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The Effect of Non-Simultaneous Excavation of Closely-Spaced Twin Tunnels on Ground Surface Settlement

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ABSTRACT

Tunnel excavation on soil lands may lead to horizontal and vertical displacements around the tunnel. The displacements can reach the ground surface and cause damages to existing structures on the ground. Hence it is so important to estimate the ground settlement induced by excavation, particularly in urban environments. In this study, the effect of longitudinal distance between two tunnel faces on the ground surface settlement is examined during the excavation of twin tunnels. Accordingly, the ground settlement is measured for the states where the distance between tunnel faces is 0D, 0.5D, 1D, 1.5D and 2D. The most important results suggest that creating a longitudinal distance (lagging) between the faces of twin tunnels during excavation operations causes changes in surface ground settlement. The maximum surface ground settlement along the width and length of tunnels decreases as the distance between two tunnel faces increases.

Keywords: **twin tunnels, ground settlement, tunnel face, excavation, lagging distance**

1. INTRODUCTION

The increasing population growth and density in cities, on the one hand, and technological progress, on the other hand, has enhanced the demand for development of public spaces, e.g. underground metros. The density of urban spaces and rapid rise in the number of cars pose problems with appropriate communications throughout cities. Hence the construction of traffic tunnels and urban rail transit systems has become an overriding priority for the efficiency of urban transport. One of the most challenging aspects of tunnel engineering is to evaluate the impacts of deformation on the ground surface and potential holes which may emerge in buildings placed above the tunnel and its surrounding area [1]. Tunnel excavation on a soil land may result in horizontal and vertical displacements around the tunnel. The displacements can reach the ground surface and cause damages to existing structures on the ground. Therefore, it is of great importance to estimate the ground settlement induced by excavation, particularly in urban environments. There are a variety of factors in the tunneling-induced ground settlement, e.g. the excavation method, type of excavating machines and natural and artificial factors during excavation. Thus, it is necessary to investigate the settlement induced by each of these factors for more precise analyses [2]. A variety of factors play a key role in this displacement, e.g. soil conditions, underground water, specifications of structures, tunnel depth, tunnel diameter, excavation length and pressure on tunnel face. It is of great importance to estimate the settlement and predict its distribution before excavation due to its adverse effects on adjacent buildings and facilities. There are two general methods for the prediction of excavation-induced ground surface settlements: the numerical methods and the techniques based observations and measurements by instrumentation [3-4]. Nowadays, twin tunnel excavation is growing in developed communities. Today, an important factor which poses challenges to engineers and designers in regard to this type of tunnels is to assess the effect of two tunnels driven in a close proximity to their surrounding area [5-6]. Researchers have already conducted many studies on the excavation of twin tunnels; the investigation into the effect of excavation of closely-spaced twin tunnels on ground surface settlement indicated that the settlement caused by each of twin tunnels rises as the tunnel overburden declines [7]. The research on the effect of twin tunnels construction beneath existing shield-driven twin tunnels suggested that the tunnel settlement profiles are W-shaped, while the ground surface settlement profiles are U-shaped [8-9]. The study on the impact of twin-parallel tunnels on the seismic ground response demonstrated that seismic responses of the ground above the tunnel are highly different from the responses of unexcavated ground. The distance between tunnels and excavation depth are of important effective factors in the ground response [10]. Analytical investigations into stress and displacements of deeply buried twin tunnels in viscoelastic rocks showed that the distance between tunnels has more significant impact on ground surface settlement than the stress [11]. The twin tunneling in hard soils showed that the tunneling initially softens the soil between the tunnels, while it causes soil hardening in the tunnel crown [12]. In twin tunnels, an important parameter is how to select the distance between the tunnels and to schedule the excavation of successive tunnels in order to induce the least ground surface settlement during excavation and minimize the influence posed by the tunnels on each other. On the other hand, given the big diameter of excavation area in single tunnels compared to parallel tunnels, the suitable excavation depth is the most influential parameter; so that the minimum cut is required for the construction of metro stations in addition to the minimum ground settlement during tunneling. As the distance between the two tunnels rises, the force applied to the tunnel lining and also its settlement decline [13-14]. When two tunnels are horizontally constructed parallel to each other (in close proximity), the ground surface soil settlement and the forces applied to the lining of both tunnels (bending moment, axial force and shear moment) decrease as the distance between the tunnels increases [15-16]. The investigation into the impacts of twin tunnel construction and building settlements on Milano Metro line 5 suggested that the calculated results are properly compatible with the data observed during settlements and can capture the interaction between twin tunnels during construction process and describe the development of effective mechanisms in buildings [17-18]. Given the research about twin tunnel excavations and their influence on the ground, it is essential to notice all situations during twin tunnel excavations. In this study, it is thus attempted to assess the effect of non-simultaneous excavation of two adjacent tunnels on the ground surface settlement.

