Soils and Rocks

An International Journal of Geotechnical and Geoenvironmental Engineering

www.soilsandrocks.com

ISSN 1980-9743
ISSN-e 2675-5475

A numerical approach to evaluating the asymmetric ground settlement response to twin-tunnel asynchronous excavation

Alireza Seghateh Mojtahedi[1], Ali Nabizadeh[2#]

Article

Keywords
Twin-tunnel
Ground surface settlement
Centrifuge test
Numerical modeling

Abstract

Due to the importance of surface and subsurface settlements to prevent damages to building foundations and sensitive structures in the urban cities, in this study, the ABAQUS finite element software has used to conduct a series of numerical modeling analysis on ground surface settlement caused from the asynchronous excavation of twin-tunnel. The effects of tunnel diameter, center-to-center tunnel spacing, and tunnel depth are discussed in detail and the shape of the surface settlement curves is also plotted. The numerical modeling has been verified by the results of three sequential twin-tunneling centrifuge tests conducted by the City University of London with 94.22%, 98.71% and 99.56% accuracy, respectively. Based on the results of this study, reducing the tunnel diameter decreases the amount of the maximum ground surface settlements and reducing the depth of tunnels and the distance between twin-tunnel to less than 2D (D is the diameter of the tunnels) increase the maximum surface settlements. Installation of 30 cm of tunnel lining can decrease the maximum ground surface settlement up to almost 79%.

1. Introduction

Due to the scarcity of available land within cities, underground structures such as transportation tunnels and water supply are continuously developing in populous cities. The tunnel boring machine (TBM) is an efficient excavation equipment and tunneling method, which makes highly advanced excavation machines by a high level of circular cutting control. Underground excavation causes ground surface displacements and may in effect damage the foundation of buildings and sensitive structures. Therefore, foreseeing ground surface settlements caused by the excavation of single or twin-tunnel is of great concern and should be considered before the start of excavation operations. These ground surface movements can be reduced by the use of modern tunneling technology. The difference between the shapes of an excavated tunnel and a final designed tunnel in the cutting process, which the shape of excavated tunnel is always larger than the final shape and causes volume differences due to 'volume loss' and is normally presented as a percentage. The soil mass deformation phenomenon, observed especially at the surface, leads to the possibility of structural failure caused by ground deformation (Mair & Taylor, 1997). Many researchers have studied the effect of single tunnel excavation on ground surface displacements (e.g. Attewell & Yeates, 1984). Mair & Taylor (1997) conducted research on the ground deformation caused by tunneling. Almost all transportation tunneling systems are excavated in twin-tunnel (e.g. Jubilee Line Extension described by Burland et al., 2001). To estimate the surface settlement of twin-tunnel using superposition of each single tunnel is a common theory, which assumes that excavating the second tunnel is not affected by the first close tunnel. Initial numerical investigations have shown that the superposition technique may not be enough. Hunt (2005) investigated the consequence of low spacing in construction tunnels employed by the finite element method and proffered several differences from the superposition method. Ground deformation and tunnel excavation were widely controlled in certain critical projects, such as the St James Park located in UK (Nyren, 1998), Lafayette Park located in USA (Cording & Hansmire, 1975), and The Heathrow Express located in UK, (Cooper & Chapman, 1998). Twin-tunnel excavations were observed in each of the surface settlements, which were asymmetric to the ground displacements. Divall & Goodey (2012) explored ground behaviour following the excavation of close tunnels in over consolidated clay.

Moreover, several plane strain centrifuge tests were performed on over consolidated clay to investigate ground

#Corresponding author. E-mail address: ali.nabizadeh@sru.ac.ir
[1]Amirkabir University of Technology (Tehran Polytechnic), Department of Civil and Environmental Engineering, Tehran, Iran.
[2]Shahid Rajaee Teacher Training University, Department of Civil Engineering, Tehran, Iran.

Submitted on May 11, 2021; Final Acceptance on January 27, 2022; Discussion open until August 31, 2022.
https://doi.org/10.28927/SR.2022.071021

surface settlements caused by twin-tunnel excavations in different horizontal, vertical, or oblique arrangements. In these experiments, ground displacements are calculated in a vertical direction perpendicular to the tunnel, and the important contents presented by the investigators are summarized as follows (Divall, 2013; Zlatanovic & Lukic, 2014).

a) Single tunneling surface and subsurface settlement can also be calculated by Gaussian distributions; although, the modification of ground surface settlements can improve twin-tunneling estimations because of second tunnel excavations;
b) Volume loss (given as a percentage) can be best described as the comparison of relative increases in settlements caused by the second tunneling. Wider spacing between the twin-tunnel can reduce the influence of second tunneling;
c) Researchers (Peck, 1969; O'Reilly & New, 1982; Mair et al., 1981) investigated modifications of equations to better estimate ground surface settlements caused by second tunnel excavation. They found the maximum displacement and curve shape of surface deformations to be wider than the first tunnel displacement.

Results of the numerical analysis of this research are in good agreement with the above explorations. Ranken & Ghaboussi (1976) conducted one of the first numerical researches in the ground surface settlement of parallel tunnels. Herzog (1985) presented a prediction for the maximum amount of ground surface displacement. Addenbrooke & Potts (2001) investigated the two-dimensional finite element analysis using a nonlinear elastic-perfectly plastic soil model for multiple tunnels. A numerical analysis which employed isotropic models with a linear elastic-perfectly plastic soil behaviour calculated the surface movement to be slightly wider than that perceived by the Gaussian scatter (Mair et al., 1981). Nonlinear elastic-perfectly plastic models have improved the estimations that change the curve shape of the results, making them more similar to those of field observations. Chehade & Shahrour (2008) investigated the effect of tunnel spacing on the curved shape and value of a settlement. They found that the maximum amount of settlement occurs at a distance of twice the diameter of the tunnels (SP/D=2, SP is the spacing of the tunnels and D is the diameter of the tunnels). They also observed that a spacing of three times the tunnel diameter did not significantly influence the excavation (SP/D=3). Chakeri et al. (2011) investigated the interactions between tunnels and concluded that two close tunnels in transportation tunnel line scan be excavated with the maximum spacing of three times the tunnel diameter (SP/D=3; Divall & Goodey, 2012; Zlatanovic & Lukic, 2014). Chakeri et al. (2015) investigated the effect of fault zone on twin-tunnel driven with EPBM in urban areas. Zhu & Li (2017) investigated surface displacement caused by shield tunneling at Xi'an metro. Yang & Zhang (2018) investigated the failure mechanism of circular twin-tunnel by considering surface displacements as a theoretical basis for designing twin-tunnel roofs. Wu et al. (2020) investigated the impact of tunnel construction on an adjacent existing tunnel using the 3D discrete element and propose a new method to protect the existing tunnel.

