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Analysis of Underground Concrete Structures in Weak Soil Profiles

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ABSTRACT

Underground concrete structures are widely used in mega construction projects in newly developed areas in Egypt, especially in East Port Said. Designing these structures considering such site conditions in Port Said soil is an engineering challenge. This paper provides general guidelines for the designers for the expected behavior of the underground structures constructed at different depths considering many design parameters. A 2D numerical model using Plaxis software is created with the soil parameters and water table of this site. Mohr-Coulomb model for the sand soil layer and Hardening Soil model for the clay soil layer are used. The effect of overburden depth and the structure width in case of whether surface structure is constructed near the underground one or not. The effect of changing the number of floors of the surface structures and the distance between the surface and the underground structures. Moreover, the effect of construction of an adjacent underground structure is also studied. The maximum vertical settlement, the max. internal forces induced in the structure: maximum normal force and maximum bending moment are used to describe the structural behavior. Design recommendations and guidelines were drawn to facilitate the design of these types of structures in such site conditions.

Keywords: Underground R.C Structures, Mohr-Coulomb Model, Hardening Soil Model, East-Port Said soil.

1 INTRODUCTION

As The Egyptian government orientation to the utilization of the lands of east of Port Said for the development of Port Said industrial zone by construction of more factories and port piers, the need for connecting the industrial zone with developed roads networks at west side of the Suez Canal and the increasing population, the interest of construction of underground structures has been increased. The designers of the underground structures study a certain case of the location and the position at which the underground structures would be constructed. There is need for providing general guidelines for the designers for the expected behavior of the underground structure when placing this structure at different depths with changing many parameters and the effect of construction of surface and underground structures near the existing one. There are many types of underground structures such as tunnels, syphons, culverts, …. etc.

The loads acting on tunnels and the modeling techniques used for modeling them using Plaxis and DIANA programs are shown by D.J. Kunst [1]. He recommended using Plaxis compared to DIANA for large models as it is much quicker Also when the construction phases are not included in the analysis, it's better to model the tunnels in 2D. The design methods of shield tunnels are shown by Working Group no. 2 [2]. These methods are Bedded Frame Model Method – Finite Element Method - Elastic Equation Method -Schultze and Duddeck Method – Muir Wood Model. Ngoc-Anh Do [3] used another method which is Einstein and Schwartz's Method [4]. Ngoc-Anh Do [3] compared between The Einstein and Schwartz's Method [4] and The Elastic Equation Method using FLAC^{3D} program. He concluded that the maximum bending moment obtained by Einstein and Schwartz's Method is higher than that obtained by Elastic Equation Method. For Einstein and Schwartz's Method, the lower the young's modulus of the surrounding soil, the higher the bending moment induced the tunnel lining.

Chi Thanh Nguyen [5] improved The Hyperstatic Reaction Method to be used in estimation of the values of the internal forces in square and rectangular tunnel linings. He compared the results with those obtained from Finite Element Method for the validation of the improvement of HRM method. He also showed that the internal forced induced in tunnel lining decrease with the increase of flexibility ratio of tunnel lining. The maximum bending moment has the smaller value when the lateral earth pressure coefficient K_0 value is equal to 1 and its value decreases with the increase of the value of K_0. The change in K_0 value results for a normal force variation at the top and the bottom parts of the lining and its influence on normal force at the sidewalls of the tunnel is negligible.

Mohamed F. Mansour [6] investigated the behavior of bored tunnels in Port Said clay. He used El-Tina Plain, north-eastern Egypt soil profile and showed that the primary governing factors that controls the long-term surface settlement are the tunnel diameter and face/grouting pressure. The short-term behavior is primarily governed by the reference hydrostatic pressure. It is not recommended that the face pressure has lower value than the reference hydrostatic pressure due to their adverse effect on short-term serviceability. Huasheng Sun [7] showed that the excavation of clay soil above the tunnel causes the tunnel to heave, the vertical diameter increasing and the horizontal diameter compression.

The simulation of the interaction between the tunnel and the surrounding soil can be done using Discrete Beam-Spring Model and Continuous FE Model according to Elefterija Zlatanović [8]. He concluded that The FE Models are more accurate than Beam-Spring Models when taking into account the kinematic soil-structure interaction. The FE Model allows to account the static and dynamic effects together in single analysis, on contrary Beam-Spring Model doesn’t allow to do that except with simple superposition only. The influence of the equivalent approaches: The Convergence-Confinement Method [9] and The Volume Loss Method on tunnel built in urban areas in terms of surface settlement and internal lining forces taking in consideration the effect of segment joints is studied by Ngoc-Anh Do [10]. He showed that when using Convergence – Confinement Method for the analysis of the reference case of study, the ground above the tunnel fails when the stress release ratio > 0.75. The internal forces induced in the flexible jointed segmental lining tunnel is lower than that of continuous jointed segmental lining.

Daniel W. Wilson [11] studied the undrained stability of dual adjacent square tunnels. He used Finite Element Limit Analysis and Semi-Analytical Rigid Block techniques. He concluded that while the distance between the tunnels increases, the stability of them decreases till it gets to the minimal value then it increases until the tunnels fail independently of each other. The Numerical Upper and Lower Bound Methods accurately bound the true stability. For a very small distance between the tunnels, The Rigid Block Methods results are very close to those of Finite Element Methods. Saied Mohammad [12] investigated the effect of the distance between twin tunnels and the advancing of the second tunnel on the induced internal forced in the first constructed tunnel. He concluded that the settlement and the induced bending moment of the first tunnel decrease with the increase of the distance between the tunnels. Ngoc Anh Do [13] showed that when constructing a new tunnel besides an old one, the greater the distance between the tunnels, the lower the influence of the construction of the second tunnel on the induced normal forces in the first tunnel. If the distance between the tunnels is equal to or greater than two times the diameter of them, the variation of the normal forced induced in the old tunnel can be neglected.

The effect of the joint segments and the distance between twin tunnels on the first constructed one is studied by Ngoc Anh Do [13]. The joint segments were modeled using a set composed of rotational springs, axial springs, and radial springs. He showed that the jointed lining makes the tunnel more sensitive to the impact of construction of a new tunnel beside it than the continuous lining. The location of the joints of the newly constructed tunnel has no effect on the normal force and the bending moment induced in the old one. The effect of construction of new tunnels under existing tunnels was investigated by Ren-Peng Chen [14], Xiang Liu [15]. Ren-Peng Chen [14] showed that the settlement curves of the existing underground structures caused by the second tunnel of the newly constructed tunnels crossing under the existing tunnels are asymmetric with respect to the second tunnel centerline. The settlement and volume loss caused by the second tunnel under-crossing are larger than those induced by the first under-crossing. Xiang Liu [15] proposed an analytical method for studying the behavior of an existing tunnel due to construction of a new tunnel below it. He applied The Winkler Foundation Model. He showed that the value of maximum deflection of the existing tunnel increases with the decrease of coefficient of subgrade reaction and the vertical distance between the new and the existing tunnels and with the increase of the length of the distributed soil.

In this paper, a study to investigate the behavior of underground structures in weak soil was conducted. The effect of some parameters related the underground structure it- self, the underground or surface structures constructed near to the old underground one was studied. The current research aims to provide guidelines for the designers for the expected behavior of any underground structure that would be constructed in such soil types.

