*Journal of Structural Engineering and Geotechnics,*
*13(1), 49-64 , Winter & Spring 2023*

# Optimization of Surficial Settlement Originated from the Excavation of Twin Tunnels on Surface Structures with Finite Dimensions

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Received 17 April 2024, Accepted 28 May 2024

## Abstract

In urban regions, the stability and safety of surface structures are essential. With the development of cities and increasing building density in metropolitan areas, the construction of underground structures like subway tunnels will be considered more and more. The tunnels are located close to the ground surface in most urban regions. Therefore, excavating these tunnels causes some displacements in the soils around the tunnels, leading to some adverse effects on the surface structures. Predicting deformations looks essential to reducing these effects, showing the importance of tunnel and structure interaction.

In this paper, using three-dimensional numerical simulation and parametric studies, the effect of various parameters on the displacement of tunnels and their adjacent buildings are studied. The optimum surface settlement values are predicted using the neural network and developed optimization algorithms. The parameters under study are composed of: the horizontal distance between tunnels, the depth of tunnels, the angle between tunnels, the excavation distance between two tunnels, the diameter of the tunnels, tunnels' contraction, the soil's internal friction angle, and the soil's cohesion. Using a neural network and optimization algorithms can considerably help optimize the design and significantly reduce adverse effects on the surface structures during the tunnel excavation. The results from the neural network showed that the optimum state of displacement happens when the soil's cohesion, tunnels' contraction, diameter, and depth are the minimum values, and the excavation distance between two tunnels is the maximum value.

***Keywords:*** Optimization, surficial settlement, twin tunnels, structure with finite dimensions

## 1.Introduction

The increase of population in the big cities and the existence of traffic problems have caused the construction of urban tunnels in the big cities to be considered more. In most metropolitan regions, tunnels are located close to the ground surface. Tunnel excavation leads to the settlement of the surface structures close to the tunnel under excavation. It also creates some stresses in the soil, which impact the surface structures. Since deformations get bigger at closer distances to the excavation area; consequently, the adverse effects of tunnel excavation on surface structures get bigger. Predicting deformations significantly reduces these effects, showing the importance of evaluating tunnel-structure interaction.

Researchers in 2018 and 2019 have performed numerous studies to evaluate the effect of tunnel excavation on different surface structures using numerical modeling and experimental relations. Some of these studies are the evaluation of the impact of tunnel excavation on different structure parameters and assessment of tunnel-structure interaction [1-3], the evaluation of tunnel excavation effect on a bridge [4], and the assessment of tunnel excavation effect on lateral displacement and internal forces of a pile [5-6], the evaluation of the behavior of a circular tunnel under uneven seismic load [7], the assessment of long term settlement mechanism due to tunnel excavation [8], the evaluation of tunnel excavation in the sandy soils and presentation of an experimental relation for prediction of the maximum settlement value as a function of relative soil compaction [9], the evaluation of tunnel excavation effect on the soil hardness around the adjacent tunnel [10].

Also, in 2020, researchers have performed some studies in this field which include: The evaluation of the effect of twin tunnels excavation effect on underground parking in the urban regions [11], the assessment of the effect of excavation of two parallel tunnels on surficial settlement using physical models

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[12], the presentation of a formula to predict surficial settlement due to tunnel excavation using Gauss function [13]. Since historical buildings are significant, precise prediction of tunnel-structure interaction and maximum settlement under building during excavation is essential. Some studies have been done on historical buildings due to their importance [14-15]. Also, in 2021 some studies have been done in this field of them, including the evaluation of long-term deformation using neural network and PSO algorithm [16], the evaluation of the effectiveness of safety measures in the tunnel during excavation, which is close to it [17], the presentation of a model to predict surficial settlement due to excavation of twin tunnels and the assessment of tunnels' deformation [18], modeling and prediction of deformation of segmental cover and settlement of the ground due to tunnel excavation by EPB method in different soils [19].

In recent years, the application of neural network and optimization algorithms in the analysis, prediction of data, and optimization of obtained results from the numerical analysis have been used abundantly. Pourakbar et al. evaluated the settlements of the structure under different scenarios. They obtained an equation to predict the settlement of the structure under the impact of tunnel excavation of a circular tunnel using a two-dimensional parametric study and neural network [20]. After that, in 2018, Mousazadeh et al. performed some investigations on the damages due to tunnel excavation close to the surface structures and predicted these damages using the artificial neural network and particle swarm optimization (PSO) [21]. In the same years, Moghadasi et al. presented a new combinational model from an artificial neural network (ANN) using independent component analysis (ICA) entitled ICA-ANN to predict the maximum surficial settlement. They predicted the maximum settlement of the surface structure using this method [22]. These studies are part of the investigations that show the importance of using neural networks and optimization algorithms to improve the results.

In 2007, Azadi and his team investigated the impact of underground tunnel excavation on adjacent buildings during an earthquake on the Shiraz underground metro [23]. Later in 2010, Azadi et al. conducted a study to investigate the effect of seismic behavior on the lining of shallow tunnels in liquefiable grounds. The study analyzed the force and seismic behavior of the tunnel lining, while examining different parameters, including loading frequency, loading amplitude, earthquake vertical cceleration, lining material properties, tunnel lining thickness, and the effect of the plastic bending moment [24]. Later in 2012, Azadi et al. conducted another study using FLAC software to examine the impact of liquefaction of a sand lens on a tunnel lining. The study involved changing the position of the sand lens and analyzing the effects of liquefaction at various locations relative to the tunnel. The forces and deformations of the lining were then investigated [25].

Numerous studies have been performed on the tunnel excavation effects on surface structures, and the impact of different parameters was evaluated. However, the effect of tunnel excavation on a building with finite dimensions has been considered less. If the dimensions of the building cannot be modeled in two dimensions (plain strain), we model it in three dimensions (a building with finite dimensions). In this paper, using three-dimensional numerical simulation and parametric studies, the effect of different parameters on the displacement of tunnels and their adjacent structure with finite dimensions has been evaluated. The optimum values of the surficial settlement have been predicted using a neural network and developed optimization algorithms. Investigated parameters in this paper are the horizontal distance between tunnels, the depth of tunnels, the angle between tunnels, the excavation distance between two tunnels, the diameter of tunnels, the tunnels' contraction, the soil's internal friction angle, and the soil's cohesion..

## 2. Modeling

This study evaluated the effect of twin tunnel excavation on each other and a structure with finite dimensions. Since the building has different dimensions in different directions, it is impossible to model it in two dimensions (plain strain); we model the building in three dimensions (building with finite dimensions). It is assumed that the tunnels have been excavated using the tunnel boring machine method (TBM) followed by an installation lining. In this method, the soil has been excavated more than the required amount (more than the final tunnel's diameter), so the tunnel segments get installed conveniently. Also, in this method, two tunnels do not get excavated concurrently, and there is a defined distance between excavating machines in the first and second tunnels. In this study, the tunnel displacement at the excavation time has been evaluated. For this purpose, eight influencing parameters on the surface settlement during the twin tunneling process have been modeled. The parameters under study are composed of: the horizontal distance between tunnels, the depth of tunnels, the angle between tunnels, the excavation distance between two tunnels, the diameter of the tunnels, tunnels' contraction, the soil's internal friction angle, and the soil's cohesion.

## 2.1. Dimensions and Materials

The geometric dimensions of the base model include a width of 100 m, a length of 100 m, and a depth of 40 m. Geological features in the base model of the desired location consider the soil in one layer. The soil layer is 40 m and is made of clay, eventually reaching the rock bed. The base model has no groundwater, and soil material is drained. Hence, the water level is selected with the bedrock surface. The behavioral model of soil materials is the Mohr-Coulomb.