2. METHODOLOGY

Any changes in a point of the environment affect the stress distribution in that region. When a structure is excavated into the ground, some parts of its surrounding soil and rocks are subjected to elastic or plastic changes. Circular tunnels 9 m in diameter with lagging distance of 18 m (twice the diameter) are considered parametrically in this study in order to examine the effect of longitudinal distance (lagging) between two tunnel faces on the ground surface settlement during twin tunnel excavation and the impact of tunneling changes at different depths on the ground surface settlement. PLAXIS 3D Tunnel software is used to model the tunnel excavation in this study. The models are parametrically considered as a function of tunnel diameter for longitudinal distances (lagging between two tunnel faces) of 0D, 0.5D, 1D, 1.5D and 2D to show the effects of longitudinal distance between two tunnel faces. The tunnel center is considered at a depth of 12.5 m in this study to demonstrate the impact of changes in tunnel excavation at different depths on the ground surface settlement. The Mohr-Coulomb behavior model is employed to model the soil behavior via the software. This behavior model is utilized for the numerical analysis of behavior of underground structures due to simplicity of calculation of parameters and relatively good compatibility with the behavior of soil under loading.

Table 1. Utilized soil parameters

Parameters	Non-porous	Amount	Unit
Identification	-	Concrete	-
Material model	Model	Linear-elastic	-
Material type	Type	Non-porous	-
Volumetric weight	γ_{unsat}	24	(kN/m3)
Young's modulus	E_{ref}	26000000	(kN/m3)
Poisson's ratio (constant)	ν	0.2	-

For the soils in contact with the tunnel, the coefficients of $R = 1$ and $R = 0.8$ are defined to consider the effect of interface between two soil types [19].

Table 2. Parameters of tunnel lining (segments) [19]

Layer type	Saturated unit weight γ_{sat} (kN/m3)	Dry unit weight γ_{unsat} (kN/m3)	Elastic modulus E (kPa)	Poisson's ratio ν	Cohesion C (kPa)	Fricton angle $\emptyset$ (degree)	K_0
Clay	16	18	10000	0.35	5	25	0.5

The groundwater level is considered below the surface of models; it means that dry environmental conditions are considered for the soil mass. According to Figure1, the software calculated the pore water pressure equal to zero.

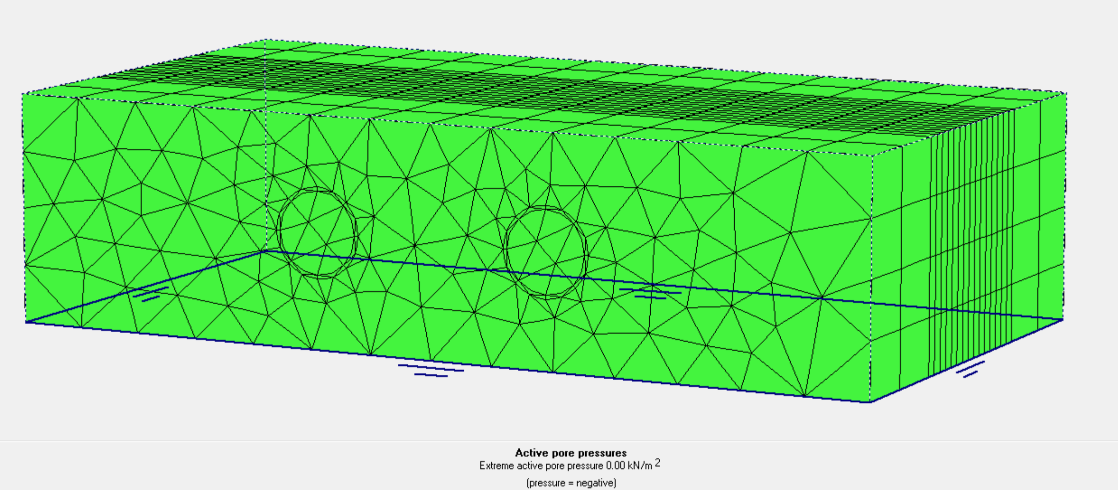

Figure 1. Pore water pressure

The results of a study by Dias et al are evaluated to assess the performance of software, prepared model and its conditions, in which a 3D investigation into the twin tunnels excavated in soft soil was conducted considering the lagging distance between two tunnel faces. Figure 2 illustrates the geometrical conditions of tunnel modeled by Dias et al [20].