2 GEOMETRIC MODELLING

A 2D plain strain model is developed using Plaxis 2D software. The model geometry is as shown in Figure 1. The underground structures cross-sections considered in this study are circular, square, and double-vent sections. Different cross-section widths are considered which are 6 m, 8 m, 10 m and 12 m. The thickness of the lining is assumed to have a value equal to structure width divided by 20. The material of the lining and the surface structure with piles is concrete.

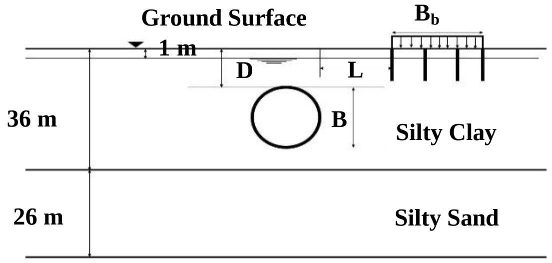

Figure 1: Representation of model used in this study

The concrete grade is C45/55. Model size is 300 m x 62 m. The height of the model is taken as the soil profile of East Port Said soil height. Two construction stages are used for modeling the construction process: the initial phase and the underground structure construction phase. In case of studying the effect of construction of a surface structure or an adjacent underground structure near the underground one, a third construction phase is added.

3 MATERIALS PROPERTIES AND FINITE ELEMENT MODELING

3.1. Soil Properties

The used East Port Said soil profile according to M. A. El Hamed [16] consists of two layers. The top layer is silty clay with a depth of 36 m. This layer is modeled using hardening soil model. T. Schanz [17] showed the model for this type of soil behavior. The Second layer is silty sand with depth of 26 m. This layer is modeled using Mohr-Coulomb model according to Joseph F. Labuz [18] which is the best model for modeling the behavior of cohesionless soil.

The Properties of the silty sand and silty clay layers are shown in Table 1.

Table 1. Properties of Soil Layers Models

Soil Layer	E-Modulus	Friction Angle	Cohesion	Poisson's Ratio	Saturated Density
	E [MPa]	φ [˚]	c [kPa]	ν [-]	γ [KN/m^3]
Silty Sand	58	38	0.0	0.3	20
Silty Clay	-	25	0.0	0.4	16.5

Soil Layer	Hardening Soil Parameters							
	E_{50}^{ref} [MPa]	E_{oed}^{ref} [MPa]	E_{ur}^{ref} [MPa]	m [-]	νur [-]	K_0^{NC} [-]	G_0^{ref} [MPa]	$\gamma_{0.7}$ [-]
Silty Clay	0.98	0.78	6.35	1.0	0.2	0.65	25.0	6e-4

The groundwater table is at 1 m below the ground surface. The shear strength of the saturated soil is reduced compared to that of the dry soil and the pore water pressure increases. Stresses and deformations in the soil are influenced by the increase of groundwater table which leads to the development of pore pressure in the soil according to Mudassir Ali Khan [19].

3.2. Concrete Properties

The behavior of concrete material for the underground and surface structures is modeled using the linear elastic model with the properties mentioned in Tables 2 and 3.

Table 2. Properties of concrete linear elastic model for underground structure

Structure Width (m)	Axial stiffness "EA" (KN/m)	Flexural rigidity "EI" (KN m^2 / m)	Specific weight (KN/m/m)	Poisson's ratio
6	1.080E+07	8.100E+04	40.350	0.200
8	1.440E+07	1.920E+05	36.300	0.200
10	1.800E+07	3.750E+05	33.850	0.200
12	2.160E+07	6.480E+05	32.200	0.200

Table 3. Properties of concrete linear elastic model for surface structure and piles

Element	Width / Length (m)	Axial stiffness "EA" (KN/m)	Flexural rigidity "EI" (KN m^2 / m)	Specific weight (KN/m/m)	Poisson's ratio
Surface Structure	10	1.540E+07	6.288E+05	17.500	0.200
Piles	10	1.106E+07	8.847E+05	12.566	0.200

3.3. Finite element modelling

Plaxis 2D software is used in this study to investigate the effect of changing the underground structure geometry parameters, changing the underground structure position, surface structure construction and adjacent underground structures construction on the behavior of the underground structures with different cross-sections.

The following assumptions has been applied:

a) 2D plain strain conditions for the underground structure are applied.
b) Soil is isotropic, incompressible and homogeneous.
c) Pore pressure is constant up to a specific water level in each case

4 MESH AND ELEMENT TYPE AND BOUNDRY CONDITIONS

A 2D soil – underground structure model has been developed using Plaxis software. 15-node triangular elements are used to model the soil layers. The 15-node triangle element is a very accurate because it produces high quality stress results for difficult problems. 5-node plate beam elements are used to model the structures. The beam elements are based on Mindlin's beam theory. This theory allows beam deflections due to shearing as well as bending according to Bathe, K.J. [20]. The equivalent plate thickness d_{eq} is calculated from the equation:

$$d_{eq} = \sqrt{12\frac{EI}{EA}}$$

The vertical boundaries of the model are assigned with roller supporting to prevent horizontal displacement (Ux = 0). The lower horizontal boundary is assigned with fixed supporting to prevent all the vertical and horizontal displacements (Ux = Uy = 0).

5 METHODOLOGY

A 2D plain strain finite element model is performed using Plaxis 2D software. The dimensions of the model are taken as shown in geometric modeling section. Material properties, underground water table level and boundary conditions are taken as mentioned in the previous sections. The modeling methods are validated using case study of Mashad, Iran Metro line by D.J. Kunst [1]. In order to investigate the behavior of underground structures in Port Said soil which is described as the maximum vertical settlement, maximum normal force and maximum bending moment induced in the lining. Some values of parameters are changed to obtain their effect on the underground structures in case whether surface structure is constructed near the underground one or not also in case of construction of an adjacent underground structure near the existing one. These parameters are as the following:

1) Parameters related to the underground structure:
    a) Changing the cross-section of the underground structure as shown in Figure 2.
    b) Changing the width of the underground structure.
    c) Changing the overburden depth.
2) Parameters the surface structure:
    a) Changing the number of floors of the surface structure (The weight of floor is assumed to be 10 KN/m/m).

Soil Layer	E_{50}^{ref} [MPa]	E_{oed}^{ref} [MPa]	E_{ur}^{ref} [MPa]	m [-]	νur [-]
Clay	13.4	33.5	13.4	0.5	0.5045
Silt	19.6	49	19.6	0.5	0.4820
Sand	20.9	52.3	20.9	0.5	0.4598

    b) Changing the horizontal distance between the surface and the underground structures.
3) Parameters related to the adjacent underground structure:
    a) Changing the horizontal distance between the two underground structures.

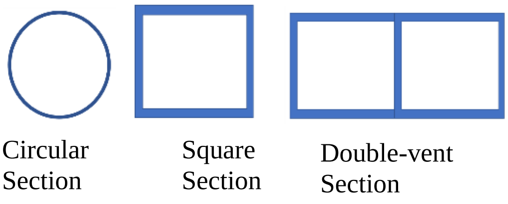

Figure 2: Different cross-section of underground structures

6 MODEL VALIDATION

The modeling techniques that are used to create the models in this research are verified with D.J. Kunst [1] numerical model of Mashhad, Iran. Table 4 shows the Properties of the used chosen section for the validation purpose. The Profile of the surrounding soil is mentioned in Table 5 and the properties of the soil layers for the verification section are as shown in Table 6. Figure 3 shows the numerical model in Plaxis 2D for the validation section.