According to the normalized results of this study, the ground surface displacements caused by the excavation of twin-tunnel in urban regions can be estimated for the same soil properties and geometric conditions of different geometric arrangements of twin-tunnel or ground characteristics; and the same numerical simulation analysis of twin-tunnel excavation procedures can give the maximum displacement value and shape of the ground surface deformations. Numerical modeling can also be considered in arbitrary configurations and with different values of tunnel diameters, tunnel spacing, or tunnel depths, either by excavating underground twin-tunnel simultaneously or excavating new tunnels adjacent to old ones. Therefore, to prevent maximum ground surface movements caused by the excavation of twin-tunnel and damage to structure foundations, accurate prediction and control of ground surface displacements caused by excavation are the most important issues to consider prior to excavation.

A series of numerical modeling was conducted for the present study using the finite element method (FEM), ABAQUS software, to study ground surface displacement caused by the asynchronous excavation of twin-tunnel. The effect of four parameters, specifically tunnel diameters, center-to-center tunnel spacing, tunnel depth, and tunnel lining are described in details. Results of the numerical modeling were verified by the results of three sequential twin-tunneling centrifuge tests conducted by Divall & Goodey (2012) and Divall et al. (2012) in the City University London with 94.22%, 98.71% and 99.56% accuracy for center-to-center tunnels spacing of 1.5D, 3D and 4.5D (D is the tunnel diameter), respectively.

2. Verification of numerical modeling via centrifuge test of twin-tunnel

The finite element method (FEM), ABAQUS/CAE, was used to conduct numerical analyses on surface settlements resulting from the excavation of twin-tunnel and the effects of the parameters. Modeling analyses were verified by the following procedure of three centrifuge tests of twin-tunneling with center-to-center spacing of 1.5D, 3D and 4.5D (D is the diameter of the tunnel).

2.1 Summary description of the centrifuge modeling and its geometry

In order to predict ground surface displacement caused by twin-tunnel excavation, several centrifuge tests performed in the City University London were conducted in 2012 to simulate prototype conditions. The results of these tests are used as basis for verifying the numerical modeling analysis in this study. These tests were carried out in the plane strain condition and in a special box called 'strongbox' at an acceleration of 100g with two circular tunnels over consolidated clay. The tunnel holes in the strongbox were maintained by pouring fluid into the latex membranes to simulate the excavation of each tunnel. The fluid control system that was used to control fluid extraction is referred to as the 'volume loss' (Divall & Goodey, 2012). The twin-tunnel and soil model dimensions are presented in Figure 1. Clay samples were prepared at a cover depth equal to twice the diameter of the tunnel ($H_c/D=2$). The tunnel diameters of the twin-tunnel were 40 mm, the center of the tunnels was about 82 mm higher than the bottom of the strongbox and the center-to-center tunnel spacing was about 120 mm in the middle of the strongbox, which was drilled according to the test conditions (Divall & Goodey, 2012).

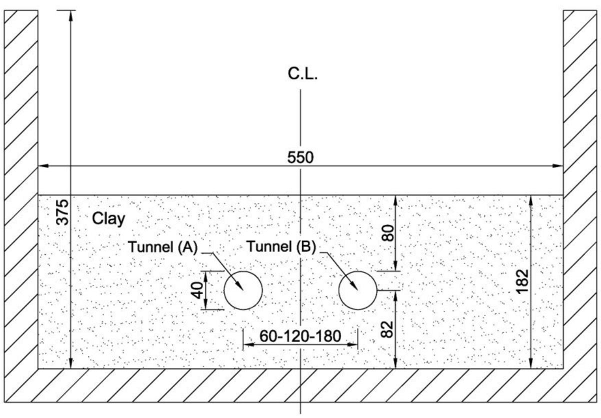

Figure 1. Twin-tunnel arrangements in the centrifuge test strongbox (dimensions in mm and C.L. is the center line of the strongbox) (Divall & Goodey, 2012; Divall et al., 2012).

2.2 Two-dimensional finite element mesh and boundary conditions of twin-tunnel modeling

Figure 2 shows the two-dimensional finite element mesh and boundary conditions used to analyze the aforementioned centrifuge test of twin-tunnel. The mesh dimensions used in the numerical analysis were 550 mm × 182 mm and were adapted to the centrifuge test exactly. A 4-nodes bilinear plane strain quadrilateral reduced integration with hourglass control continuum element type (CPE4R) was used to model the twin-tunnel (Mirhabibi & Soroush, 2012). The mesh dimension of the numerical models was selected almost 4 mm × 4mm around the tunnel cavities at the model scale (dense meshing) which was increase to 10 mm × 10 mm near the model boundaries, based on several sensitivity analyses the results were not influenced. The Nlgeom (geometric nonlinearity) condition was active during all steps of the analysis, controlling the inclusion of the nonlinear effects of large displacements and affecting the subsequent steps. The movements were restricted in a perpendicular direction of the outer boundaries (at both left and right sides of the model) of the mesh. Pinned supports were utilized to constrain the displacements in two directions of the base boundary of the model.

2.3 Constitutive models and soil parameters

The linear elastic perfectly- plastic Mohr-Coulomb (MC) yield criterion model was selected for the Speswhite kaolin clay in the ABAQUS/CAE with a critical state of friction angle (ϕ) and saturated unit weight (γ) of 23º and 17.44 kN/m^3, respectively. A Poisson's ratio (υ) and dilation angle (ψ) of 0.3 and 0.1° were selected, respectively. The Young's modulus (E) and undrained shear strength (S_u) used for the model were 11500 kN/m^2 and 49.8 kN/m^2,

