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ORIGINAL RESEARCH PAPER

3D FEM Model on the Parameters' Influence of EPB-TBM on Settlements of Single and Twin Metro Tunnels During Construction

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Abstract

The present research exposes the investigation on three-dimensional modeling of the single and twin metro tunnels for the case of the Tehran metro line. At first, simulation implemented on the comparison of the ground movements in the single and twin tunnels. Then the simulation has been performed on the influence of effective parameters of EPB-TBM on the surface settlements throughout excavation. The overcutting, shield conicity, grouting, and the final lining system modeled and the influence of face supporting pressure, grout injection pressure, as well as the clear distance of the tunnels, has been analyzed. The initial results showed a valid ground settlement behavior. The maximum settlements occurred at the end of the shield tail and it was higher in the single tunnel. The face supporting pressure had more effect on the surface settlement in comparison to the grout injection pressure. By increasing the face pressure in the single tunnel, the place of maximum settlement moved back while the grout pressure is insignificant for decreasing the settlements. Furthermore, the influence of the clear distance in the twin tunnels led to zero after the length of 30 m. Accordingly, for more distances, the tunnels must be examined independently and as two different single tunnels.

Keywords Twin tunnels · 3D modeling · Finite element · Metro tunnel · Numerical method · Plaxis

1 Introduction

The rapid increase rate of the population in cities and urban areas has developed the transportation methods such as subways around the world [1–5]. Most of the subways tunnels are excavated by the tunnel boring machine (TBM) for the direct line sections and some stations due to its safety, small disturbance area, high effective, low cost, and low excavating volume in comparison to the other methods [6, 7]. In recent years, the use of TBM has been widened around the world and Earth Pressure Balance- Tunnel Boring Machine (TBM-EPB) is one of them among a lot of different types of these machines [8–10]. Earth Pressure Balanced (EPB) TBMs were introduced about 40 years ago as an excavation

method for fine aggregate soils [11]. However, by further development, this machine used in more types of soils like fine aggregates, coarse aggregates (gravels and sands), and hard rocks [12, 13]. The simulation methods are used for high-efficiency working and performance prediction of the machine in the projects. Three-Dimensional modeling on the deformation of subway tunnels caused by EPB tunneling on the above and down of Shanghai subway has been investigated for predicting the soil displacements during construction. The results showed a good correlation with the field monitoring data and predicted values of the simulation [14]. Twin tunnels have many advantages including controlling the soil movements and reduces stresses in the linings [15, 16]. Due to the specification of these two types of tunnel and their application method, comparison of them is essential for describing the performance and their effects on the soil and ground movements. Hence, a lot of studies have been proposed on the settlements and movements of the soils caused by tunneling [17]. With any excavation in the ground, the in situ stress will be disturbed [18] and it causes displacements of soil and surface. Moreover, the adjacent underground spaces have interaction between each other and they should be assumed and performed together [19, 20]. Thus

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the twin tunnels have effects on the soil displacement in a different way of two single tunnels that called closely-spaced tunnels [21, 22]. Therefore the effect of the tunnel type on the ground should be investigated for predicting the ground displacements before starting the constructions.

In earlier studies, researchers have presented many investigations in the effect of tunneling on the soil movement by 2D and 3D numerical and analytical methods to simulate the tunnel excavation procedure and TBM. Mroueh et al. [23] presented a simplified 3D numerical model for predicting the soil movements caused by the tunneling with TBM. They used two coefficients for optimization which are the length of the unlined zone and the released partial stress. The study results were acceptable just for the shallow tunnel in the soft soils. Also, the simulation of the twin circular tunnels on the two and three-layered formation has been conducted by Chu et al. [24]. The strain and displacement around the tunnel caused by the excavation have been measured. The results of the simulation had a 2–4% error with the monitored values of the construction. Also, they showed that by considering initial stress, the module of ratio, and the coefficient of earth pressure (K), the major displacements occur at the location of major stresses.

Moreover, some researchers have presented studies on the parallel tunnels in the case of tunnels size, face lagging distance, face pressure, and ground situations [25–27]. In most of these studies, the parameters of ground settlement and surface displacements have considered as the main criteria. Fang et al. [28] investigated the effect of the geometric arrangement of the closely-spaced twin tunnels on the ground settlements. The results showed an increase in surface settlements in the shallow tunnels and also they showed the possibility of settlement controlling by the construction of deeper twin tunnels,. In regarding the tunnels lagging distance, Chen et al. [29] used iterative Fourier transformation via the Schwarz alternating method to find the complex potentials of liners, geomaterial, stress, and displacement. Then they compared these parameters with the numerical case and they found that the lagging of tunnels has a great impact on the soil displacements. But with considering space 6 times larger than the radius and more, the interaction between the twin tunnels disappeared and they acted as two single tunnels. As general, the structural forces and lining displacement caused by the simultaneous excavation of twin tunnels are much less than those in the construction with the lagging distance [25]. Do et al. [30] proposed a 3D numerical investigation on the lagging distance of twin tunnel construction and showed that the critical situation for stability will appear when the face of the following tunnel stands at the transverse section of the front tunnel. The 3D finite element investigation on the effect of EPB-TBM parameters on the ground settlements caused by twin tunnel excavation of Shiraz metro has been done by Afifipour et al.

[31]. The face pressure, grout pressure, and thrust jack force have been studied. The results showed complicated relation between interaction of twin tunnels and near structures, and the face pressure of TBM has a more significant effect on the soil movements around the excavation area rather than the grout pressure and jack force. Also, Fargnoli et al. [32] studied the effects of twin tunnel excavation of Milan metro on the surface settlements. The results showed that by the construction of the second tunnel, the settlement above the first tunnel axis will increase and it is different from the superposition of two single tunnels. Although they showed that these movements will affect by the EPB parameters, no relationship has been found between the settlements above the first tunnel and excavation parameters of EPB.

Although the simulation can be used for any sections of the machine such as cutter head, the applied force, and chamber temperature [33–35], it can be used to simulate total movement during excavation of the machine. The 3D simulation on the mechanized excavation of TBM-EPB for its overall processes has been done in many studies. In most of these studies, the comparison study has been done between the ground displacements obtained from the simulation and in situ data as a controller parameter [36–40]. In the design stages of the subways maybe the type of tunnel as a single or twin tunnel is the most important parameter. In the past, most of the tunnels were excavated in a single tunnel type [41], but nowadays there are a lot of metro lines excavated as twins for different purposes [15, 42, 43]. A lot of studies have investigated the modeling of the tunnel excavating by TBM, but 3D simulation on the comparison of the soil movements caused by single and twin tunnels is inevitable before implementation.

In this study, the comparison of the single and twin tunnels has been studied. Also, the effect of different parameters of EPB-TBM machine on the soil stresses and ground settlements has been studied for in-situ monitoring throughout the implementation. The purpose of the study at the first is deciding the best plan of tunneling among single and twin tunnels and the second, assessment of the most efficient parameters of excavation on the soil displacements. The study has been done based on the case of Tehran metro line 7. Tehran Metro Line 7 is around 27 km length with 25 station[44] and consist of two parts which is an east–west part that is following by the south-north part. The investigated section is located at the east–west part of this line between the stations of A7 and N7. The costs analysis has been done for the tunnels based on the local prices presented by country. In this case, the diameter of the single tunnel and twin tunnel has been considered 9 m and 6 m respectively.