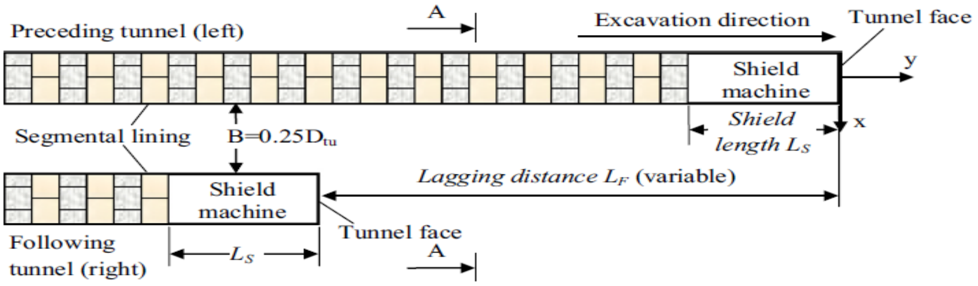

Figure 2. Geometry of tunnel modeled by Dias et al [20]

Figure 3 represents the settlements calculated both through the modeling by Dias et al and the modeling in this study. Obviously, there is good agreement between the results of models of Dias et al and this study.

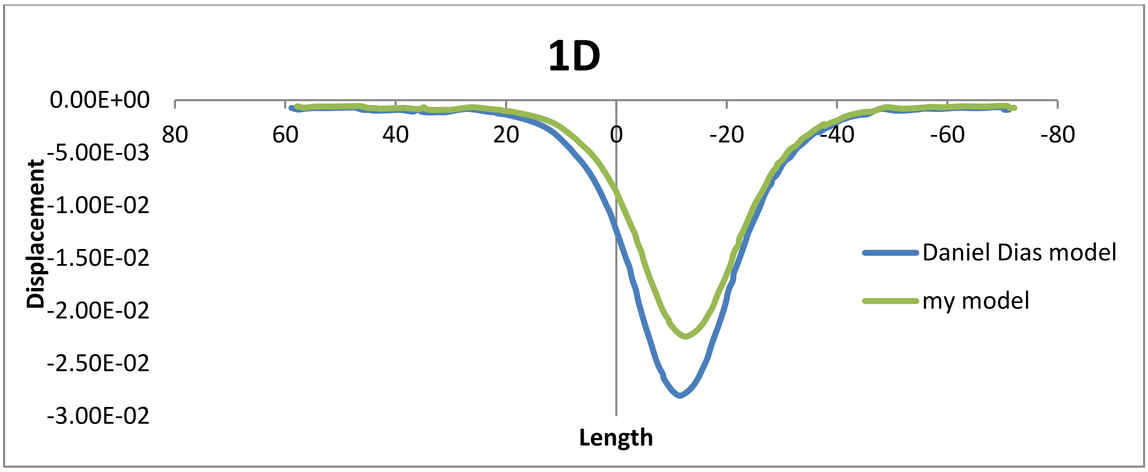

Figure 3. Diagram of settlement along length of tunnel [20]

3. Results and Discussion

The results are evaluated in four situations, i.e. maximum ground surface settlement along the width of tunnels (along the X-axis), maximum ground surface settlement at the center of soil mass in transverse section (along the X-axis), maximum ground surface settlement at the center of left tunnel along the length of tunnel (along the Z-axis) and maximum ground surface settlement at the center of right tunnel along the length of tunnel (along the Z-axis), for lagging distances of 0D, 0.5D, 1D, 1.5D and 2D between two tunnel faces in order to investigate the effect of non-simultaneous excavation of two closely-spaced tunnels on the ground surface settlement.