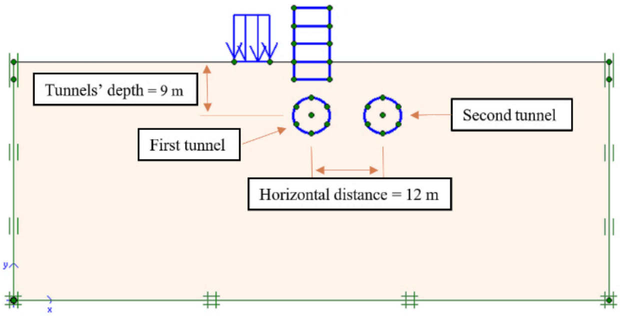



Fig 1. The geometry of the base model

Moreover, total displacements for tunnels and buildings have been studied separately. Material specifications of the soil and tunnels are shown in Tables 1 and 2 based on Isfahan's subway geotechnical investigations, and the specification of the building can be seen in Table 3. The middle section of Isfahan's subway tunnels comprises two circular tunnels 6 meters in diameter, excavated by TBM equipment. In the base model, the first tunnel is located at 9 meters. The second tunnel is located at the same depth and with a 12-meter distance from the first tunnel (horizontal distance from center to center) (as seen in Fig. 1). The thickness of the tunnel wall has been considered 30 centimeters. As shown in Fig. 1, a four-story building has been modeled in the base model. one of the stories is located under the ground surface. The height of each story has been considered equal to 3 meters, and its width is equal to 6 meters. The building load on each floor was considered equal to 10 kN/m2. The traffic load was considered in the 4 meters distance from the building and equal to 20 kN/m2. The geometry of the base model is shown in Fig. 1. The model is made with a 15-node wedge type. The base model's mesh size and three-dimensional meshing have been shown in Fig. 2. Since the PLAXIS software uses the finite element method when performing calculations, it considers the effect of interaction between the soil, tunnel, and structure. It is also possible to increase the accuracy of investigating these interactions by considering the interface elements. When modeling in PLAXIS, standard boundary conditions (Standard Fixities) were considered, showing the soil's state as a semi-infinite environment.

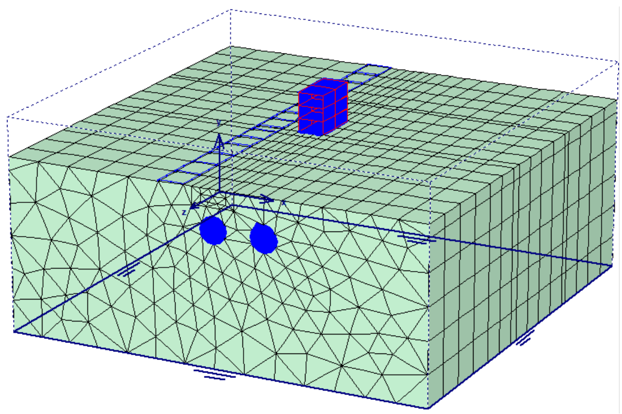


Fig 2. The three-dimensional meshing of the base model

Table 1
Specification of soil layer according to Mohr-Coulomb behavior

| Parameter | Unit | Value |
|---|---|---|
| E | MPa | 26 |
| ν | | 0.35 |
| ϕ | Degree | 25 |
| C | kN/m2 | 30 |
| γ | kN/m3 | 20 |

Table 2
Specification of the tunnels' lining

| Parameter | Unit | Value |
|---|---|---|
| E | MPa | 29700 |
| W | kN/m /m | 7.2 |
| d | m | 0.3 |

Table 3
Specification of building

| Parameter | Unit | Value |
|---|---|---|
| EA | kN/m | $5*10^6$ |
| EI | kN $m^2$/m | 9000 |
| d | m | 0.147 |
| W | kN/m /m | 5 |
| ν | | 0.1 |

## 2.2. Software

Calculations and analyses are performed by PLAXIS software. The next step is using MATLAB software. The results of the analysis software PLAXIS with neural network methods have been optimized using MATLAB software. Meanwhile, 18 of the data are placed in the test network, and 84 of the data are placed in this MATLAB's training network.

## 2.3. Analysis

This manuscript evaluated the effect of different parameters in the displacement of the tunnels and their adjacent building using three-dimensional numerical simulation and parametric studies. It has been assumed that a long time has passed since the structure's construction, and the structure has reached its final location. Then, an artificial neural network is developed using output data of parametric studies, and then the structure of the network is saved as a function. Then, the input matrix for neural network functions is produced using developed codes and considering the concurrent effects of understudy parameters. Further, using these functions, the tunnel and building displacements are predicted. In the end, the optimum values of the surficial settlement are determined through the developed optimization algorithms. The procedure of the performed calculation in this study in summary is:

- Parametric study and the evaluation of the effect of different parameters on the displacement of tunnels and their adjacent building using three-dimensional numerical simulation
- Development of neural network considering output data from the parametric study and saving the network structure as a function
- The production of suitable inputs for neural networks considering concurrent effects of studied parameters with the employment of developed codes (input matrix)
- The prediction of tunnels and building displacement using input matrix, neural network function, and creation of output matrix
- The calculation of optimum values of the surficial settlement using developed optimization algorithms on output matrix data

## 2.4. List of Abbreviations

After modeling, a parametric study was performed, and the effect of different parameters on the settlement of tunnels and an adjacent building was evaluated. Before evaluating the results, for abbreviation and better expression, the parameters shown in the parametric study results have been presented in Table 4. Then we continue to assess the results of these investigations in the next section.

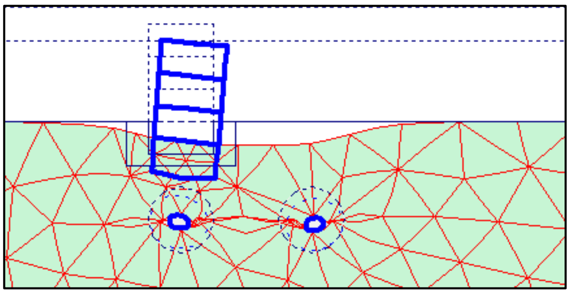
Table 4
The parameters shown in the parametric study result

| Parameter | Name |
|---|---|
| $U/U_0$ | The ratio of displacement (tunnels and building) over displacement (tunnels and building) in the base model, which for the abbreviation is called relative displacement (tunnels and building) |
| $d/d_0$ | The ratio of horizontal distance between tunnels over the horizontal distance between tunnels in the base model is the relative horizontal distance of tunnels for the abbreviation. |
| $H/H_0$ | The ratio of tunnels' depth over tunnels' depth in the base model is called relative tunnel depth for the abbreviation. |
| A | The angle between tunnels based on the degree |
| $S/S_0$ | The relative excavation distance between tunnels over the excavation distance between tunnels in the base model, which is called in the abbreviation, is the relative excavation distance between tunnels. |
| $D/D_0$ | The ratio of tunnels' diameter over tunnels' diameter in the base model is called the relative diameter of tunnels in the abbreviation. |
| $C_1/(C_1)_0$ | In the abbreviation, the ratio of the tunnel contraction over tunnel contraction in the base model is called relative tunnel contraction. |
| $\phi/\phi_0$ | In the abbreviation, the ratio of soil's internal friction angle over soil's internal friction angle in the base model is the relative soil's internal friction angle. |
| $C/C_0$ | The ratio of soil's cohesion over soil's cohesion in the base model is called the relative soil's cohesion in the abbreviation. |

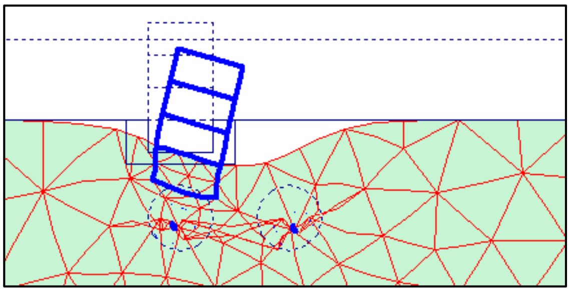
## 3. Interpretation and Evaluation of the Obtained Results from the Parametric study

### 3.1. The Effect of Horizontal Distance between Tunnels

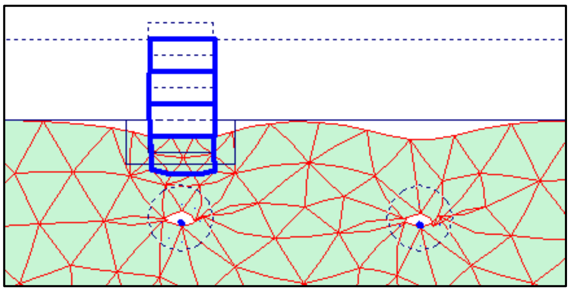
In this state, the first tunnel located under the building is considered the fixed one, and the horizontal distance of the second tunnel was changed relative to the first tunnel. The distances of 10 to 22 meters and a state in which just one tunnel exists were evaluated. The effect of horizontal distance between tunnels on the soils located below the building has been shown in Fig. 3. The relative displacement (tunnels and building) versus the relative horizontal distance between tunnels has been shown in Fig. 4.