Table 4. Properties of the chosen section of Mashhad, Iran that is used for validation

Parameter	Value	Unit
Depth of Tunnel Axis	-35.4	m below surface
Outer Diameter	9.1	m
Inner Diameter	8.4	m
Wall Thickness	0.35	m
Water Table	-38.5	m below surface
Model Width	120	m
Model Height	54.5	m

Table 5. The soil profile of the used section

Soil Layer	Top of Layer (m from Surface)	Bottom of Layer (m from Surface)
Sand	0	19.7
Silt	19.7	22
Clay	22	26
Sand	26	28.5
Clay	28.5	31.5
Sand	31.5	38.3
Clay	38.3	41.5
Sand	41.5	54.5

Table 6. The properties of the soil layers

Soil Layer	γbulk [KN/m^3]	γsat [KN/m^3]	c' [kPa]	φ' [°]	V_{ur} [-]
Clay	19.1	20.1	6.4	29.7	0.2
Silt	19.1	20.4	5.6	31.2	0.2
Sand	19.5	21.1	4.7	32.7	0.2

The Normal force and the bending moment of the reference model analysis are mentioned in Table 7. The validation model results used for validating the modeling techniques in this paper is mentioned in Table 8.

Table 7. Reference model results

Internal Straining Actions	Max. Value	Min. Value
Normal Force (KN / m)	-1604	-2674
Bending Moment (N.m / m)	482.1	-412.4

Table 8. Validation model results

Internal Straining Actions	Max. Value	Min. Value
Normal Force (KN / m)	-1721.6	-2672.15
Bending Moment (N.m / m)	379.76	-403.62
Absolute Value of Error Percentage in Normal Force	7.33 %	0.07 %
Absolute Value of Error Percentage in Bending Moment	21.2 %	2.13 %

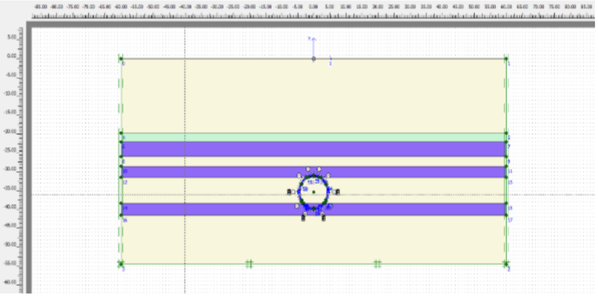

Figure 3: Numerical model of the validation section

7 RESULTS AND DISCUSSION

7.1. The Effect of changing the underground structure depth

For the different underground structures cross-sections as shown in Figures 4 to 6, Increasing the overburden depth of the soil above the underground structures for different structures widths of same cross-section:

- The maximum vertical settlement of the underground structures decreases with the increase of the underground structure width till the overburden depth = 32 m after that the maximum vertical settlement is almost equal for different underground structures widths as shown in Figures 7 to 9.
- The maximum compressive normal force and maximum absolute value of bending moment induced in the concrete lining of the underground structure increase with the increase of the underground structure width as shown in Figures 9 to 15.

Increasing the overburden depth of the soil above the structure for same underground structures widths of different cross-sections leads to:

- Decreasing the maximum vertical settlement of the underground structure as shown in Figure 16 as it gets closer and then into the stiffer soil.
- Increasing the maximum compressive normal force and maximum absolute value of bending moment induced in the concrete lining of the underground structure as shown in Figures 17 and 18.
- The maximum vertical settlement is almost equal for different underground structures cross-sections.
- The maximum compressive normal force and maximum absolute value of bending moment induced in the concrete lining for double-vent underground structures are higher than those of the square underground structures which in turn are higher than those of the circular underground structures.

This behavior also happens in case of construction of surface structure near the underground structure.

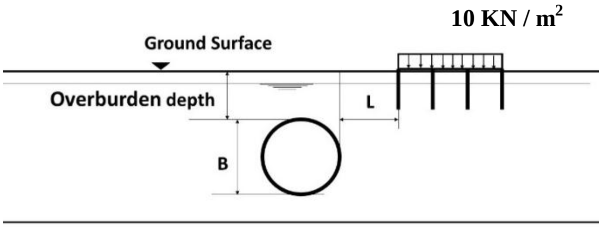

Figure 4: Circular underground structure cross-section

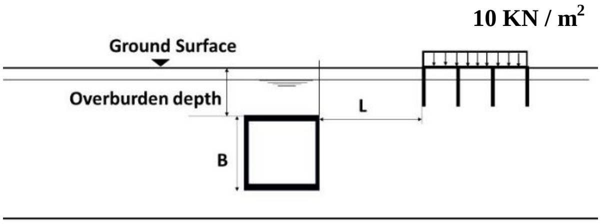

Figure 5: Square underground structure cross-section

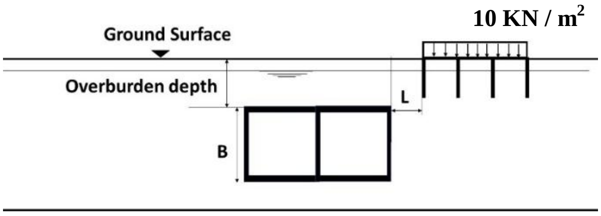

Figure 6: Double-vent underground structure cross-section

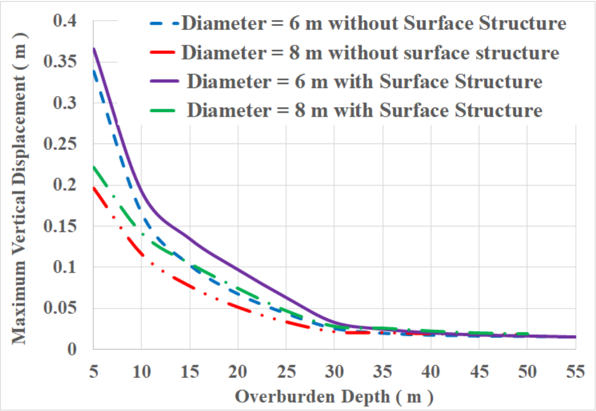

Figure 7: Maximum vertical settlement for circular underground Structures in case with and without surface structure

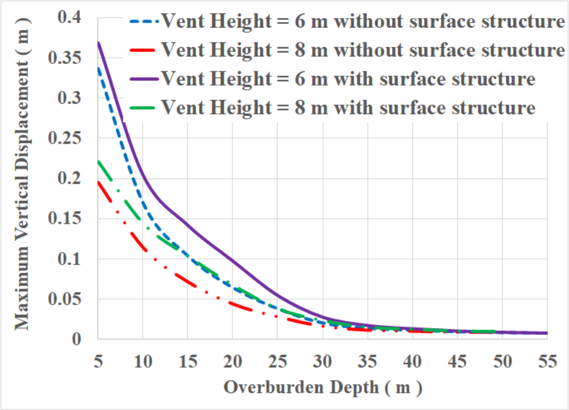

Figure 8: Maximum vertical settlement for square underground Structures in case with and without surface structure