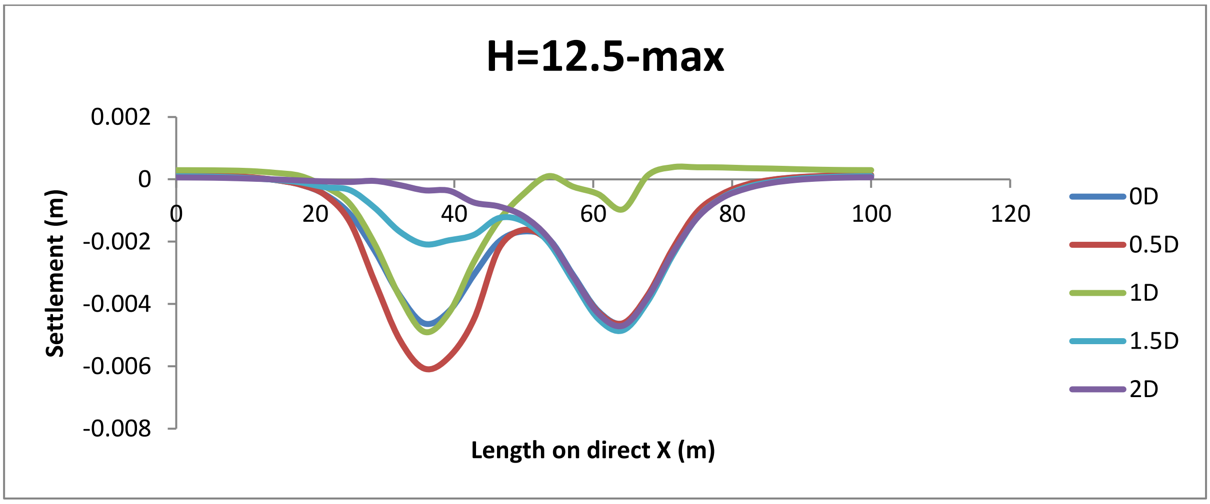

Figure 4. Maximum ground surface settlement along width of tunnels at depth of 12.5 m

Figure 4 indicates the maximum ground surface settlement along the width of tunnels at a depth of 12.5 m. According to the figure, the maximum ground surface settlement occurs when the lagging distance between two tunnel faces is half the tunnel diameter (0.5D) and as the lagging distance between two tunnel faces increases, the ground surface settlement decreases; so that the maximum ground surface settlement equals 6 mm.Figure 5 shows the maximum ground surface settlement at the center of soil mass in the transverse section when the tunnel center is at a depth of 12.5 m. As illustrated in the figure, the maximum ground surface settlement at the center of soil mass happens when the lagging distance between two tunnel faces is equivalent to the tunnel diameter, i.e. 9 m, which equals 6.92 mm.

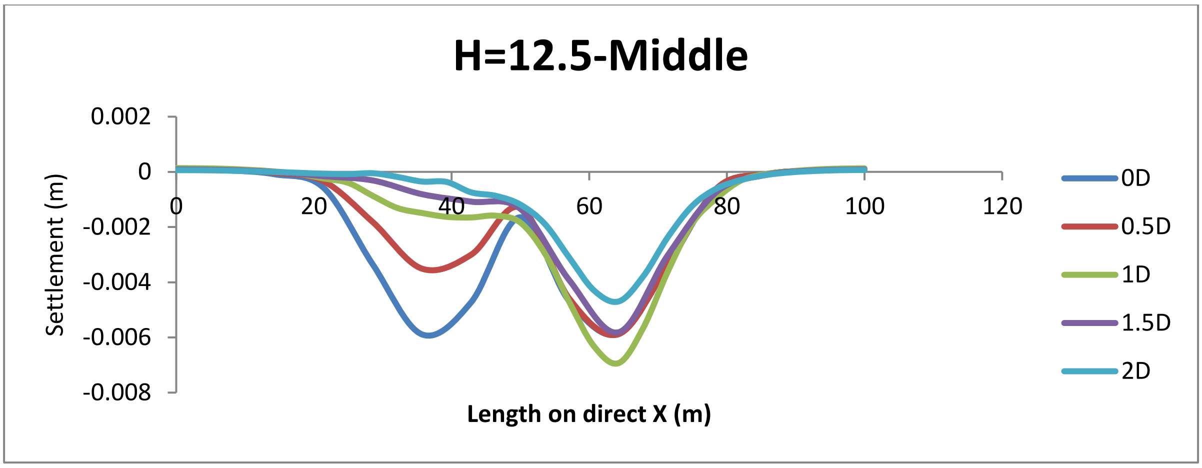

Figure 5. Maximum ground surface settlement at center of soil mass in transverse section

The evaluations demonstrate that the maximum ground surface settlement along the length of left tunnel occurs when the lagging distance between the face of this tunnel and the face of right tunnel is equivalent to the tunnel diameter, i.e. 9 m, which equals 6.63 mm. Figure 6 indicates the maximum ground surface settlement at the center of left tunnel along the length of tunnel when the tunnel center is at at depth of 12.5 m.