a) 10 meter



b) 12 meter



c) 16 meter

Fig 3. The effect of horizontal distance between tunnels on the soils located below the building

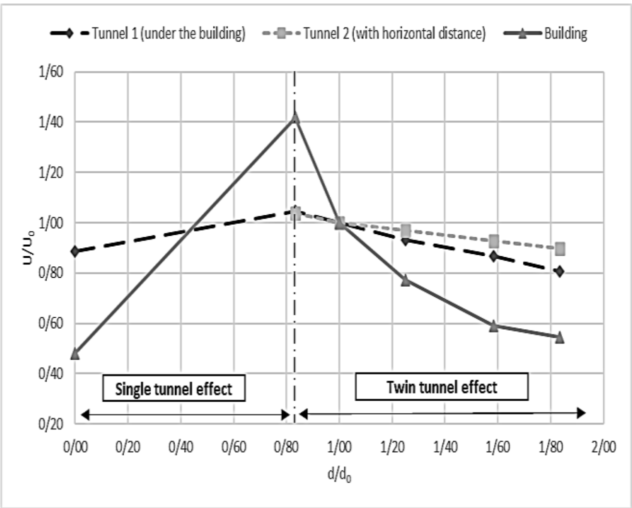
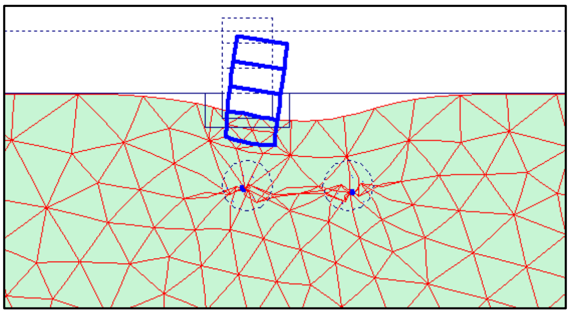



Fig 4. The relative displacement (tunnels and building) versus the relative horizontal distance between tunnels

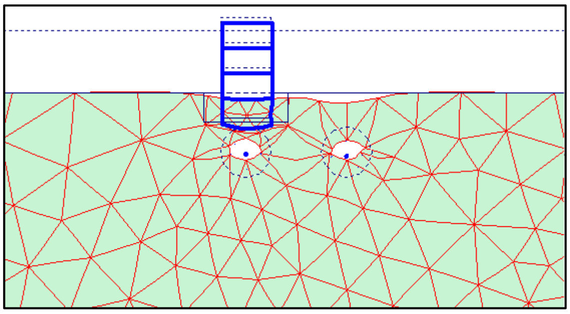
During the excavation of each tunnel, the stress status of the soil changes, and new displacements occur in the soil. With the increase in the distance between the two tunnels, these displacements get smaller. By increasing the horizontal distance between two tunnels from 10 to 22 meters relative to the base model, the displacement of the first tunnel decreases up to 24% (four centimeters). The displacement of the second tunnel decreases up to 14% (two centimeters), and the building displacement decreases up to 87% (nine centimeters). When this distance reaches 22 meters, the second tunnel does not impact the displacement of the building, and the value of the displacement approximately becomes equivalent to a state in which just one tunnel exists and the second tunnel has been deleted. By deleting the second tunnel relative to the base model, the displacement of the first tunnel decreases 11% (two centimeters), and the displacement of the building decreases 52% (5 centimeters).

### 3.2. The Effect of Tunnels Depth

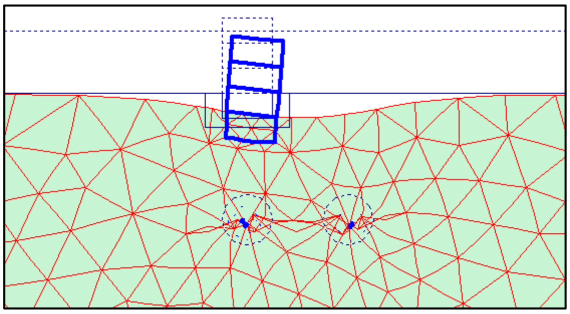
In this state, the depth of the two tunnels was changed equally and was assessed in the values of 4 to 16 meters. The effect of the depth of the tunnel on the displacement of the soil under the building has been shown in Fig. 5. The relative value of displacement (tunnels and building) versus the relative value of tunnels' depth has been shown in Fig. 6.



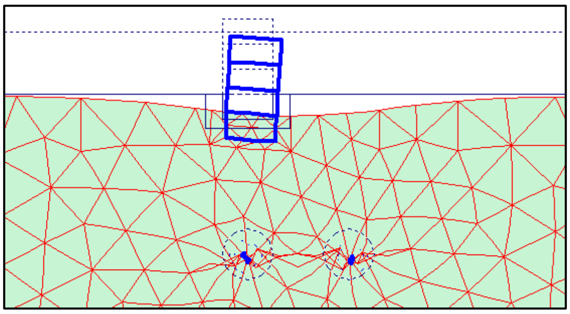
a) 4 meter



b) 8 meter



c) 16 meter



d) 16 meter

Fig 5. The effect of the depth of the tunnel on the displacement of the soil under the building

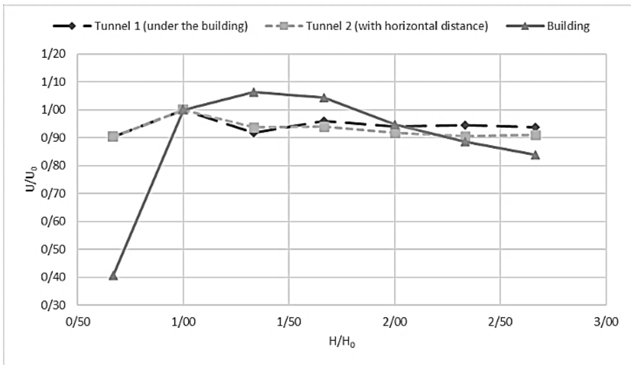


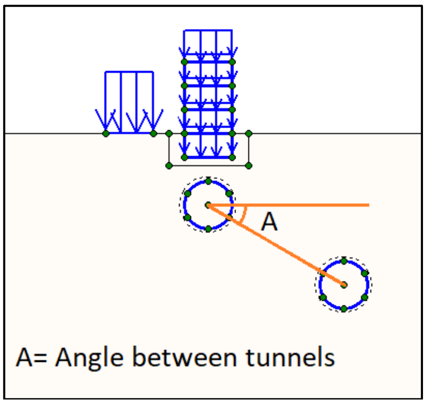

Fig 6. The relative value of displacement (tunnels and building) versus the relative value of tunnels' depth

Studies showed that the increase of the tunnels' depth does not significantly impact the displacement of the tunnels. By increasing the tunnel's depth to more than 10 meters, the displacement of the tunnels becomes stable. Two topics should be considered in evaluating tunnels' depth on the building displacement during the excavation. In the priority, the effect of the tunnel's depth and its distance up to the ground level on the surficial settlement value, and in the second priority, the amount of the effect of soil settlement over each tunnel on the building settlement should be considered. During the excavation of each tunnel, the stress status of the soil changes, and new displacements occur in the soil, which leads to the soil's settlement over the tunnel. More the depth of the tunnel, the more the distance between the tunnel and the ground surface, in which the surficial settlement occurs in the broader area but with low intensity.

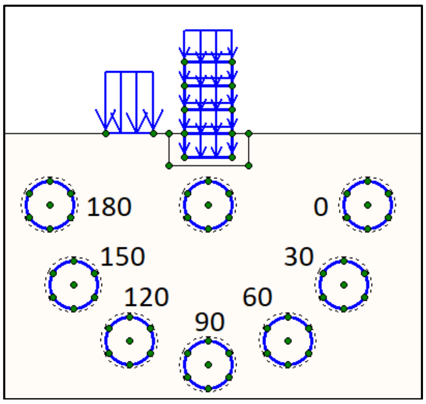
On the other hand, when the building goes under the impact of the soil settlement over both tunnels, its settlement increases. When the tunnels are located at 4 meters, the building is influenced by the soil's settlement over the first tunnel, and the soil's settlement over the second tunnel has less impact on the building. By increasing the tunnels' depth to 8 meters, the building settlement gets impacted by the soil settlement over two tunnels, increases 6% relative to the base model, and reaches 11 centimeters. By increasing the depth of tunnels up to 16 meters, the settlement of the building becomes 8 centimeters, which is 16% less than the base model. Actually, in the depth of 16 meters, the soil settlement above the tunnels occurs in the broader area, and the increase of the excavation distance to the ground surface decreases the settlement of the building.