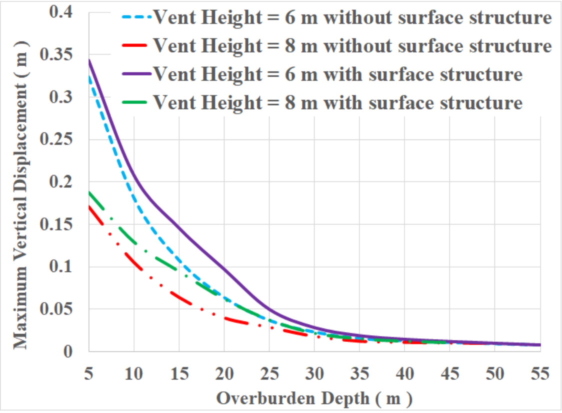

Figure 9: Maximum vertical settlement for double-vent underground Structures in case with and without surface structure

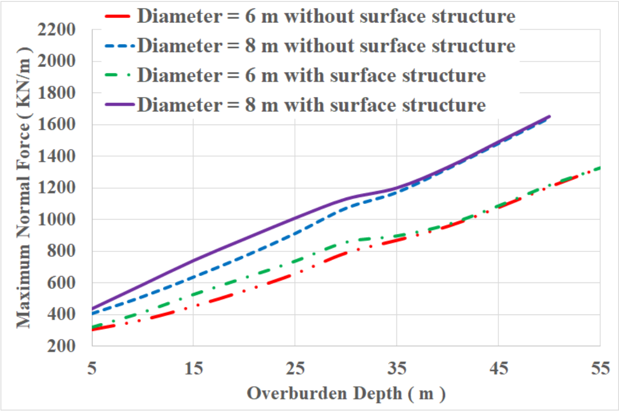

Figure 10: Maximum compressive normal force for circular underground Structures in case with and without surface structure

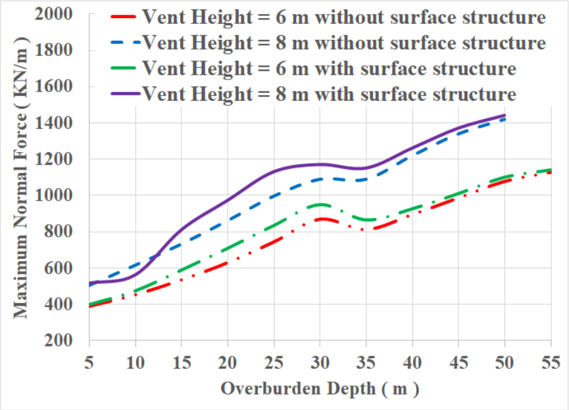

Figure 11: Maximum compressive normal force for square underground Structures in case with and without surface structure

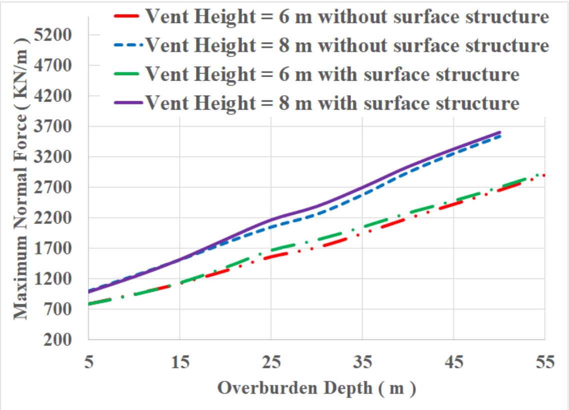

Figure 12: Maximum compressive normal force for double-vent underground Structures in case with and without surface structure

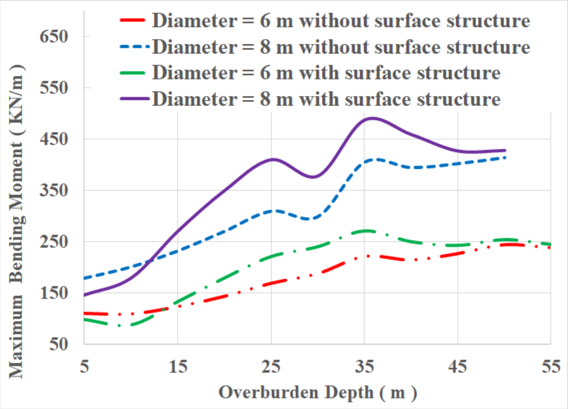

Figure 13: Maximum absolute value of bending moment for circular underground Structures in case with and without surface structure

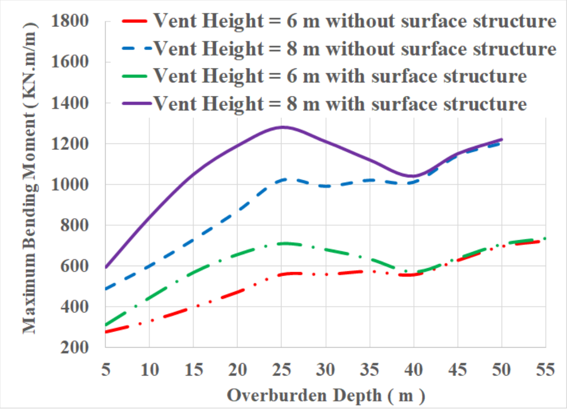

Figure 14: Maximum absolute value of bending moment for square underground Structures in case with and without surface structure

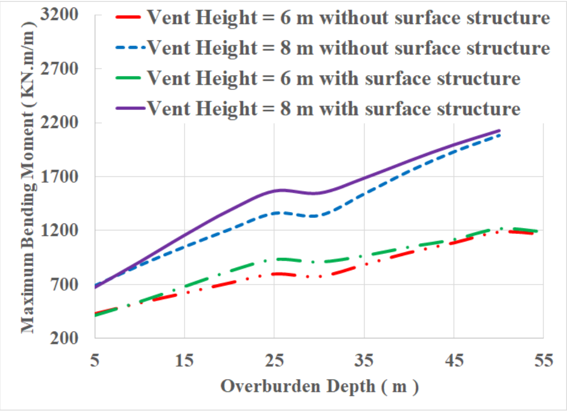

Figure 15: Maximum absolute value of bending moment for double-vent underground Structures in case with and without surface structure

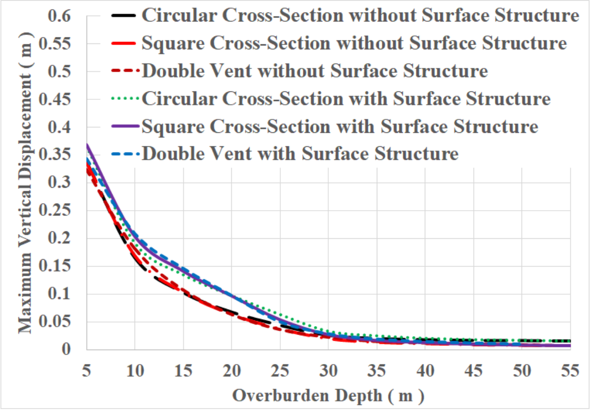

Figure 16: Maximum vertical settlement for circular, square and double-vent underground structures of width = 6m in case with and without surface structure

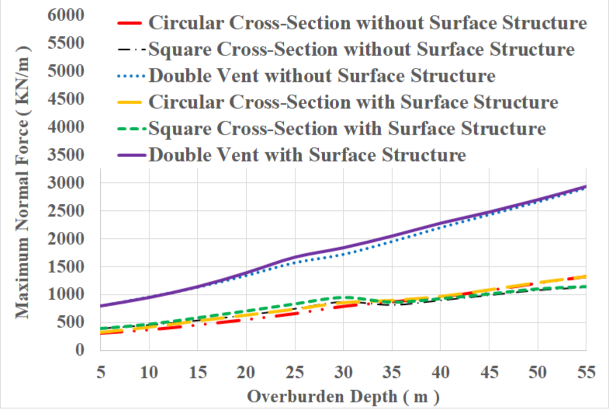

Figure 17: Maximum compressive normal force for circular, square and double-vent underground structures of width = 6m in case with and without surface structure