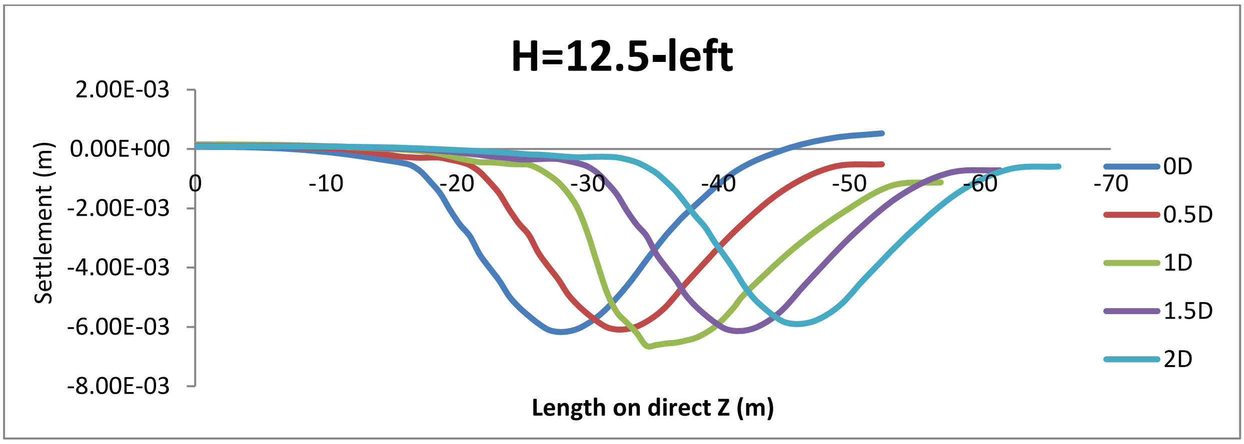

Figure 6. Maximum ground surface settlement at center of left tunnel along length of tunnel at depth of 12.5m

According to the figure, as the lagging distance between two tunnel faces increases, the ground settlement declines; so that the minimum settlement occurs when the lagging distance between two tunnels faces is equal to 2D. Figure 7 illustrates the maximum ground surface settlement at the center of right tunnel along the length of tunnels when the tunnel center is located at a depth of 12.5 m. As observed, the maximum ground surface settlement along the length of right tunnel is almost the same for all lagging distances of 0D, 0.5D, 1D, 1.5D and 2D. The reason is that the location of right tunnel is constant in all models. If it is sought to determine the maximum settlement more accurately, the value generally occurs when the lagging distance between the face of left tunnel and the face of right tunnel equals the tunnel diameter (9 m), which is 7 mm.

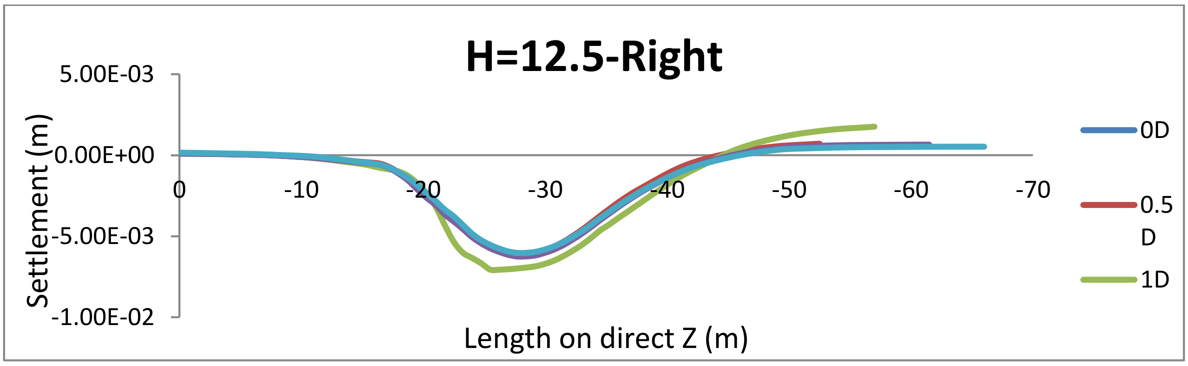

Figure 7. Maximum ground surface settlement at center of right tunnel along length of tunnel

The impact of increase in the depth on maximum ground surface settlement is evaluated for lagging distances of 0D, 0.5D, 1D, 1.5D and 2D. Figure 8 displays the maximum ground surface settlement at the center of soil mass across the tunnel for lagging distance of 0D at three depths of 12.5, 17.5 and 22.5 m. Evidently, as the depth rises, the settlement declines. When the tunnel faces are displaced together, the maximum settlement happens at a depth of 12.5 meters and equals 5.9 mm.