The void between the tunnel perimeter and segment rings was grouted by means of two-component grouting material. The grout was modeled as a thin elastic layer behind the lining system with a thickness of 2 cm. Also, in order to

consider the grout pressure, a spherical pressure was considered around the linings toward the border.

With the focusing on the excavation stage and using Life-Cycle Cost Analysis method [45, 46], the TBM excavation price showed 2.0 million dollar for the single tunnel which has located in the depth of 15 m underground and this amount for the twin tunnel with the depth of 10 m was 1.9 million dollars per kilometer. Although the cost analysis on the tunnels shows no difference between single and twin tunnel, some other parameters such as safety, ventilation, and level of service, should be taken to account for better serviceability.

2 Three-Dimensional Numerical Model

The finite element methodology and nonlinear modeling have been presented throughout the previous studies [47–49]. In this study, a contribution will be given to the modeling of EPB-TBM with the help of PLAXIS 3D Tunnel finite element software to simulate the soil movements and stresses induced by tunnels excavation. The study is intended to discuss the influence of the effective parameters of the excavating procedure including soil characteristics, TBM parameters, and tunnels position. Since the Finite Elements (FE)-mesh coarseness of the model is important and it has some effects on the results [50, 51]. the 15-node triangular element used for simulating soil behavior in the model. The dimension of the model is one of the important parameters that should be as wide as to have no effects on the tunnel excavation simulating. Lambrughi et al. [36] proposed the dimension of H + 4D, 2(H + 4D), and 2(H + 4D) for height, length, and wide respectively, where the H is the depth of tunnel and D is the diameter. In this study, considering the

Table 1 The peripheral soil specification of the model

Parameters	Unit	Value
Cohesive (c)	kPa	15.0
Internal friction angle (φ)	degree	32
Elasticity module (E)	MPa	75.00
Poisson ratio (υ)	–	0.3
Dry unit weight (γ)	kN/m^3	18.4

single tunnel diameter that was 9.17 m, the dimension of the model has been chosen 30 m, 50 m, and 75 m for wide, height, and length respectively. The boundaries of the model were considered free at the top and completely hinged constraint at the bottom, right and left of the model edges. In both single tunnel and twin tunnels, the simulation has been done for half-tunnel shape with the purpose of decreasing the processing time.

The "step by step" approach method consists of 5 steps has been selected for the machine movement. This approach has been used the first time by Dijk & Kaalberg in 1998 for the shield tunneling model [52]. Each section has 1.5 m length and accordingly, the TBM moves ahead 1.5 m per step. Also, there is a 1.5 m gap (one step) between the end of the shield and lining segments location which has been considered for the grout injection. The tunnels axis has been placed on a depth of 25 m and the water level was considered 2 m below the ground surface. The cross-section of the tunnel is shown in Fig. 1. Although in some areas "very silty clayey sand" can be seen (green color), most of the route has a gravely sand environment and the tunnel alignment has been located in this part. Hence, with considering an small simplification, the gravely sand with silt was considered and the details of the soil are shown in Table 1.
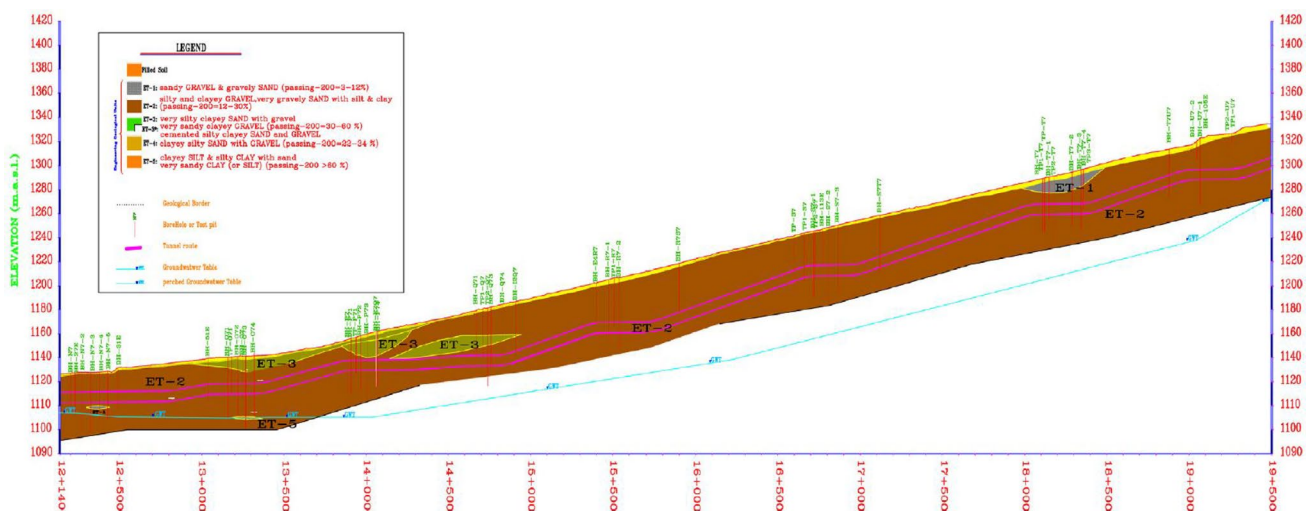
Fig. 1 The tunnel geology cross-section [44]

The soil disturbance around the shield induced by cutter head activity, moving forward of the machine, and especially the conicity shape of the shield is one of the most critical parts of the tunnel modeling [6]. For this purpose, some ictitious displacement has been performed along with the shield to simulate of the ground subsidence induced by overcutting of the machine and the conicity shape of the shield. These displacement has been considered by contraction coefficient around the shield which are 0.1, 0.2, 0.3, 0.4, and 0.5. Furthermore, the shield strength and its thickness, machine weight, interaction between soil and shield, and final lining system have been considered in the modeling (Table 2, Table 3).

The same procedure consist of 5 steps has been assumed for the twin tunnels. On one hand, for avoiding any interaction between the tunnels, the horizontal clear distance between the tunnels was kept 20 m and on the other hand for noticing construction one of tunnels before the other, the left tunnel has considered 100 m ahead. In the EPB machines, the face supporting pressure must be as enough to withstand the soil weight [53]. Then the minimum value should be known in the first stage which is based on the active pressure coefficient of the soil (k) (Eq. 1).

$$k = \frac{1 - \sin\varphi}{1 + \sin\varphi} \tag{1}$$

In this study, the minimum value obtained by implementing 150 kPa as the face pressure and decreasing gradually until the falling of the face. The achieved results for the face-top were150kPa and 100 kPa for single and twin tunnels respectively and this amount for the face-down were 200 kPa in the single and 130 kPa for the twin tunnels (Table 4).

