



The Effect of Soil Reinforcement on the Stress and Strain Field Around Underground Square-Shaped Areas and its Internal Lining Efforts in Urban Areas

Alireza Darvishpour ^{a*}, Asadollah Ranjbar ^b, Amirmohammad Amiri ^c

^a Department of Civil Engineering, Robatkarim Branch, Islamic Azad University, Robatkarim, Iran.

^b Department of Civil Engineering, East Tehran Branch, Islamic Azad University, Tehran, Iran.

^c Department of Civil Engineering, Faculty of Engineering, university of Lorestan, Lorestan, Iran.

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Abstract

The passage of underground structures from the bottom of the structures on the ground causes a change in the stresses and strains created in the structure as well as the soil environment surrounding the tunnel due to the existence of an interaction between these two sides. In this way, the existence of the surface structure leads to a change in the strain and stress conditions around the tunnel, and in contrast, the tunnel also leads to a change in the stress and settlement around the structures. Therefore, such a reciprocal behavior is very important. In this research, with the help of Abaqus finite element software, two main possible conditions are considered: the creation of an underground structure in the presence of the superstructure, as well as the reverse state of the concept of constructing a building in the state in which the underground structure already exists. One of the subjects studied in this research is the physical modelling effect of the structure, rather than the effect of its wide load on the ground. Other parameters considered in this research are the number of story, the depth of the tunnel, the width of the tunnel, the thickness of the lining, the effect of changes in the soil parameters in the depth and the horizontal distance of the tunnel center from the building center. The results of this research are validated based on the results obtained by other researchers. According to the results obtained in this research, by the increase of the distance between the tunnel center and structure center and depending on the stiffness of the tunnel lining, significant asymmetric stresses are created in the superstructure. The construction of the structure before and after the tunnel construction can affect the unsymmetrical settlement of the structure. The stress and strain created in the lining of the tunnel and the surrounding area are also different due to the amount of mobilized force in the reinforcements.

Keywords: Soil Structure Interaction; Soil Reinforcement; Lining; Underground Structure; Surface Structure.

1. Introduction

Investigating the interaction between tunnels and surface structures has long been of interest to researchers and there has been a lot of research on this subject. In all the analyses, the structure load is stress-induced and the surface structure modelling is avoided. One of the first studies on the effect of underground cavity on surface structures properties was done by Wang et al. [1]. In this research, the effect of underground cavity on the bearing capacity of shallow foundation has been investigated. The shallow foundation is on dense clay soil and the analyses were performed using a 3D computer software based on finite element. The analyses are performed for different conditions consisted of the shape of the foundation (strip or mat foundation), the cavity shape and the effect of the distance between the cavity axis and

* Corresponding author: alireza.darvishpour@gmail.com

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the foundation axis. The yield criterion of Drucker Prager was employed for the soil media. There is a critical depth above which the underground cavity is located, and it will affect the stability of the foundation. Critical depth will change with various factors including the shape of the foundation and cavity, the size of the cavity and the type of soil.

In another analysis, the effect of the underground cavity on the undrained capacity of the shallow foundation has been investigated. Lee et al. [2] investigated the undrained capacity of the surface strips on the saturated clay. In their study, the subsoil is assumed to have single and double underground cavities continuously.

Lee et al. [3] studied the foundations under inclined load and the results indicated that the soil stiffness has a small effect on the capacity of shallow foundation on clay with and without cavity. Their results indicated that the failure criterion in the vertical and horizontal positions, followed a single curve which is independent from the stiffness of the soil. Frischman et al. [4] performed a numerical analysis on the effect of the tunnel excavation on the Mansion Building.

Franzius [5] has numerically studied the effect of the building weight under the assumption that for realistic values of weight and ground loss, no gap can develop between the soil and the building. Rots [6] showed that no-tension interface between the soil and the structure reduced the effect of a greenfield settlement profile directly applied to the structure.

Yan et al. [7] presented the laboratory investigation that involved a series of model footing load tests over the reinforced sandy soil cover-conduit system in a rigid test tank. The pressure distribution around the conduit was investigated against the applied surface footing pressure for both reinforced and unreinforced conditions along with the footing settlement. The results showed that the reinforcement layer improves the load-bearing capacity of the footing and reduces the pressure on the crown and spring line of the conduit. For a given applied pressure, an increase in the width of reinforcement is found to be more effective in reducing the pressure applied on the crown and springline of conduit along with the reduction in both vertical and horizontal deflections of conduit.

Zheng et al. [8] suggested a numerical study of the maximum reinforcement tensile forces for geosynthetic reinforced soil (GRS) bridge abutments. The backfill soil was characterized using a nonlinear elastoplastic constitutive model that incorporates a hyperbolic stress-strain relationship with strain softening behavior and the Mohr-Coulomb failure criterion. The geogrid reinforcement was characterized using a hyperbolic load-strain-time constitutive model. Their research results indicated that the reinforcement vertical spacing and backfill soil friction angle have the most significant effects on the magnitudes of the maximum tensile forces at the service load condition.

Wang et al. [9] suggested two earth pressure coefficients to analyze the reinforcement loads at the potential failure surface of vertical geosynthetic-reinforced soil retaining walls under working stress conditions based on the nonlinear elastic theory and the stress-dilatancy theory. The earth pressure coefficients take into account the force equilibrium and compatible deformations between the soil and reinforcement. Their results showed that the lateral deformations of the soils under vertical loading are considerably influenced by their dilatancy properties.

Yun and Kim [10] performed a series of laboratory tests to investigate the settlement and scour characteristics of the seabed according to different reinforcement types, reinforced area and the soil type. Two reinforcement types with different reinforced areas were applied to reduce the settlement and the scour of ground: geogrid and geogrid-bamboo mat. The ground soil types were clay, silt and sand deposits. The test results indicated that the reinforced artificial reef had less settlement and scour depth than the unreinforced artificial reef. Especially, the artificial reef reinforced with geogrid-bamboo mat had more improved stability than that of with geogrid due to the high bending stiffness of the bamboo mat.

Abu-farsakh et al. [11] performed a three-dimensional (3D) Finite Element (FE) analysis to simulate the fully-instrumented geosynthetic reinforced soil integrated bridge system (GRS-IBS) at Maree Michel Bridge in Louisiana. The soil-structure interaction was simulated using zero thickness interface elements, in which the interface shear strength is governed by Mohr-Coulomb failure criterion. The results predicted by the 3D-FE showed that the range of maximum reinforcement strain under service loading is between 0.6% and 1.5%, depending on the location of the reinforcement layer. The results obtained by the FHWA analytical method are 1.5–2.5 times higher than those predicted by the FE analysis, depending on the loading condition and the reinforcement location.

Several other influential factors have also been studied by other researchers. Such as nonlinear behaviour of the building material (Boonpichetvong and Rots [12]; DeJong et al. [13]; Laefer et al. [14]; Giardina et al. [15], [16]; Amorosi et al. [17]) and the presence of large openings (Son and Cording, [18]; Melis and Rodríguez Ortiz, [19]; Giardina et al. [20]) and the nonlinear interface between the structure and the soil is used by other researchers such as netzel [21] and Giardina et al. [20].

In this paper, the numerical study of the soil structure interaction effects on the static behavior of underground structures such as stresses and strains created in the lining elements and structures has been performed. The effect of the reinforcements on the reduction of the surface structure effect on the static behavior of tunnels has also been investigated. One of the most important parameters which is studied in this research is determining the building drift due to the

deviation of the underground cavity center from the structural foundation center. Because the structure is tilted nonuniform, the internal forces are produced in the lining. Another important parameter studied in this research is the effect of the reinforcement element on the reduction of the internal forces of the lining or structure. It was observed that the use of the reinforcement element did not have a significant effect on the reduction of the internal forces of the lining. Determination of the necessity or unnecessity of the physical modeling of the structure in the Abaqus finite element software for investigating the effect of the surface structure on the stresses and strains created in the tunnel lining will be discussed, because in most of the previous studies, the structure has been modeled as a distributed load on a strip foundation. The effects of the tunnel lining and its type on the surface structure have not been investigated in the previous studies while they will be discussed here in this research.

2. Methodology

In general, the present research will be examined in the following two general ways:

In the first mode, the superstructure exists and then a tunnel is created below it.

In the second mode, the tunnel exists and then a superstructure is created on it.