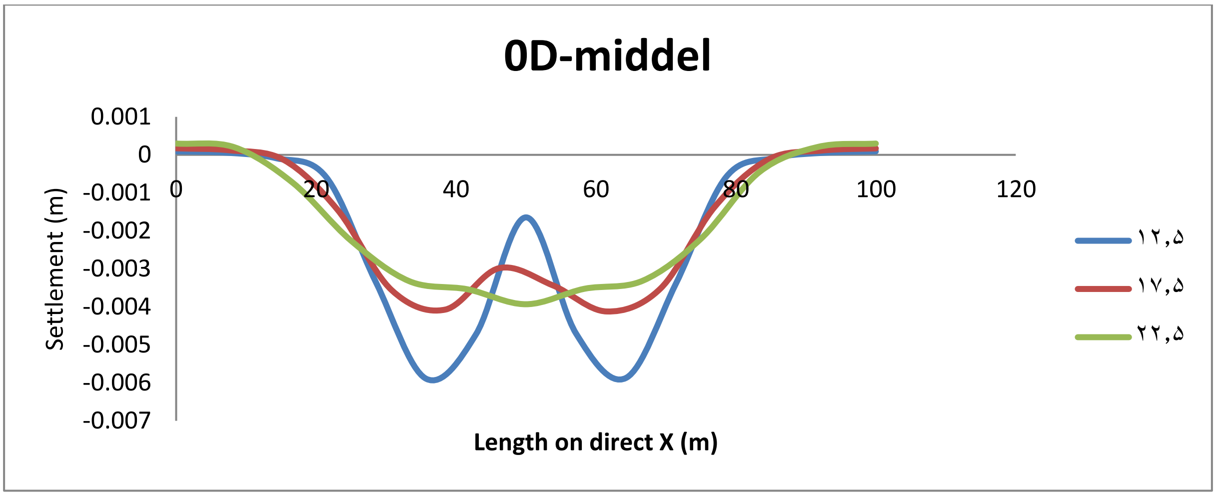

Figure 8. Maximum ground surface settlement at center of soil mass along width of tunnel at three depths of 12.5, 17.5 and 22.5 m for lagging distance of 0D

For the lagging distance of 0.5D, the settlement decreases as the depth increases. When the tunnel faces are displaced together, the maximum settlement occurs at a depth of 12.5 m and equals 5.88 mm.

Figure9 exhibits the maximum ground surface settlement at the center of soil mass along the width of tunnel for lagging distance of 0.5D at three depths of 12.5, 17.5 and 22.5 m.

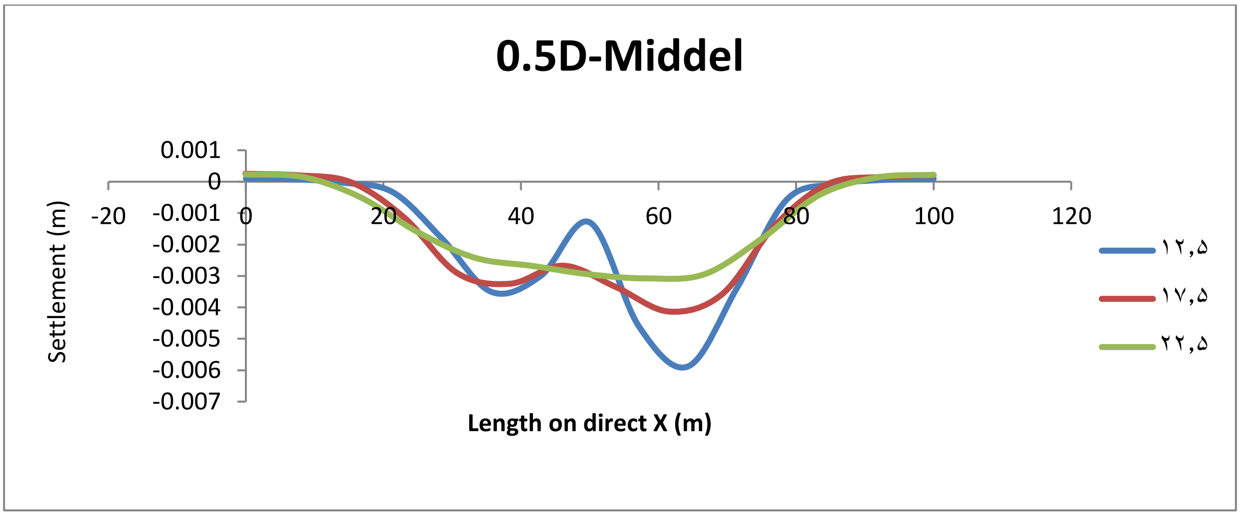

Figure 9. Maximum ground surface settlement at center of soil mass along width of tunnel at three depths of 12.5, 17.5 and 22.5 m for lagging distance of 0.5D

Figure 10 shows the maximum ground surface displacement at the center of soil mass along the width of tunnel for lagging distance of 1D at three depths of 12.5, 17.5 and 22.5 m. Obviously, the settlement decreases as the depth rises. When the lagging distance between tunnel faces is 9 m, the maximum settlement occurs at a depth of 12.5 m and equals 4.89 mm.