3 Results and Discussion

According to the finite element simulation, the stress and displacement analysis of the tunnel's excavation were conducted. To measure the tunnel's interactions, it is necessary to understand the surface settlement and ground movements around the tunnels. Therefore, in this study, surface settlements are selected as the reference to investigate the reliability of the FEA results. The results have been explicated

by focusing on the stresses and displacements around the tunnels and surface. The stress graphs and longitudinal displacements for the single tunnel and twin tunnels are shown in Figs. 2, 3 respectively.

Based on the longitudinal profile, the most settlement amount occurred at the end of the shield and just before grout injection in both single and twin tunnels. All settlement values were less than 2 cm in single tunnels and 1 cm in twin tunnels which had a good correlation with the field monitoring. The existence of stress and strain caused by environmental loads can lead to failure in different modes [54], however, the stresses around the tunnels becoming more uniform by passing forward of the tail.

The analysis was conducted on the influence of different parameters such as the face supporting pressure, grout injection pressure, soil cohesive as well as the clear distance of the twin tunnels. At the first stage and for the single tunnel, the supporting face pressure increased from 130 to 190 kPa in the three steps by the rate of 20 kPa per step (Figs. 4, 5).

Increasing the pressure from 130 to 150 kPa led to a 1 mm reduction in the settlements. However, this reduction rate stopped at the cumulative settlement of 1.5 mm. It shows the limit effect of the face pressure on the ground movements. Moreover, the place of the maximum settlement moves toward the tail by implementing higher amounts of face pressure. This can be associated with the stability area generated by the high pressure of the face which continues to the tail.

The same analysis has been performed for the twin tunnels. Since the default face pressure of the twin tunnels was 100 kPa, then the pressure increased to 160 kPa in the 3 steps (Fig. 6). The results showed a 1 mm decrease in the surface settlement for changing the pressure from 100

Table 2 The specifications of simulated TBM shield

Parameters	Unit	Value
Elasticity module in area (EA)	MPa	8200
Elasticity module in inertia (EI)	kN/m²/m	32
Poisson ratio	–	0.3
Thickness	cm	15.0

Table 3 The specification of the final lining system

Parameters	Unit	Value
Module of elasticity (E_{ref})	MPa	38,000
Dry unit weight (γ)	kN/m³	25
Poisson ratio (υ)	–	0.2

Table 4 The EPB pressure parameters specifications

Item	Single tunnel	Twin tunnel
Face pressure (kPa)	150 at the top-face 200 at the down-face	100 at the top 130 at the down
Grout pressure (kPa)	100	70
Hydraulic jacks pressure (kPa)	2100	730
Longitudinal distance (m)	–	100
Clear distance (m)	–	20, 25, 30
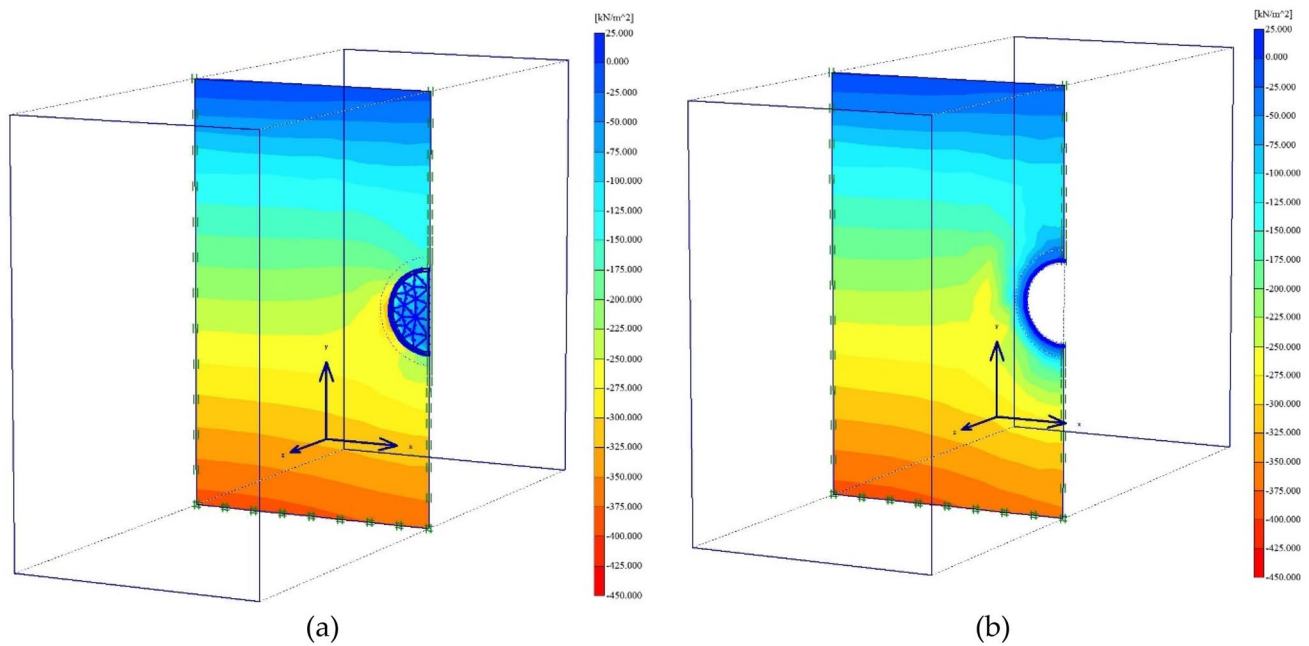
Fig. 2 The stress results caused by excavation **a** At the face and **b** At the end of tail
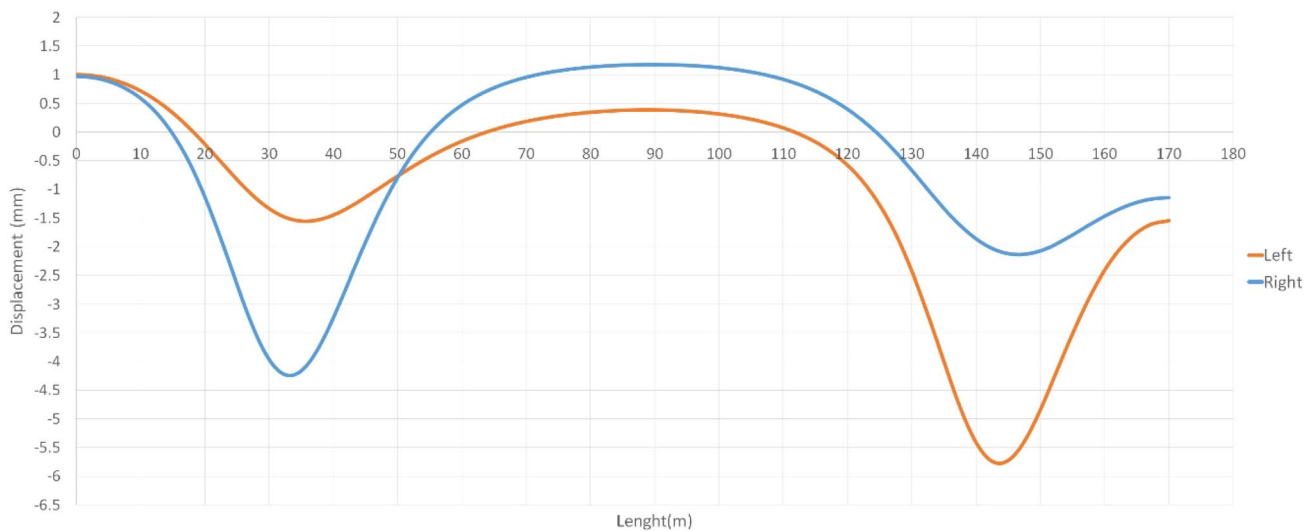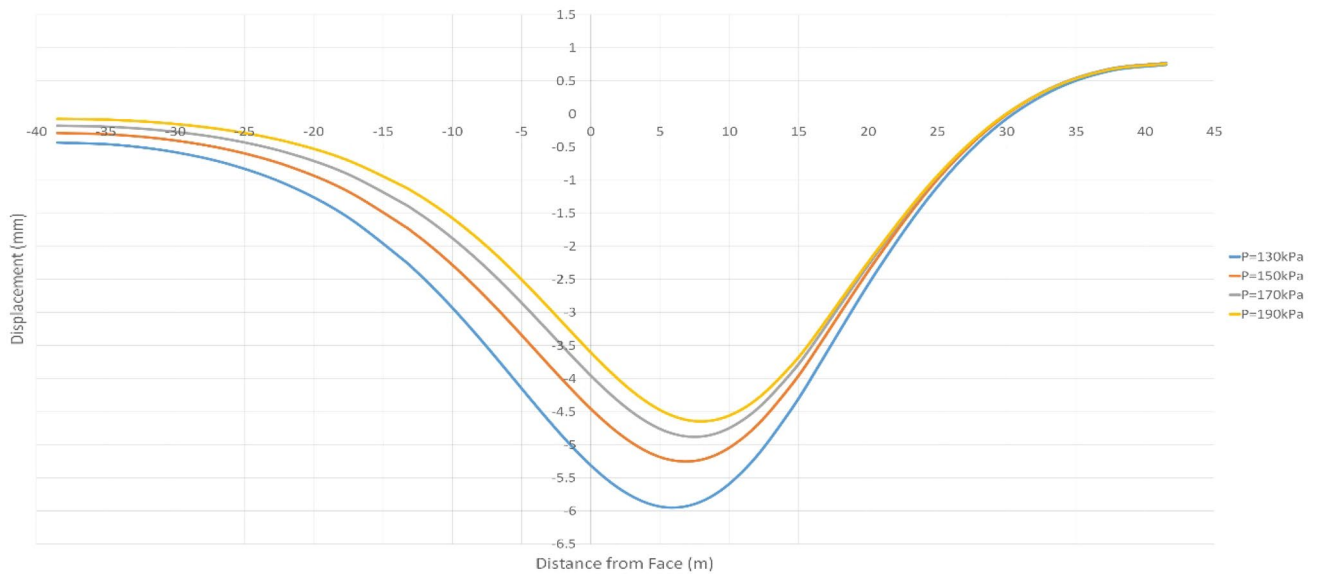