### 3.3. The Effect of Angle Between Tunnels

In this parameter, the first tunnel is fixed in the center, and the second is located at a determined angle relative to the horizon. The distance between the two tunnels equals the horizontal distance between the two tunnels in the base model (12 meters). In this parameter, as shown in Fig. 7 (a), based on the agreement, the angle between the second tunnel and the horizon is the angle between tunnels Fig. 7 (a), in which the center of this angle is the first tunnel. Its first vertex is the horizon line, and its second vertex is the location of the second tunnel. Also, based on the agreement, the clockwise direction for this angle is considered the positive direction. In the base model, the amount of this angle is considered equal to zero. By changing this angle, the positioning of the second tunnel changes relative to the first tunnel, and the effects of this parameter on the displacement of the tunnels and the building were evaluated. The studied angles are shown in Fig. 7 (b). The relative value of displacement (tunnels and building) versus the angle between tunnels has been shown in Fig. 8.




(a)




(b)

Fig 7. a) Angle between the tunnels, b) studied angles.

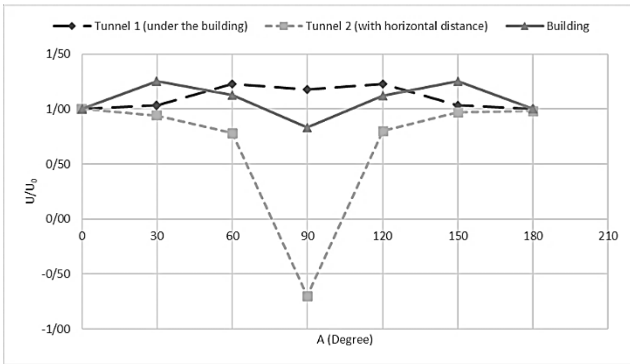



Fig 8. The relative value of displacement (tunnels and building) versus the angle between tunnels

Based on the obtained results, the trend of tunnels and building displacement when the angle between tunnels changes from zero to 90 degrees is symmetrical relative to the status in which the angle between tunnels changes from 90 to 180 degrees. Since the second tunnel has been excavated with a defined distance after the first tunnel, the soil will move toward the excavation location after the excavation of the second tunnel. Increasing the depth of the level in which the second tunnel is located increases soil movement, and therefore the settlement of the first tunnel increases. The reduction of the settlement of the first tunnel when the second tunnel is located under the first tunnel is related to the interaction between the two tunnels. The obtained results showed that by changing the angle of two tunnels up to 90 degrees (when the second tunnel is located under the first tunnel), the displacement decreases 5% (one centimeter). The displacement of the building is a function of the displacement of the first tunnel. By the change in the angle between two tunnels from 0 to 30 degrees, the displacement of the building relative to the base model increases 25% (three centimeters), and by the angle change up to 90 degrees, this displacement decreases 42% (five centimeters). By changing the angle between two tunnels from zero to 90 degrees, the displacement of the second tunnel relative to the base model decreases 170% (24 centimeters). This decrease is because of the displaced soils from the first tunnel excavation location, which leads to a decrease in the settlement and creates a heave when the second tunnel is located under the first tunnel.

### 3.4. The Effect of Excavation Distance Between Tunnels

The excavation of two tunnels is not done concurrently, and the second tunnel is excavated after a specific distance after the first tunnel. In this state, the excavation distance between two tunnels was changed, and the values of 12 to 40 meters were evaluated. The relative value of the displacement (tunnels and building) versus the relative value of excavation distance between two tunnels has been shown in Fig. 9.

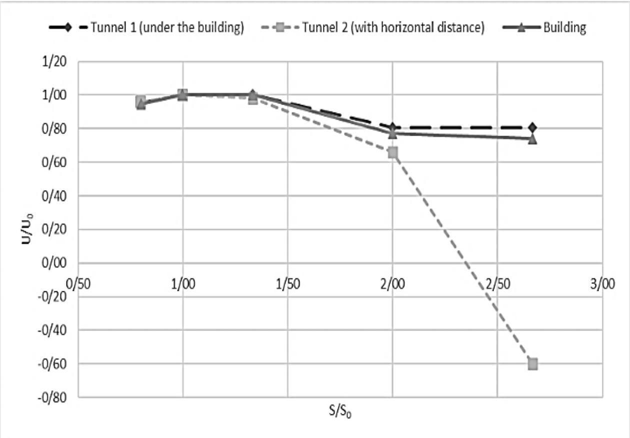



Fig 9 . The relative value of the displacement (tunnels and building) versus the relative value of excavation distance between two tunnels

The results showed that when the excavation distance between two tunnels is considered less than 20 meters, the interaction between two tunnels increases. This interaction decreases with the increase of distance to more than 20 meters. When this distance reaches 40 meters, two tunnels do not impact each other, and no interaction between the two tunnels occurs. The results showed that when the excavation distance between two tunnels is around 12 meters, the displacement of the first tunnel decreases 5% less than the base model; the second tunnel decreases 4%. The building is 5% less than the base model. By increasing the excavation distance between two tunnels, up to 15 meters, the displacement of the first tunnel, the second, and the building increases and becomes equal to the base model ones. By increase of the excavation distance between two tunnels up to 40 meters relative to the base model, the displacement of the first tunnel decreases 20% (three centimeters), the second one decreases 160% (22 centimeters), and the building one decreases 26% (three centimeters). Actually, by increasing the excavation distance of the two tunnels from 15 to 35.25 meters, the settlement of the second tunnel decreases. By increasing the distance of the two tunnels up to 40 meters, the displacement of the second tunnel becomes the form of a heave.

### 3.5. The Effect of Tunnels Diameter

In this state, the diameter of the tunnels was changed, and the values of 4 to 7 meters were evaluated. The relative value of the displacement (tunnels and building) versus the relative value of the diameter of the tunnels has been shown in Fig. 10. The results showed that by increasing the diameter of the tunnels, the required space for the excavation increases, which leads to the settlement of the soil under tunnels and building and increment of the displacement of the tunnels and building. The results showed that by increasing the diameter of the tunnel from 4 to 7 meters, relative to the base model, the displacement of the first tunnel increased 63% (eight centimeters). The second tunnel increased by 59% (eight centimeters), and the building increased by 140% (fourteen centimeters).

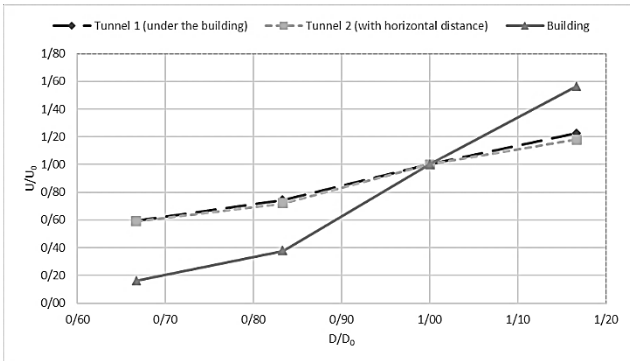



Fig 10.The relative value of the displacement (tunnels and building) versus the relative value of the diameter of the tunnels

### 3.6. The Effect of Tunnel Contraction

During tunnel excavation by TBM, the excavation diameter is considered more than the proposed diameter of the tunnel's lining, so the tunnel's lining segments can easily fit in the tunnel's excavated area. Therefore, a small distance between 0.5 to 2 centimeters is created between the soil around the tunnel and the tunnel's lining, which later becomes zero by the soil settlement around the tunnel. This procedure is called tunnel contraction. The relative value of the displacement (tunnels and building) versus the relative value of the tunnels' contraction is shown in Fig. 11.

By increase of the tunnel contraction, the space between the surrounding soil and the tunnel's lining increases, and the soil around the tunnel's lining settles over time. Bigger the space, the more the settlement happens in the soil around the tunnel's lining. The obtained results showed that by the tunnel contraction equal to 0.5 to 2% relative to the base model, the displacement of the first tunnel increases 184% (24 centimeters), and the settlement of the second tunnel increases 185% (27 centimeters). The building settlement increases 166% (17 centimeters), and the increasing displacement amounts are almost equal in both tunnels.