The hypotheses in this research are:

- The short and tall structures will be selected, whose components are designed in the Etabs software, but the heights of all the structures are less than 40 meters.
- Foundation material is concrete and it will be modeled for the proper transfer of the structure load to the soil.
- In the initial models, the soil is assumed to be homogeneous and single-layered, and in a more advanced state, its properties will be introduced according to the non-homogeneous conditions. For example, the effect of increasing the soil compaction will be examined in depth. Rising compaction in depth leads to the increased density and stiffness.
- Soil behavior will be modeled using Mohr-Coulomb criterion. The parameters of the model, in this case, are soil dry density, Young modulus, Poisson ratio, friction angle, cohesion, and soil tensile strength. One of the research variables is the effect of the soil type. For this purpose, three different types of the soil in homogeneous and non-homogeneous states are assumed.
- The lining of the tunnel is assumed to be in the three modes of 15 and 30 cm shotcrete lining, and a concrete casing of 70 cm as the final lining. This lining can be modeled under tunnel drilling conditions using NATM and TBM methods, in terms of the effect of the stress relaxation from drilling operations to tunnel lining.
- The geometric variables of the cavity are the diameter of the cavity and the distance of the cavity center from the center of the foundation structure (horizontal and vertical).

3. Proposed Methodology and Validation of the Performed Modeling

In order to verify the results obtained from the Abaqus software, the results of the modelling done by Lee et al. [4] by the Plaxis software have been compared with the results of Abaqus modelling. Lee et al. [4] investigated the effect of the load inclination on the undrained bearing capacity of shallow foundations on the ground cavity. In their research, the homogeneous soil was used for modelling and they provided nondimensional failure envelopes that determined the condition of the bearing capacity for different soil conditions and underground cavity geometry.

In their study, the software used is Plaxis2D and the plane strain condition is assumed. Modeling was done using the linear elastic behavior model along with the Mohr-Coulomb criterion. In Figure 1, the geometry of the model and mesh used by Lee et al. [4] was compared to the mesh used in the Abaqus software. As it is considered, they used dimensional analyzing for determining the model dimensions. Dimensions of the model have been introduced as the multiple of the foundation width. By choosing width of 2 meters for the foundation, the width and height of the model are 40 and 30 meters, respectively. In order to model the underground cavity, a square cavity with the width of two meters is considered, with depth of two meters. The reference element used in Plaxis is a six-node element, while the element used in Abaqus is the 4-node element with linear geometric power. The method used by Lee et al. [4] for the described model, created about 8,000 elements, while in the Abaqus software, with different element type, about 10,000 elements were created.

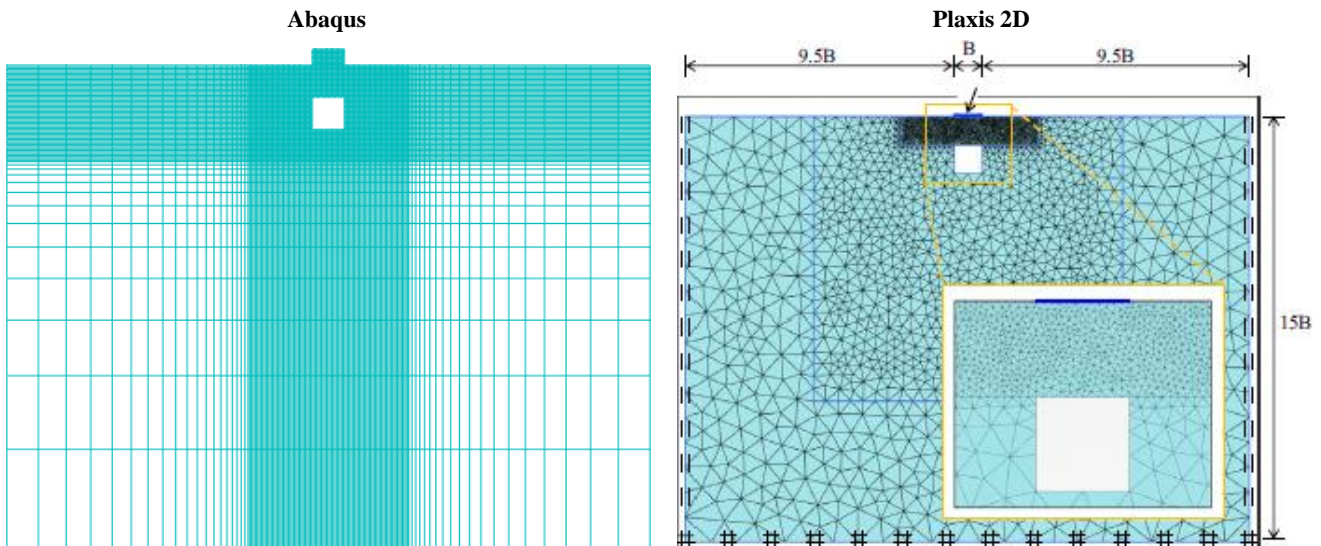


Figure 1. Mesh used in two-dimensional Plaxis2D and Abaqus software

The materials used are as shown in Table 1 and it is observed that the properties of the materials are in undrained conditions. In the undrained modelling, the load weight is not entered into the soil mass, pore pressure during the analysis is not unknown and its effect is considered in the parameters. In other words, the difference between this methods of analysis with the dry soil mass is the lack of the weight load and the differences in the parameters of the soil model.

Table 1. Properties of materials used in Lee et al. [4] Modeling

Homogeneous	Unit	Parameters
2000	Kg/m ²	Saturated density
30	MPa	Undrained young modulus
0.495	-	Undrained Poisson's ratio
0	Degree	Undrained friction angle
100	KPa	Undrained cohesion

In the undrained conditions, without the application of weight load to the ground, the load of the foundation continues gradually until it reaches the final condition. In Figure 2, the displacement-load diagram obtained from the Abaqus software is plotted according to the conditions shown in Figure 30 (i.e. black color), and the load bearing capacity calculated by Lee et al. [4] is indicated with the red line. The axes of the figure are normalized as described in Lee et al. [4] and the normalization relations between the vertical axis and the horizontal axis are given in Equation 3 and 4. In the mentioned figure, the model's settlement rate near the foundation elements is also shown.

$$y - \text{axis value} = \frac{\text{vertical load}}{B \times C_u} \quad (1)$$

$$x - \text{axis value} = \frac{\text{settlement}}{B} \quad (2)$$

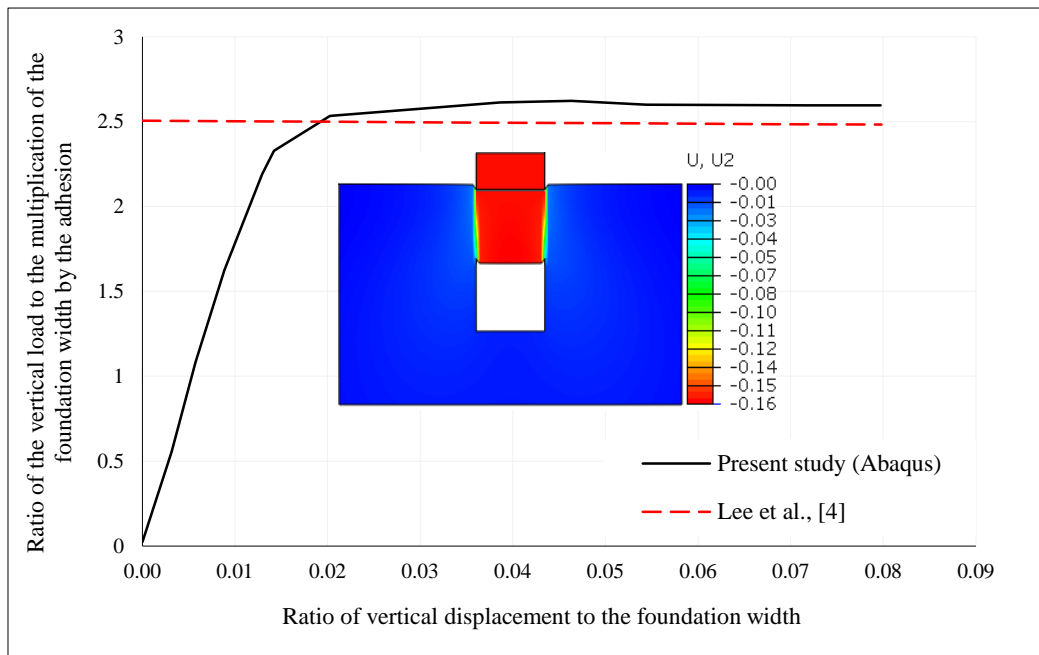


Figure 2. Comparison of the Abaqus normalized load-settlement diagram with the amount of bearing capacity obtained by Lee et al. [4] for conditions where the horizontal distance of the cavity center from the foundation center is zero (m)