Fig. 3 Longitudinal settlement profile for the twin tunnels

to 120 kPa. But for other pressures, neither surface settlement nor the place of maximum settlement changed. Thus, increasing the face pressure in the field up to 120 kPa can decrease the settlements and for more pressures, it has no effect on the ground movements. The maximum value of the settlement on the right tunnel was 1 mm less than the left one which was 100 m ahead (Fig. 7).

In addition, the transverse influenced domain has been investigated (Fig. 8). As can be seen, the ground settlements did not become zero after 20 m lengths of the tunnel axis.

It means that in this case, these two tunnels may have some interaction with each other. For this purpose, the analysis of the clear distance effect has been performed to clarify the impact of the distance between the tunnels.

New tunnel construction in proximity to existing ones, which happens in twin tunnels, has a considerable negative effect on the existing tunnel [55, 56]. Therefore the clear distance between the tunnels was investigated for three different lengths of 20 m, 25 m, and 30 m. According to the finite element model, examining the other distances was

Fig. 4 Effect of the supporting face pressure on the longitudinal settlement profile of single tunnel
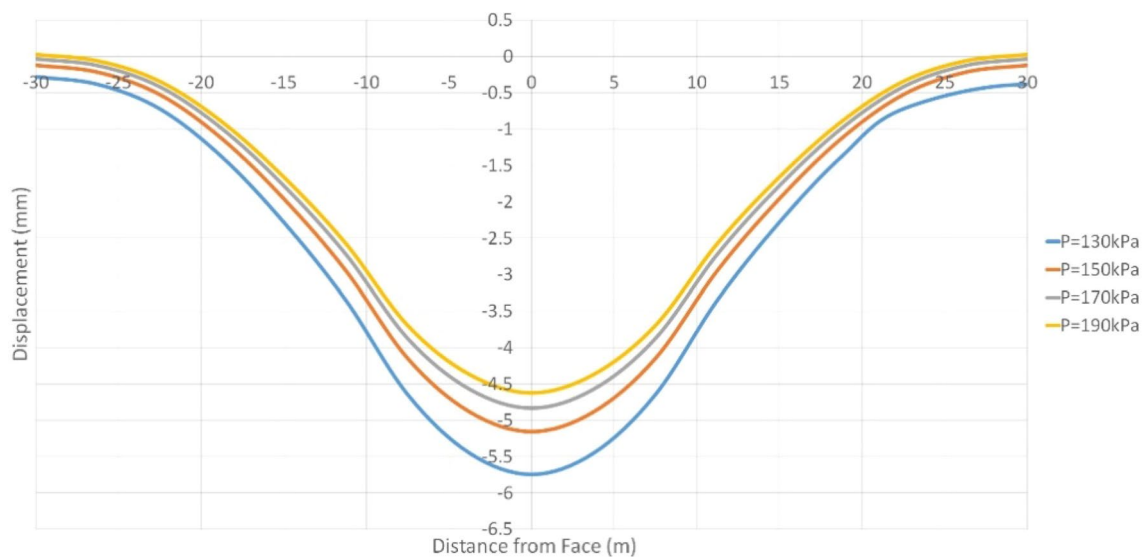
Fig. 5 Effect of the supporting face pressure on the transverse settlement profile of single tunnel

difficult because of the huge amount of the elements and long run-time. The results showed that the tunnels have some interaction with each other on distances of 20 m and less. (Figs. 9, 10).