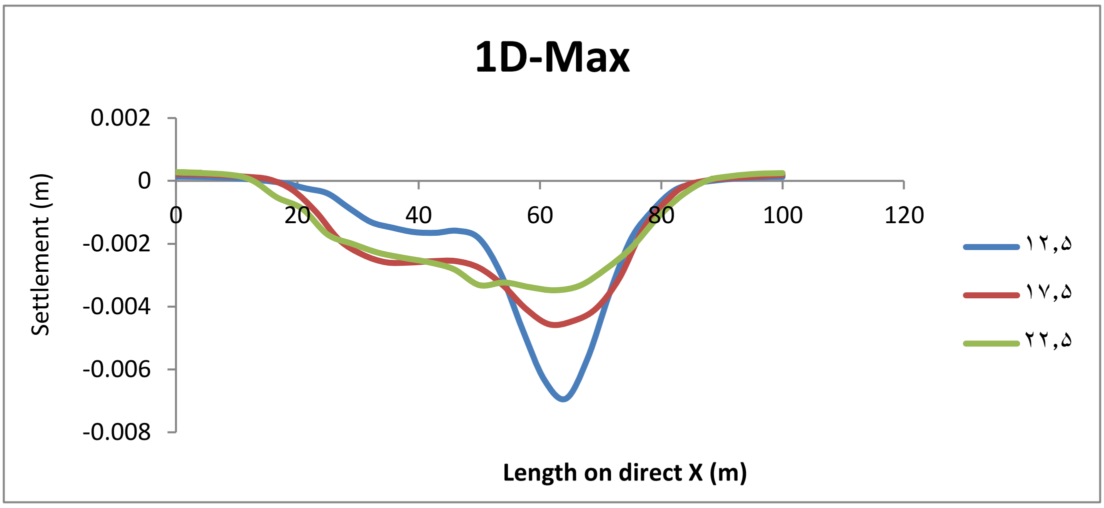

Figure 10. The Maximum ground surface settlement at center of soil mass along the width of tunnel at three depths of 12.5, 17.5 and 22.5 m for lagging distance of 1D

Figure 11 illustrates the maximum ground surface settlement at the center of soil mass along the width of tunnel for lagging distance of 1.5D at three depths of 12.5, 17.5 and 22.5 m. Apparently, the settlement declines as the depth increases. When the lagging distance between tunnel faces is 13.5 m (1.5D), the maximum settlement happens at a depth of 12.5 m and equals 4.89 mm.

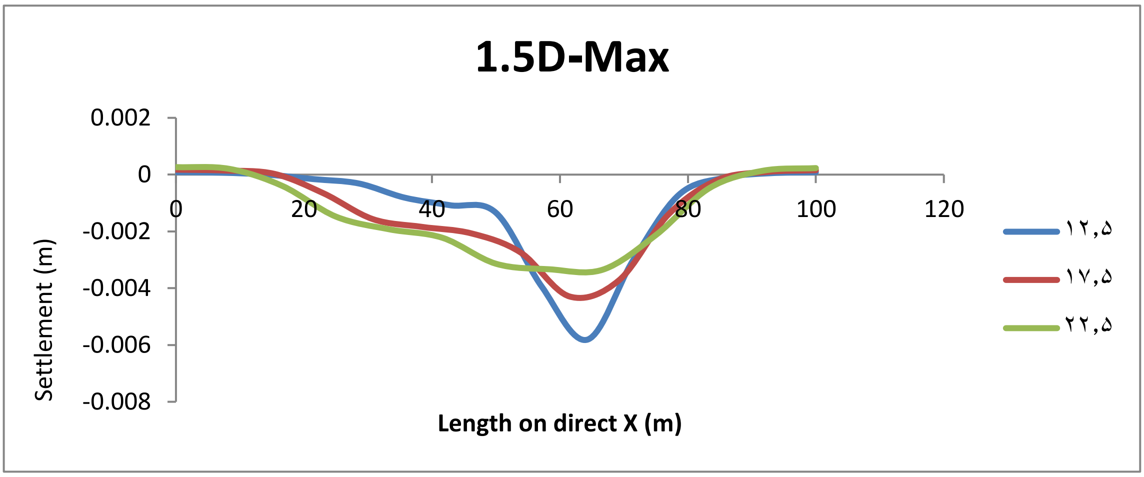

Figure 11. Maximum ground surface settlement at center of soil mass along the width of tunnel at three depths of 12.5, 17.5 and 22.5 m for lagging distance of 1.5D

For the lagging distance of 2D at three depths of 12.5, 17.5 and 22.5 m, the settlement decreases as the depth increases. When the lagging distance between tunnel faces is 18 m (2D), the maximum settlement occurs at a depth of 12.5 m and equals 4.69 mm. Figure 12 demonstrates the maximum ground surface settlement at the center of soil mass along the width of tunnel for lagging distance of 2D at three depths of 12.5, 17.5 and 22.5 m.