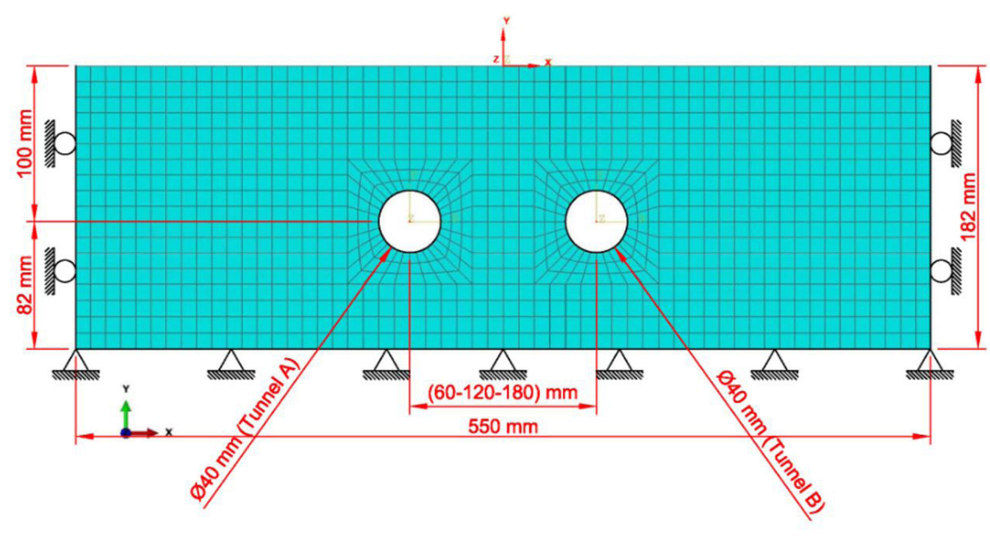

Figure 2. Two-dimensional finite element mesh and boundary conditions of twin-tunnel centrifuge excavation tests in this study.

respectively (Divall, 2013). The coefficient of lateral earth pressure (K_0= 1- Sin ϕ) was assumed to be 0.61.

2.4 Numerical modeling procedure

Once the pore water pressure was balanced in the test model, the following procedure was conducted: a) Tunnel valve B was closed so that tunnel A was controlled individually by the control system. b) Water from tunnel A was extracted to simulate tunnel excavation. c) A time period was considered to simulate the construction time. d) During this time, the valve of tunnel A was closed and the valve of tunnel B was opened. e) Water from tunnel B was extracted to simulate tunnel asynchronous excavation (Divall & Goodey, 2012; Divall, 2013).

The numerical modeling of the twin-tunnel asynchronous excavation basically followed the centrifuge test procedure. Detailed of the simulation procedure is summarized as follows:

a) The initial boundary and geostatic stress conditions at an acceleration of 100g were assigned as the initial steps (i.e., geostatic stress condition with the coefficient of lateral earth pressure, K_0= 0.61);
b) Body forces and horizontal and vertical equilibrium forces on all circumference nodes of both tunnel A and tunnel B cavities at an acceleration of 100g were assigned as step-1. These equilibrium forces of circumference nodes are calculated in a separate model by defining the displacement constraints in two directions for all circumference nodes of tunnel A and tunnel B cavities;
c) In this step, only tunnel A excavation is simulated by reducing uniformly and then eliminating the horizontal and vertical equilibrium forces of all tunnel A circumference nodes, while the horizontal and vertical equilibrium forces of tunnel B nodes from step-2 are still active in this step;
d) In this step, all nodes of tunnel A are restrained once the excavation simulation of tunnel A is completed, and regarding to asynchronous excavation of twin-tunnel, the excavation simulation of tunnel B is activated as mentioned in step-3 by reducing and eliminating the horizontal and vertical equilibrium forces of all nodes of tunnel B cavity.

2.5 Verification of the modeling of center-to-center spacing of 1.5*D*, 3*D* and 4.5*D*

The two-dimensional numerical analysis of center-to-center spacing of 1.5*D*, 3*D* and 4.5*D* of the twin-tunnel, shown in Figure 3, was verified by comparing the results to those of the centrifuge tests conducted by Divall & Goodey (2012) and Divall et al. (2012) at the City University of London, respectively. Table 1 and Figure 3 show comparison of these results. According to Figure 3 shows the maximum results of the surface settlements obtained by the twin-tunnel excavations of center-to-center spacing of 1.5*D*, in which a centrifuge device of -517.68 μm is used in the model scale (S_{max}/D = -0.01294), (Divall et al., 2012). According to Figure 3, the maximum results obtained from the surface settlement caused by the twin-tunnel were -487.77 μm in the model scale (S_{max}/D = -0.01219). These values are in agreement with the centrifuge test results and the curve shape of surface displacements created by the numerical analysis of the twin-tunnel with 94.22% accuracy.

According to Figure 3, the maximum results of surface settlements obtained by excavating the twin-tunnel at 3D center-to-center spacing through the centrifuge device was found to be -316.18 μm in the model scale (S_{max}/D = -0.00790; Divall & Goodey, 2012). As shown in the figure, the maximum result of the surface settlement resulting from the twin-tunnel generated by a numerical analysis is -312.11 μm in the model scaling (S_{max}/D = -0.00780). Comparing these values shows a good agreement between the centrifuge test results and the curve shape of surface displacements created by the numerical analysis of the twin-tunnel with 98.71% accuracy.

According to the safety factors used in geotechnical designs, 1.29% of the verification error between the results is acceptable. The errors and slight differences between the results may be caused by:

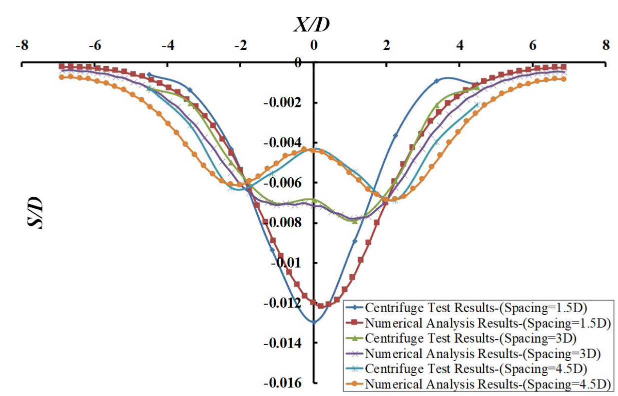

Figure 3. Verification of the numerical analysis results through the centrifuge test results of center-to-center spacing of 1.5*D*, 3*D* and 4.5*D* (*X/D*: Horizontal distance from center of twin-tunnel (or center of strongbox)/Diameter of the tunnel, *S/D*: Vertical settlement of the ground surface/Diameter of the tunnel).

Table 1. Comparison of the normalized results of the maximum surface settlements.

Tunnel Spacing	Max. vertical settlement / tunnel diameter (S_{max}/D)		Accuracy (%)
	Centrifuge test	Numerical analysis	
1.5*D*	-0.01294	-0.01219	94.22
3*D*	-0.00790	-0.00780	98.71
4.5*D*	-0.00688	-0.00685	99.56

a) Errors in the results of both the centrifuge test and numerical modeling analysis;
b) The Mohr-Coulomb yield criterion model selected for the material behaviour in the ABAQUS/CAE software;
c) Assumption of the plane strain condition in the numerical modeling;
d) The difference between the boundary conditions defined in the numerical modeling and the conditions in the strongbox of the centrifuge test;
e) The difference in the accuracy of the results at the top and bottom of the strongbox of the centrifuge test;
f) The difference between assumptions of continuous media conditions in numerical modeling and conditions in the centrifuge test soil;
g) The length of the device arm (rotational radius of the centrifuge test).