As expected, the distance analysis showed that for more distances between two tunnels, the settlements at the top spot decreasing. It can be related to eliminating soil disturbance around the tunnel which has created by the excavation of another tunnel. For the distances of 20 m and 25 m, the settlements were affected on the lengths of + 110 m and -110 m for the left tunnel and right tunnel respectively. Nevertheless,

this effect has disappeared for the distance of 30 m and the diagram has a smooth slope at this point. Therefore the distance of 30 m can be present as the minimum clear distance for avoiding any interaction between the tunnels. Indeed for the more distances, the tunnels should be analyzed separately and as two single tunnels. Similarly in the transverse profile graph (Fig. 11), the settlements in the affected area of the tunnels were zero at this distance. Although for more distances the transverse settlements decreased, still there are some ground movements for the distances of 20 m and 25 that are 1 mm and 0.5 mm.
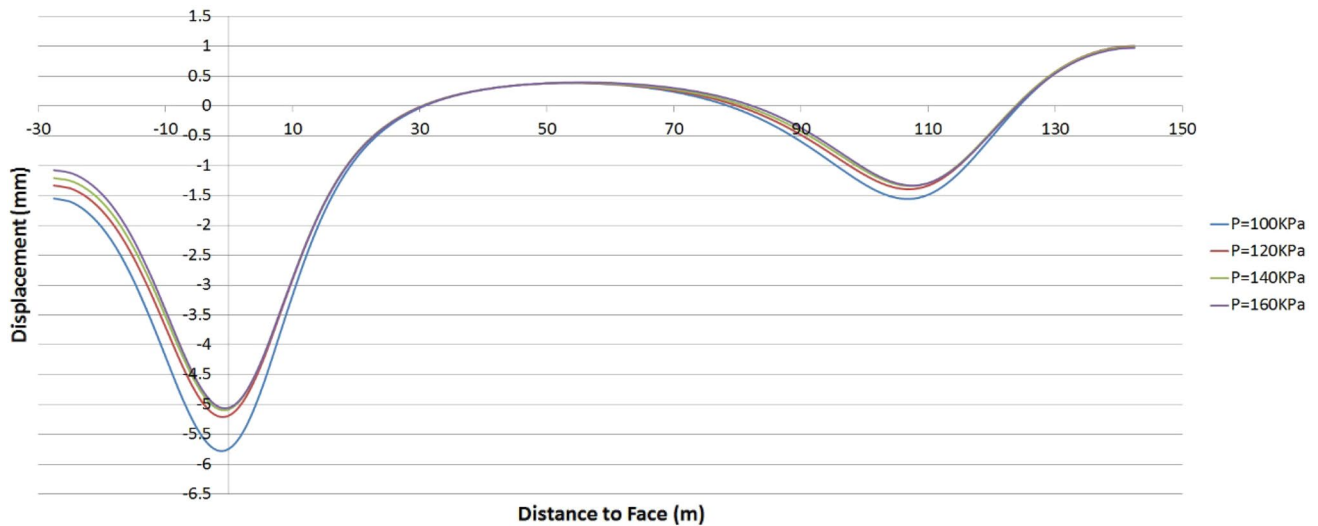
Fig. 6 Effect of the supporting face pressure on the longitudinal settlement profile of left tunnel
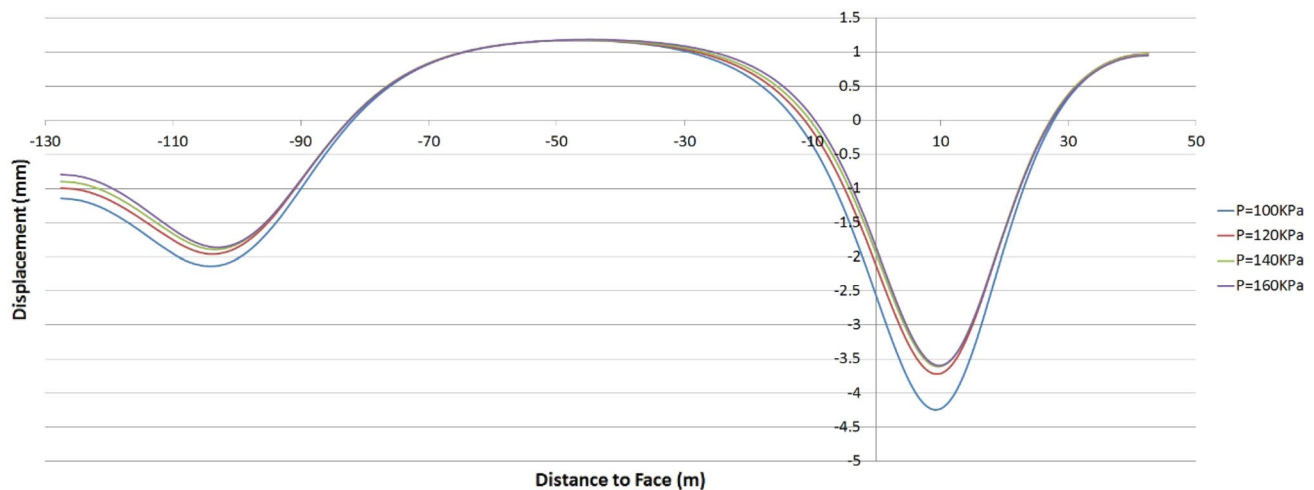

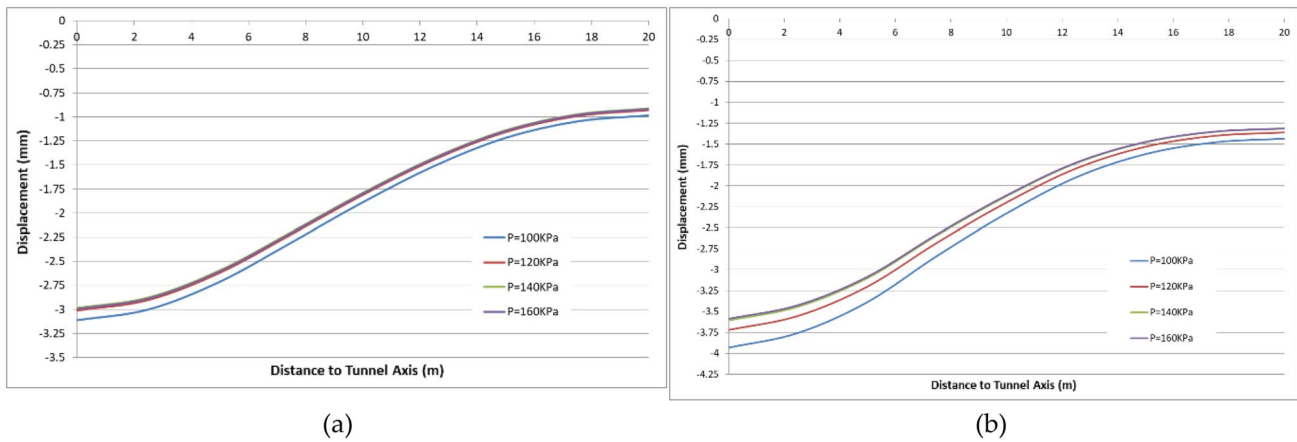**Fig. 7** Effect of the supporting face pressure on the longitudinal settlement profile of right tunnel

At the end of the tail and just after that, there is 1.5 m space between the shield and the lining segments and this is the place that grout injection is applied. The grout injection simulated as the circumferences force with the first pressure of 130 kPa for the single tunnel and 70 kPa for twin tunnels. (Fig. 12). The results of the grout pressure effect on the surface movements had shown in Figs. 13, 14 for a single tunnel in longitudinal and transverse profile respectively. The same results for the twin tunnels had shown in Figs. 15, 16, 17.

As can be seen, the grout pressure has a few influences on the long-distance settlements and the near zones are more subjecting to the change. The rate of decrease is more constant in the transverse graphs. However, the total amount of recovery is less than 1 mm for increasing the pressure

from 130 to 250 kPa and 70 kPa to 160 kPa for single and twin tunnels respectively. Therefore it implies that the pressure of grout is not an effective parameter for surface settlements. The main responsibility of the grout is providing stable zones around the excavation area for avoiding the later pressure on the linings from outside.