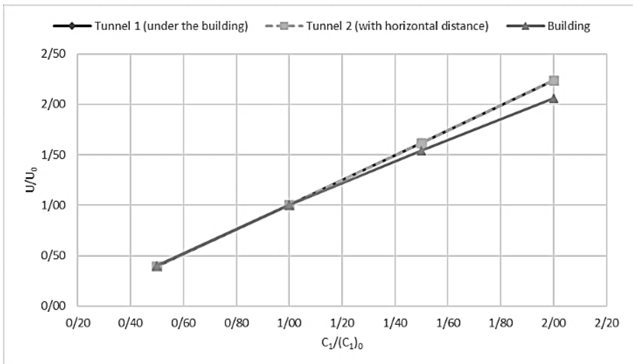



Fig 11. The relative value of the displacement (tunnels and building) versus the relative value of the tunnels' contraction

### 3.7. The Effect of Soil's Internal Friction Angle

The relative displacement (tunnels and building) versus the relative soil's internal friction angle is shown in Fig. 12. In this state, by the increase of soil's internal friction angle, the soil's lateral pressure coefficient decreases, and soil settlement around the tunnel and under the building decreases. By increasing the soil's internal friction angle from 25 to 40 degrees, the displacement of the first tunnel decreases 19% (two centimeters) relative to the base model. The second tunnel decreases 25% (three centimeters), and the building decreases 75% (two centimeters) relative to the base model. Soil's internal friction angle is not corresponding to the total or effective stress state.

### 3.8. The Effect of Soil's Cohesion

The relative displacement (tunnels and building) versus the relative cohesion of the soil has been shown in Fig. 13. In this state, the soil cohesion was changed, and the results were assessed. The obtained results showed that by increasing the soil's cohesion from 10 kN/m$^2$ to 35 kN/m$^2$, the displacement of the first tunnel decreased 11% (one centimeter) relative to the base model. In the second tunnel, displacement decreases by 12% (two centimeters) relative to the base model. In the building, displacement decreases 41% (four centimeters) relative to the base model. It can be concluded that by considering the Mohr-Coulomb relation, increasing the soil's cohesion increases the soil's shear strength and makes the soil more stable.

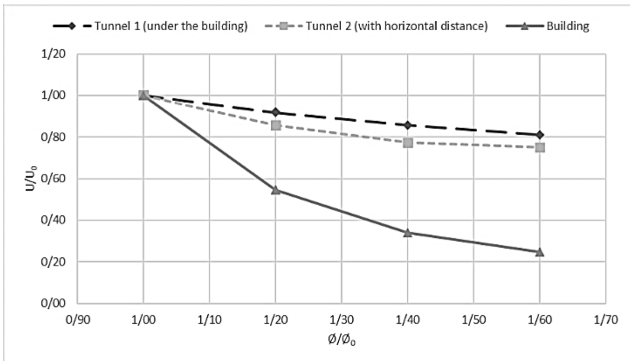



Fig 12. The relative displacement (tunnels and building) versus the relative soil's internal friction angle

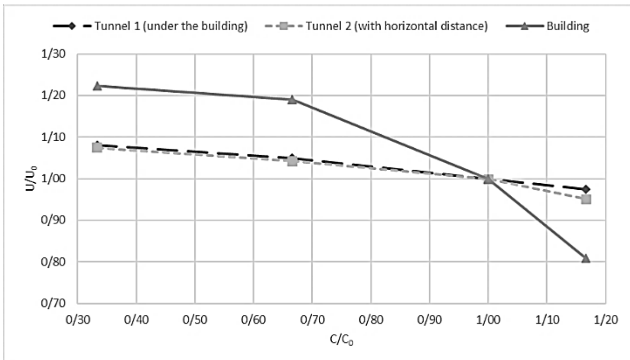



Fig 13. The relative displacement (tunnels and building) versus the relative soil's cohesion

## 4. Evaluation and Interpretation of the Obtained Results from Neural Network and Optimization Algorithm

After performing a parametric study, the obtained results were modeled using a multilayer perceptron neural network (MLP). The schematic view of a used neural network is shown in Fig. 14. The Levenberg-Marquardt algorithm has been selected as the neural network's training algorithm, and the neural network's performance has been evaluated by mean squared error (MSE). 70% of the input data were used for the training of the neural network, 15% were used for evaluation, and the remaining 15% were used to test the neural network accidentally. The number of hidden layers and the number of neurons effectively optimize the network, and developed optimization algorithms have determined this matter. The optimization algorithm has considered the number of hidden layers to mean squared error between the output data and the target variable to be the minimum value and the correlation coefficient (R) close to the one.

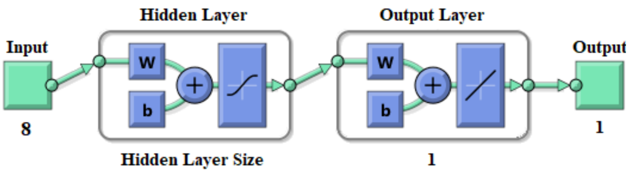



Fig 14. The schematic view of a used neural network

Three neural networks have been modeled to calculate the displacement of the tunnels and the building separately. In each neural network, eight input variables and one target variable were used; which input variables are: the horizontal distance between tunnels, the depth of tunnels, the angle between tunnels, the excavation distance between two tunnels, the diameter of the tunnels, tunnels' contraction, the soil's internal friction angle, and the soil's cohesion, and the target variable is the displacement. The negative value of the displacement has been considered as the settlement. The performance of the neural networks is shown in Table 5.

Table 5
The performance of the neural networks

| Neural Network | RMSE | R |
|---|---|---|
| Tunnel 1 | 0.0049873 | 0.99023 |
| Tunnel 2 | 0.0090076 | 0.99028 |
| Building | 0.0050946 | 0.99109 |

The correlation coefficient (R) between input data (obtained data from PLAXIS) and the target variable (Predicted data by Neural Network) was 0.99132 and has been shown in Fig. 15. Error between output data and the target variable (MSE) was 4.398E-05. and has been shown in Fig. 16. These results show that the neural network works with high accuracy. Fig. 17 shows the difference between output data from PLAXIS and the predicted value by Neural Network, which shows the deficient error of the neural network.

