Geomechanics and Engineering, *Vol. 16, No. 6 (2018) 643-654*
DOI: https://doi.org/10.12989/gae.2018.16.6.643

Effect of the lateral earth pressure coefficient on settlements during mechanized tunneling

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(Received May 28, 2018, Revised August 15, 2018, Accepted November 8, 2018)

Abstract. Tunnel excavation leads to a disturbance on the initial stress balance of surrounding soils, which causes convergences around the tunnel and settlements at the ground surface. Considering the effective impact of settlements on the structures at the surface, it is necessary to estimate them, especially in urban areas. In the present study, ground settlements due to the excavation of East-West Line 7 of the Tehran Metro (EWL7) and the Abuzar tunnels are evaluated and the effect of the lateral earth pressure coefficient (K_0) on their extension is investigated. The excavation of the tunnels was performed by TBMs (Tunnel Boring Machines). The coefficient of lateral earth pressure (K_0) is one of the most important geotechnical parameters for tunnel design and is greatly influenced by the geological characteristics of the surrounding soil mass along the tunnel route. The real (in-situ) settlements of the ground surface were measured experimentally using leveling methods along the studied tunnels and the results were compared with evaluated settlements obtained from both semi-empirical and numerical methods (using the finite difference software FLAC3D). The comparisons permitted to show that the adopted numerical models can effectively be used to predict settlements induced by a tunnel excavation. Then a numerical parametric study was conducted to show the influence of the K_0 values on the ground settlements. Numerical investigations also showed that the shapes of settlement trough of the studied tunnels, in a transverse section, are not similar because of their different diameters and depths of the tunnels.

Keywords: tunnel boring machine; ground settlement; numerical model; lateral earth pressure coefficient

1. Introduction

Excavation of tunnels and other underground spaces disturbs the initial stress state of the soil mass. This process induces displacements of the soil surrounding the tunnel. Depending on the depth of the tunnel and on the soil characteristics, the tunnel boundary convergence can propagate towards the surface which causes ground settlements. Many surface and sub-surface structures make underground construction works very delicate due to the influence of these ground settlements, which should be definitely controlled to acceptable levels

This problem was studied by different authors. Most of the studies are based on the work of Peck (1969) who analyzed a number of cases and indicated that the transverse profile of surface settlements can be described by an inversed normal distribution (Gaussian) curve. Ding *et al.* (2017) shows that the surface settlements curves can present skewed and normal distribution characteristics when the tunnel is respectively within the scope of the disturbance and outside the scope of the disturbance.

This topic is generally relevant to shallow tunnels and has attracted interest from researchers during the last 50 years (Cording and Hansmire 1975, OReilly and New 1982, Mair and Taylor 1997, Leca and New, 2007, Guglielmetti *et al.* 2008, Mair 2008, Migliazza *et al.* 2009, Fargnoli *et al.* 2013, Standing and Selemetas 2013, Carranza-Torres, *et al.* 2013, Fang *et al.* 2014, Janin *et al.* 2015, Xie *et al.* 2016, Yang and Li 2017 and Yang and Wang 2018).

The settlement trough is widely influenced by the geological and the geotechnical characteristics of the soil. Leca and New (2007) pointed out that geological characteristics of the ground surrounding the tunnel, the tunnel geometry and its depth, the excavation method, the workmanship and management quality are parameters affecting the ground settlements caused by the excavation of shallow tunnels.

The coefficient of lateral earth pressure (K_0) is one of the most important geotechnical parameters of the soil mass. This parameter is defined as the ratio of the horizontal in-situ stress over the vertical in-situ stress, (σ'_h/σ'_v). The effect of K_0 on ground settlement due to tunneling was analyzed by several authors (Gunn 1993, Addenbrooke *et al.* 1997, Lee and Ng 2002, Guedes and Santos Pereira 2002, Dolezalova 2002, Franzius *et al.* 2005,

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http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

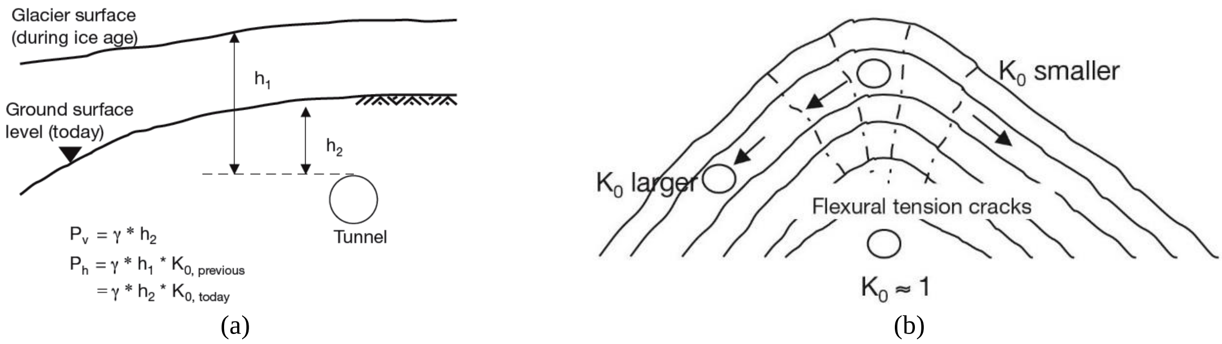


Fig. 1. Examples of K_0 greater than regular value (Chapman *et al.* 2010)

Möller 2006, Masin 2009, Namazi *et al.* 2012). Estimation of the initial stresses and of an accurate value of K_0 is one of the most important issues in geotechnical engineering. K_0 is greatly influenced by geological factors such as the soil type, the groundwater configuration, the overburden thickness (tunnel depth), etc. According to Möller (2006), the initial stress distribution in the ground is mostly unknown and quite a number of factors such as tectonic movements, thermic, creep or weathering can influence it. The following formulas are often adopted

$$K_0 = (1 - \sin\varphi') \text{ For granular soils} \quad (1)$$

$$K_0 = (1 - \sin\varphi')(OCR)^{\sin\varphi'} \text{ For cohesive soils} \quad (2)$$

where φ', and OCR are respectively the internal friction angle and the over-consolidation ratio of the soil. The over-consolidation ratio (OCR) is defined as the ratio of the maximum past pressure to the existing effective overburden pressure. In general, for NC (Normally Consolidated) clays, OCR=1 and for OC (Over Consolidated) clays, OCR > 1. This parameter is used to estimate some of the geotechnical parameters of soil such as consolidation in clays, for correlation of strength properties, and for estimating K_0. Chapman *et al.* (2010) considering several examples of tunneling in various situations, pointed out that the K_0 values can be in an extensive and conceptual range of values ($0.1 < K_0 < 3$).

Fig 1 shows examples of conditions for that K_0 is greater than regular values. In the case of Fig. 1(a), the pressures of glaciers from past ice ages as well as pre-consolidation pressures are the factors which cause to the K_0 parameter exceeds values higher than 1. Fig. 1(b) shows the tunnel excavation case of folded geological layers such as synclines and anticlines. In this case, due to the ground surface topography, the value of σ_v can be higher and lower than the one in case of a flat ground. Then the value of K_0 can be higher and smaller than regular values. It can be said that tunneling in the vicinity of very large and weighty structures, such as towers and skyscrapers is similar to the conditions described through Fig. 1(b). Table 1 represents the previous studies done by researchers to investigate the effect of K_0 on ground settlements due to tunneling. As seen in this Table, the used K_0 values are in the range from 0.5 to 2.0.