Figure 3 shows the results of the twin-tunnel numerical analysis of surface settlements created by the excavation of tunnels A and then B, respectively, according to the centrifuge test conditions. Figure 3 also shows a good agreement between the curves and surface settlement results of the numerical analysis of 3*D* center-to-center spacing and the aforementioned centrifuge test. Those centrifuge test results generally agree with the numerical predictions of researchers such as Hunt (2005) and works conducted on field measurements at St James Park, where large surface settlements were placed upon the construction of the second tunnel (Standing et al., 1996).

Figures 4 and 5 show numerical analysis results of twin-tunnel vertical displacement contours (U2) of 3*D* center-

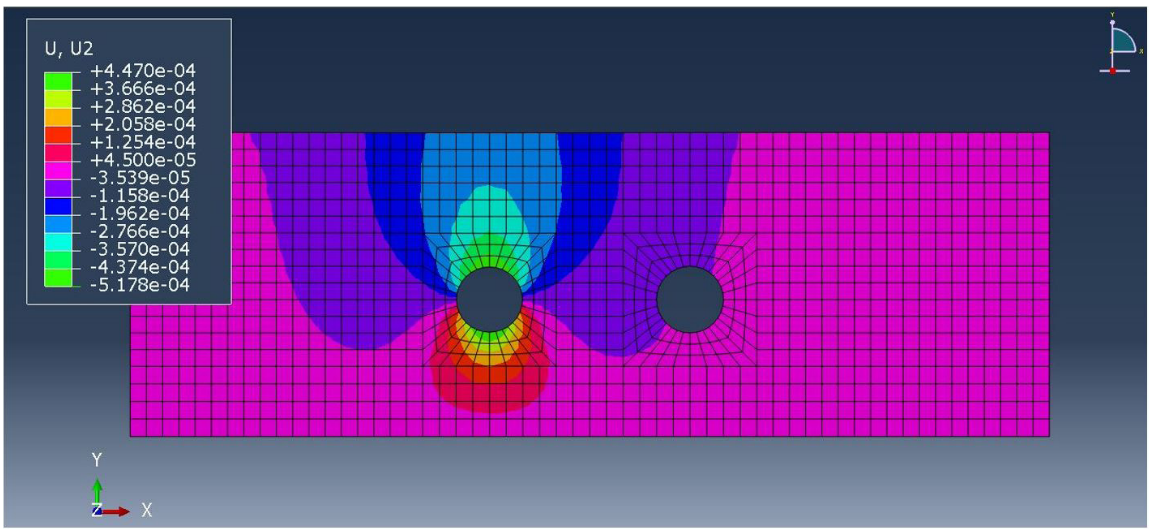

Figure 4. Vertical displacement contours (U2) of center-to-center spacing of 3*D* generated by the excavated tunnel A, (dimensions in m).

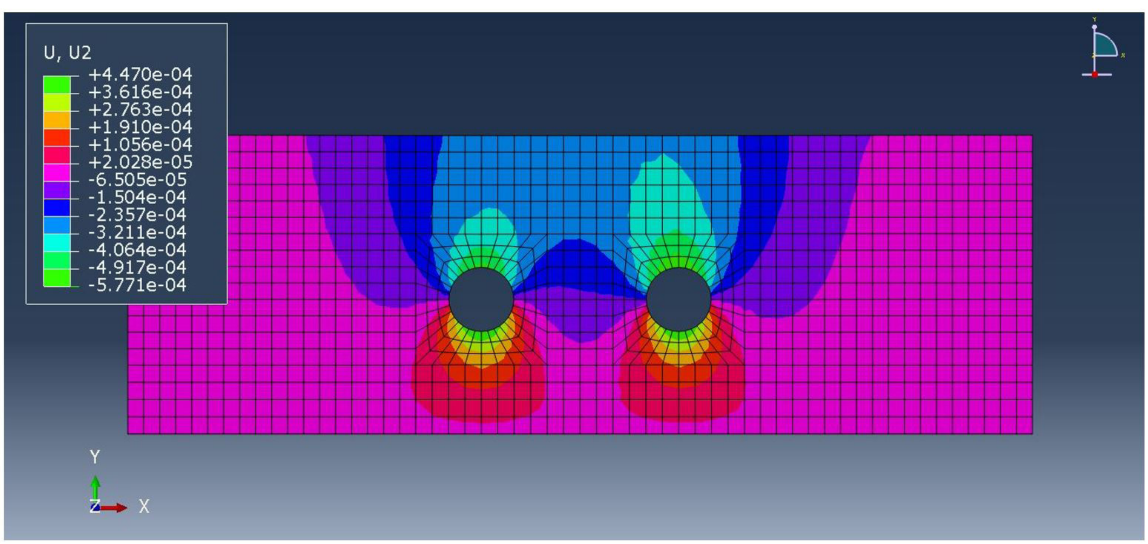

Figure 5. Vertical displacement contours (U2) of center-to-center spacing of 3*D* generated by the excavation of tunnel A and tunnel B, respectively (dimensions in m).