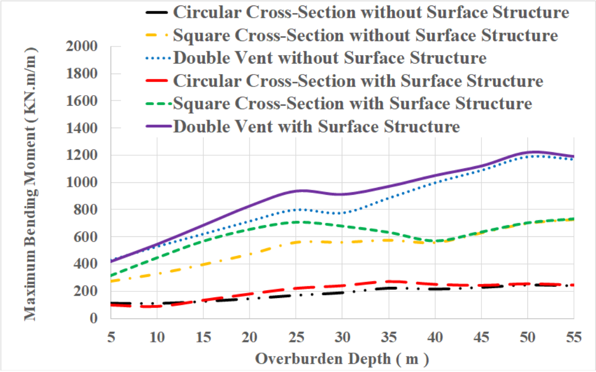

Figure 18: Maximum absolute value of bending moment for circular, square, and double-vent underground structures of width = 6m in case with and without surface structure

7.2. The Effect of piled foundation

As shown in Figures 19 to 21, Construction of surface structures with piles near the underground structure leads to:

- Increase of the maximum vertical settlement of the underground structure as shown in Figure 19.
- Increase of the maximum compressive normal force and maximum absolute value of bending moment induced in the lining of the underground structure as shown in Figures 20 and 21.

The loads from the surface structure are transferred to the piles which carries it with friction effect which in turn transfers the load to the soil that surrounds the underground structure which cause loads and stresses on it.

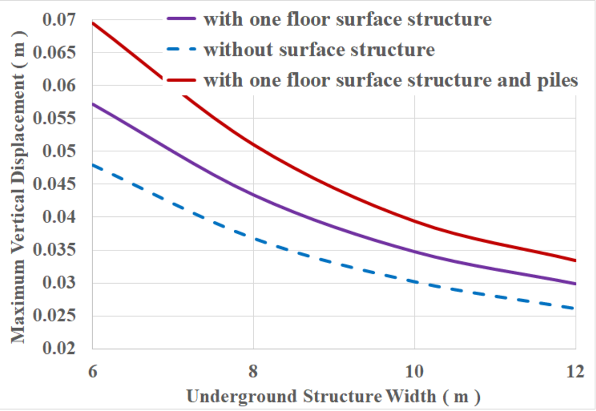

Figure 19: Maximum vertical settlement for circular underground structure with depth = 24 m

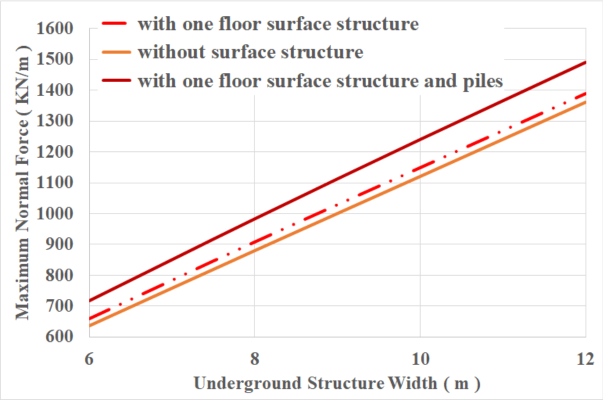

Figure 20: Maximum compressive normal force induced in the lining of circular underground structure with depth = 24 m

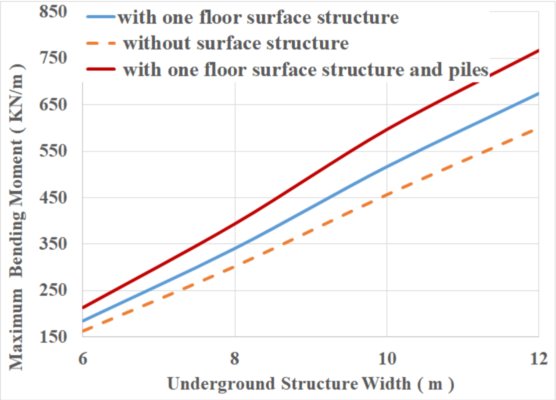

Figure 21: Maximum absolute value of bending moment induced in the lining of circular underground structure with depth = 24 m

7.3. The Effect of changing number of floors of surface structure

For the different underground structures cross-sections, when increasing the number of floors of newly constructed surface structure near the underground one which has an overburden depth = 24 m for different underground structures widths of same cross-section:

- The maximum vertical displacement of the underground structures decreases with the increase of the underground structure width as shown in Figures 25 to 27.
- The maximum compressive normal force and maximum absolute value of bending moment induced in the concrete lining of the underground structures increase with the increase of the underground structure width as shown in Figures 28 to 33.

Increasing the number of floors of the newly constructed surface structure near the underground one with an overburden depth equal to 24 m for same underground structure widths of different cross-sections leads to:

- The maximum vertical settlement of the square underground structures is higher than that of the circular underground structures which in turn is higher than that of the double-vent underground structure as shown in Figure 34.
- There is slight effect on the maximum compressive normal force and maximum absolute value of bending moment induced in the concrete lining of the underground structure as shown in Figures 35 and 36.
- The maximum compressive normal force and maximum absolute value of bending moment induced in the concrete lining of double-vent underground structures are higher than those of square underground structures which in turn higher than those of circular underground structure as shown in Figures 35 and 36.

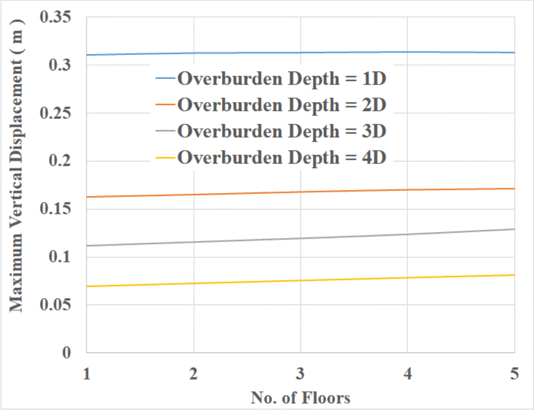

Figure 22: Maximum vertical settlement for circular underground Structures of width = 6 m for different overburden depths

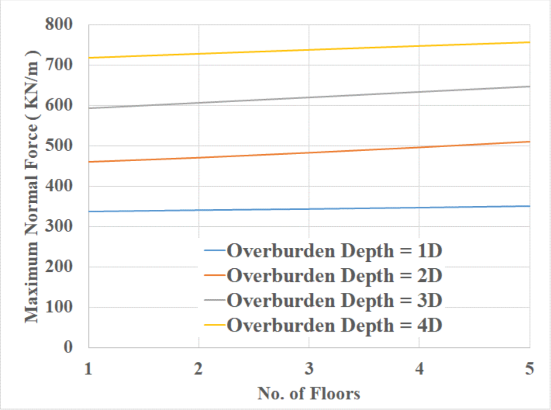

Figure 23: Maximum compressive normal force for circular underground Structures of width = 6 m for different overburden depths