In this study, a numerical parametric study on the effect of K_0 on the ground settlements due to tunneling is presented. For this purpose, at first, real settlements obtained from two tunnel sites are used to validate numerical models. Then the effect of K_0 on ground settlement due to the excavation of the tunnels is investigated considering the change in tunnel diameters and depths.

2. Tunnel sites description

Two cases studies are presented in this work: East-West Line 7 excavation of the Tehran Metro (EWL7) and the Abuzar tunnels. They are respectively located in the South and in the South-East of Tehran. The geographical position of the studied tunnels is shown in Fig. 2.

The EWL7 tunnel, with the length of approximately 12 km, is circular shaped with an external diameter of 9.16 m. It was excavated using an Earth Pressure Balanced – Tunneling Boring Machine (EPB-TBM). In the present research, because of geological homogeneity, the tunnel part from chainage 1500 to chainage 2000 is selected for the numerical analysis.

The Abuzar water conveyance tunnel has a length of approximately 4 km and was also excavated using an EPB-TBM. This tunnel is circular shaped with the external diameter of 4.2 m. In this study, only the tunnel section from chainage 0 to chainage 500 m is considered because of the low overburden above the tunnel and of the available monitoring data of the ground settlements.

3. Geological situation of Tehran

Tehran city is located in the quaternary sediments originated from adjacent hills and mountains. Geological findings confirm that the quaternary alluvia and moraine deposits are present in the Tehran plain. Tehran plain (involves the Tehran city) mainly consists of alluvial materials, which are often the product of erosion and re-deposition of former sediments and are called, in general, Tehran's alluvia. Rieben (1955, 1966) and Pedrami (1981) classified the Tehran's alluvia into four formations identified as A, B (Bn and Bs), C, and D from the oldest to the youngest (Fig. 2). According to the geological situation of Tehran plain, illustrated in Fig. 2, the proposed tunnel route (EWL7 and Abuzar tunnels) passes through the D formation. According to Cheshomi *et al.* (2009) the

Table 1 Values and ranges of K_0 used by researchers

Researcher	Soil type	K_0 value	Method of research	Brief results
Gunn (1993)	London Clay	K_0=1	Numerically, 2D	Wider settlement troughs were obtained by comparison with the Gaussian curve.
Addenbrooke *et al.* (1997)	London Clay	K_0=1.5	Numerically, 2D and 3D	Obtained surface settlement troughs are wider than the natural case. The three-dimensional results present more credible results.
Lee and Ng (2002)	Remolded Soil Similar to London Clay	K_0=1.5	Numerically, 3D	The results were similar to the results of Addenbrooke *et al.*, 1997
Guedes and Santos Pereira (2002)	Remolded Soil with Varying E	0.5< K_0 <1	Numerically, 2D	For K_0=0.5 and K_0=1.0 both two-dimensional and three-dimensional analysis give almost the same shape of the settlement trough.
Dolezalova (2002)	Remolded Soil	0.5< K_0 <1.5	Numerically, 2D and 3D	The results of K_0=0.5 were satisfactory when compared to the shape of the measured real settlement trough.
Franzius *et al.* (2005)	London Clay	0.5< K_0 <1.5	Numerically, 2D and 3D	Comparing the results of surface settlements to field (real) data, neither the two-dimensional analysis nor the three-dimensional analysis was precise enough to match the measurement.
Möller (2006)	Sandy clay or Clayey sand (Remolded)	0.5< K_0 <2	Numerically, 2D and 3D	Ground settlement generally decreases with increasing of K_0. Ground heaves can occur instead of ground settlements if K_0 is larger than the unity.
Xie *et al.* (2016)	Silty clay, Sandy silt, and Silty Sand	0.5< K_0 <1.3	Numerically, 3D	Ground settlement generally decreased with increasing of K_0.

thickness of this formation is generally lower than 10 m. Thus, considering the soil cover thickness above the tunnels (C), 21.43 meters for the EWL7 tunnel and 5.07 meters for the Abuzar one, and the low thickness of the alluvial layers, it can be said that the EWL7 tunnel also encounters older alluvia such as the C formation (Golpasand *et al.* 2014).

4. Geotechnical investigations

Geotechnical properties of the soil layers and the location of the groundwater level were determined through site investigations included borehole and test-pits drilling, performing in-situ tests, and laboratory tests. The geological profile of the route of the tunnels are presented in Fig. 3. As seen in this Figure, soils of the studied tunnels were categorized into three geological units called soil types that are named ET-1, ET-2, and ET-3 (Table 2). Soils categorization were done based on the recommendations of Takano (2000) and DAUB (1997). Accordingly, the content of fine grains is the main factor for soil categorization in mechanized tunneling. In the present study, this factor and other geotechnical parameters were used to categorize the soils into three engineering geological types (soil types) that are shown in Fig. 3 and described in Table 2. As shown in Fig. 3, EWL7 tunnel was driven into ET-1 and ET-3 soil types, whereas Abuzar tunnel has been mainly driven into ET-2 soil types. It is also seen that the groundwater level is above the EWL7 tunnel and is lower than Abuzar tunnel. It means that excavation of Abuzar tunnel was conducted into dry and unsaturated zone whereas EWL7 tunnel has been excavated in the saturated zone. Physical and mechanical properties of the soil types are presented in Table 3.

5. Settlement analysis

Ground settlement caused by the excavation of the EWL7 and the Abuzar tunnels is analyzed using several methods. Firstly, real settlements measured experimentally by leveling methods are presented. Then, semi-empirical and numerical methods are employed to evaluate the settlement of ground surface. Comparison of the results obtained by different methods is then conducted to estimate the performance of numerical models. Finally, the effect of K_0 on ground settlement due to tunneling will be investigated by numerical modeling methods.

5.1 Measuring the real (in-situ) settlements at tunnel sites

Leveling and surveying methods were carried out in order to measure the surface settlements induced by excavation of EWL7 and Abuzar tunnels. Some control points were selected on the ground surface above tunnel center line (C.L.) and measuring equipment, pins, were installed at these points. Locations of pins installed above Abuzar and EWL7 tunnels center line are indicated in Figs. 4 and 5, respectively. Installation of the pins and monitoring of their displacement was done based on the principals recommended by Dunnicliff (1993). The ground surface is often covered by asphalt or pavement in urban areas. Therefore, the measuring equipment must be bolted in depths lower than the level of the asphalt or pavement and the upper part of the equipment's rod (approximately 20 cm) must be free from the ground. The ground settlement was measured using leveling techniques. Required precision to measure ground displacement is 0.5 mm. Regarding the main purpose of this study and the practical limitations in urban areas, only the Smax (maximum ground settlement which occurred above the C.L. of the tunnels) was measured and subjected to more discussion. The monitoring of the displacements was started before the passing of shield machine and continued until reaching a constant