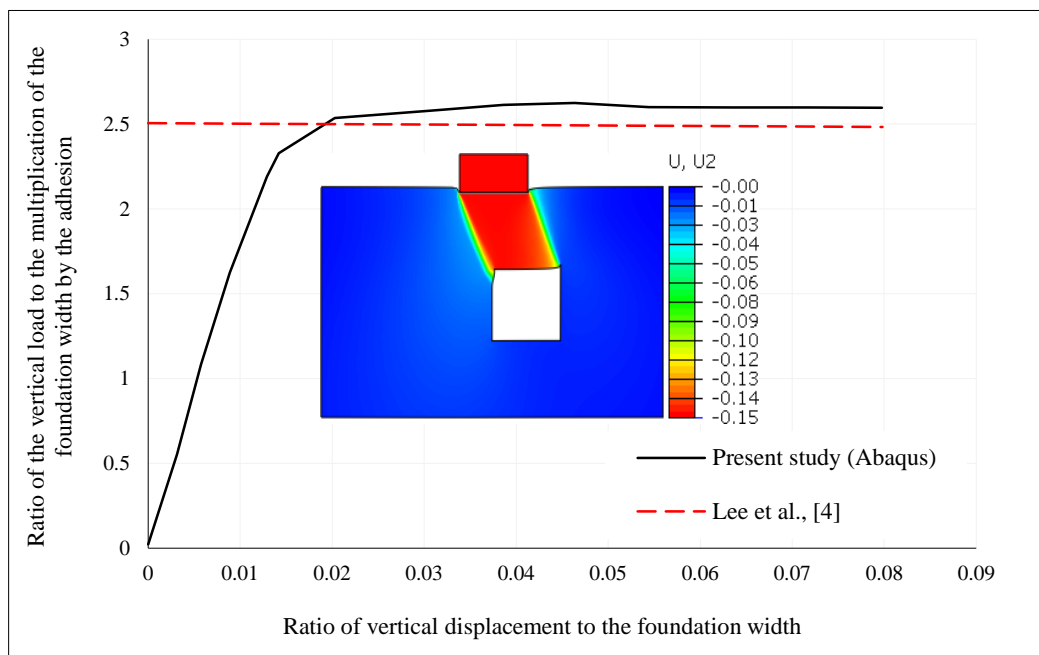


Figure 3. Comparison between the Abaqus normalized load-settlement diagram and the amount of bearing capacity obtained by Lee et al. [4] for conditions where the horizontal distance of the cavity center from the center of the foundation is one meter (m)

One of the variables in the research by Lee et al. [4] is the horizontal distance of the cavity center from the center of the foundation. The results of their modelling show that the bearing capacity of the foundation increases by the increase of the horizontal distance of the underground cavity center from the foundation center. For one of their modelling conditions, the horizontal distance of the cavity center from the foundation center was one meter. The mentioned condition is modelled by Abaqus software and the results are shown in Figure 3. With regard to the final settlement plotted in Figure 3, it is seen that if the horizontal distance of the cavity center from the center of the foundation is one meter, then foundation is rotated clockwise, and a block of soil will be collapsed into the cavity.

The comparison of the results obtained by Abaqus software and the results obtained by Lee et al. [4] shows that the method used to model the foundation near the square cavity is well-executed and can be used to model the issues of this paper.

4. Finite Element Modeling

In this section, the results of the numerical modelling performed in Abaqus software (finite element method) are considered. In this research, two major conditions of the numerical modelling have been proposed. In the first condition, the cavity is created in a situation where the building is located on the ground, and in the latter case the building is constructed while there is a cavity in the ground. Creation of a cavity in the ground can be due to the development of a small cavity due to scouring, or after the completion of tunnelling operation, etc.

The buildings under consideration in this paper are five, seven and ten-story and are of concrete type with the roof of the steel deck. Due to the low amount of structural forces (service loads) compared to the design load (maximum), the nonlinear behaviour of the super structure is ignored in the modelling with Abaqus software. It is worth noting that the components of these buildings are designed in the Etabs and Safe software and therefore the sections used are sufficient for the imported loads of the study. In Figure 4, the structure geometry of the ten-story building which is designed in Etabs software is shown.

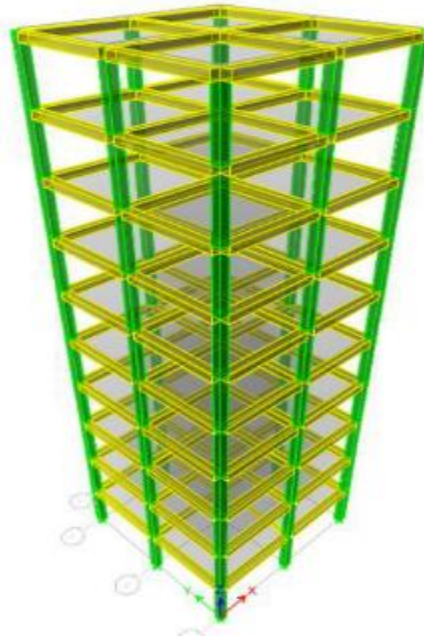


Figure 4. Ten-story building used in this research

The cavities discussed in this paper are square shapes with three, five and seven meters dimensioned sides. These cavities were created in three conditions including the 15 cm lining of shotcrete, the second case with a 30 cm lining and eventually the last case a 70 cm coating (concrete coating applied on shotcrete). It is worth noting that the square cavities in the assumed soil of this paper are not self-stable and therefore, in the weakest state of the cavity, a shotcrete lining of 15 cm is considered. In Figure 5, the geometries of the general models made in Abaqus software are shown.

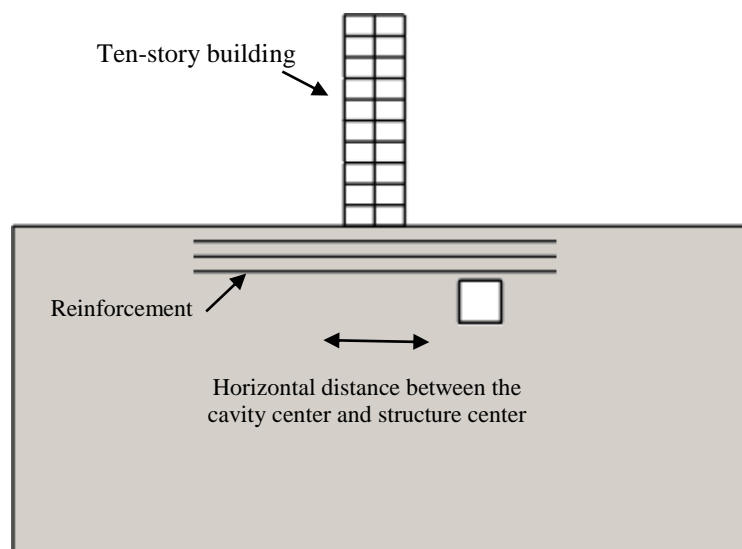


Figure 5. The geometries of the general models made in Abaqus software

For each cavity in addition to the size, the depth of the cavity and the eccentricity of its center relative to the center of the structure have also been changed. For overload height of 9 and 15 meters, in order to examine the eccentricity of cavity center from the center of the foundation, the amount of half to two and a half times the width of the cavity is used for the eccentricity. Eccentricity of the cavity center relative to the foundation center leads to the nonuniform settlements of structures and for high building can get the tilting value close to a critical value, so this parameter is also an important parameter in the modelling of this research. In order to construct finite element models in this research, the field depth and width were 100 and 200 meters, respectively.

The geometry of the model is shown in Figure 6, and it is seen that the size of the mesh elements near the ground surface and the location of the cavity has been significantly reduced, and consequently, the size of the largest and smallest elements in the section of the ground are selected to be five and half meters respectively. Since the accuracy of the deformation calculation in the earth surface and the surrounding of the cavity is most important, the smallest size of the elements is used in that areas. The element used for the soil is a four-node plane strain whose strain and stress between the nodes of the element are linearly assumed.