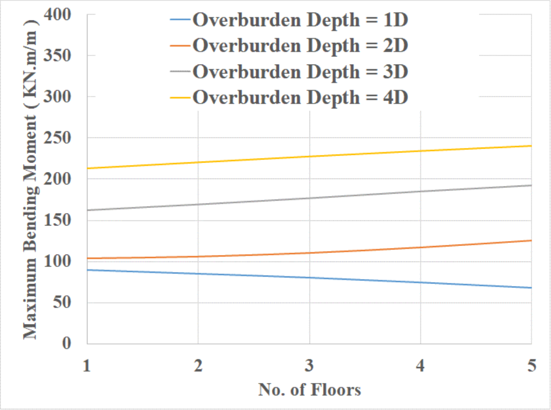

Figure 24: Maximum absolute value of bending moment for circular underground Structures of width = 6 m for different overburden depths

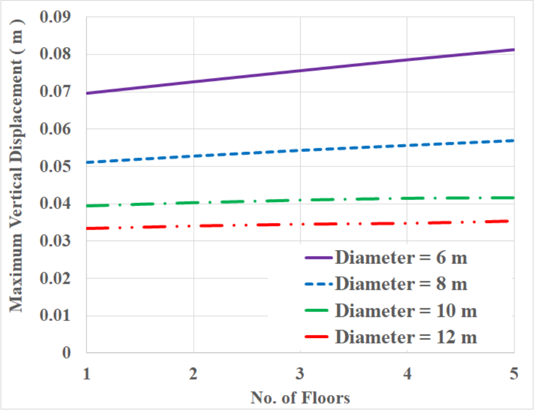

Figure 25: Maximum vertical settlement for circular underground Structures with overburden depth = 24 m

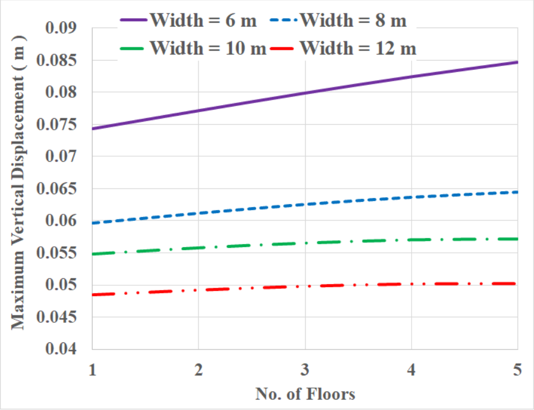

Figure 26: Maximum vertical settlement for square underground Structures with overburden depth = 24 m

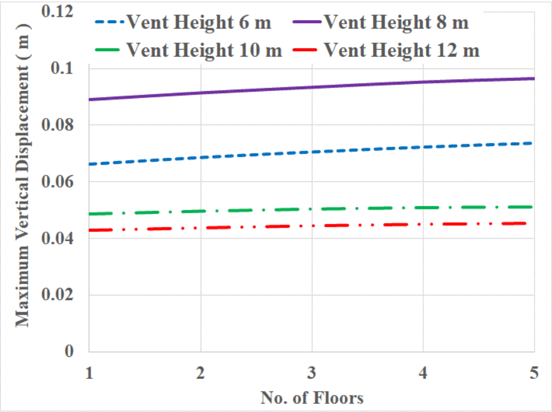

Figure 27: Maximum vertical settlement for double-vent underground Structures with overburden depth = 24 m

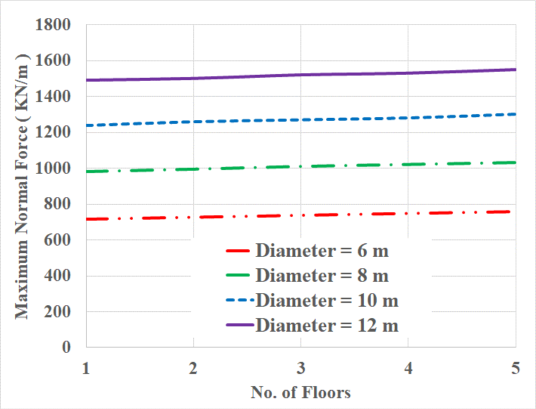

Figure 28: Maximum compressive normal force for circular underground Structures with overburden depth = 24 m

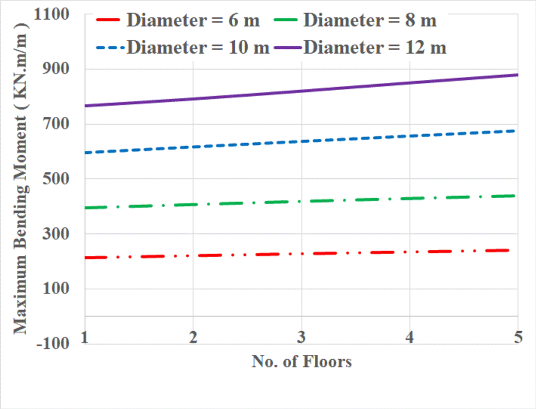

Figure 31: Maximum absolute value of bending moment for circular underground Structures with overburden depth = 24 m

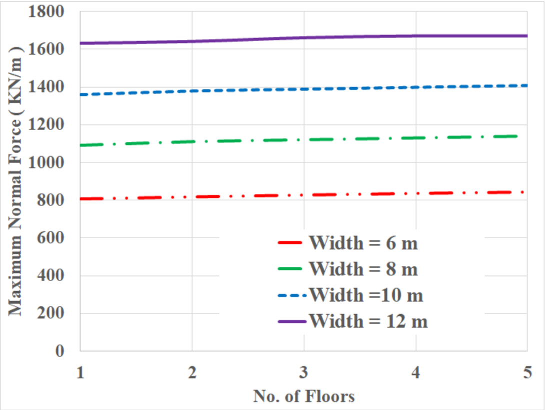

Figure 29: Maximum compressive normal force for square underground Structures with overburden depth = 24 m

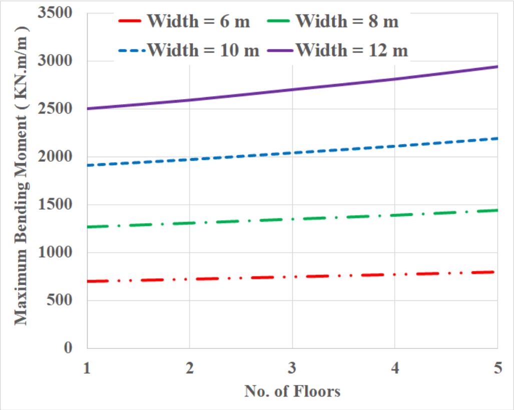

Figure 32: Maximum absolute value of bending moment for square underground Structures with overburden depth = 24 m

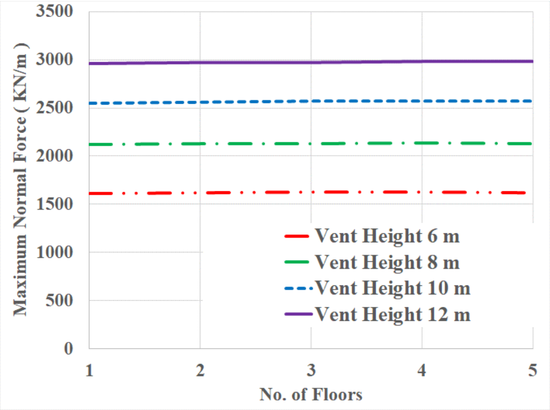

Figure 30: Maximum compressive normal force for double-vent underground Structures with overburden depth = 24 m