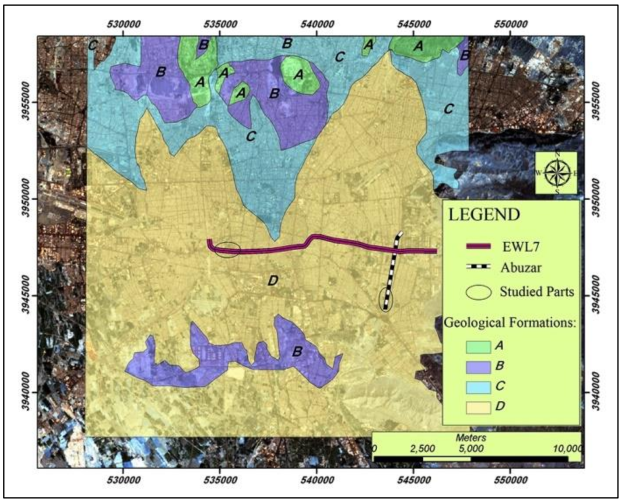
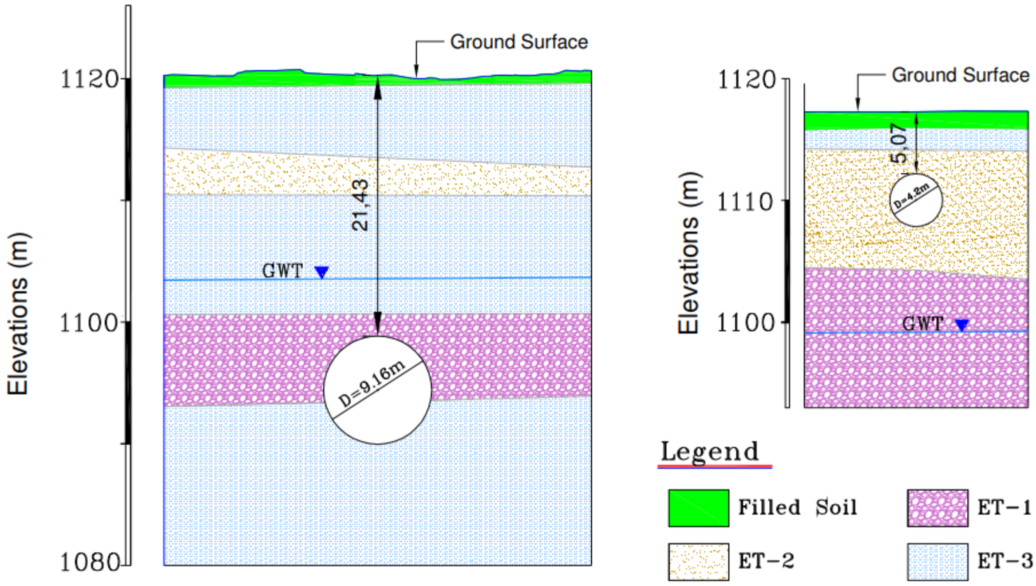


Fig. 2 Geological properties of the Tehran city and location of the studied tunnels (JIKA 2000)



(a) EWL7 (b) Abuzar

Fig. 3 Geological profile of the tunnels in the studied section

Table 2 Geological categorization of the soils

Soil types	Description	Passing from 75 µm	USCS*
Fill	Very soft sandy clay	Various	-
ET-1	Gravely sand with clay	12 to 30%	GC, GM, GW SC, SC-SM
ET-2	Silty/clayey sand with gravel	30 to 60%	SC, SM, CL
ET-3	Silty clay with sand	Over 60%	CL, ML, CL-ML, rarely CH

*Unified Soil Classification System

Table 3 Geotechnical parameters of soil types

Soil types	C′ (kPa)	φ' (degrees)	E′ (MPa)	ν	γ_d (kN/m^3)	γ_{sat} (kN/m^3)	OCR	K_0	ψ (degrees)
Fill	6	20	15	0.35	16	19	1	0.65	0
ET-1	14	33	53	0.31	18.5	20.5	2	0.66	3
ET-2	20	31	35	0.33	19	21.5	2	0.70	1
ET-3	25	28	25	0.35	18.5	21	2	0.77	0

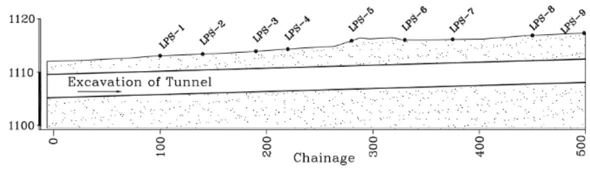


Fig. 4 Location of the monitored points above the Abuzar tunnel

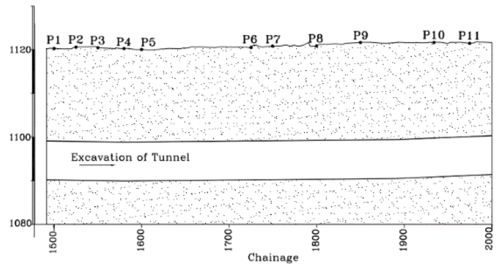


Fig. 5 Location of the monitored points above the EWL7 tunnel

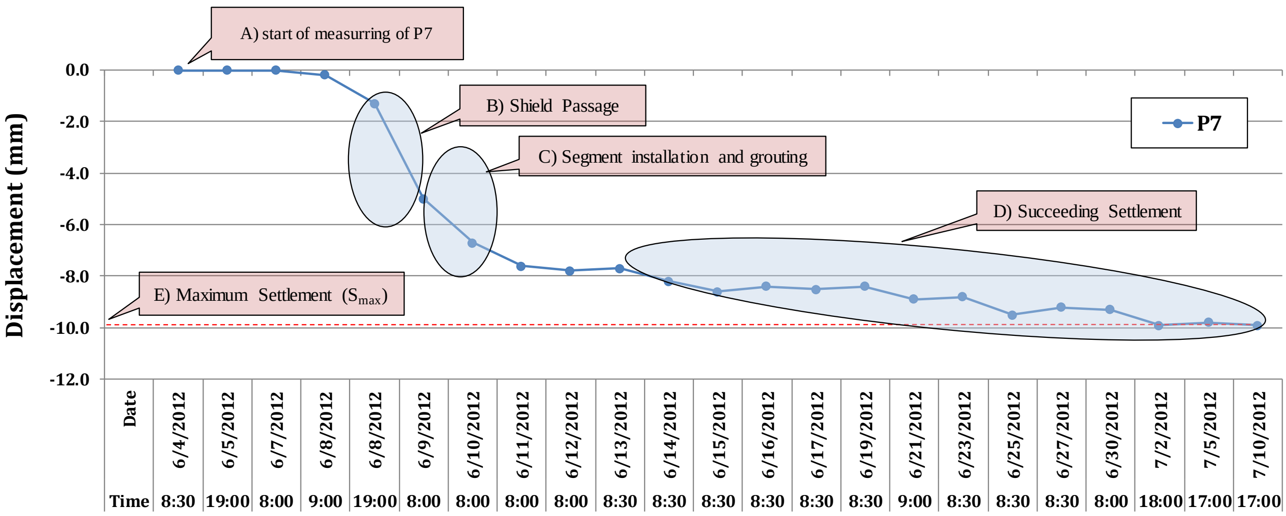


Fig. 6 A sample of settlement measuring diagram (P7 on EWL7 tunnel route)

