Strain Soil Model

To evaluate the performance of the Mohr-Coulomb and Hardening Soil models to estimate the ground surface settlement caused by tunnel excavating at various depths and to investigate the pattern of movement in the area around the tunnel, the geometry of the tunnel with a diameter of 7 meters for different depths was modeled, as shown in Figure 4. The intent was to investigate the effect of depth factors (h/d) for different values 1, 2, 3 and 4. Simulations for different depths for both types of models, Mohr-Coulomb and Hardening Soil, was done. The distance between the boundary of the floor of the model and the lower boundary of the tunnel plays an important role in the pattern of displacement, particularly with high-scurry on the floor of the tunnels in the simulation (Schweiger, 2008). To eliminate the effect of this factor, the bottom line intended at a fixed distance (2d) for all models and the only variable is the depth of tunnel placement in each model.

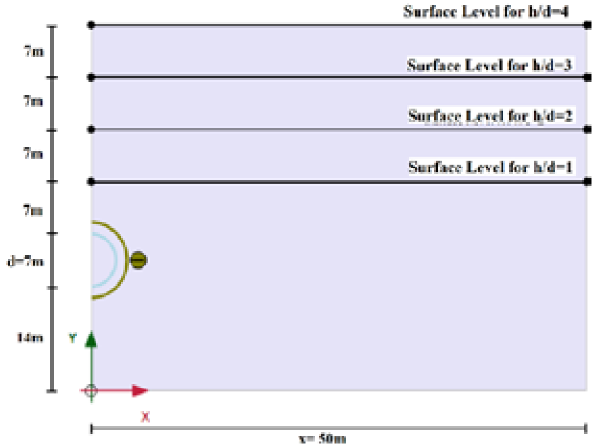

Figure 4. Geometry of the tunnel for different depths

In Table 1, the physical and mechanical parameters of a medium dense sand sample used for both models is shown (Das and Sobhan, 2016; Brinkgreve and Al-Khoury, 2016).

Table 1. Properties of dense sand for MC and HS models

Material	Type	γ_{wet}	γ_{sat}	υ	c_{ref}	ϕ	Ψ	m			
		kN m^{-3}	kN m^{-3}	kN m^{-2}	kN m^{-2}	kN m^{-2}	-	kN m^{-2}	[°]	[°]	-
Medium dense Sand	HS	16.5	18	34e3	34e3	102e3	0.35	0.2	32	0	0.5
	MC	16.5	18	34e3	-	-	0.35	0.2	32	0	-

One of the reasons for using the Hardening Soil model is its association with the parameters of the Mohr-Coulomb model. As with the Mohr-Coulomb model, parameters such as cohesive strength, friction angle, and angle of dilation control failure area. As mentioned before, the major difference between these two models is the definition of soil stiffness during loading/unloading and behavior of stress-strain before nonlinear failure.

RESULTS AND DISCUSSIONS

Results of the modeling are presented in Figure (5) and Figure (6). In Figure (5), maximum ground surface settlement and in Figure (6), the pattern of displacement for different values of (h/d) are presented for both models.

It can be observed from Figure (5a) that in simulations with the Mohr-Coulomb model the increase in settlement does not occur along with reduction in depth. In this way, the maximum amount of surface settlement is estimated for (h/d =1), but the process of settlement reduction is not be repeated along with the ratio of (h/d).

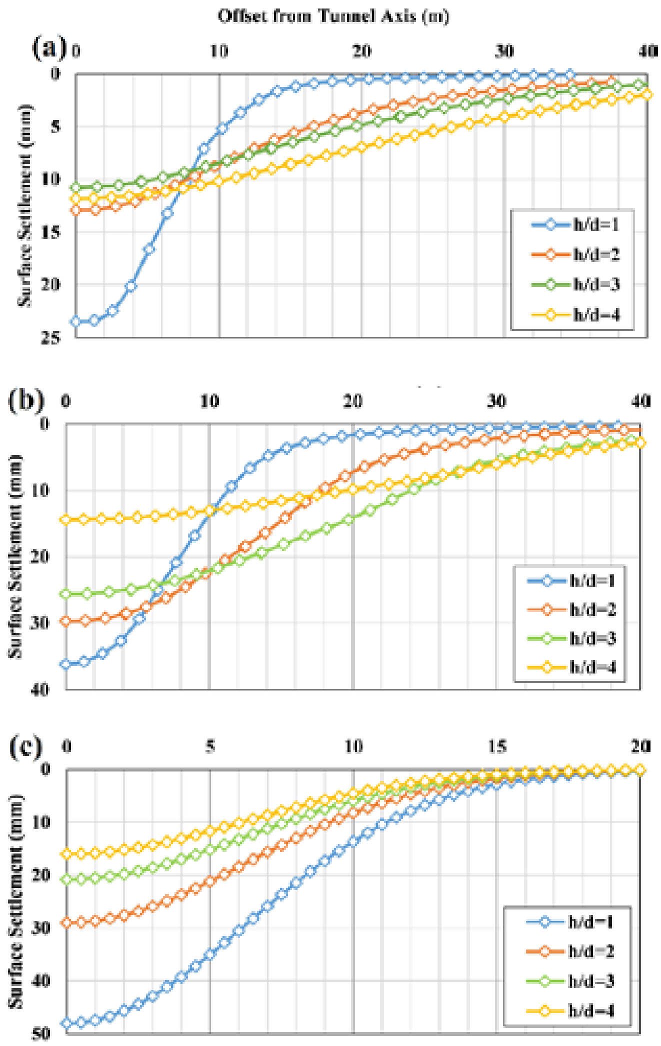

Figure 5. Surface settlement curves due to tunneling in different depths (a) MC model (b) HS model (c) Peck equation