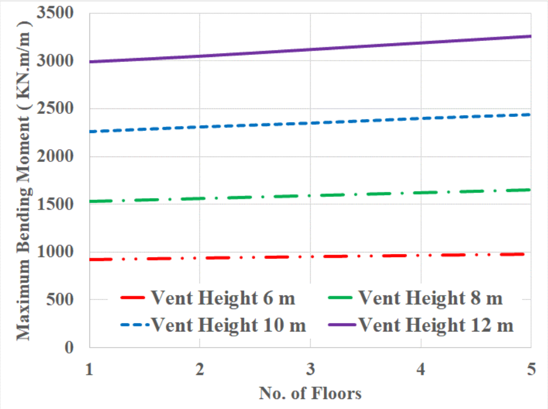

Figure 33: Maximum absolute value of bending moment for double-vent underground Structures with overburden depth = 24 m

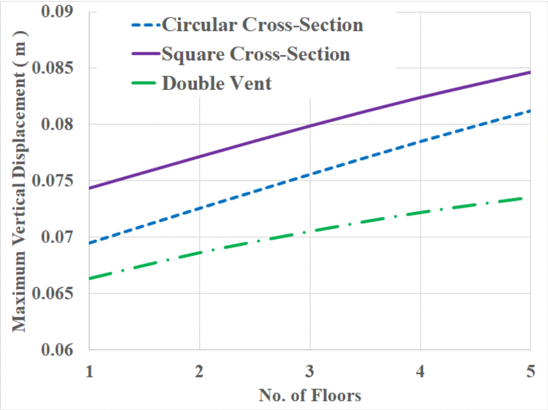

Figure 34: Maximum vertical settlement for circular, square and double-vent underground Structures of width = 6m with overburden depth = 24 m

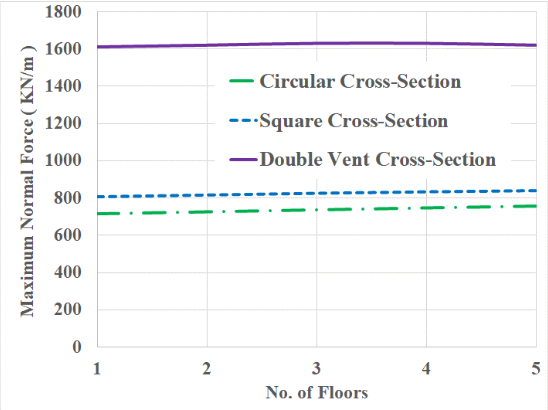

Figure 35: Maximum compressive normal force for circular, square and double-vent underground Structures of width = 6m with overburden depth = 24 m

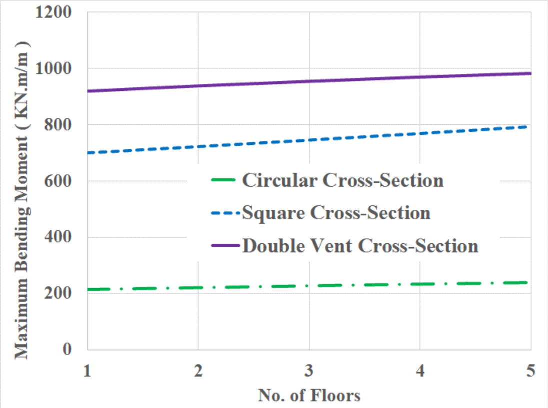

Figure 36: Maximum absolute value of bending moment for circular, square and double-vent underground Structures of width = 6m with overburden depth = 24 m

7.4. The Effect of changing the distance between surface and underground structures

For the different underground structures cross-sections, Increasing the horizontal distance between the underground structure and the surface structure for different underground structures widths of same cross-section leads to:

- Decreasing the maximum vertical settlement of the underground structure as shown in Figures 37 to 39.
- Decreasing the maximum compressive normal force and maximum absolute value of bending moment induced in the concrete lining of the underground structures as shown in Figures 40 to 45.

Increasing the horizontal distance between the newly constructed surface and the underground one for same underground structures widths of different cross-sections leads to:

- Decreasing the maximum vertical settlement of the underground structure as shown in Figure 46.
- Decreasing the maximum compressive normal force and maximum absolute value of bending moment induced in the concrete lining of the underground structures as shown in Figures 47 and 48.
- The maximum vertical settlement is almost equal for the circular and square underground structures and it is lower than that of the double-vent underground structures as shown in Figure 46.
- The maximum compressive normal force and maximum absolute value of bending moment induced in the concrete lining of double-vent underground structures are higher than those of square underground structures which in turn higher than those of circular underground structure shown in Figures 47 and 48.

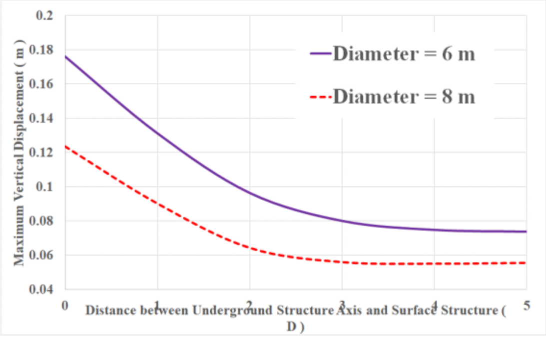

Figure 37: Maximum vertical settlement for circular underground Structures with overburden depth = 18 m

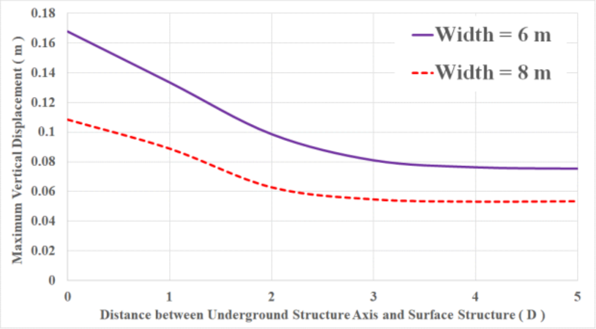

Figure 38: Maximum vertical settlement for square underground Structures with overburden depth = 18 m

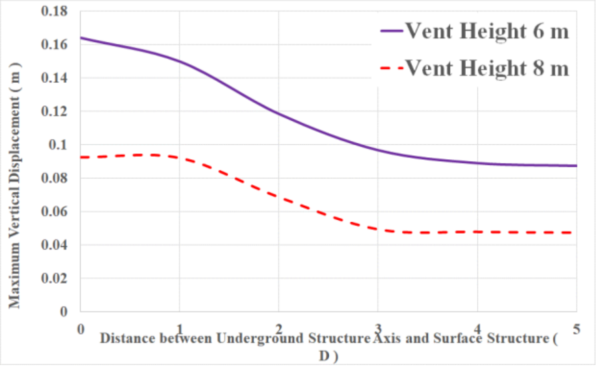

Figure 39: Maximum vertical settlement for double-vent underground structures with overburden depth = 18 m

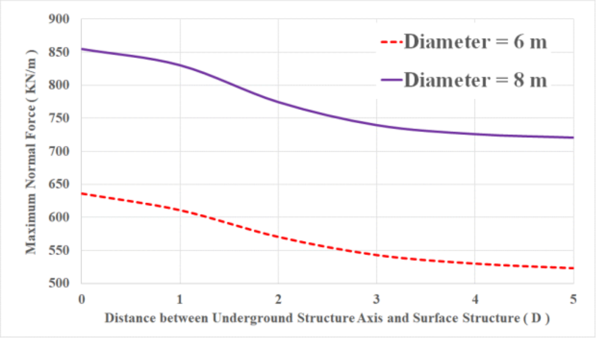

Figure 40: Maximum compressive normal force for circular underground Structures with overburden depth = 18 m