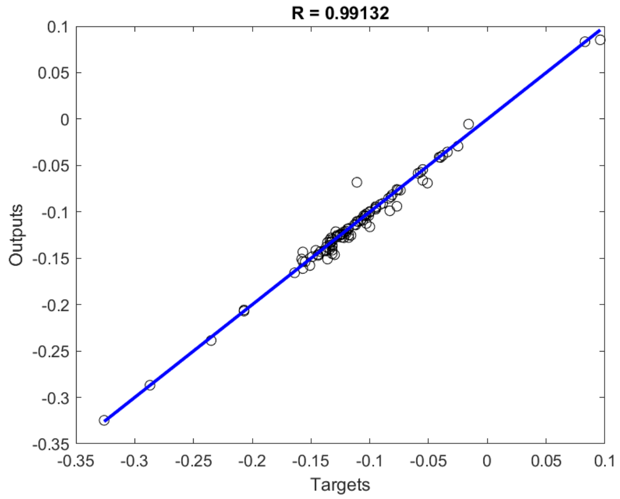



Fig 15. The correlation coefficient between input data and the target variable

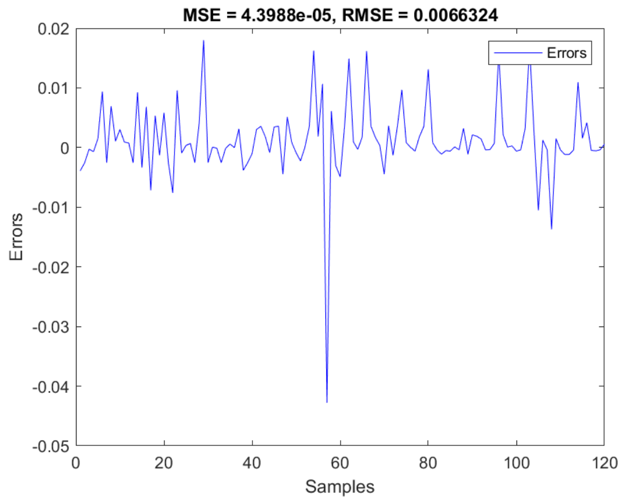



Fig 16. Error between output data and the target variable

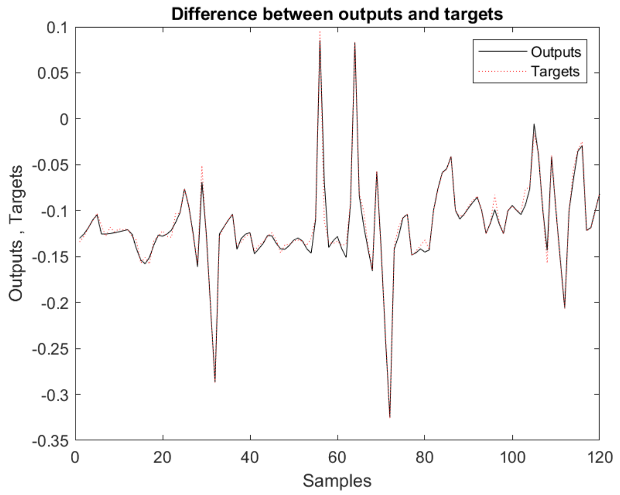



Fig 17. The difference between output data and the target variable

After the modeling and training of the neural network, the network's structure has been saved as a function called "neural network functions" in this paper for abbreviation and better expression. These functions have been used in the following steps to be called by the optimization algorithms. Again, the input matrix parameters were analyzed using the neural network functions, and the obtained results from the neural networks and software output were compared and calibrated. Hence, the performance of the neural network is trustworthy. The results showed a minor error between the obtained results from the neural networks and the software output. Therefore, the neural network's performance is trustworthy, and the neural network code works correctly.

After calibrating the neural network and ensuring it performs well, it was developed to evaluate the concurrent effects of understudy parameters. The development of the neural network needs a more extensive matrix for calculation. This matrix should be selected to evaluate the concurrent effects of all understudy parameters on the displacement of tunnels and building. This matter looks very important for optimization and defining the optimum value of the settlement. The input matrix parameters for the development of the neural network have been shown in Table 6.

Table 6
The input matrix parameters for the development of the neural network

| Parameter | Unit | Name |
|---|---|---|
| d | m | The horizontal distance between tunnels |
| H | m | The depth of tunnels |
| A | Degree | The angle between tunnels |
| S | m | The excavation distance between two tunnels |
| D | m | The diameter of the tunnels |
| $C_1$ | % | Tunnels' contraction |
| Φ | Degree | The soil's internal friction angle |
| C | kN/m$^2$ | The soil's cohesion |

In this step, the input matrix for calculating and developing the neural network has been produced using the developed algorithm and considering the proposed maximum, minimum, and step values for each parameter. The maximum, minimum, and primary step values of the parameters for producing the neural networks' input matrix of the neural networks have been shown in Table 7.

Table 7
The maximum and minimum, and primary step values of the parameters for producing the input matrix of the neural networks

| Parameter | d (m) | H (m) | A (Deg) | S (m) | D (m) | $C_1$ (%) | Φ (Deg) | C (kN/m$^2$) |
|---|---|---|---|---|---|---|---|---|
| Min | 7 | 4 | 0 | 12 | 6 | 0/5 | 25 | 10 |
| Max | 45 | 36 | 180 | 40 | 11 | 2 | 45 | 40 |
| Step | 1 | 1 | 30 | 1 | 1 | 0/5 | 1 | 1 |

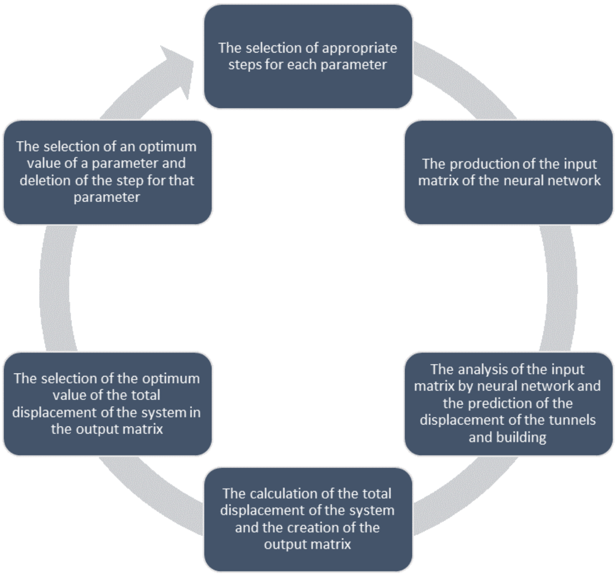



Fig 18. The procedure for calculation of data production and optimization algorithm

As shown in Fig. 18, the calculation procedure for the algorithm was designed so that the algorithm, in the beginning, selects the appropriate step for each parameter and then produces the input matrix for the neural network, considering the selected steps for all parameters. As said, this matrix should include all different states of the parameters in the defined range to calculate the concurrent effects of all parameters on the displacement of tunnels and the building. Then, the algorithm predicts the displacement of tunnels and the building using the input matrix and neural network functions and produces the output matrix of the neural network. In the next step, the total displacement of the system for each row of the output matrix (every state of the parameters) is calculated, considering $U_T = \sqrt{{U_{T1}}^2 + {U_{T2}}^2 + {U_B}^2}$. Then, the new output matrix is produced. The output matrix parameters have been shown in Table 8.

Table 8
The output matrix parameters.

| Parameter | Unit | Name |
|---|---|---|
| $U_T$ | cm | The total displacement of the system |
| $U_{T1}$ | cm | The displacement of the first tunnel |
| $U_{T2}$ | cm | The displacement of the second tunnel |
| $U_B$ | cm | The displacement of the building |

After creating the output matrix, the algorithm defines the optimum value of the displacement of tunnels and the building based on the total displacement of the system. Assuming that the steps related to each parameter are taken into account based on Table 6, the total number of input data will be too many for the development of the network (4,081,941,864). Due to time and hardware limitations, analyzing this much data is impossible. To solve this problem, at first, a limit was considered. The algorithm would not have limitations from time and hardware aspects for producing data and performing data processing. The value of this limit was considered 40 million input matrix rows. The algorithm was designed in such a way that by the selection of the bigger steps, the processing procedure is done. In the following steps, a parameter is selected as the optimum one, and the step related to that parameter gets deleted. Then, the algorithm repeats the processing procedure for other parameters by defining new steps. This procedure is repeated when the input matrix data for the neural network stands below the assumed limit. The algorithm decreases the volume of further calculations. It increases their accuracy by repeating the input data production procedure in the bigger steps, selecting the optimum values from the obtained results for a parameter, and deleting the selected parameter from the following calculations. This reduction in the calculation volume increases the calculation's speed, and the optimum results are finally produced. The algorithm performs the processing procedure in three repetition steps. The maximum, minimum, and step values in each stage are shown in Table 9. The number of data in the input matrix for each stage is shown in Table 10. The algorithm considered the obtained results in the third stage as the output matrix and performed the optimization procedure. Table 11 shows that the optimum results of the system's total displacement have been defined in 5 ranges. If the minimum and maximum values of each parameter get selected based on Table 11, the total displacement of the system will be in the presented range. This range shows the values between 5 to 4, 4 to 3, 3 to 2, 2 to 1, and less than 1 centimeter.

Based on the obtained results, the optimum state of displacement happens when the soil's cohesion, the tunnel contraction, the diameter of the tunnel, and the tunnel depth are minimum values, and the excavation distance between two tunnels is the maximum value. The results showed that the most appropriate soil's internal friction angle is 31 degrees. The most suitable horizontal distance between two tunnels is 25 meters producing the minimum interaction between two tunnels. Also, the system's displacement would be less when the angle between two tunnels is 60 degrees. The displacement values of the system are less than two centimeters, and the corresponding parameters are shown in Table 12.