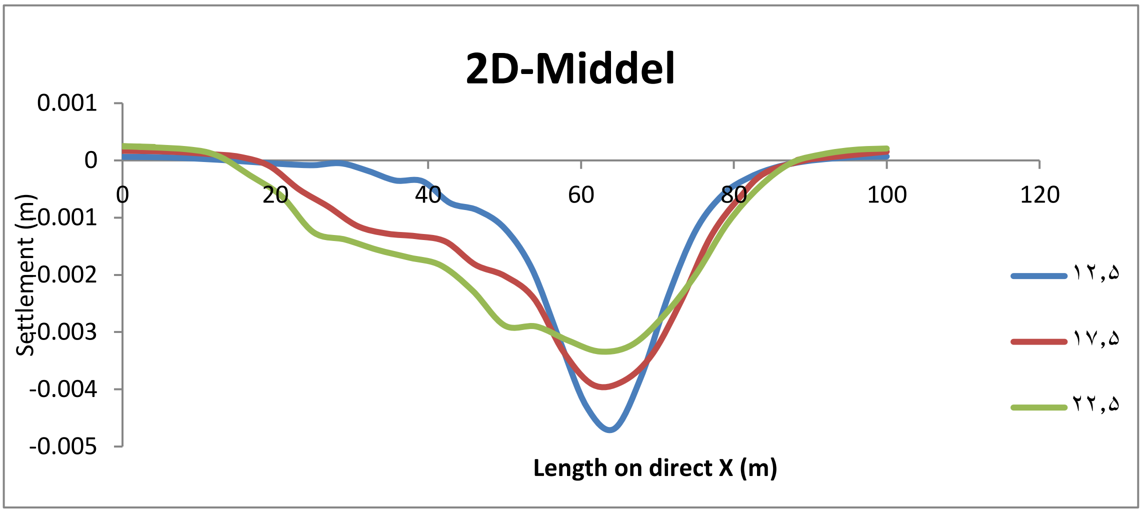

Figure 12. Maximum ground surface settlement at center of soil mass along width of tunnel at three depths of 12.5, 17.5 and 22.5 m for lagging distance of 2D

4. CONCLUSION

In this study, it is attempted to provide a variety of conditions in order to assess the ground surface settlement during tunnel excavation for non-simultaneous excavation of tunnel faces. Accordingly, the lagging distance between tunnel faces is considered 0D, 0.5D, 1D, 1.5D and 2D and the effect of non-simultaneous excavation of tunnel faces on the ground settlement is evaluated when the tunnels are at depths of 12.5, 17.5 and 22.5 m. The results of these investigations are as follows:

- Considering a longitudinal distance (lagging) between the faces of twin tunnels causes changes in the ground surface settlement during excavation operations.
- The maximum ground surface settlements decrease along the width and length of tunnels as the distance between both tunnel faces is reduced. The maximum longitudinal and transverse ground settlements occur for lagging distances of 0D, 0.5D and 1D, which is because of the stress concentration on the soil mass when two machines operate near each other.
- For all lagging distances, the ground surface settlement varies according to the changes in the depth of tunnels. For each 5 m increase in the tunnel depth, the ground surface settlement for lagging distances of 0D, 0.5D and 1D decreases by 32.4%, 32.13% and 36.91%, respectively.
- The maximum ground surface settlement along the length of tunnels occurs for the lagging distance of 1D at a depth of 12.5 m and the maximum ground surface settlement along the width of tunnels happens for the lagging distance of 0.5D at a depth of 12.5 m.
- The maximum ground surface settlement at the center of soil mass in the transverse section occurs for the lagging distance of 1D at a depth of 12.5 m. The effect of longitudinal distance between the faces of twin tunnels on the ground surface settlement is less than that for the depth of tunnels.
- The lagging distance of 2D is the optimum longitudinal distance between the twin tunnel faces

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AUTHORS CONTRIBUTION
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CONFLICT OF INTEREST
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