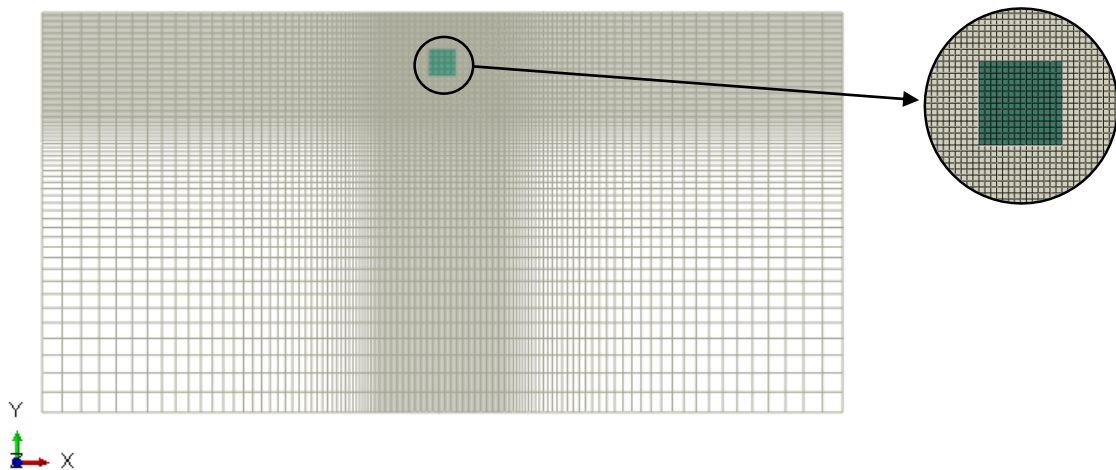


Figure 6. The geometry of the ground along with the enlargement of the cavity

Super structure and cavity lining are some of the other components used in the modelling. The hypothesized structures of this paper are assumed to be five and ten-story with regular geometry, column spacing and the elevation of the building floors are equal to 5 and 3.5 meters, respectively, which are based on a mat foundation with the thickness of 60 cm. In order to meshing the components of the beam and the structural column, the three-node beam element is used, which is highly accurate in the deformation calculations. The linings of the underground cavity are considered to be square with three, five and seven meters width and the thicknesses of 15, 30 and 70 cm, and for the mesh of the structure and foundation the two-node element is used. When a coarsely meshed surface is used as a slave surface for node-to-surface contact, the master surface nodes can grossly penetrate the slave surface without resistance. This situation is common when nonmatching meshes come into contact. Refining the slave surface tends to alleviate this problem, however, unless perfectly matching meshes are used, local oscillations in the contact stress may still be observed, even in the refined models [4]. In Figure 7, the modelled components of the five-story building with the cavity lining are shown and the circular symbols on the lines of these elements represent the nodes of the mesh component.

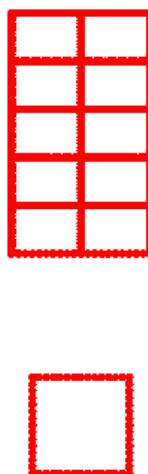


Figure 7. The five-story building components with 7 meters width

The last members of the model are the steel reinforcements, which have the depth of 2.5 meters and extend from each side of the building to 25 meters around. Thus, the minimum length of the reinforcement was six times the building width, and in selecting these values, it was attempted to use an optimum arrangement of three layers of the reinforced soils using the results of the previous research [17, 18]. In the mesh of the reinforcement parts, the two-node truss element was used, and the reason for using a truss element instead of a beam element was to ignore the flexural stiffness of the elements (due to its negligible thickness). In Figure 8, the geometry of the three-layer steel reinforcement below a ten-story building has shown that the distance of the first layer from the foundation of the structure is equal to the distances between the layers (i.e. 2.5 meters).

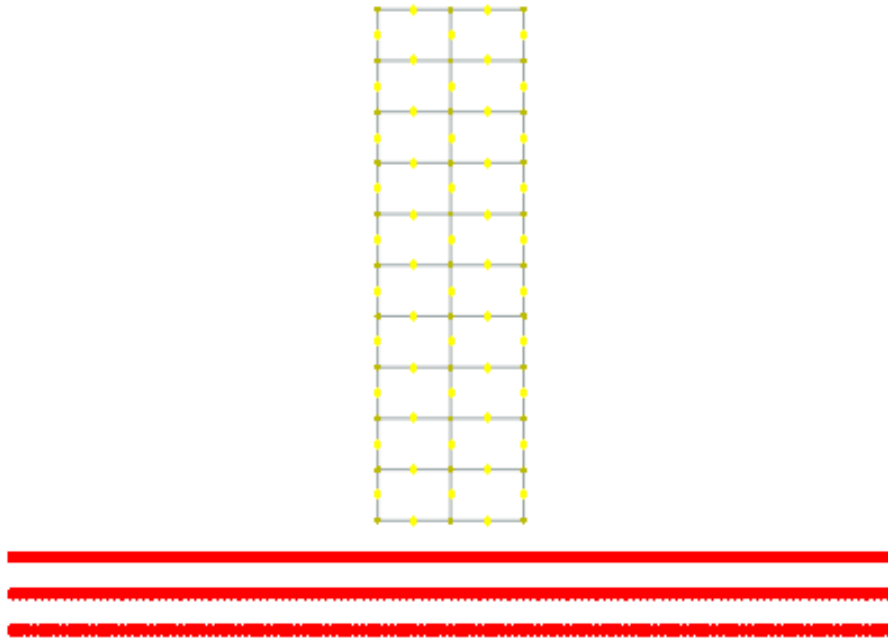


Figure 8. The geometry of the three-layer steel reinforcement below a ten-story building

Material properties used in this research are shown in Table 2.

Table 2. Material properties used in the modelling

Parameter	Steel	Structural concrete	Shotcrete	Homogeneous soil
Density (kg/m ³)	7850	2500	2400	1700
Young modulus (MPa)	210000	25000	15000	19
Poisson ratio	0.3	0.17	0.2	0.3
Yield stress (MPa)	240	-	-	-
Friction angle (Degree)	-	-	-	30
Cohesion (KPa)	-	-	-	25

5. Modeling Results

The first step, which is static and standard, has been created in all the models, the square-shaped cavity and its concrete lining has been activated. In other models, this step has been devoted to the addition of the soil reinforcement elements along with the foundation elements and super structures. In Figure 9, the stress field changing in horizontal and vertical direction is shown, in which the forms are related to the situation where the underground cavity was first activated with its concrete lining before the building. According to the figure below, the cavity formation reduces vertical and horizontal stresses in the adjacent elements in the middle of the cavity sides, but stress concentration has been created in the corners of the cavity. The existence of the stress concentration in the wedge of the cavity with a corner geometry is one of the disadvantages of choosing such geometries for tunnels.

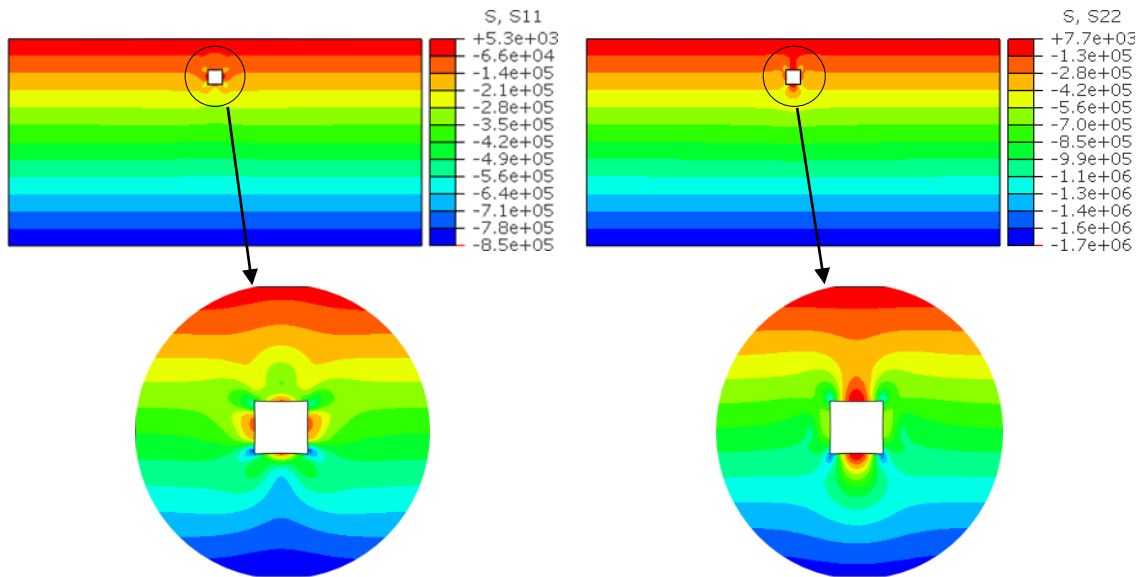


Figure 9. Vertical and horizontal stress field at the end of the second step, in models where the cavity was first created and the lining is activated (Pa)

In Figure 10, the internal forces diagram for the lining thickness of 70 cm with 7 meters width and 15 meters depth is shown and it is seen that the bending moment in the middle of the sides has maximum value and it has critical value at the corner of the lining. The bending moment in those areas is more than twice the bending moment value in the middle of the sides. It is worth noting that due to the symmetry in the internal forces diagram, the results are plotted for half of the lining geometry, but the modelling has been done with the full geometry.