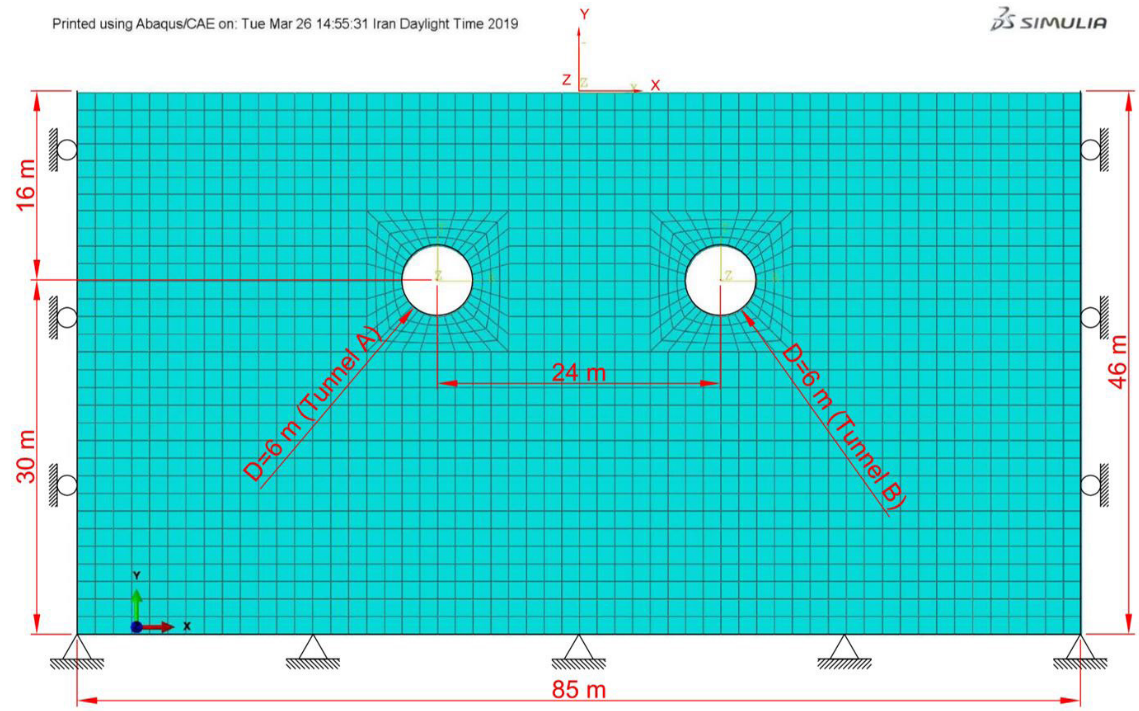

Figure 6. Maximum dimension of two-dimensional finite element mesh and boundary conditions of twin-tunnel excavations in this study.

to-center spacing generated by the excavations of tunnel (A) and tunnel (B), respectively. As shown in Figure 5, the contours of vertical displacements have not reached to the bottom boundary constraints. The maximum vertical reaction force (RF2) before starting the excavation in step-1 is equal to 3174 N, whereas this amount is decreased in the model scaling to 3128 N after the excavation of the twin-tunnel in step-3. A 1.45% difference is acceptable. But since the vertical displacements of the surface are strongly dependent on the model depth, the model used in the numerical modeling of this study was expanded to 5D) center-to-center spacing for each configuration of the twin-tunnel, see Figure 6.

Figure 3 shows the maximum results of surface settlements obtained by the excavation of the twin-tunnel with 4.5D center-to-center spacing using the centrifuge device to be -275.18 μm in the model scaling (S_{max}/D = -0.00688), (Divall et al., 2012). According to Figure 7, the maximum result of surface settlement obtained from the twin-tunnel and generated by the numerical analysis is -273.97 μm in the model scaling (S_{max}/D =-0.00685). These values show a good agreement between the centrifuge test results and the curve shape of surface displacements created by the numerical analysis of the twin-tunnel with 99.56% accuracy.

In addition to the abovementioned reasons for the differences in the results, the 5.78% verification error between the results of center-to-center spacing of 1.5D may be due to the proximity of the tunnels, which cause inaccuracy either in the centrifuge test results or in the modeling results.

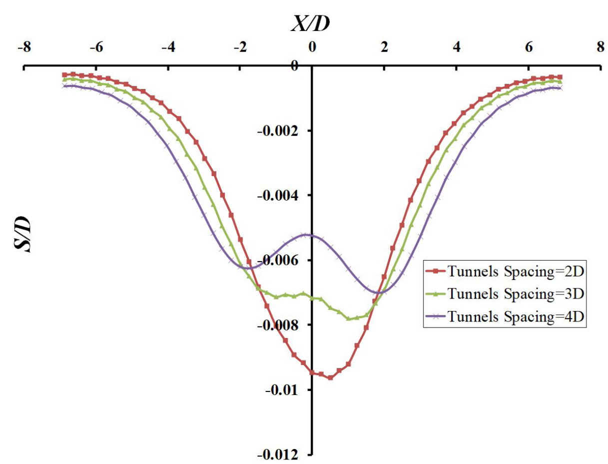

Figure 7. Numerical results of the asymmetric ground surface settlement curves generated by asynchronous excavation of the twin-tunnel (H=10 m and D=4 m).

3. Expansion of two dimensional numerical modeling for different dimensions and geometric arrangements of twin-tunnel

To investigate the effects of three parameters: tunnels diameter, center-to-center tunnel spacing, and tunnel depth on surface settlement caused by the excavation of twin-tunnel, 24 numerical analysis modeling were conducted using the

ABAQUS software and according to the condition and procedures of the verified modeling; the results are presented in Table 2. The geometric dimensions of the models were changed (Figure 6 shows the maximum dimensions of the numerical modeling which is changed to 85 m × 46 m for maximum tunnel spacing of 4*D*) to allow for the development of any possible collapse mechanism. According to the Chakeri et al. (2015) approach and as well as several constructed models, showed that by choosing the model lateral distance and model depth equivalent to 5*D* from center of each tunnel, any influence of the boundaries on the results can be ignored. The discussions pertaining the effects of those parameters on the ground surface settlements are as follow.

3.1 The effects of center-to-center tunnels spacing

Until only recently, only a limited part of the interaction of twin-tunnel and its effect on the asymmetric ground surface settlements has been investigated, and more research is needed to illustrate these effects. Three values of center-to-center tunnel spacing (2*D*, 3*D*, and 4*D*; *D* is the diameter of the tunnel) were selected to explore their effects. Figures 7 and 8 show the numerical results of the ground surface settlement value resulting from asynchronous excavation of the twin-tunnel at similar tunnel depth of *H*=10 m and *D*=4 m and 6 m, respectively.

It is clear that the distance between the twin-tunnel influences both the maximum value of ground surface vertical displacements and the curve shape. According to the numerical ABAQUS results, in low distances between tunnels, the shape of the ground settlement curve resulting from twin-tunnel excavation is similar to the curve shape of a single tunnel, except that the ground surface settlements have a greater value due to the interactions between the twin-tunnel. The maximum ground surface displacement value of a single tunnel is -26.01 mm shown in Table 2, while this value is 38.48 mm of the twin-tunnel excavations at a 2*D* distance between the tunnels (*SP*/*D*=2), 10 m depth and 4 m tunnel diameter. Increases in the amount of ground deformation at the ground surface caused by the excavation of twin-tunnel is a major and challenging issue that should be considered before beginning any excavating operation. The effect of interaction between tunnels is decreased in larger distances between twin-tunnel (tunnel spacing of more than 3*D*), and the curve shape and magnitude of maximum ground surface displacements over each tunnel are changed to single tunnel conditions. For example, the maximum surface settlement value at a distance of 4*D* between twin-tunnel (*SP*/*D*=4) is equal to -28.02 mm in the model scaling, in which *H*=10 m and *D*=4 m.