Table 9
The maximum, minimum, and step values in each stage

| Parameter | | d (m) | H (m) | A (Deg) | S (m) | D (m) | $C_1$ (%) | Φ (Deg) | C (kN/m$^2$) |
|---|---|---|---|---|---|---|---|---|---|
| Process #1 | Min | 7 | 4 | 0 | 12 | 6 | 0/5 | 25 | 10 |
| | Max | 45 | 36 | 180 | 40 | 11 | 2 | 45 | 40 |
| | Step | 3 | 2 | 60 | 2 | 2 | 1 | 2 | 2 |
| Process #2 | Min | 7 | 4 | 0 | 12 | 6 | 0/5 | 25 | 10 |
| | Max | 45 | 36 | 180 | 40 | 11 | 2 | 45 | 10 |
| | Step | 2 | 2 | 30 | 1 | 1 | 0/5 | 1 | 0 |
| Process #3 | Min | 7 | 4 | 0 | 12 | 6 | 0/5 | 31 | 10 |
| | Max | 45 | 36 | 180 | 40 | 11 | 2 | 31 | 10 |
| | Step | 1 | 1 | 30 | 1 | 1 | 0/5 | 0 | 0 |

Table 10
The number of data in the input matrix for each stage

| Process Number | Size of Data |
|---|---|
| #1 | 30,159,360 |
| #2 | 34,786,080 |
| #3 | 6,270,264 |

Table 11
The optimum results of the system's total displacement and the corresponding parameters

| Parameter | d | H | A | S | D | $C_1$ | Φ | C | $U_T$ |
|---|---|---|---|---|---|---|---|---|---|
| | Inputs | | | | | | | | Output |
| Unit | M | m | Deg | m | m | % | Deg | kN/m² | mm |
| Min | 7 | 4 | 0 | 16 | 6 | 0/5 | 31 | 10 | 50-40 |
| Max | 43 | 8 | 180 | 40 | 8 | 0/5 | 31 | 10 | |
| Min | 7 | 4 | 0 | 17 | 6 | 0/5 | 31 | 10 | 40-30 |
| Max | 37 | 6 | 180 | 40 | 8 | 0/5 | 31 | 10 | |
| Min | 7 | 4 | 30 | 19 | 6 | 0/5 | 31 | 10 | 30-20 |
| Max | 36 | 5 | 120 | 40 | 7 | 0/5 | 31 | 10 | |
| Min | 7 | 4 | 60 | 30 | 6 | 0/5 | 31 | 10 | 20-10 |
| Max | 26 | 4 | 90 | 38 | 6 | 0/5 | 31 | 10 | |
| Min | 7 | 4 | 60 | 37 | 6 | 0/5 | 31 | 10 | Less than 10 |
| Max | 25 | 4 | 60 | 40 | 6 | 0/5 | 31 | 10 | |

Table 12
The displacement values of the system are less than two centimeters and the corresponding parameters

| Inputs | | | | | | | | Output |
|---|---|---|---|---|---|---|---|---|
| d (m) | H (m) | A (Deg) | S (m) | D (m) | $C_1$ (%) | Φ (Deg) | C (kN/m²) | $U_T$ (mm) |
| 25 | 4 | 60 | 40 | 6 | 0/5 | 31 | 10 | 4/5 |
| 25 | 4 | 60 | 39 | 6 | 0/5 | 31 | 10 | 5/9 |
| 25 | 4 | 60 | 38 | 6 | 0/5 | 31 | 10 | 8/2 |
| 7 | 4 | 60 | 37 | 6 | 0/5 | 31 | 10 | 9/3 |
| 7 | 4 | 60 | 36 | 6 | 0/5 | 31 | 10 | 10/3 |
| 8 | 4 | 60 | 36 | 6 | 0/5 | 31 | 10 | 10/5 |
| 25 | 4 | 60 | 37 | 6 | 0/5 | 31 | 10 | 10/7 |
| 8 | 4 | 60 | 35 | 6 | 0/5 | 31 | 10 | 10/8 |
| 9 | 4 | 60 | 35 | 6 | 0/5 | 31 | 10 | 11/5 |
| 9 | 4 | 60 | 34 | 6 | 0/5 | 31 | 10 | 11/6 |
| 10 | 4 | 60 | 34 | 6 | 0/5 | 31 | 10 | 12/3 |
| 10 | 4 | 60 | 33 | 6 | 0/5 | 31 | 10 | 12/8 |
| 11 | 4 | 60 | 33 | 6 | 0/5 | 31 | 10 | 13/0 |
| 25 | 4 | 60 | 36 | 6 | 0/5 | 31 | 10 | 13/2 |
| 12 | 4 | 60 | 32 | 6 | 0/5 | 31 | 10 | 13/7 |
| 11 | 4 | 60 | 32 | 6 | 0/5 | 31 | 10 | 14/5 |
| 13 | 4 | 60 | 31 | 6 | 0/5 | 31 | 10 | 14/7 |
| 25 | 4 | 60 | 35 | 6 | 0/5 | 31 | 10 | 15/8 |
| 12 | 4 | 60 | 31 | 6 | 0/5 | 31 | 10 | 16/7 |
| 14 | 4 | 60 | 30 | 6 | 0/5 | 31 | 10 | 17/0 |
| 7 | 4 | 60 | 35 | 6 | 0/5 | 31 | 10 | 17/1 |
| 7 | 4 | 60 | 38 | 6 | 0/5 | 31 | 10 | 17/6 |
| 8 | 4 | 60 | 34 | 6 | 0/5 | 31 | 10 | 18/0 |
| 25 | 4 | 60 | 34 | 6 | 0/5 | 31 | 10 | 18/4 |
| 13 | 4 | 60 | 30 | 6 | 0/5 | 31 | 10 | 19/5 |
| 9 | 4 | 60 | 33 | 6 | 0/5 | 31 | 10 | 19/5 |
| 7 | 4 | 90 | 35 | 6 | 0/5 | 31 | 10 | 19/6 |
| 8 | 4 | 60 | 37 | 6 | 0/5 | 31 | 10 | 19/7 |
| 26 | 4 | 60 | 35 | 6 | 0/5 | 31 | 10 | 19/9 |

## 5. Conclusion

This paper evaluated the effect of different parameters on the displacement of tunnels and their neighboring building using three-dimensional numerical simulation and parametric studies. The studied parameters included: the horizontal distance between tunnels, the depth of tunnels, the angle between tunnels, the excavation distance between two tunnels, the diameter of tunnels, the tunnel contraction, the soil's internal friction angle, and the soil's cohesion. Then using a multilayer perceptron neural network and the developed optimization algorithm, the concurrent effects of the understudy parameters were evaluated on the total displacement of the system, and the optimum values of surficial settlement and its corresponding parameters were determined. The obtained results are as follows:

- During the excavation of each tunnel, the stress status in the soil changes, and new displacements in the soil occur. With the increase in the distance between two tunnels, these displacements decrease. The obtained results showed that when the horizontal distance between two tunnels is more than 22 meters, the second tunnel does not impact the displacement of the building. The displacement of the first tunnel decreases 11% (two centimeters), and the displacement of the building decreases 52% (five centimeters) relative to the base model.
- The increase in the depth of tunnels does not significantly impact the displacement of the tunnels and is almost a constant value. The obtained results showed that the more the tunnel depth, the more the distance between the tunnel and the ground surface, in which the surficial settlement occurs in the broader area. On the other hand, when the building is impacted by soil settlement over both tunnels, its settlement gets bigger. Therefore, when the tunnels are located at a depth of 4 meters, the building settlement becomes 4 centimeters, and this settlement is influenced by soil settlement over the first tunnel, and the soil settlement over the second tunnel has a more negligible influence on the building. By increasing the depth of tunnels up to 8 meters, the building settlement gets impacted by the soil settlement over two tunnels and reaches 11 centimeters. By increasing the depth of tunnels up to 16 meters, the excavation distance up to the ground surface increases, surficial settlement occurs in the broader area, and the settlement of the building reaches 8 centimeters.
- Since the second tunnel has been excavated with a defined distance after the first tunnel, by the excavation of second tunnel, the soil moves toward the excavation location. If the second tunnel gets located at a lower level, the soil movement would be more, and therefore the settlement of the first tunnel will increase. Reducing the settlement of the first tunnel when the second tunnel is located under the first tunnel is related to the two tunnels' interaction.
- The obtained results showed that by changing the angle between two tunnels from 0 to 60 degrees, the displacement of the first tunnel increases 23% (three centimeters) relative to the base model. Increasing the angle up to 90 degrees decreases this displacement by 5% (one centimeter). By the change in the angle between two tunnels from 0 to 30 degrees, the displacement of the building relative to the base model increases 25% (three centimeters), and by the angle change up to 90 degrees, this displacement decreases 42% (five centimeters). By changing the angle between two tunnels from zero to 90 degrees, the displacement of the second tunnel relative to the base model decreases 170% (24 centimeters). This decrease is because of the displaced soils from the first tunnel excavation location, which leads to a decrease in the settlement and creates a heave when the second tunnel is located under the first tunnel.
- The results showed that when the excavation distance between two tunnels is selected to less than 20 meters, the interaction between two tunnels increases. By increasing the distance to more than 20 meters, this interaction decreases. When this distance reaches 40 meters, two tunnels do not impact each other, and no interaction between the two tunnels occurs. The results showed that when the excavation distance between two tunnels is around 12 meters, the displacement of the first tunnel decreases 5% less than the base model; the second tunnel decreases 4%. The building is 5% less than the base model. By increasing the excavation distance between two tunnels, up to 15 meters, the displacement of the first tunnel, the second, and the building increases and becomes equal to the base model ones. By increase of the excavation distance between two tunnels up to 40 meters relative to the base model, the displacement of the first

tunnel decreases 20% (three centimeters), the second one decreases 160% (22 centimeters), and the building one decreases 26% (three centimeters).