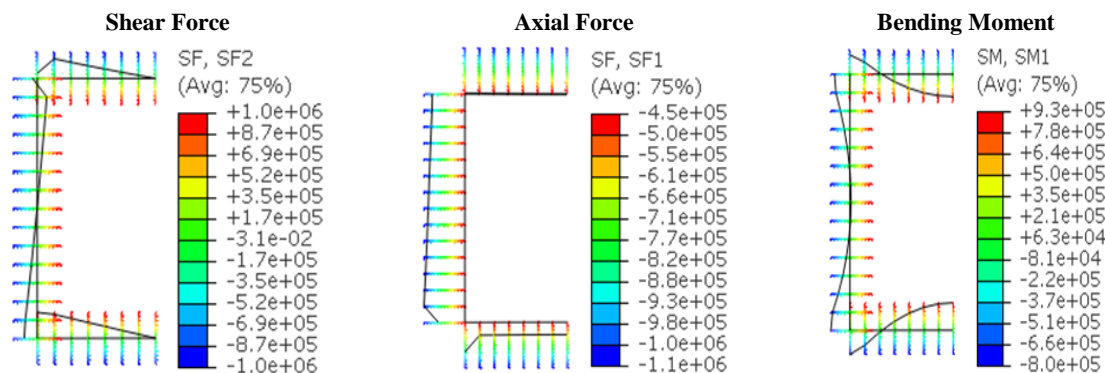


Figure 10. The lining internal force diagram with 70 cm thickness and 15 meters depth, the cavity is created before the structure (N, N.m)

Also, in Figure 10, the axial force and shear force diagrams in the lining with 70 cm thickness and 15 meters depth are shown. In the mentioned model the cavity is initially created and the lining is activated later. It is observed that the axial forces in the covering walls are much larger than the maximum values in the floor and ceiling elements. The reason for this object is that the values of vertical stresses are large relative to the horizontal stresses. (Because of choosing the horizontal pressure coefficient to be 0.5 for the soil). The shear force diagram of the lining indicates that the shear force is increased by approaching the corners of the lining and its value is approximately zero in the middle of the sides. According to the maximum amount of the internal efforts in the lining section, it can be concluded that the concrete section with sufficient strength should be used in these cases. It is clear that using the weak sections in the numerical analysis caused serious damage to the cross section, and these damages are not considered in the elastic behavioural models. Therefore stress and strain control of the lining in such cases is more important.

In Figure 11, the field settlement of the model after applying the structure load on the ground consisting underground cavity is shown, and it is observed that the largest amount of the settlement has occurred in the building area, where the maximum settlement is 7.8 centimeters and its position is in the center of the building roof. The amount of the settlement caused by the load of the structure is reduced in the direction of the foundation axis and by going deeper in the ground, and it is observed that at the depth of 80 meters of the ground, the sum of the settlement reached 5 millimeters and the effect of the structure at this depth has decreased significantly.

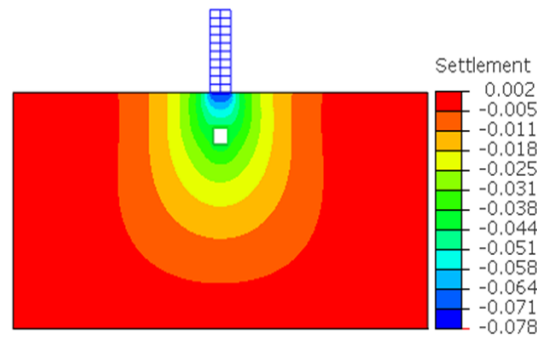


Figure 11. Field settlement of the model after applying the load of the 10-story structure on the ground, underground cavity has a width of 7 meters and a height of 15 meters and a concrete lining thickness of 70 cm (m)

In Figure 12, the internal forces of the lining with 70 cm thickness is shown in the three desired states. In the first and second states, the soil reinforced by the steel section with 3 and 6 square millimetres of the cross section area per meter, and in the third state, the no reinforced soil are modelled.

As shown in Figure 12, the soil reinforcement has failed to change the internal forces of the 7 meters width cavity with the depth of 15 meters, which is influenced by the dead load of the 10-story building. However, by comparing the values shown in Figure 12 with the results shown in Figure 11, the bending moment, axial force and shear force increased by 7.5%, 9.1% and 10%, respectively. However, the low effect of the soil reinforcement on decreasing the internal forces of the lining does not mean that the soil reinforcement does not affect the reduction of the building settlement under its own weight load. Subsequently, by observing the field settlement and the internal stresses of the steel reinforcement elements due to the dead load of the structure, these arrays of the reinforcement were not so effective to prevent the increase of internal forces in the lining.

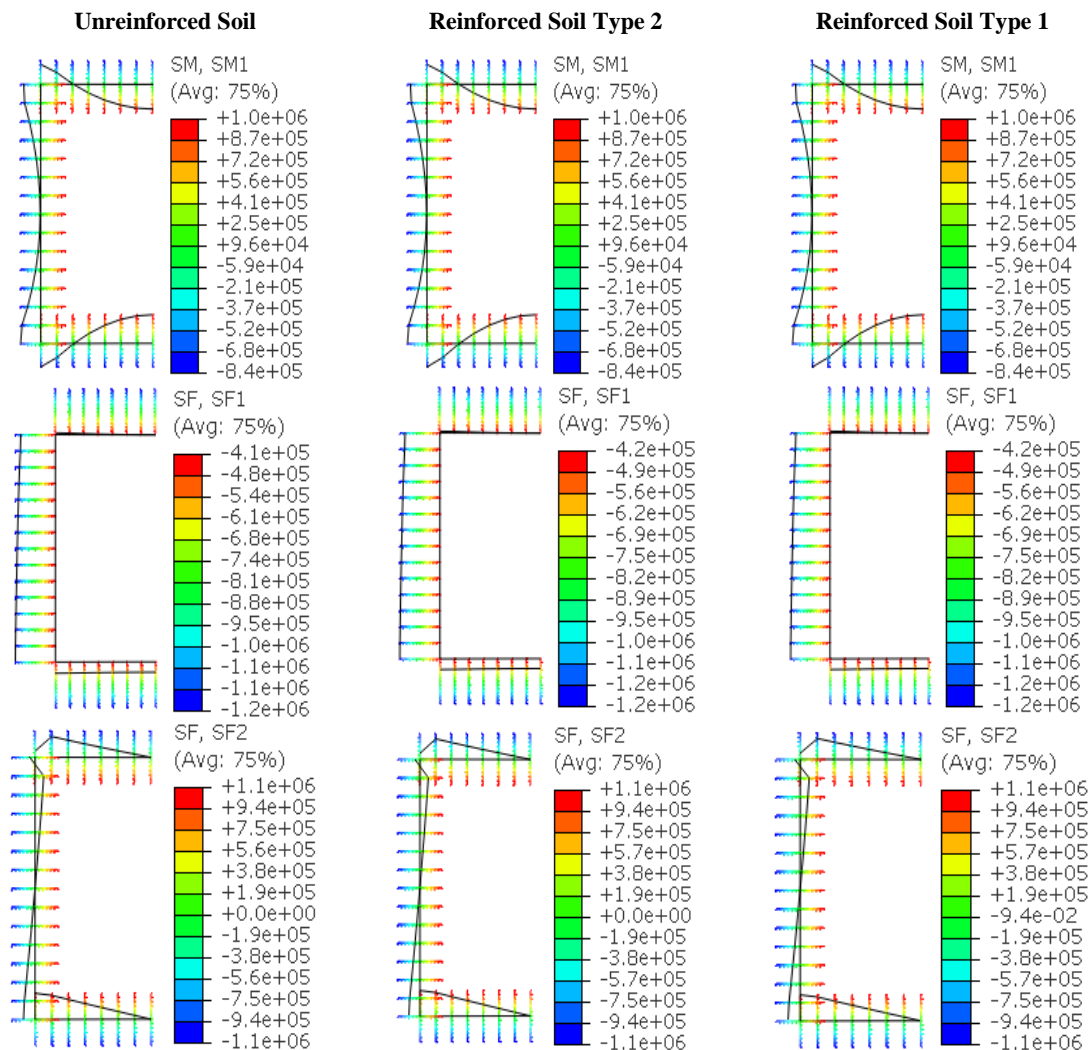


Figure 12. The internal forces diagrams for the thickness of 70 cm and 15 meters depth, for models comprising two types of the reinforced soils and unreinforced soil (N)

As can be seen in Figure 13, by adding the soil reinforcement elements, the maximum settlement in the range of the model has been reduced from 7.2 to 7 cm, which in other words, the effect of the soil reinforcement in reducing the settlement was 2.7%. The maximum principal stress mobilized in the reinforcement element is also shown in Figure 14, and it is shown that the tensile stress is maximized to 24 MPa and its location is in the center of the lower layer. Consequently, for optimum use of the reinforcement elements, the soil can be reinforced with stiffer elements at lower levels and weaker elements at higher levels.