4 Conclusions

In this study, a complete three-dimensional finite element modeling of the single and twin tunnels of the metro has been employed. The study performed an investigation on the influence of the effective parameters of the EPB-TBM

Fig. 8 Effect of the supporting face pressure on the transverse settlement profile **a** left tunnel and **b** right tunnel
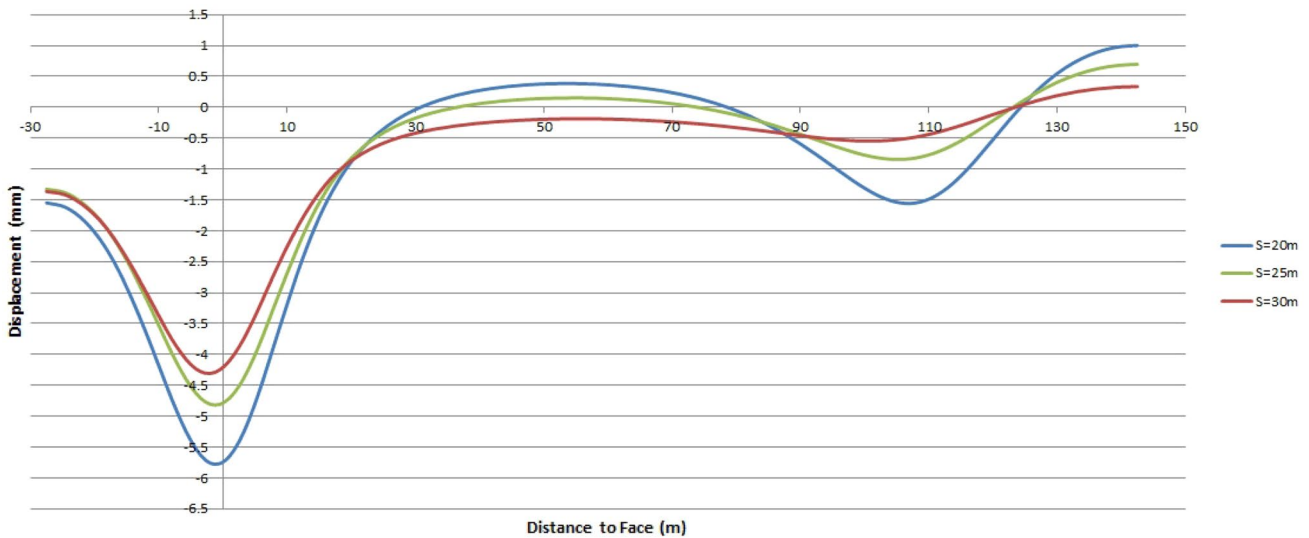
Fig. 9 Effect of the clear distance between the tunnels for the left tunnel

through excavation. Face supporting pressure, tail grout injection, overcutting of the cutter head, shield conicity, as well as the final lining system considered in the model. Also, effects of the face pressure, grout injection pressure, and clear distance of twin tunnels investigated. Based on the numerical analysis results, the achieved settlements were valid and standard in comparison to the other studies and based on the local report. The finite element analysis showed the maximum settlement of 6 mm in the single tunnel and for the twin tunnels, the maximum surface settlement was 5.7 mm and 4.2 mm for the left tunnel and right tunnel respectively. Moreover, the following results have been drawn from the 3D numerical analysis:

1. The maximum settlement induced by the machine excavation occurred in the end tail of the shield which is the place of grouting. In the twin tunnels, the achieved settlement from the first tunnel excavation is close to the single tunnel settlement. But for the second tunnel, the settlements are less. It seems to be the effect of soil disturbance created by the first tunnel excavation or existing final lining system.

2. The face supporting pressure has more effects on the settlements than grout injection. Also, this amount was higher in the single tunnel than the twin tunnels. The surface movements improved 1.5 mm in the single tunnels by 60 kPa increasing of the face pressure. But in the
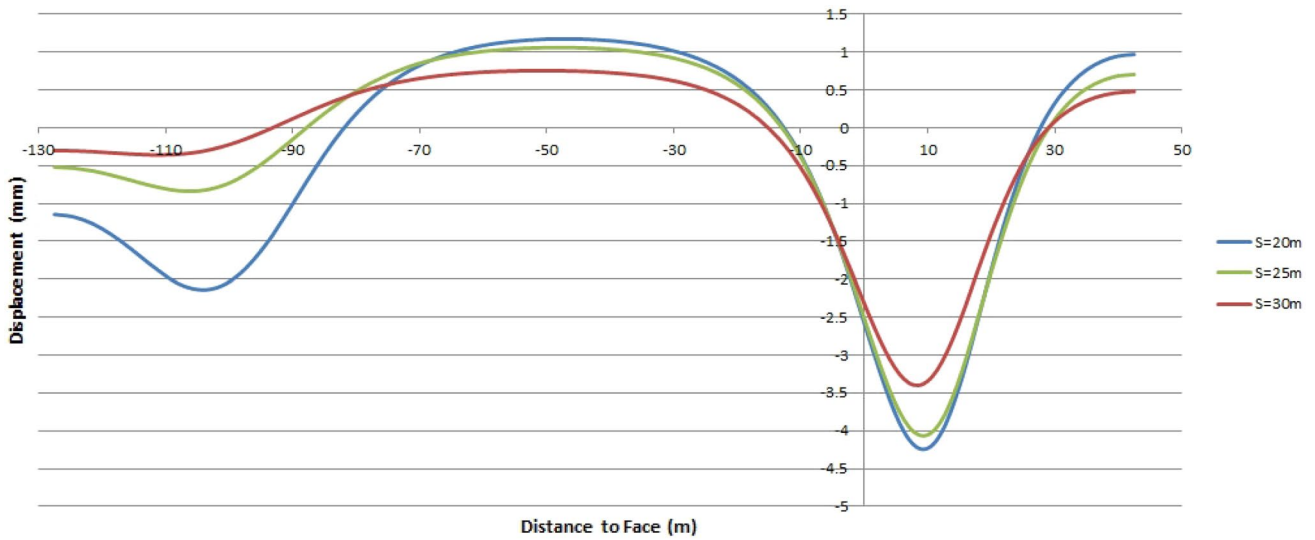
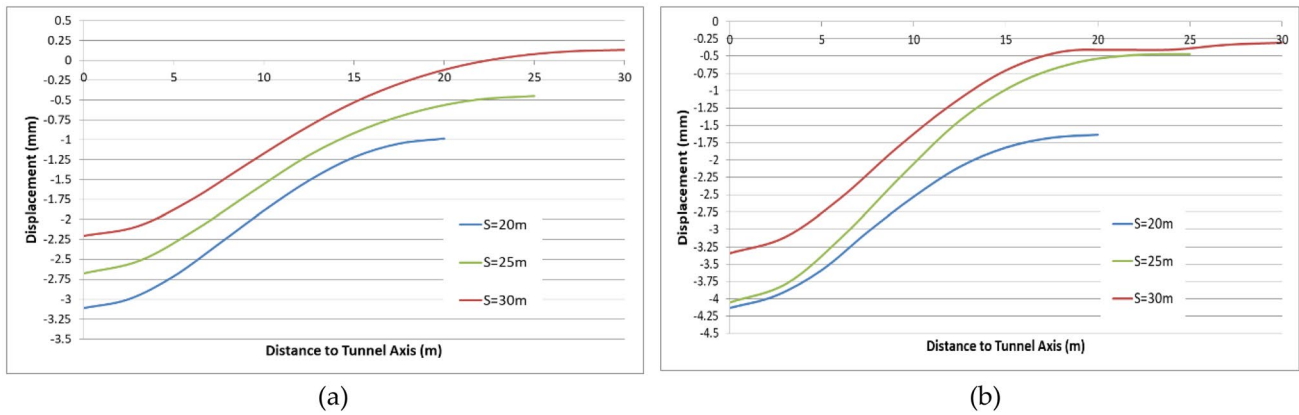**Fig. 10** Effect of the clear distance between the tunnels for the right tunnel