The pattern of deformation around the tunnel in Mohr-Coulomb model is shown in Figure (6a). According to the figure, it is observed that the high-scurry on the floor of the tunnels modeled with Mohr-Coulomb occurs even for shallow depths of tunnel insertion, and this makes the paradigm shift in the movement of the crown of the tunnel and, as a result, the surface settlement of the ground. In this case, the upward force in the area of the floor (uplift) has reduced deformation down the tunnel walls and the crown. Thus, in the Mohr-Coulomb model, the value of surface settlement is less than the Hardening Soil model. On the other hand, according to Figure (5b) by using the Hardening Soil model, with reducing the depth of the tunnels, the settlement steadily increased and the trough shape became narrower and deeper, a position also demonstrated according to the empirical analysis of the settlement, as mentioned in the introduction and shown in Figure (5c). According to Figure (6b), it is observed that the movement concentration is on the crown of the tunnel, and with increasing excavation depth, part of the movement is seen in the range of the tunnel excavation (as the high-scurry on the floor). These values are more rationally obtained than those from the Mohr-Coulomb model. Compared with Hardening Soil model, the Mohr-Coulomb model shows a large amount of uplift, even at shallow depths, less often seen in the implementation of shallow tunnels.

(a)

(b)

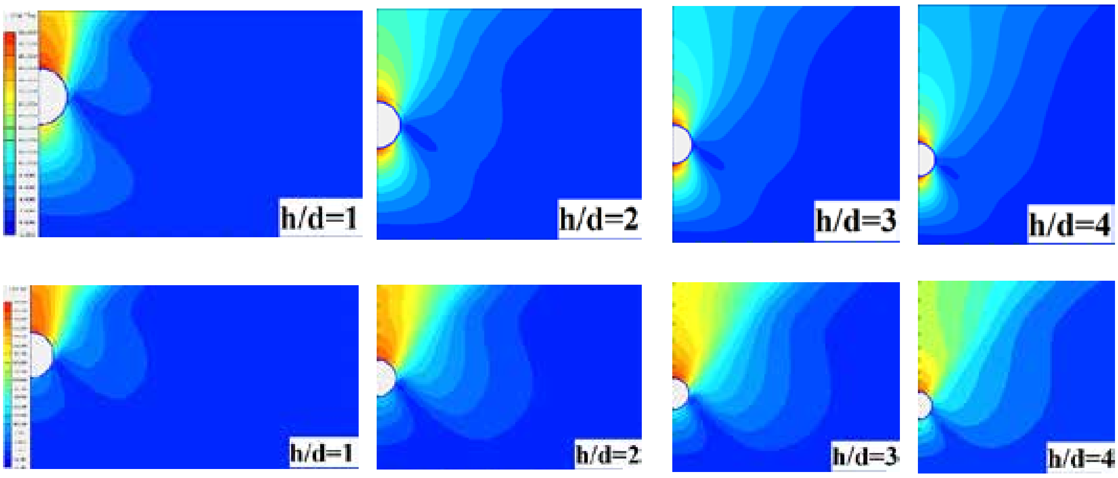

Figure 6. Pattern of deformation around tunnel (a) Mohr-Coulomb model (b) Hardening Soil model

CONCLUSION

Materials behavior in numerical modeling of geotechnical engineering problems has an important role in predicting movement patterns. Overall, a reasonable estimate of the ground movement, especially in urban areas, due to the impact of underground excavating, requires use of suitable models having the ability to simulate the behavior of the most important aspects of the soil. Stiffness of stress in the behavioral models and distinguishing of stiffness between initial loading and unloading/reloading are important aspects of simulation in the discussion of excavation issues, all which play an important role in the prediction of ground movement. The overall pattern of movement due to high-scurry on the floor is the most important issue in numerical simulation of underground excavating. In this paper, it will be evident that the pattern of movement represented by the Hardening Soil model is a more accurate representation of reality than that rendered by the Mohr-Coulomb model for a number of reasons having to do with factors such as: stiffness definition and difference in loading/unloading stiffness, high-scurry on the floor of the tunnel, and its focus of movement of the tunnel's crest and walls. In the Hardening Soil model, increases in ground surface settlement have been well anticipated along with a decrease in depth. Therefore, it is recommended that analysts employ advanced models to simulate excavation issues.

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