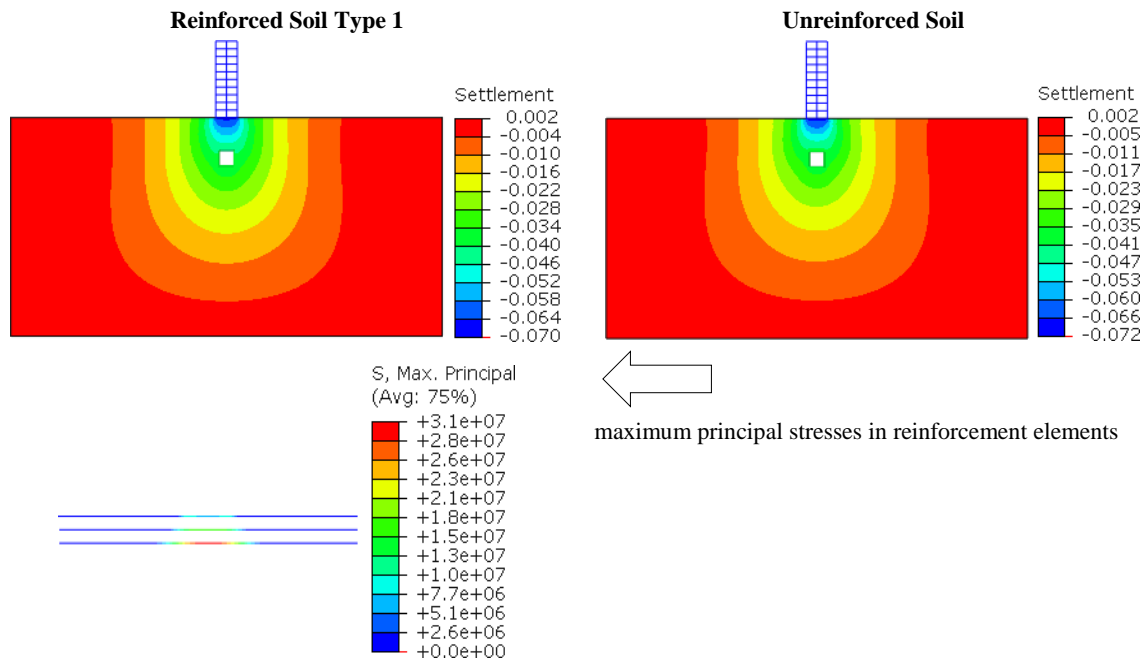


Figure 13. Effect of the soil reinforcement type 1 on the ground field settlement and stress mobilization, 7 meters width cavity, 15 m depth and the lining thickness of 70 cm ($m, N/m^2$)

The effect of the soil reinforcement on the reduction of the model settlement with 10-story structure on the ground consisting the underground cavity with the width of 7 meters and 15 cm lining thickness is shown in Figure 14. As can be seen from the Figure 14, the soil reinforcement has reduced the maximum settlement by about 5% and the maximum mobilized stress in the first type of the reinforcement element has reached 31 MPa.

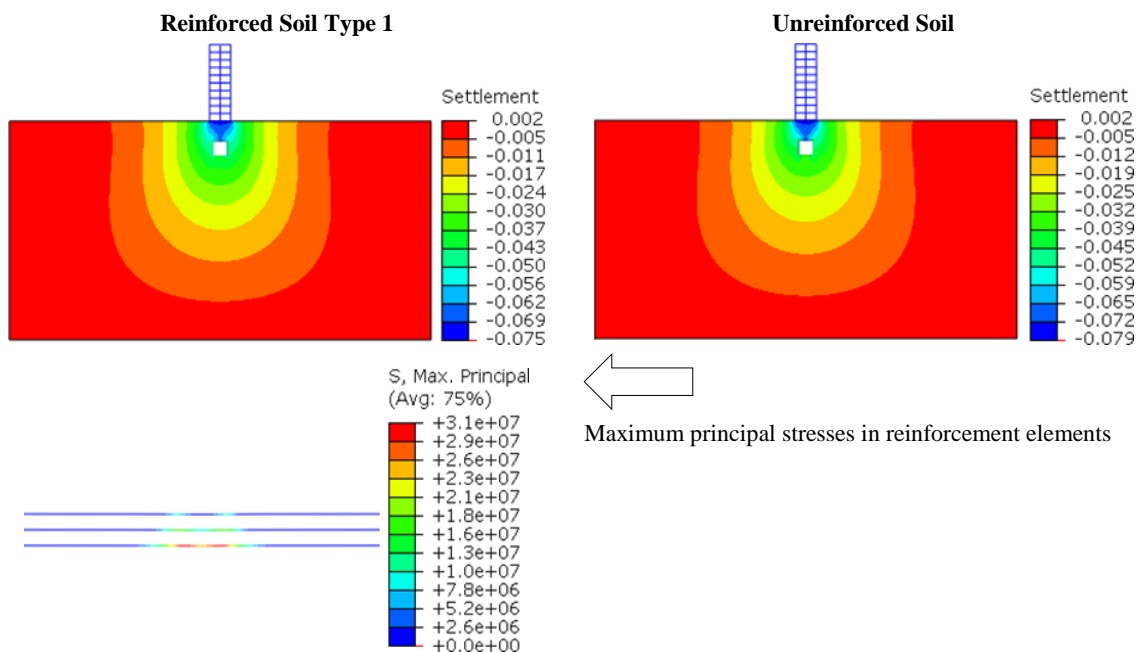


Figure 14. Effect of the first type of soil reinforcement on the ground field settlement and stress mobilization, 7 meters width cavity, 9 meters depth and the lining thickness of 15 cm ($m, N/m^2$)

In Figure 15, the structural drift relative to its original position is plotted for different values of the deviation of the buried cavity center with the thickness of 70 cm from the building center, and it should be noted that the cavity is assumed to be on the right and under the structure. For the best imagination of this situation Figure 18 is plotted. In Figure 16, it can be seen that the structure's rotation increases with the deviation up to an approximate distance of twice the width of the cavity or fourteen meters, and in more deviations, the foundation of the structure will sustain uniform settlement.

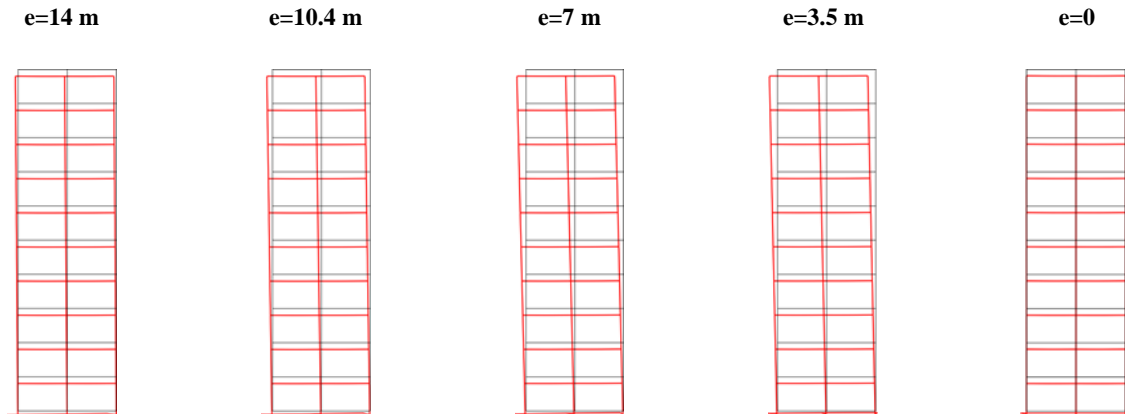


Figure 15. Structural drift relative to its original position by increasing the deviation of the cavity center from building center with the 70 cm lining thickness, in which the building was created after the cavity

In Figure 17, the nonsymmetrical settlement of the building under its dead load on the ground comprised a cavity of 7 meters in width and 15 cm lining thickness is shown. It should be noted that the non-uniform settlement direction of the structure on the cavity with 15 cm lining thickness is opposed the condition that 70 cm lining is assumed for the cavity. In this case, as long as the building is located at approximately four times the width of the cavity boundary, or 28 m, the building is rotated and, at distances away from the above value, the structure will be settled uniformly.