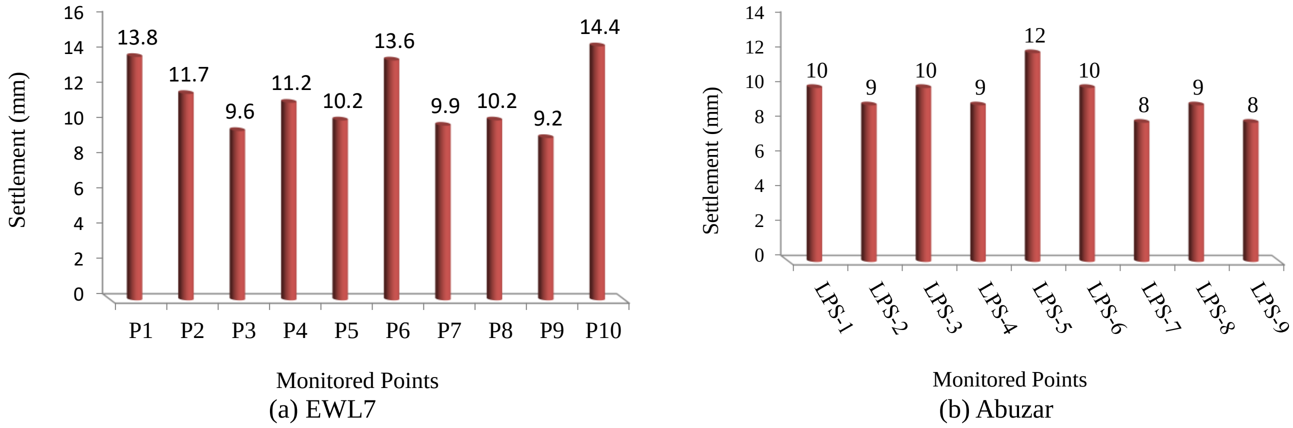


Fig. 7 Monitored maximum settlements (Golpasand 2015)

Table 4 Predicted ground settlements evaluated from the semi-empirical method

Tunnel	Engineering Geological Types	Input parameters to predict settlement					S_{max} (mm)
		V_L(%)*	k*	z_0 (m)	D (m)	i (m)	
Abuzar	ET-2	0.5 ±1	0.43	7.17	4.35	2.58	(7.7) ~ (11.5)
EWL7	ET-1, ET-3	0.6 ±1	0.43	26.01	9.16	10.75	(11.7) ~ (16.4)

*The values of k and V_L are based on Golpasand *et al.* (2014, 2016)

value corresponding to the maximum settlement (Smax). The process of the settlement recording was continued nearly around 15 to 30 days after the crossing of the shield machine.

Fig. 6 shows the displacement of the pins (for example P7 on EWL7 tunnel route). As seen in this figure, vertical displacement at this point reaches a value of 9.9 mm after a 36-day period. As previously indicated, settlement measuring has been continued until the pins would be reached to the constant level or their displacements were stopped. Fig. 7 shows the bar chart of the monitored maximum settlements due to the excavation of the tunnels. The settlements are in the ranges of 9 mm~14 mm for the EWL7 tunnel and of 8 mm~12 mm for the Abuzar tunnel, respectively.

5.2 Semi-empirical method

Peck (1969) proposed an equation to study ground settlements due to tunneling in transverse section

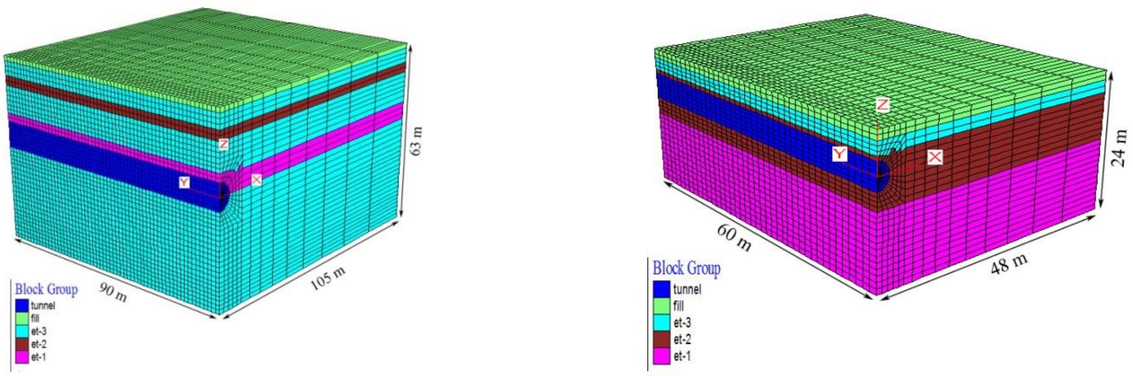
$$S(x) = S_{max} \exp(-x^2/2i^2) \tag{3}$$

where S is the ground surface settlement at the distance x, S_{max} is the maximum ground surface settlement above the tunnel center line, x is the distance measured in the transverse section from the selected point to the center line of the tunnel and i is the transverse distance between the center line of the tunnel and the inflection point of settlement trough.

O'Reilly and New (1982) proposed a linear relationship between i and z0 as follows

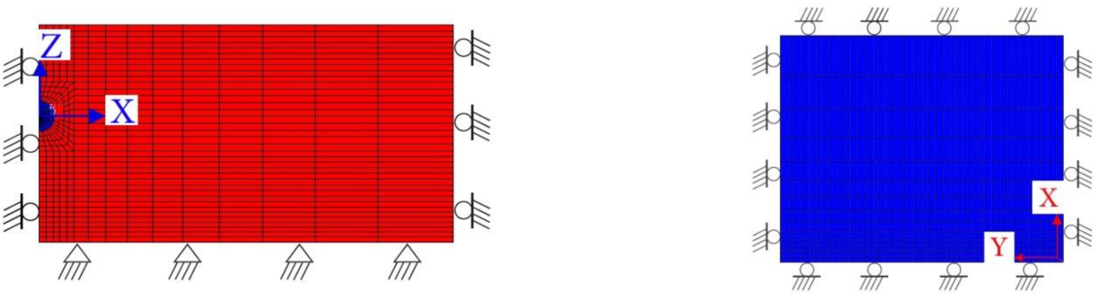
$$i = kz_0 \tag{4}$$

where z_0 is the tunnel axis depth and k is the trough width parameter. The recent parameter is largely independent on the construction method and is estimated based on the soil type. Mair and Taylor (1997) summarized a wide range of field data and suggested that $0.4 < k < 0.6$ for clays and $0.25 < k < 0.45$ for sands and gravels. Considering the cohesion of soil, Guglielmetti, *et al.* (2008) proposed that



(a) EWL7 tunnel (b) Abuzar tunnel

Fig. 8 Geometric dimensions of the numerical models



(a) Front (profile) view (b) Plan view

Fig. 9 Boundary conditions of models (e.g., EWL7 Tunnel)

k=0.5 for cohesive materials and k=0.3 for cohesion less materials.

Several empirical methods were suggested for the prediction of the maximum surface settlement (S_{max}). A simple method to calculate S_{max} was proposed by O'Reilly and New (1982)

$$S_{max} = 0.313 V_L (D^2/i) \tag{5}$$

where, D is the diameter of the tunnel, and V_L is the volume loss defined as the ratio of settlement trough area developed on the ground surface to the cross-section area of the tunnel. Based on the geological and geotechnical characteristics of soil and the method of tunnel excavation, researchers suggested a range of V_L value in the range between 0.2-2% (Golpasand 2015, Golpasand *et al.* 2016).