According to the results of this research, it is understood that in order to reduce the effect of the twin-tunnel excavation on the ground movements, it is necessary to increase the distance between the tunnels as much as possible to control the amount of the ground settlements and minimizing damage to the building foundations. It is important to note that the effect of center-to-center spacing between the tunnels depends on the tunnel diameter. This means that for a specific *SP*/*D*, the effect of center-to-center tunnel spacing between twin-tunnel is greater for a tunnel with a smaller diameter, and the curve shape of the surface deformation is more similar to that of a single tunnel.

3.2 Effects of twin-tunnel diameter

In order to explore the effects of the diameter of twin-tunnel, two values of tunnel diameters (*D*= 4 m and 6 m) were considered. Figure 9 shows the numerical results of the asymmetric ground surface displacement value obtained from asynchronous excavation of the twin-tunnel for three

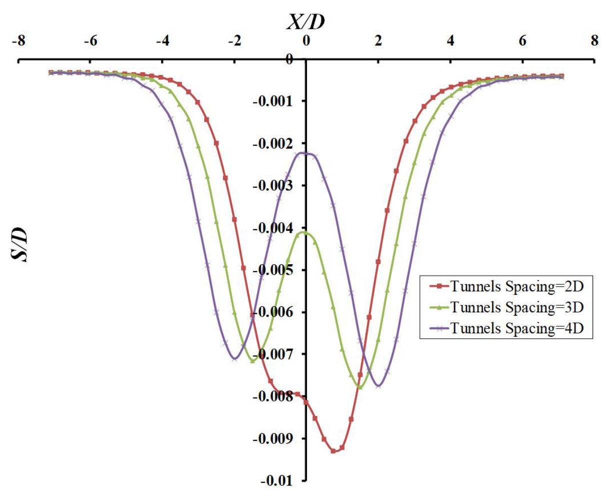

Figure 8. Numerical results of the asymmetric ground surface settlement curves generated by asynchronous excavation of the twin-tunnel (*H*=10 m and *D*=6 m).

Table 2. Modeling results of the maximum vertical settlement/ tunnel diameter (S_{max}/D) ×10^3 after excavation of single tunnel and twin-tunnel in prototype scale (all results should be multiplied by 10^{-3}).

Tunnel Height		*H* =10 m			*H* =12 m			*H* =14 m			*H* =16 m		
Tunnel Spacing (*SP*)		2*D*	3*D*	4*D*	2*D*	3*D*	4*D*	2*D*	3*D*	4*D*	2*D*	3*D*	4*D*
D=4 m	Tunnel (A)	-6.503	-6.155	-6.579	-4.465	-4.537	-4.367	-4.616	-4.746	-4.692	-7.294	-6.966	-6.996
	Tunnel (B)	-9.621	-7.803	-7.006	-9.479	-6.679	-5.923	-12.228	-8.493	-7.928	-15.188	-12.245	-10.771
D=6 m	Tunnel (A)	-6.899	-6.903	-6.883	-5.913	-6.016	-6.439	-6.594	-6.686	-9.848	-7.192	-10.363	-6.941
	Tunnel (B)	-9.890	-7.886	-7.755	-10.221	-7.574	-7.407	-13.576	-10.403	-8.697	-17.059	-13.989	-12.373

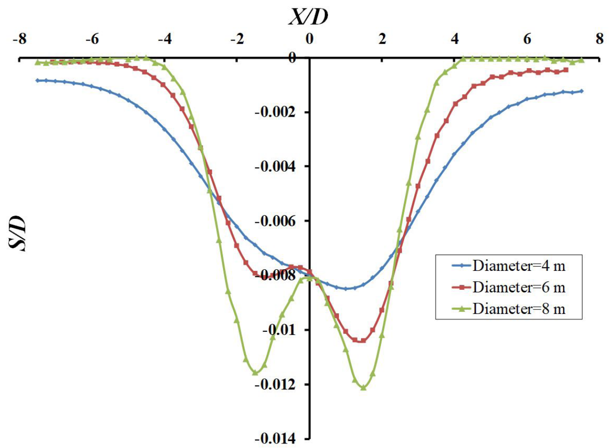

Figure 9. Numerical results of the asymmetric ground surface settlement curves generated by asynchronous excavation of the twin-tunnel (*H*=14 m and *SP*=3*D*).

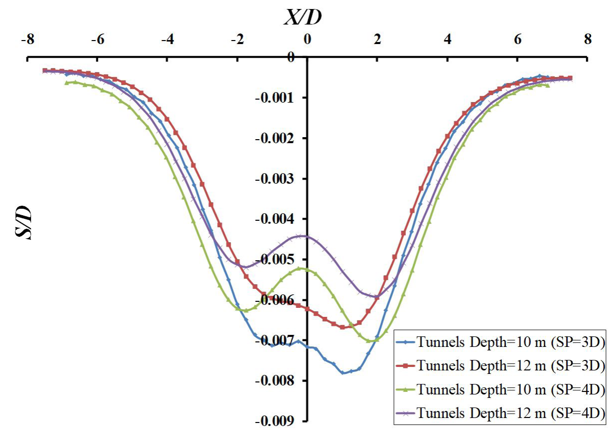

Figure 10. Numerical results of the asymmetric ground surface settlement curves generated by asynchronous excavation of the twin-tunnel (*D*=4 m and *SP*=3*D* and 4*D*).

values of tunnel diameter (*D*=4 m, 6 m and 8 m), center-to-center distance between the tunnels equal to 3*D* and at the same depth of the tunnels, *H*=14 m.

The numerical results of this study show that increasing the tunnel diameter increases the ground surface settlement, and its value depends on twin-tunnel spacing. This spacing should be increased as far as possible in order to decrease the ground surface settlement value and reduce any damage to the existing foundations of buildings. This paper shows that the largest vertical displacement caused by the excavation of twin-tunnel occurs at a 6 m diameter in the model scaling. The maximum vertical displacement value of the ground surface for a 6 m diameter, shown in Table 2, has a tunnel depth of *H*=10 m and a 4*D* center-to-center tunnel spacing of -46.53 mm; whereas, this value is -55.74 mm for a tunnel spacing of 2*D* for same depth and diameter size of the prototype scaling. The maximum vertical displacement value of the ground surface (Table 2) for a 4 m diameter, 16 m tunnel depth and 2*D* tunnel spacing is -60.75 mm in the model scaling (S_{max}/D = -0.015188); whereas, this value reaches -102.356 mm after twin-tunnel excavations in the prototype scaling (S_{max}/D = -0.017059) for a 6 m tunnel diameter, 2*D* tunnel spacing and 16 m tunnel depth.