(a)   (b)

Fig. 11 Effect of the clear distance between the tunnels on the transverse settlement profile **a** left tunnel and **b** right tunnel
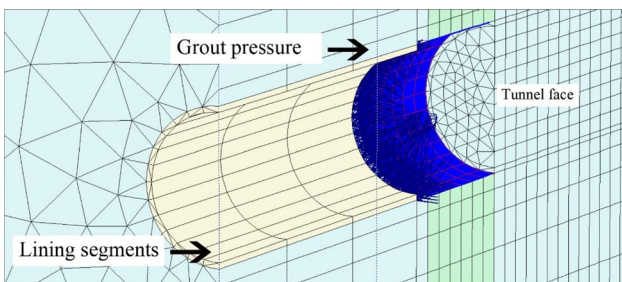

Fig. 12 The applied grout injection pressure as the circumference force in the 1.5 m gap

twin tunnels, the most surface settlement improvement obtained around 0.5 mm.

3. Influence of the grout injection pressure on the surface settlements is insignificant. The best settlements improvement reported as 1 mm by 120 kPa increasing of the injection pressure in the twin tunnels. However, the grout pressure has more influence on the twin tunnels. It can be associated with the smaller radius of the tunnels.

4. The influence of the clear distance of the tunnels decreased to zero after S = 30 m. As a result, this space can be reported as the maximum clear distance between the tunnels for considering them as twin tunnels. For
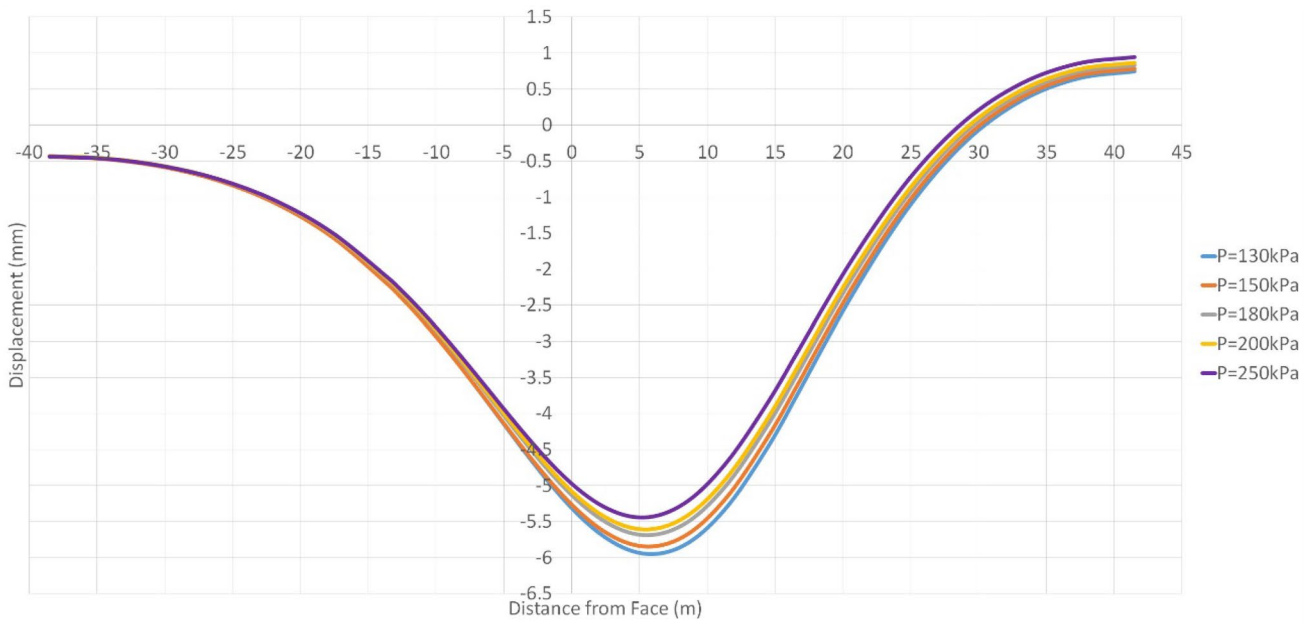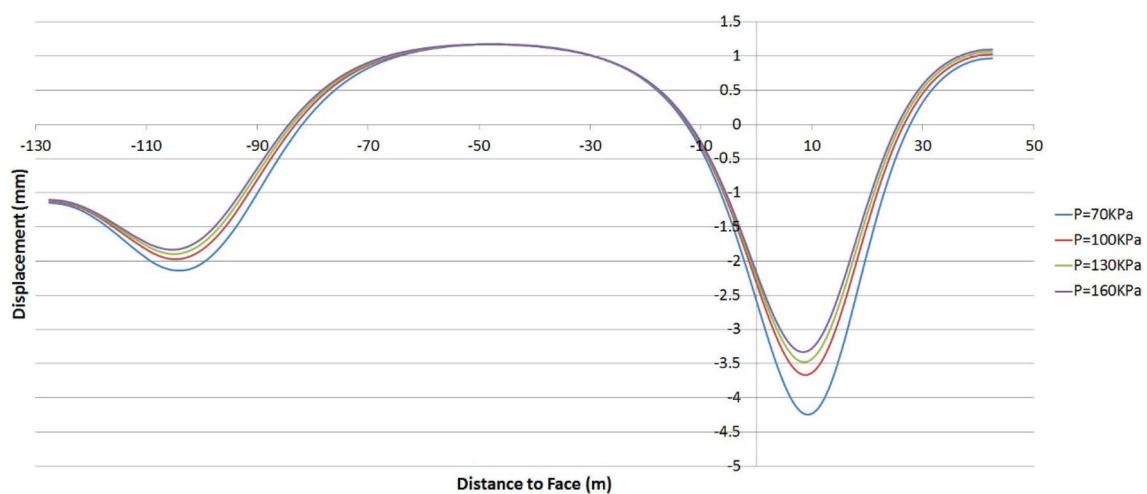
Fig. 13 The effect of grout injection on the longitudinal settlement profile
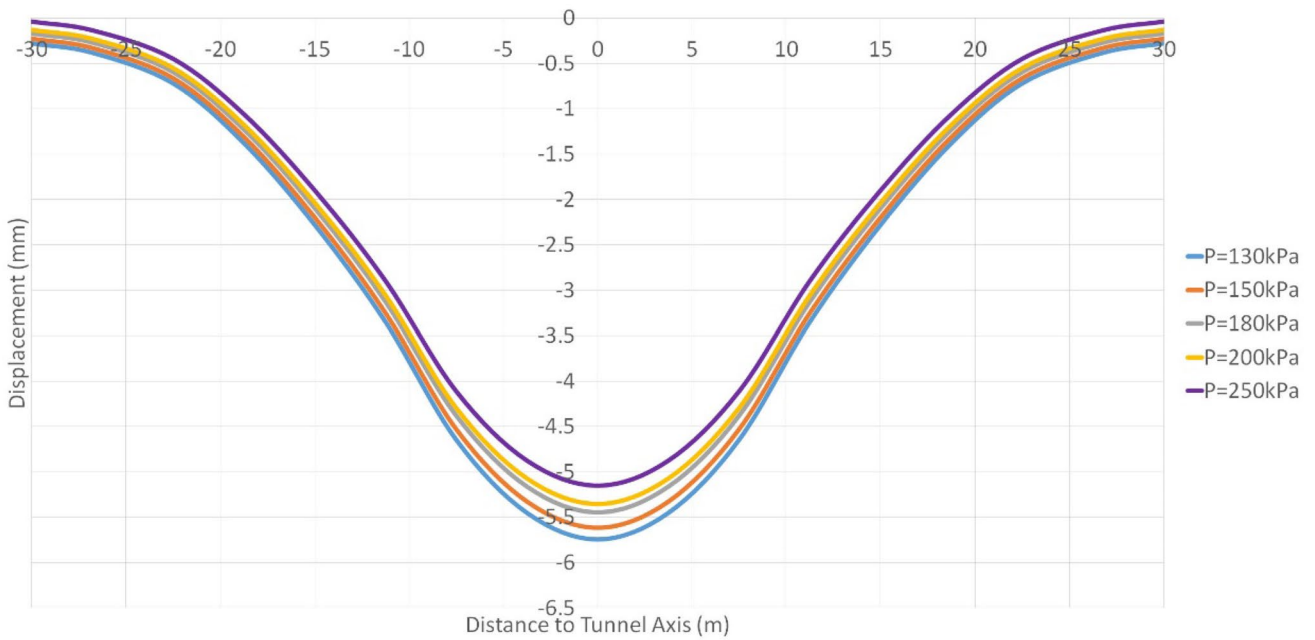
Fig. 14 The effect of grout injection on the transverse settlement profile
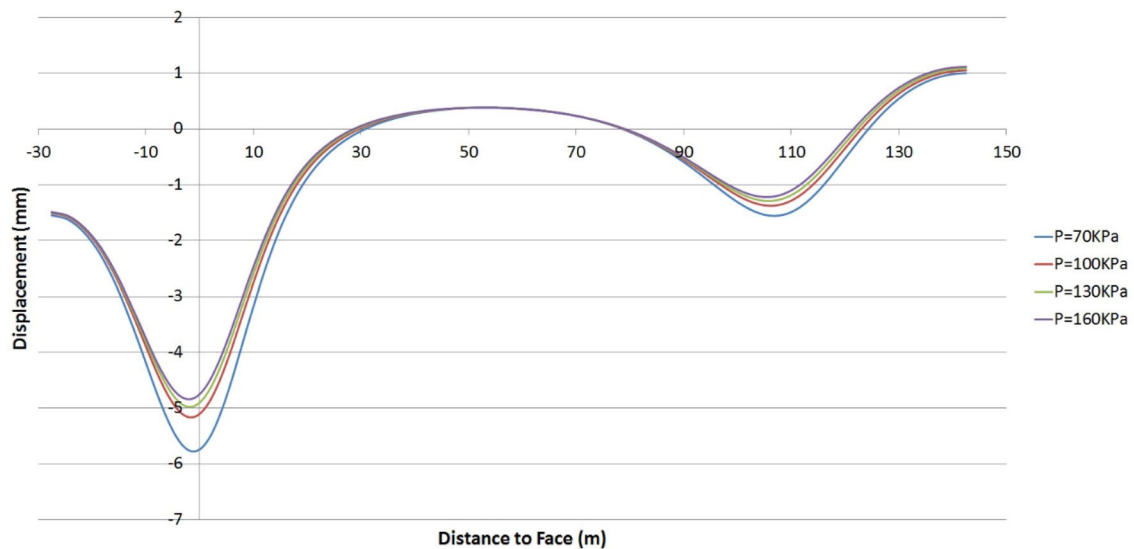
Fig. 15 The effect of grout injection on the longitudinal profile for the left tunnel