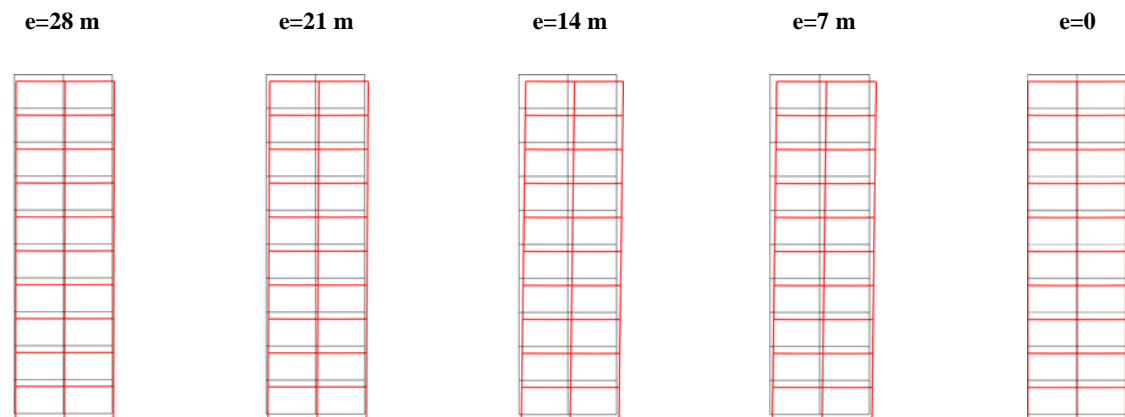


Figure 16. Structural drift relative to its original position by increasing the deviation of the cavity center from building center with the 15 cm lining thickness, in which the building was constructed after the cavity

In Figure 17, the field settlement of the model is illustrated by the application of 10-story building load on the ground with 7 meters wide cavity with 9 meters depth. Also in Figure 17 unreinforced soil and reinforced soil type 1 condition for the three values of the deviation of the cavity center from the center of the structural foundation is considered. It is noteworthy that the increase in the amount of deviation in the reinforced and unreinforced soil increases the maximum settlement in the range, so that in the reinforced soils, the maximum settlement with the deviation value equal to twice the cavity width is 5.4% higher than the maximum settlement in the case which deviation is equal to zero. Also, by increasing the amount of deviation of the cavity center from the structure center, the reinforcements did not have more effect on the structure settlement.

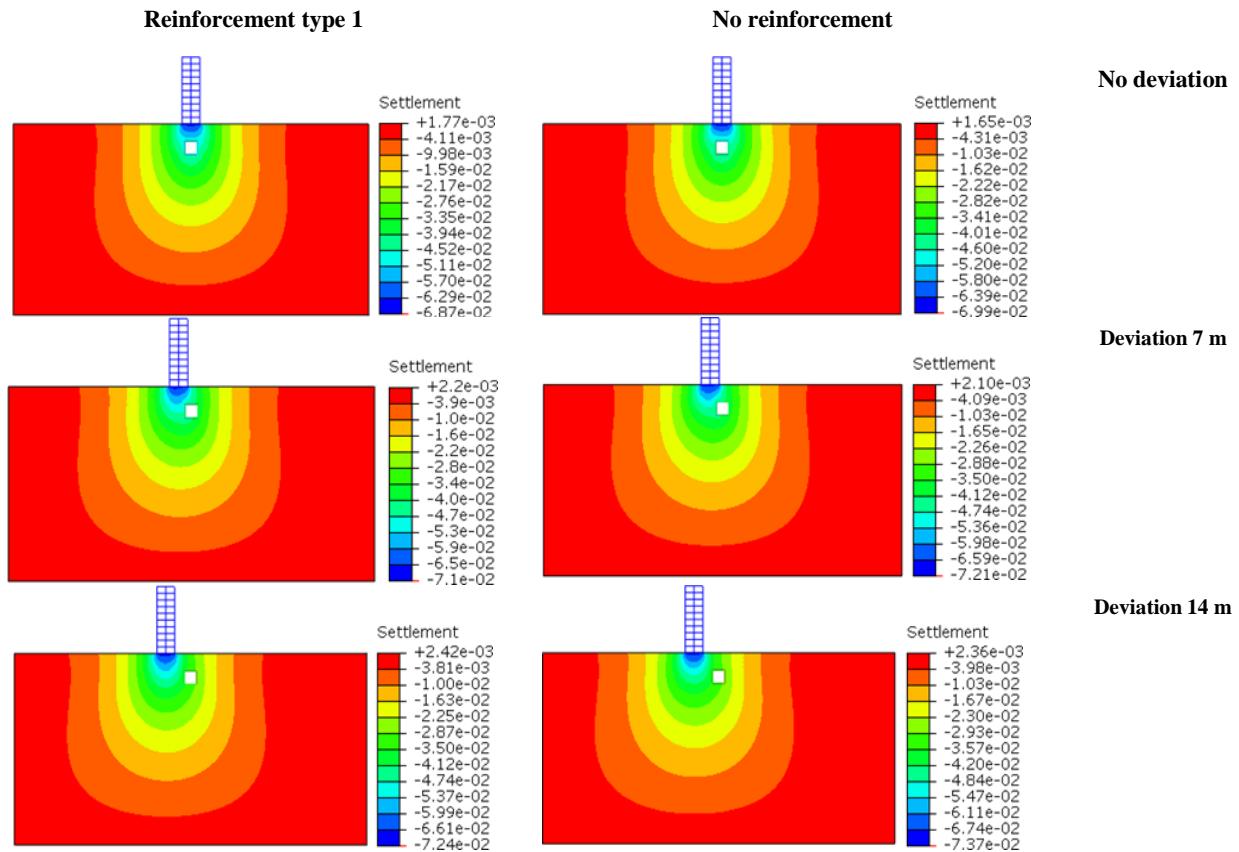
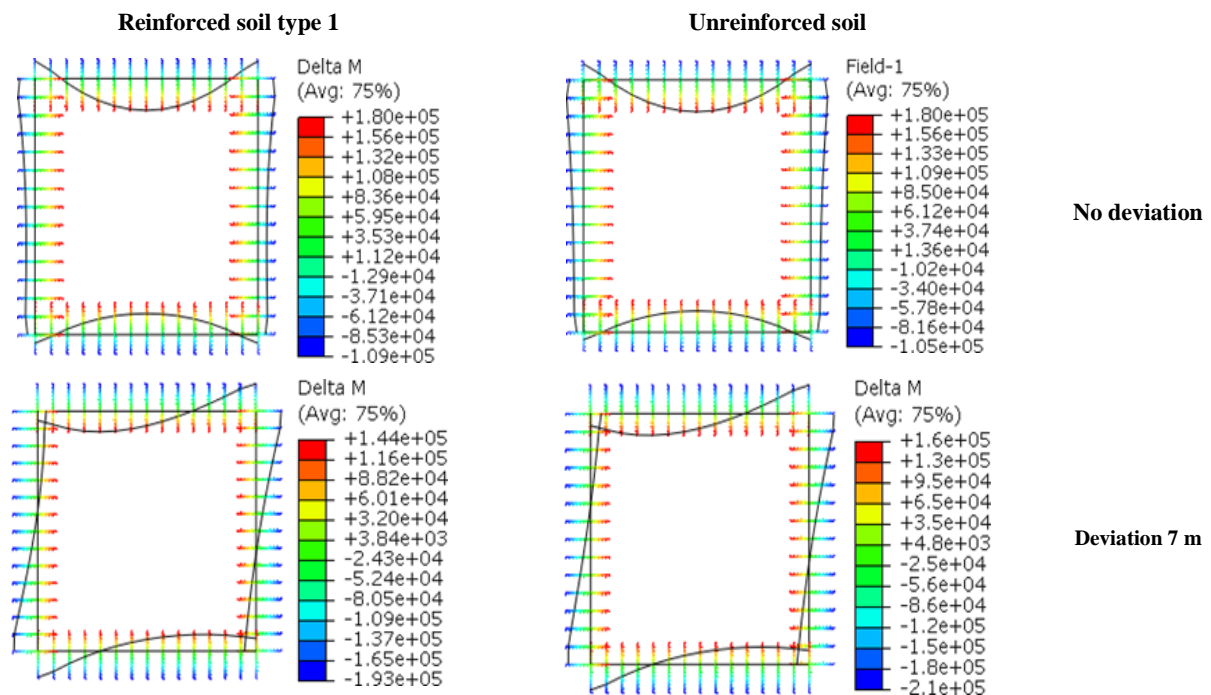


Figure 17. Settlement caused by the use of 10-story building load on the homogeneous reinforced and unreinforced soil containing underground cavity with width of 7 m, the lining thickness of 70 cm and overload height 9 m (m)

The excess bending moment diagram of the cavity lining under the influence of the 10-story building dead load on the unreinforced and reinforced soil type 1 is shown in Figure 18, note that the underground cavity has 7 meters width, 70 cm lining thickness and 9 meters depth.