5.3 Settlement evaluation

Both the EWL7 and Abuzar tunnels were excavated using EPB-TBMs in the alluvia which are composed of cohesive and cohesion-less soils. In order to predict the ground settlements due to the excavation of the tunnel, the rational values of k and V_L were estimated according to geological characteristics of the soils presented in Fig. 3 and Tables 2 and 3. Geometrical parameters of D and z_0 can be seen from Fig. 3. The values of Smax are calculated using equation (5) and are presented in Table 4. Due to the finer soils crossed by the EWL7 tunnel are less than those in the Abuzar tunnel, a higher value of V_L in the case of EWL7 tunnel was selected compared to the case of the Abuzar tunnel. In addition, due to the irregularity of soil layers and their unknown lateral extension, average values of of V_L were assigned (see Table 4).

5.4 Numerical models

Numerical modeling is usually adopted to evaluate the ground settlement induced by shallow tunneling. In this study, the finite difference code of FLAC^{3D} (Itasca, 2006) was used to model the excavation of EWL7 and Abuzar tunnels. The models were constructed based on the recommendations of Lambrughi *et al.* (2012), Zhao *et al.* (2012), Dias and Kastner (2013), Do *et al.* (2014, 2018). Geometrical characteristics of the models are shown in Fig. 8. As seen in this figure, the model of the EWL7 tunnel, including 45150 zones and 48990 grid-points, is larger than the model of Abuzar tunnel which contains 18600 zones and 20418 grid-points. Because of symmetry conditions of the problem (geometry and loading), only a half of the tunnels was considered.

Appropriate boundaries were applied along lateral sides of the models to prevent any movement in the x, y and z directions, whereas the upper surface in the z-direction is free. In addition, the bottom boundary in z-direction has been fixed. This situation was applied to both of models. Boundary conditions of the model of the EWL7 tunnel are indicated in Fig. 9.

5.4.1 Tunneling simulation

Excavation of TBM were simulated with respect to the actual stages and processes that are taken place during the tunnel construction. The mechanized tunneling is basically

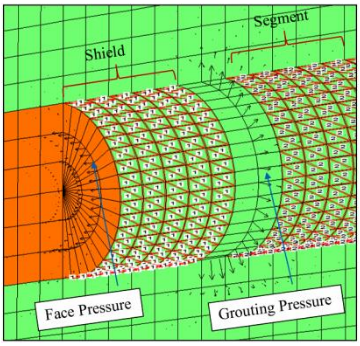


Fig. 10 Numerical modelling of mechanized tunneling

Table 5 Technical properties of the shield and segment lining

Tunnel		Thickness (mm)	Elasticity modulus (GPa)	Poisson's ratio	Density (kg/m^3)
EWL7	Segment	350	18.0	0.25	2500
	Shield	350	200	0.20	7800
Abuzar	Segment	250	18.0	0.25	2500
	Shield	300	200	0.20	7800

Table 6 Values of grouting pressure and face pressure applied in the models

	Face Pressure (kPa)	Grouting Pressure (kPa)
EWL7	150	170
Abuzar	65	75

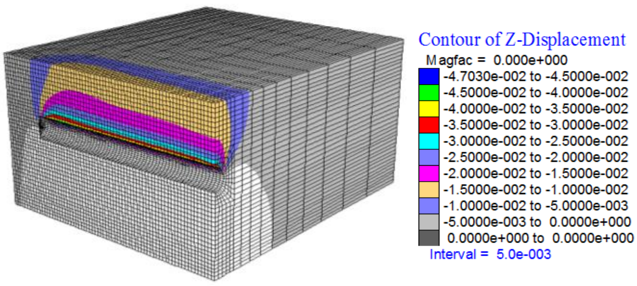


Fig. 11 Contours of Z-displacements (EWL7 Tunnel)

a sequential and multi-stage process that all of them have been considered in numerical modeling as follows:

• Excavation of tunnel equal to the length of a segmental lining ring;

• Generation of EPB machine elements for the new excavation length of the tunnel;

• Application of the face pressure on the new excavation face of the tunnel;

• Allowing the relaxation and movement (convergence) of the soil caused by the conicity of the shield. The soil movements were fixed when reaching to the gap between the outer surface of the shield and the inner surface of the excavated tunnel (Lee *et al.* 1992 and Loganathan 2011);

• Application of the grouting pressure;

• Generation of lining ring elements behind the shield tail (Fig. 10);

• Solving the model to reach the equilibrium state;

• Repeating the above stages.

Fig. 10 shows the positions of the above stages considered through the numerical modeling. Technical data obtained from the site of Abuzar and EWL7 tunnel projects were used for the model construction. The body of the shield was simulated using shell elements. The interaction between shield and soil is modeled by interface elements along which sliding or separation are allowed. The tunnel segmental lining was set at a defined distance from the tunnel face. Technical properties of the shield and segment elements are presented in Table 5. Geotechnical properties of soil layers used in numerical models were previously presented in Table 3. The grouting pressure was modeled as a linearly varied normal stress applied to the excavated boundary of the tunnel and along the length of a segmental ring behind the shield tail. The face pressure applied to the tunnel face has been modeled as a linearly varied normal stress changing from the top to the bottom of the face. Average values of grouting and face pressures shown in Table 6 were selected according to the real site data.

A uniform pressure of 20 kPa was applied on the top of the models to simulate the weight of structures on the ground surface. To simulate the initial stress conditions, vertical stresses were applied considering the gravity effect, and the ratio of horizontal in-situ stress to vertical in-situ stress was applied as the coefficient of lateral earth pressure (K_0) which is calculated by the equation (3) using the soils' parameters presented in Table 3. Soil layers were modeled by an elastic-perfectly plastic constitutive model based on Mohr-Coulomb failure criterion. This criterion is widely used in tunnel modeling because of its simplicity and availability of geotechnical parameters (Zhang *et al.* 2013 and Xie *et al.* 2016).

5.4.2 Numerical results

The results of numerical modeling are presented in Figs. 11 and 12. As shown in these Figures, maximum z-displacement on the ground surface along the tunnel axis (Smax) is between 8 mm and 10 mm for Abuzar tunnel and is between 10 mm and 15 mm for EWL7.

To evaluate the displacement of the ground surface in the transverse section of the tunnels, some points were selected on the top of models (corresponding to the ground surface) and z-displacements of these points have been recorded. The distance of selected points measured from the tunnel center line and the corresponding maximum z-displacements in the transverse section are presented in Table 7. As seen in Table 7 and Fig. 13, z-displacement (settlement) at these points decreases when the distance of the points from the tunnel center-line increases. The same findings were obtained by other authors (Peck 1969, Cording and Hansmire 1975, O'Reilly and New 1982, Mair and Taylor 1997, etc.).