- With the increase in the diameter of the tunnels, the required space for the excavation gets bigger. This fact leads to soil settlement under the tunnel, and an increase in settlement of tunnels happens. The amount of the settlement in the two tunnels is almost equal. The increase in tunnel settlement leads to an increase in the soil settlement under the building, which is almost two times that of the tunnel settlement.
- The space between the surrounding soil and the tunnel's lining increases by increasing tunnel contraction. Bigger the space, the larger the settlement of tunnels and buildings. The obtained results showed that by the tunnel contraction equal to 0.5 to 2% relative to the base model, the displacement of the first tunnel increases 184% (24 centimeters), the settlement of the second tunnel increases 185% (27 centimeters), and the settlement of building increases 166% (17 centimeters).
- In this state, by increasing the soil's internal friction angle, the soil's lateral pressure coefficient decreases, and soil settlement around the tunnel and under the building decreases. By increasing the soil's internal friction angle from 25 to 40 degrees, the displacement of the first tunnel decreases 19% (two centimeters) relative to the base model. The second tunnel decreases 25% (three centimeters), and the building decreases 75% (two centimeters) relative to the base model.
- Considering the Mohr-Coulomb equation, an increase in soil's cohesion increases the shear strength of the soil and its stability. The obtained results showed that by increasing the soil's cohesion from 10 $kN/m^2$ to 35 $kN/m^2$, the displacement of the first tunnel decreased 11% (one centimeter) relative to the base model. In the second tunnel, displacement decreases by 12% (two centimeters) relative to the base model. In the building, displacement decreases 41% (four centimeters) relative to the base model.
- The results from the neural network showed that the optimum state of displacement happens when the soil's cohesion, tunnel contraction, tunnel's diameter, and tunnel's depth are the minimum values, and the excavation distance between two tunnels is the maximum value. The results showed that the most appropriate soil's internal friction angle is 31 degrees. The most suitable horizontal distance between two tunnels is 25 meters producing the minimum interaction between two tunnels. Also, the system's displacement would be less when the angle between two tunnels is 60 degrees.

## References


[1] Haji, T. K., Marshall, A. M., &Tizani, W. (2018). A cantilever approach to estimate bending stiffness of buildings affected by tunnelling. Tunnelling and Underground Space Technology, 71, 47-61.

[2] Haji, T. K., Marshall, A. M., &Franza, A. (2018). Mixed empirical-numerical method for investigating tunnelling effects on structures. Tunnelling and Underground Space Technology, 73, 92-104.

[3] Boldini, D., Losacco, N., Bertolin, S., &Amorosi, A. (2018). Finite Element modelling of tunnelling-induced displacements on framed structures. Tunnelling and Underground Space Technology, 80, 222-231.

[4] Wang, Z., Zhang, K. W., Wei, G., Li, B., Li, Q., & Yao, W. J. (2018). Field measurement analysis of the influence of double shield tunnel construction on reinforced bridge. Tunnelling and Underground Space Technology, 81, 252-264.

[5] Zhang, Z., Huang, M., Xu, C., Jiang, Y., & Wang, W. (2018). Simplified solution for tunnel-soil-pile interaction in Pasternak's foundation model. Tunnelling and Underground Space Technology, 78, 146-158.

[6] Nematollahi, M., & Dias, D. (2019). Three-dimensional numerical simulation of pile-twin tunnels interaction–Case of the Shiraz subway line. Tunnelling and Underground Space Technology, 86, 75-88.

[7] Fabozzi, S., Bilotta, E., Yu, H., & Yuan, Y. (2018). Effects of the asynchronism of ground motion on the longitudinal behaviour of a circular tunnel. Tunnelling and Underground Space Technology, 82, 529-541.

[8] Jallow, A., Ou, C. Y., & Lim, A. (2019). Three-dimensional numerical study of long-term settlement induced in shield tunneling. Tunnelling and Underground Space Technology, 88, 221-236.

[9] Moussaei, N., Khosravi, M. H., & Hossaini, M. F. (2019). Physical modeling of tunnel induced displacement in sandy grounds. Tunnelling and Underground Space Technology, 90, 19-27.

[10] Zhang, T., Taylor, R. N., Divall, S., Zheng, G., Sun, J., Stallebrass, S. E., &Goodey, R. J. (2019). Explanation for twin tunnelling-induced surface settlements by changes in soil stiffness on account of stress history. Tunnelling and Underground Space Technology, 85, 160-169.

[11] Nematollahi, M., & Dias, D. (2020). Interaction between an underground parking and twin tunnels–Case of the Shiraz subway line. Tunnelling and Underground Space Technology, 95, 103150.

[12] Zheng, G., Tong, J., Zhang, T., Wang, R., Fan, Q., Sun, J., & Diao, Y. (2020). Experimental study on surface settlements induced by sequential excavation of two parallel tunnels in drained granular soil. Tunnelling and Underground Space Technology, 98, 103347.

[13] Lu, D., Lin, Q., Tian, Y., Du, X., & Gong, Q. (2020). Formula for predicting ground settlement induced by tunnelling based on Gaussian function. Tunnelling and Underground Space Technology, 103, 103443.

[14] Bilotta, E., Paolillo, A., Russo, G., & Aversa, S. (2017). Displacements induced by tunnelling under a historical building. Tunnelling and Underground Space Technology, 61, 221-232.

[15] Miliziano, S., & de Lillis, A. (2019). Predicted and observed settlements induced by the mechanized tunnel excavation of metro line C near S. Giovanni station in Rome. Tunnelling and Underground Space Technology, 86, 236-246.

[16] Kovačević, M. S., Bačić, M., Gavin, K., & Stipanović, I. (2021). Assessment of long-term deformation of a tunnel in soft rock by utilizing particle swarm optimized neural network. Tunnelling and Underground Space Technology, 110, 103838.

[17] Meng, F., Chen, R., Xu, Y., Wu, H., & Li, Z. (2021). Centrifuge modeling of effectiveness of protective measures on existing tunnel subjected to nearby excavation. Tunnelling and Underground Space Technology, 112, 103880.

[18] Zhou, Z., Ding, H., Miao, L., & Gong, C. (2021). Predictive model for the surface settlement caused by the excavation of twin tunnels. Tunnelling and Underground Space Technology, 114, 104014.

[19] Mu, B., Xie, X., Li, X., Li, J., Shao, C., & Zhao, J. (2021). Monitoring, modelling and prediction of segmental lining deformation and ground settlement of an EPB tunnel in different soils. Tunnelling and Underground Space Technology, 113, 103870.

[20] Azadi, M., Pourakbar, S., &Kashfi, A. (2013). Assessment of optimum settlement of structure adjacent urban tunnel by using neural network methods. Tunnelling and underground space technology, 37, 1-9.

[21] Moosazadeh, S., Namazi, E., Aghababaei, H., Marto, A., Mohamad, H., &Hajihassani, M. (2018). Prediction of building damage induced by tunnelling through an optimized artificial neural network. Engineering with Computers, 1-13.

[22] Moghaddasi, M. R., &Noorian-Bidgoli, M. (2018). ICA-ANN, ANN and multiple regression models for prediction of surface settlement caused by tunneling. Tunnelling and Underground Space Technology, 79, 197-209.

[23] Azadi, M., & Hosseini, S. M. M. (2007). The impact of underground tunnel excavation on adjacent buildings during earthquake case study: shiraz underground, Iran. Electronic Journal of Geotechnical Engineering, 12, 1-10.

[24] Azadi, M., & Hosseini, S. M. M. (2010). Analyses of the effect of seismic behavior of shallow tunnels in liquefiable grounds. Tunnelling and underground space technology, 25(5), 543-552.

[25] Mir Mohammad Hosseini, S. M., & Azadi, M. (2012). Effect of the location of liquefiable sand lenses on shallow tunnels during earthquake loading. Arabian Journal for Science and Engineering, 37, 575-586.