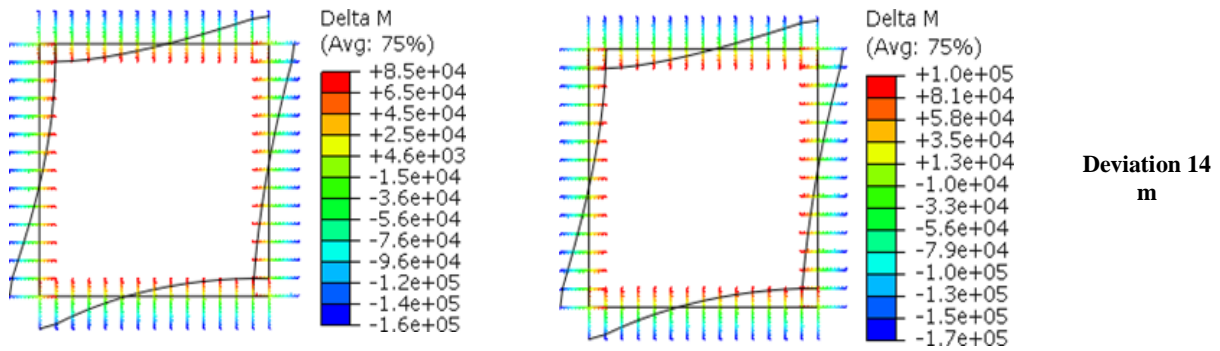


Figure 18. The excess bending moment diagram of the cavity lining under the influence of the 10-story building dead load on the unreinforced and reinforced soil type 1, the underground cavity has 7 meters width, 70 cm lining thickness and 9 meters overload height (N.m)

In order to study the structure's rotation due to the construction of the underground cavity with the deviation from the structure center, as shown in Figure 15, it is seen that the effect of the cavity has been effective up to a deviation of 14 meters or twice the width of the cavity. But the significant difference between Figure 19 and 15 is that, in the case which cavity is created after the building in the model, the amount of structural rotation is less than that of the cavity is created before the structure, also direction of the rotation for the model having the thick lining (70 cm) was clockwise, while all the rotation were in the opposite direction in Figure 16. The maximum values of the structural rotation (tilting) in the case in which the structure is created before the cavity and the case in which the cavity is created before the structure are measured as 243 and 90 micro-degrees, respectively.

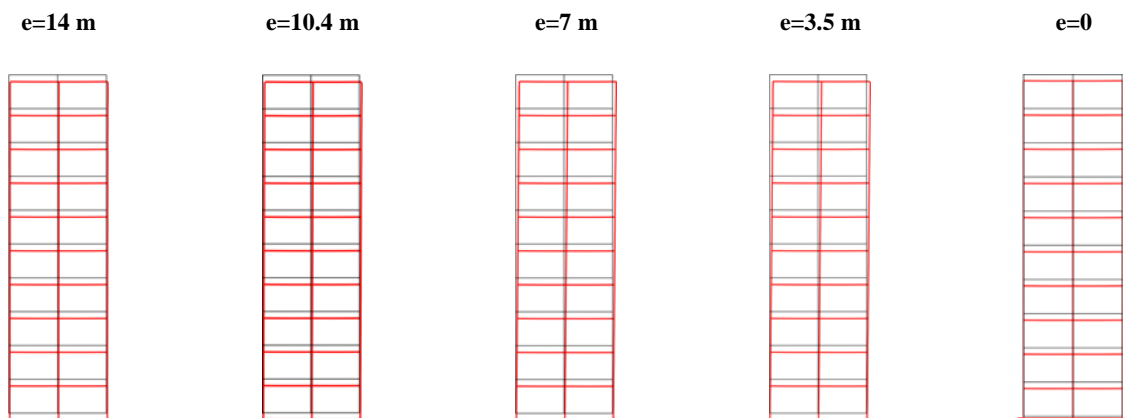


Figure 19. The structural drift compared to its original position by increasing the deviation of the cavity center from the building center, the 70 cm lining thickness in the case which the building is created before the cavity

When the lining with 15 cm thickness is used, the results are different from those shown in Figure 19. As it is seen in Figure 20, by increasing the deviation of the cavity center from the foundation center, the amount of structural rotation decreases and this trend continues until it reaches the uniform building settlement, which occurs at deviations greater than 4 times the width of the cavity or 28 meters.

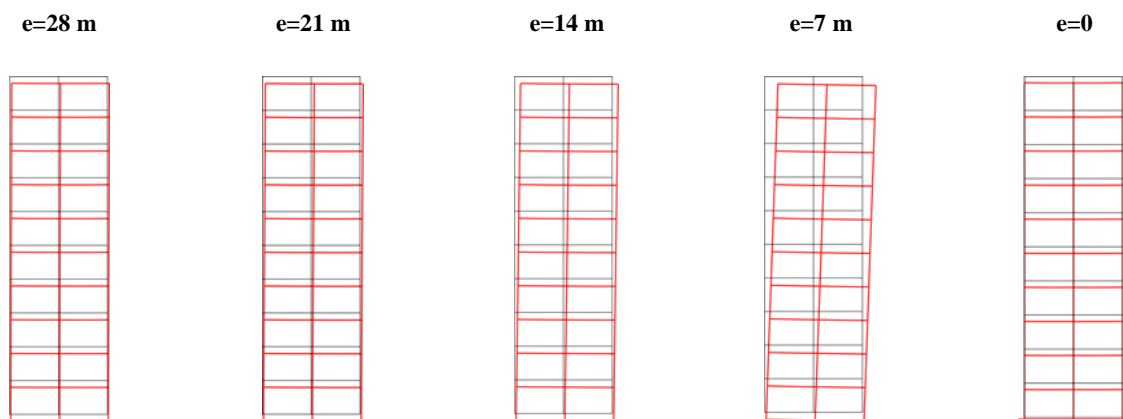


Figure 20. The structural drift compared to its original position by increasing the deviation of the cavity center from the building center, the 15 cm lining thickness in the case which the building is created before the cavity

The variations in the maximum bending moment of the lining and the excess bending moment formed in the structure resulting from the creation of the underground cavity along with the variation of the position of the cavity center from the building center, are given in Table 3. In the above mentioned table, the building is constructed before the cavity. As it is seen, the level of the bending moments in the lining with 70 cm thickness is about three times the corresponding values in the lining with 15 cm thickness, and the excess bending moment caused by the creation of the underground cavities in the structural elements has been negligible in the case of 70 cm lining thickness. Also, the comparison of table values, shows that by increasing the deviation of the cavity center from the foundation center, the bending moment in the lining and the excess bending moment in the structural elements is reduced, and the internal force variation in the structure for the 70 centimeters lining is less than 10 kN.M. It is worth noting that, all values of the maximum excess bending moment due to the cavity creation, has occurred in the foundation elements of the structure.

Table 3. The maximum bending moment variations of the lining and the maximum excess bending moment of the structure (caused by underground cavity) by changing the deviation of the cavity center from the building center where the building is constructed before the cavity

Excess bending moment (kN.m)		Type of reinforcement	Deviation of the cavity center from the building (m)	Lining thickness (cm)
structure	lining			
40	186	unreinforced	3.5	15
41	182	Type 1		
24	182	Unreinforced	7	
33	178	Type 1		
20	174	Unreinforced	10.5	
21	171	Type 1		
10	168	Unreinforced	14	70
12	165	Type 1		
Lower than 10	163	Unreinforced	17.5	
Lower than 10	141	Type 1		
Lower than 10	534	unreinforced	3.5	
Lower than 10	528	Type 1		
Lower than 10	551	Unreinforced	7	
Lower than 10	536	Type 1		
Lower than 10	536	unreinforced	10.5	
Lower than 10	518	Type 1		
Lower than 10	509	unreinforced	14	
Lower than 10	494	Type 1		
Lower than 10	483	unreinforced	17.5	
Lower than 10	473	Type 1		

6. Conclusions

This paper is aimed to investigate the effect of the underground cavity on the surface structures settlement and the effect of the surface structure on the stresses and strains created in the cavity lining and surrounding soil. In the following, the effect of the soil reinforcing on the settlement of the surface structure and internal efforts of the lining cavity were examined.

The major findings from this study can be summarized as follows:

- The reason for the low effectiveness of the reinforcement element in reducing the settlement, is the low stress mobilization of the reinforcement element, which in most of the models produced, was less than 15% of the yield stress of the steel elements.
- With increasing the distance of the cavity from the structure in vertical direction (increasing the cavity depth) and also by choosing a stronger lining for underground cavity. The structural settlement are reduced and the values of the parameters are so effective that in the conditions of 9 meters overburden depth and 70 cm lining thickness, structure settlement is lower than the condition in which there is no cavity.
- One of the most important parameters in determining the building drift is the deviation of the underground cavity center from the structural foundation center. Because the structure is tilted and non-uniform, internal forces are

produced in the lining. In the situation where the underground cavity is already in place before the building, the tilting of the building (rotation) is in the opposite direction of the situation where the building is already in place before the cavity. As long as the horizontal distance between the structure center and the underground cavity is not more than 2 to 3 times the width of the underground cavity, the structures in both of the above mentioned cases have rotated and therefore this issue should be considered.

- In examining the effect of the reinforcement element on the reduction of the internal forces of the lining or structure, it was observed that the use of the reinforcement element did not have a significant effect on the reduction of the internal forces.
- The greatest increase in the internal forces of the lining occurs when the horizontal distance of the cavity center from the structure center is equal to the width of the cavity and 15% more of the internal force is produced compared to the conditions where the gap is zero. Reinforcement of the soil has been effective in reducing the amount of the internal force inside the lining by a maximum of 40%, but depending on the conditions of the underground cavity and the building, the percentage can be reduced to zero.

6. Conflicts of Interest

The authors declare no conflict of interest.

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