3.3 Effects of twin-tunnel depths

In order to explore the effects of the twin-tunnel depths, two depths (*H*=10 m and 12 mm) were selected in the model scaling. Figure 10 shows the numerical results of the asymmetric ground surface settlement values obtained from the asynchronous excavation of the twin-tunnel for each center-to-center tunnel spacing (3*D* and 4*D*) with the same tunnel diameters of *D*=4 m, in the prototype scaling. The numerical results of this paper show a decrease in the ground surface settlement when the tunnel depth is increased and its value depends on the tunnel diameter and tunnel spacing between twin-tunnel. As seen in Figure 10 and Table 2, the values of the maximum ground surface settlement of a 3*D* tunnel spacing and tunnels depths of 10 m and 12 m for a tunnel diameter of 4 m are equal to -31.21 mm, -26.715 mm, respectively. While, the maximum ground surface settlements of a 4*D* tunnel spacing and 10 m and 12 m tunnel depth for the same tunnel diameter are equal to -28.00 mm and -23.69 mm, respectively. So if in a project with similar condition it was necessary to reduce the excavation depth of the twin-tunnel from 12 m to 10 m, increasing the distance of spacing between tunnels from 3*D* to 4*D*, due to the close values of the maximum settlement can be an appropriate solution for controlling of the ground surface settlements, instead of keeping 3*D* distance spacing between the tunnels.

It should be notice that in this study because of selecting the linear elastic-perfectly plastic Mohr-Coulomb (MC) yield criterion in numerical modelling, decreasing the vertical displacements of the ground surface was depended on the *H*/*D* ratio (*D* is the diameter of the tunnels, *H* is tunnels depth), in which the results for *H*/*D* ratio of less than 2.5 to 3 had an acceptable accuracy.

3.4 Effects of tunnel lining

In order to explore the effects of the tunnel lining, for three tunnel spacing of 2*D*, 3*D* and 4*D*, and with the depth of 10 m were selected in the prototype scaling. Figure 11 shows the amount and the shape of surface settlements in the presence of tunnel lining comparing with the asymmetric excavation condition. In the numerical modelling the thickness of lining tunnel was assumed as an isotropic linear elastic behavior with a thickness of 300 mm in prototype scale, and also the tunnel lining was connected to soil rigidly and the mesh considered as B21 a 2-node linear Timoshenko beam

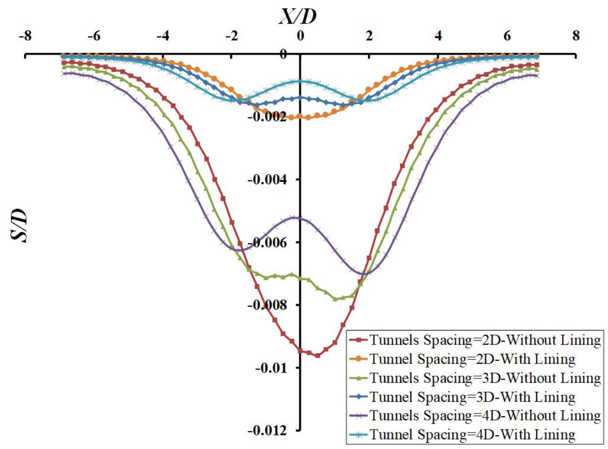

Figure 11. Numerical results of the amount and the shape of the surface settlements in the presence of tunnel lining comparing with the asymmetric excavation condition of twin-tunnel (for H=10 m and D=4 m).

element in a plane (Mirhabibi & Soroush, 2012). Tunnel lining concrete was assumed with material properties of unit weight γ=24 kN/m^3, Young's modulus E=33,700 MPa, and Poisson's ratio ν=0.2 (Mirhabibi & Soroush, 2012). According to the results of numerical modelling in Figure 11, the maximum surface settlements for the tunnel spacing of 2D, 3D, and 4D is equal to -8.146 mm, -6.540 mm, and -5.940 mm, respectively which indicates almost a 79% reduction in the amount of the maximum ground surface settlement in the presence of tunnel lining conditions.

4. Conclusion

Numerical approaches can consider more various factors and characteristics in twin-tunnel modeling, such as soil mass geo-mechanic specifications and various tunnel configurations (tunnel diameter, tunnel spacing, and tunnel depth). On the other hand, subsurface deformations and the interaction between twin-tunnel can be investigated together with different dimensions and geometric arrangements of twin-tunnel for either the concurrent excavation of twin-tunnel or the excavation of a new tunnel adjacent to an existing tunnel. For this purpose, a two-dimensional numerical analysis method by ABAQUS is employed in this study. Verification of the numerical modeling results is conducted using the actual values measured from the centrifuge test. The results of the numerical model were observed to be in good agreement with the results of the centrifuge test. A strong interaction between the twin-tunnel and curve shape of the asymmetric surface settlements was observed for the center-to-center tunnel spacing of less than 3D. In other words, tunnel spacing larger than 3D affects the shape of the asymmetric ground surface displacement curve, similar to changing it to the curve shape of the excavation of two separated tunnels and decreasing the maximum value of the asymmetric ground surface displacement. The diameters of twin-tunnel and tunnel depth have less effect than the tunnel spacing on the maximum asymmetric surface settlement. In this study was observed when the diameter of a tunnel with 12 m depth and 3D spacing is varied from 4 m to 6 m, the maximum surface displacement value increases by about 1.13 times, and changing the tunnel depth from 12 m to 10 m for tunnels with a 4 m diameter and a 3D center-to-center spacing, increases the maximum surface settlement value by about 1.17 times. while for a tunnel with 4 m diameter and 12 m depth, decreasing center-to-center distance between tunnels from 3D to 2D increases the maximum asymmetric surface settlement value by about 1.42 times. Also the ground surface settlement in the presence of tunnel lining was studied in this research which shows almost a 79% decreasing in the maximum amount of the surface settlement.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Author's contributions

Alireza Seghateh Mojtahedi: conceptualization, methodology, validation, investigation, writing – original draft, writing – review & editing, data curation. Ali Nabizadeh: supervision, writing – review & editing.