Fig. 16 The effect of grout injection on the longitudinal profile for the right tunnel

more distances, the tunnels should be analyzed separately and as two different single tunnels.

By increasing the face supporting pressure in the single tunnels, the place of maximum settlement moved to the backward. The analysis showed that increasing the pressure from 130 to 190 kPa caused moving the maximum settlement place 2 m up to 3 m backward. However, for the twin tunnels, no moving happened and it may be related to the smaller diameter or less applied face pressure.
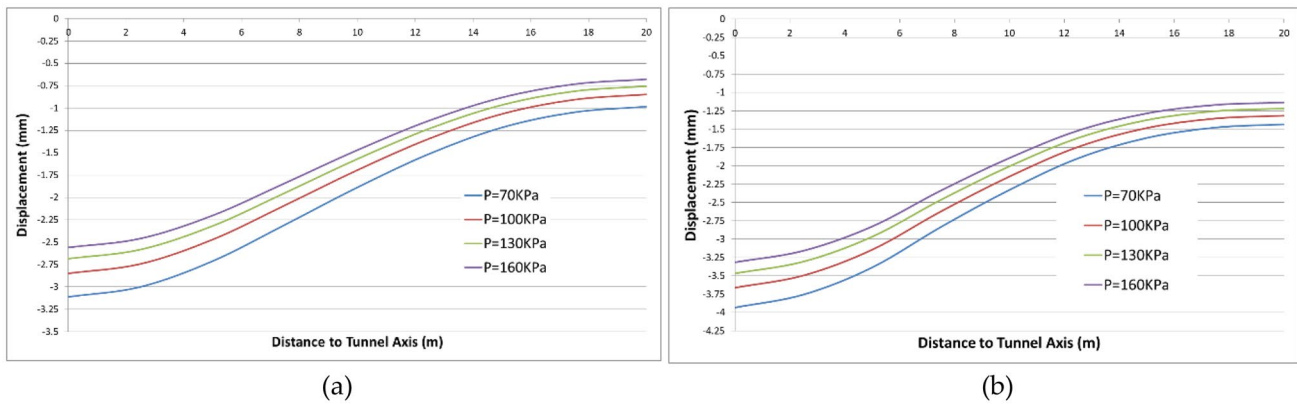
Fig. 17 Effect of grout injection pressure on the transverse settlement profile **a** left tunnel and **b** right tunnel

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