The longitudinal settlement profile based on the numerical results is also presented in Fig. 14 for the EWL7 tunnel. This figure is presented for a tunnel excavation of 27 m. It can be seen that the tunnel excavation has an influence of 20 m ahead the tunnel face. The numerical settlement at the tunnel face is equal to 5 mm. It is higher than the P7 monitored one (moreless 2 mm). It is however

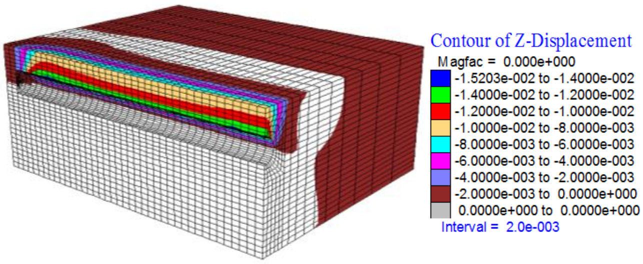


Fig. 12 Contours of Z-displacements (Abuzar Tunnel)

Table 7 Values of Z-Displacements (settlement) of the selected points

Abuzar tunnel		EWL7 tunnel	
Transversal distance from the point to the center line of tunnel (m)	Z-Displacement (mm)	Transversal Distance from the point to the center line of tunnel (m)	Z-Displacement (mm)
0	-8.2	0	-12.1
1	-7.7	1	-11.4
2	-6.5	2	-10.9
4	-3.4	4	-9.5
8	-0.2	8	-6.6
16	-0.1	16	-2.2
-	-	32	-0.75

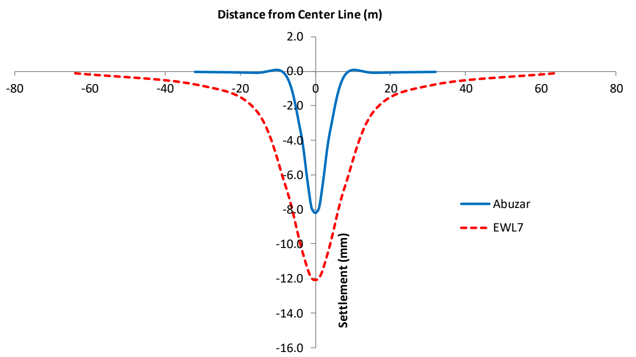


Fig. 13 Settlement troughs in transverse section, obtained by FLAC^{3D} (K_0=0.65)

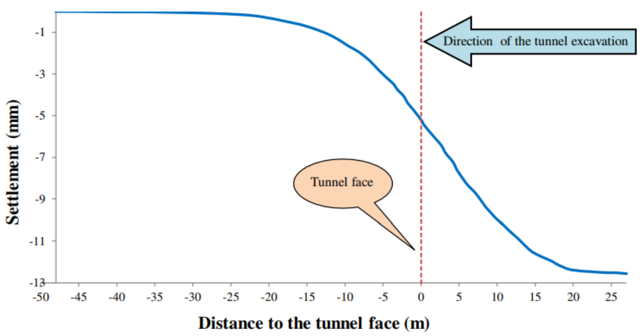
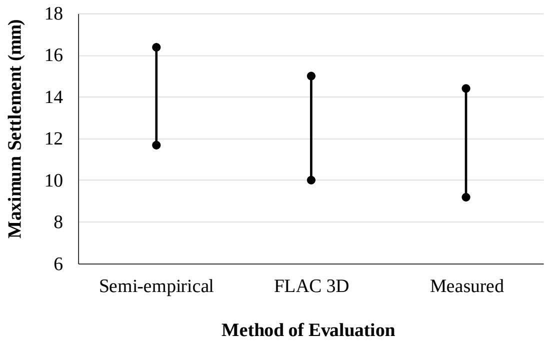


Fig. 14 Ground settlements in a longitudinal profile (EWL7 tunnel)

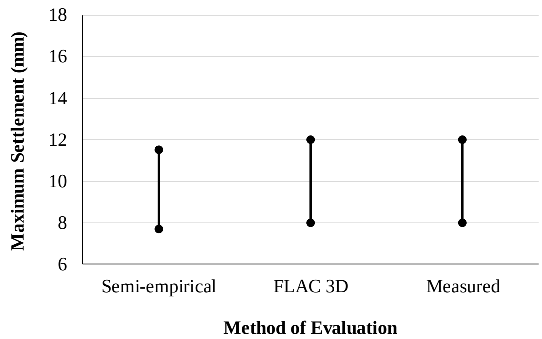
difficult to compare these two values as the maximum settlement for point P7 is equal to 10 mm (Fig. 6) while for the numerical a value of 12 mm is obtained.

Table 8 Comparison between predicted settlements and real (measured) settlements

Tunnels	S_{max} (mm)		
	Measured experimentally	Evaluated	
		Semi-Empirical	FLAC^{3D}
EWL7	9.2~14.4	11.7~16.4	10~15
Abuzar	8~12	7.7~11.5	8~12



(a) EWL7 tunnel



(b) Abuzar tunnel

Fig. 15 Comparison of the predicted settlements and monitored settlements

6. Comparison between the results

EWL7 and Abuzar tunnels were experimentally measured in the site by leveling points installed on the ground surface. These results are then used for comparison purpose with settlement values obtained by the semi-empirical method and numerical models. As mentioned above, in-situ settlements on the ground surface change in ranges from 8 mm to 12 mm and from 9.2 mm to 14.4 mm were recorded over the Abuzar tunnel axis, and the EWL7 tunnel axis, respectively (Fig. 7). Ground settlement due to the tunnel excavation was then also evaluated by the semi-empirical method. For this purpose, the equation suggested by O'Reilly and New (1982) was used and the recommendations of Mair and Taylor (1997), Guglielmetti *et al.* (2008), Chapman, *et al.* (2010) and Golpasand, *et al.* (2016), were considered to select the rational values of the k and V_L according to the geological and geotechnical properties of the soil types.

Based on this method, ranges of settlements developed over the Abuzar tunnel and EWL7 tunnel are changed from 9.2 mm to 11.5 mm and from 12.2 mm to 17.1 mm, respectively. Using the geometrical and geotechnical data of these two tunnels, numerical models built in FLAC^{3D} software were employed to evaluate the ground settlement caused by the tunnel excavations. According to the numerical results, a range of settlements between 8 mm and 12 mm were obtained for the Abuzar tunnel. In the same way, a range of settlements between 10 mm and 15 mm was observed for the EWL7 tunnel. The values of the maximum settlements (S_{max}) obtained by different methods are compared in Table 8 and presented in Fig. 15. It can be seen that the real (in-situ) settlements are approximately equal to the numerical settlements and relatively lower than those obtained by semi-empirical methods.

The discrepancy can be concerned with the accurate operation of the face pressure and grouting pressure that are included in the numerical modeling but not included in the semi-empirical method. In other words, numerical modeling can be used to efficiently estimate surface settlement caused by a mechanized tunneling. It is therefore used to further investigate the effect of K_0 value on the ground settlements due to mechanized tunneling.

7. Effect of K_0 on ground settlement due to tunneling

The effect of the K_0 value on the settlements developed above tunnels is introduced in section 1. As indicated in Table 1, the ranges of K_0 between 0.25 to 2 were proposed by other researchers. On the basis of the geotechnical parameters presented in Table 2, Table 3, and equations (1) and (2), the K_0 value changed from 0.25 to 1.0 was selected for numerical investigation purpose in this study. This range of K_0 value is usually observed in reality. The numerical calculations were therefore conducted with the K_0 values of 0.25, 0.5, 0.75, 1 and for both the EWL7 and Abuzar tunnels.