List of symbols

D	Diameter of the tunnel
E	Young's modulus
H	Depth of the tunnel (the height from center of the tunnel to the ground surface)
H_c	Burial depth of tunnel (overburden pressure)
S	Vertical settlement of the ground surface
S_{max}	Maximum vertical settlement of the ground surface
SP	Tunnel spacing (horizontal distance between the tunnels)
S_u	Undrained shear strength
X	Horizontal distance from center of twin-tunnel (or center of strongbox)
ϕ	Friction angle
γ	Unit weight
υ	Poisson's ratio
ψ	Dilation angle

References

Addenbrooke, T.I., & Potts, D.M. (2001). Twin tunnel interaction: surface and subsurface effects. *International*

Journal of Geomechanics, 1(2), 249-271. http://dx.doi.org/10.1061/(ASCE)1532-3641(2001)1:2(249).

Attewell, P.B., & Yeates, J.B. (1984). Tunnelling in soil. In P.B. Attewell & R.K. Taylor (Eds.), *Ground movements and their effects on structures* (pp. 132-215). London: Surrey University Press.

Burland, J.B., Standing, J.R., & Jardine, F.M. (2001). *Building response to tunnelling: case studies from construction of the jubilee line extension, London, Volume 2, Case studies*. London: Thomas Telford.

Chakeri, H., Hasanpour, R., Hindistan, M.A., & Ünver, B. (2011). Analysis of interaction between tunnels in soft ground by 3D numerical modelling. *Bulletin of Engineering Geology and the Environment*, 70(3), 439-448. http://dx.doi.org/10.1007/s10064-010-0333-8.

Chakeri, H., Ozcelik, Y., & Ünver, B. (2015). Investigation of ground surface settlement in twin tunnels driven with EPBM in urban area. *Arabian Journal of Geosciences*, 8(9), 7655-7666. http://dx.doi.org/10.1007/s12517-014-1722-2.

Chehade, F.H., & Shahrour, I. (2008). Numerical analysis of the interaction between twin-tunnels: influence of the relative position and construction procedure. *Tunnelling and Underground Space Technology*, 23(2), 210-214. http://dx.doi.org/10.1016/j.tust.2007.03.004.

Cooper, M.L., & Chapman, D.N. (1998). Movements of the Piccadilly Line tunnels caused by the new Heathrow Express tunnels. In *Tunnels and Metropolises. Proceedings of the World Tunnel Congress'98 on Tunnels and Metropolises,* Sao Paulo, Brazil, Balkema, pp. 254-294.

Cording, E.J., & Hansmire, W.H. (1975). Displacement around soft tunnels. In *Proceedings of the 5th Pam-Am Conf. on Soil Mechanics and Foundation Engineering* (Vol. 4, pp. 571-633), Buenos Aires, Argentina.

Divall, S. (2013). *Ground movements associated with twin-tunnel construction in clay* [Unpublished doctoral thesis]. City University London, London, UK. Retrieved in May 11, 2021, from https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.573637

Divall, S., & Goodey, R.J. (2012). Apparatus for centrifuge modeling of twin-tunnel construction. *International Journal of Physical Modelling in Geotechnics*, 12(3), 102-111. http://dx.doi.org/10.1680/ijpmg.11.00014.

Divall, S., Goodey, R.J., & Taylor, R.N. (2012). Ground movements generated by sequential Twin-tunnelling in over-consolidated clay. In *Proceedings of the 2nd European Conference on Physical Modeling in Geotechnics*, Delft. https://doi.org/10.4233/uuid:f71fabea-424b-42e5-93aa-701715eed17d.

Herzog, M. (1985). Die Setsungsmulde Über Seicht Liegenden Tunneln, Berlin. *Bautechnik*, 11, 375-377.

Hunt, D.V.L. (2005). *Predicting the ground movements above twin tunnels constructed in London clay* [PhD thesis]. University of Birmingham, Birmingham, UK. Retrieved in May 11, 2021, from https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.496150

Mair, R.J., & Taylor, R.N. (1997). Bored tunnelling in the urban environment. In *Proceedings of the 14th International Conference on Soil Mechanics and Foundation Engineering* (Vol. 4, pp. 2353-2385), Hamburg, Germany.

Mair, R.J., Gunn, M.J., & O'Reilly, M.P. (1981). Centrifugal testing of model tunnels in soft clay. In *Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering* (Vol. 1, pp. 323-328), Stockholm, Sweden.

Mirhabibi, A., & Soroush, A. (2012). Effects of surface buildings on twin tunnelling-induced ground settlements. *Tunnelling and Underground Space Technology*, 29, 40-51. http://dx.doi.org/10.1016/j.tust.2011.12.009.

Nyren, R. (1998). *Field measurements above twin tunnels in London Clay* [PhD thesis]. Imperial College, London, UK.

O'Reilly, M.P., & New, B.M. (1982). Settlements above tunnels in the United Kingdom: their magnitude and prediction. In *Proceedings in Tunneling '82* (pp. 173-181). London: Institution of Mining & Metallurgy. Retrieved in May 11, 2021, from http://worldcat.org/isbn/090048862X

Peck, R.B. (1969). Deep excavation and tunneling in soft ground. In *Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering, State of the Art Volume* (pp. 225-290), Mexico City.

Ranken, R.E., & Ghaboussi, J. (1976). *Analysis of interaction between two parallel tunnels*. Washington: Department of Transportation.

Standing, J.R., Nyren, R.J., Burland, J.B., & Longworth, T.I. (1996). The measurement of ground movements due to tunneling at two control sites along the Jubilee Line Extension. In R.J. Mair & R.N. Taylor (Eds.), *Geotechnical Aspects of Underground Construction in Soft Ground, Proceedings of the International Symposium* (pp. 751-756), London, UK.

Wu, L., Zhang, X., Zhang, Z., & Sun, W. (2020). 3D discrete element method modelling of tunnel construction impact on an adjacent tunnel. *KSCE Journal of Civil Engineering*, 24(2), 657-669. http://dx.doi.org/10.1007/s12205-020-2054-2.

Yang, X.L., & Zhang, R. (2018). Limit analysis of stability of twin shallow tunnels considering surface settlement. *KSCE Journal of Civil Engineering*, 22(5), 1967-1977. http://dx.doi.org/10.1007/s12205-017-1398-8.

Zhu, C., & Li, N. (2017). Prediction and analysis of surface settlement due to shield tunneling for Xi'an Metro. *Canadian Geotechnical Journal*, 54(4), 529-546. http://dx.doi.org/10.1139/cgj-2016-0166.

Zlatanovic, E., & Lukic, D. (2014). Ground surface settlement induced by twin tunneling. In *Proceedings of the 40th International Conference Contemporary Achievements in Civil Engineering* (pp. 921-927), Subotica, Serbia. http://dx.doi.org/10.14415/konferencijaGFS2014.123.