Figs. 16 and 17 present the ground settlements in the transverse section developed over Abuzar and EWL7 tunnels, respectively, considering the effect of the coefficient of lateral earth pressure (K_0). It can be seen from these two figures that the surface settlements generally decrease with the increase of the K_0 value.

The values of the Smax against to the chosen values of K_0 are presented in Table 9. As seen in this table, the absolute value of the maximum settlement generally decreases with an increase of K_0. Fig. 18 indicates these changes schematically as bar chart diagram. This subject is explained in the next section.

Fig. 19 shows the relationship between the ground settlements versus the K_0 values. According to Fig. 19, the ground settlements decrease with the increase of $K_{0.}$ The relation between these two parameters follows an exponential function which can be expressed using the following equation

$$S_{max} = Ae^{-BK_0} \tag{6}$$

where A and B are coefficients that are dependent mostly on the soil type, geometrical characteristics of tunnel (depth and diameter).

Investigation on the results obtained from Abuzar and EWL7 tunnels show that the ratio of the depth of tunnel on the diameter of tunnel (z_0/D) plays an important role. The

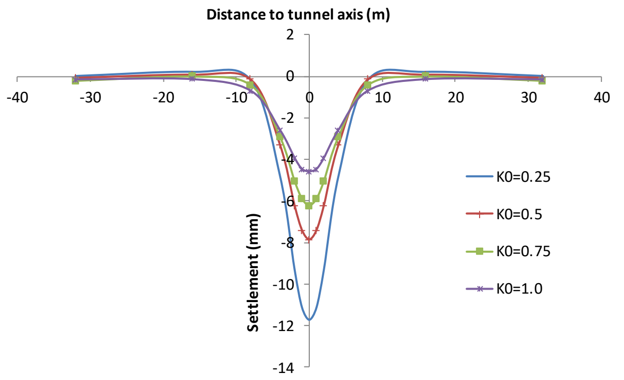


Fig. 16 Trough of ground settlement in transverse section with different K_0 values (Abuzar Tunnel)

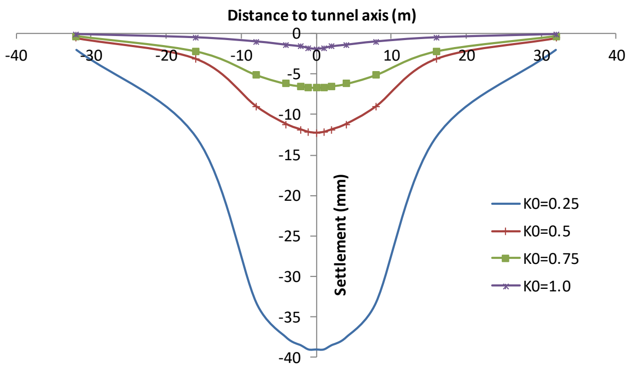


Fig. 17 Troughs of ground settlement in transverse section with different K_0 values (EWL7 Tunnel)

Table 9 Z-Displacements occurred in several values of K_0

K_0		0.25	0.5	0.75	1
Z-Displacement (mm)	EWL7	-39	-12.3	-6.7	-1.9
	Abuzar	-11.75	-7.8	-6.25	-4.61

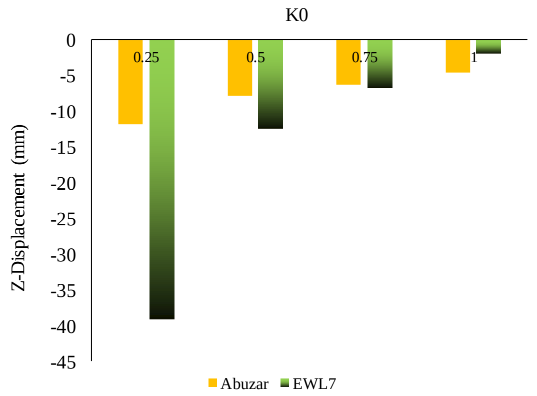
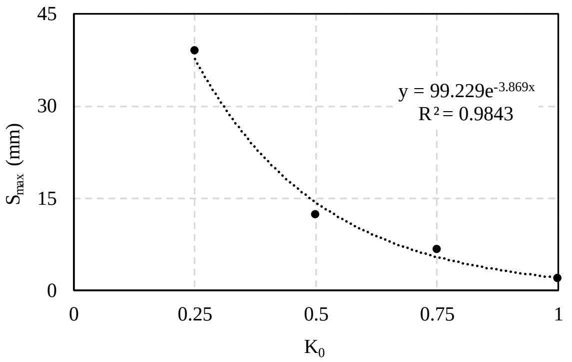


Fig. 18 Decreasing of the settlement with increasing of K_0 values

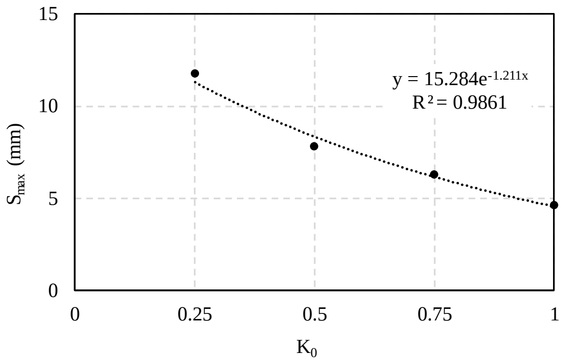
Table 10 Values of the parameters A and B

Tunnel	z_0/D	A	B
Abuzar	1.70	15.28	1.21
EWL7	2.83	99.23	3.87

values of the ratio of (z_0/D) as well as the coefficients of A



(a) EWL7 tunnel



(b) Abuzar tunnel

Fig. 19 Exponential relationship between the settlements and the K_0 values

and B for both tunnels are presented in Table 10.

As seen on Table 10, EWL7 tunnel having higher value of (z_0/D) in comparison with Abuzar tunnel, owns larger values of the coefficients of A and B. Therefore, for the EWL7 tunnel the decrease of the ground settlements versus K_0 occurs with a higher rate compared to the Abuzar tunnel.

8. Analysis

According to the results obtained from FLAC^{3D} models (Figs. 16 and 17), ground settlement generally decreases with an increase of K_0. In addition, the settlement troughs become wider and flatter with the increase of K_0. The comparison between EWL7 and Abuzar tunnels indicates that the settlement troughs of the EWL7 tunnel are wider and flatter than the ones of Abuzar tunnel. The discrepancy could be concerned with the smaller diameter and depth of the Abuzar tunnel compared to those of the EWL7 tunnel. In other words, the excavation of the Abuzar tunnel causes smaller maximum settlements and smaller width of settlement troughs at the ground surface compared to that of the EWL7 tunnel. This observation is in agreement with the fact that, the deeper the tunnel, the wider the settlements trough and the larger the tunnel, the greater the maximum settlements.

Figs. 20 and 21 present the normalized settlement troughs obtained in the EWL7 tunnel and Abuzar tunnel, respectively considering the effect of K_0 values. As indicated in the vertical axis of the graphs, the settlements of all points selected on transverse section were normalized by the maximum settlement S_{max} (occurred on the tunnel axis). Relationships are seen between Figs. 16 and 20 (Abuzar tunnel) as well as between Figs. 17 and 21 (EWL7 tunnel). It can be seen from Figs. 20 and 21 that the normalized settlements (S/S_{max}) are not considerably changed with the variation of K_0. This result is in good agreement with the results obtained by Möller (2006).

The relationship between the changes of K_0 and the value of ground settlement is very important. It was predicted that the changes of K_0 causes a change in the magnitude and direction of the stresses developed in the soils surrounding the tunnel. These changes, in turn, also cause a change in the displacement induced in the soil surrounding and finally leads to settlement of the ground surface. This phenomenon is indicated in Fig. 22, where the

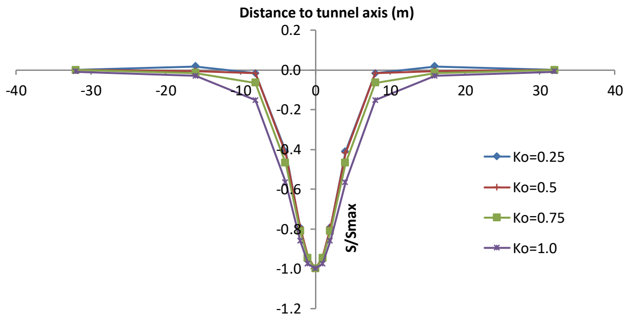


Fig. 20 Trough of normalized settlements in transverse section with different K_0 values (the case of Abuzar Tunnel)

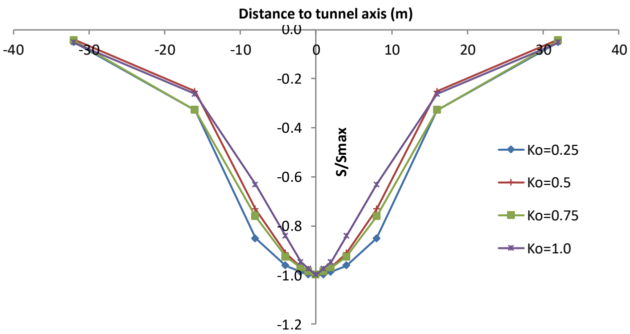
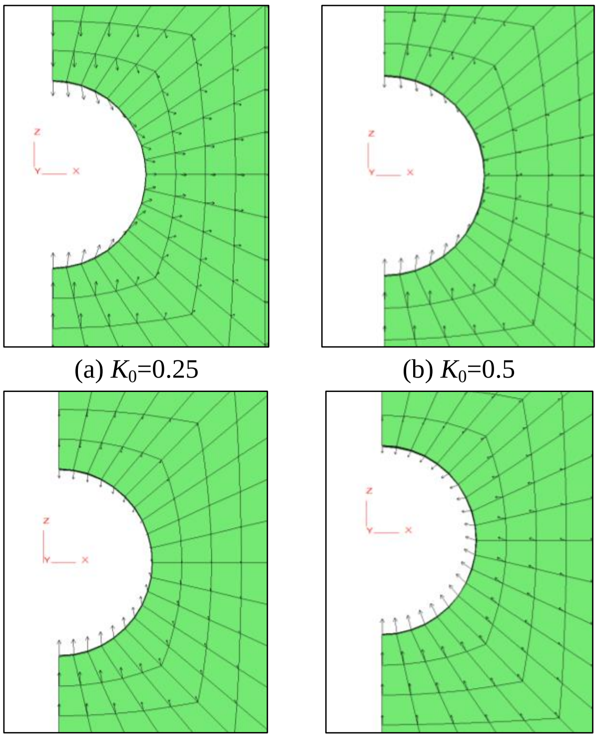


Fig. 21 Trough of normalized settlements in transverse section with different K_0 values (the case of EWL7 Tunnel)

magnitude and direction of displacement induced in the ground surrounding the EWL7 tunnel, versus K_0 variation, are shown.

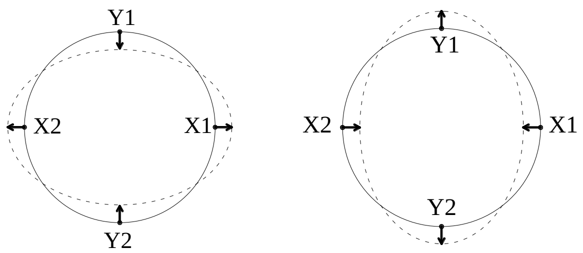
As seen in Fig. 22, for the low value of K_0, the tunnel crown moves vertically downward inside the tunnel space, whereas the tunnel's sidewall moves horizontally outward to the exterior of the tunnel. In this case, the larger ground settlement appears as indicated in Figs. 17 and 21. An inverse phenomenon is observed when the K_0 value increases. As seen in Fig. 22, for the higher values of K_0, vertical displacement of the tunnel crown is declined, and the sidewalls of the tunnel are horizontally moved toward the interior of the tunnel. As a consequence, a decrease of settlement on the ground surface can therefore be predicted in this case (Figs. 17 and 21).



(a) K_0=0.25 (b) K_0=0.5

(c) K_0=0.75 (d) K_0=1

Fig. 22 Displacement of the ground surrounding the tunnel



(a) (b)

Fig. 23 Changing in direction of points displacements with a variation of K_0

In addition to the ground displacement, the variations of K_0 may also cause a significant change in the magnitude and direction of the ground pressures acting on the segmental lining of the tunnel (Fig. 23). With the lower values of K_0 (Fig. 23(a)), inward vertical pressures applied on the crown and the floor of the tunnel (points Y1 and Y2 in Fig. 23(a)) are dominant and the deformed cross-section of tunnel is horizontal oval. With the higher values of K_0 (Fig. 23(b)), inward horizontal pressures acting on the sidewalls of the tunnel (points X1 and X2 in Fig. 23(b)) are dominant and the tunnel is vertical oval in shape. These changes may be slight, but they are very important especially in designing of the segmental lining of the tunnel, where the deformability parameters of the tunnel lining should be adequate to support tunnel stability.

9. Conclusions

In this paper, ground settlements due to the excavation of the EWL7 and Abuzar tunnels are evaluated and the effect of the coefficient of lateral earth pressure (K_0) was investigated using 3D numerical calculations. The real settlements along the tunnel axis (S_{max}) occurred due to the excavation of the tunnels were monitored and used to compare with the settlements obtained by semi-empirical and numerical methods.

• The comparison indicated that the numerical methods permit to obtain more accurate results. It was concluded that the capability of the numerical simulations to take into account all of the stages and processes taking place during the mechanized excavation of the tunnels permits to better estimate the ground settlements.

• The numerical investigation of the settlement troughs in transverse sections indicated that the settlement troughs caused by the excavation of the EWL7 tunnel are wider and flatter than the one of the Abuzar tunnel. The reason could be concerned to the higher depth and larger diameter of the EWL7 tunnel in comparison with those of the Abuzar tunnel.

• The numerical results also showed that the ground settlement exponentially decreases with the increase of K_0. To confirm this issue, the displacement of the ground surrounding the tunnel was introduced. It was found that the magnitude and direction of the pressures acting on the segmental lining of the tunnel, as well as the ovalization of the tunnel lining, changed with the K_0 variation. Therefore, it can be said that the lateral earth pressure coefficient is very important especially for designation of the segmental lining of tunnel.

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