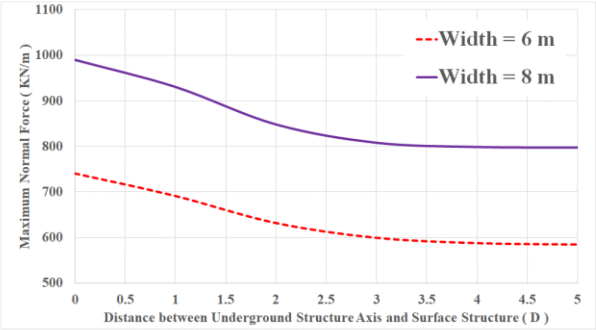

Figure 41: Maximum compressive normal force for square underground Structures with overburden depth = 18 m

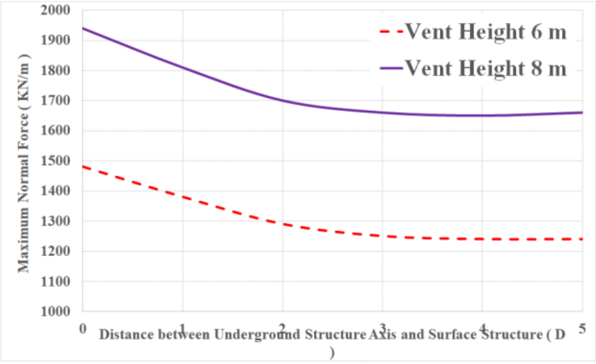

Figure 42: Maximum compressive normal force for double-vent underground Structures with overburden depth = 18 m

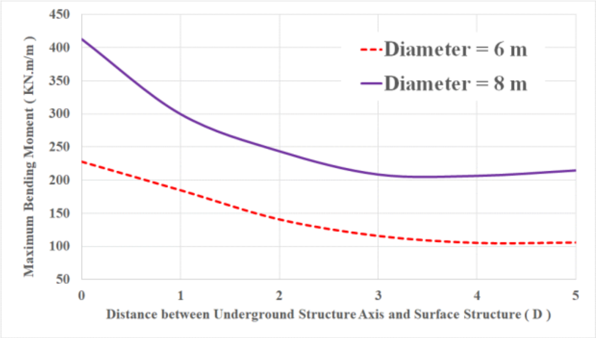

Figure 43: Maximum absolute value of bending moment for circular underground Structures with overburden depth = 18 m

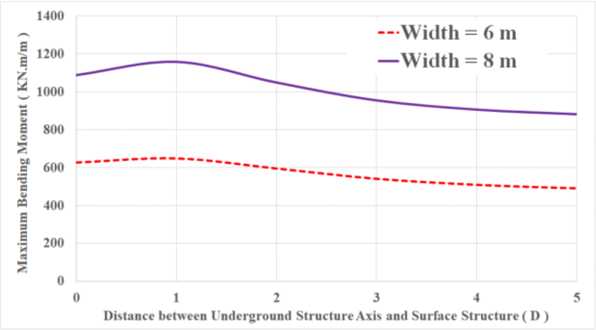

Figure 44: Maximum absolute value of bending moment for square underground Structures with overburden depth = 18 m

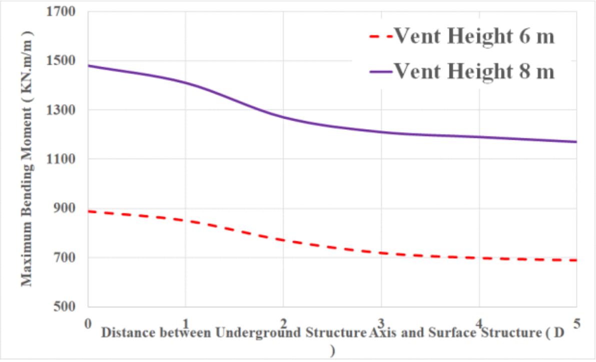

Figure 45: Maximum absolute value of bending moment for double-vent underground Structures with overburden depth = 18 m

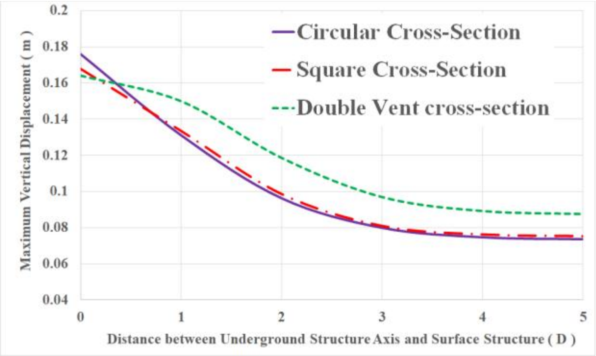

Figure 46: Maximum vertical settlement for circular, square and double-vent underground structures of width = 6m with overburden depth = 18 m

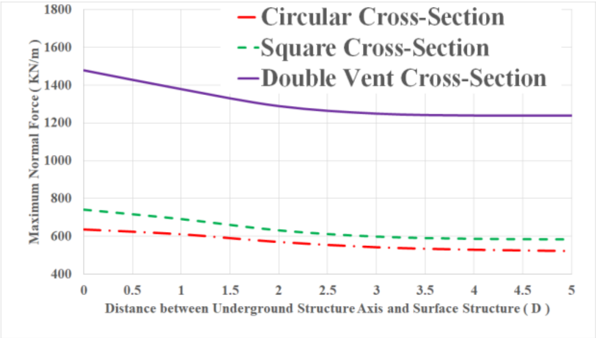

Figure 47: Maximum compressive normal force for circular, square and double-vent underground structures of width = 6m with overburden depth = 18 m

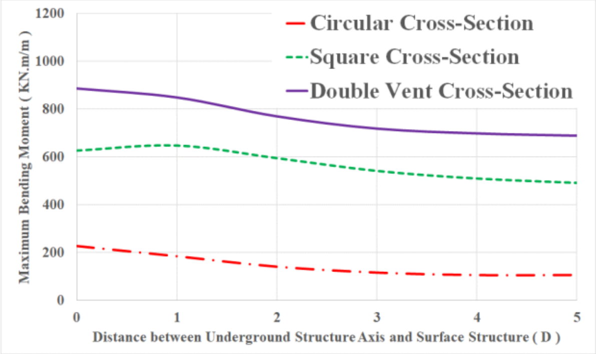

Figure 48: Maximum absolute value of bending moment for circular, square and double-vent underground structures of width = 6m with overburden depth = 18 m

7.5. The Effect of changing the horizontal distance between the newly constructed underground structure and the existing one

For the different underground structures cross-sections as shown in Figures 49 to 51, Increasing the horizontal distance between the newly constructed underground structure and the existing one for different underground structures widths of same cross-section and same overburden depth equal to 12 m:

- Decreasing the maximum vertical settlement and maximum compressive normal force and maximum absolute value of bending moment of the old underground structure as shown in Figures 52 to 60.

Increasing the horizontal distance between the newly constructed underground structure and the existing one with same overburden depth equal to 12 m and same width of different cross-sections:

- Decreasing the maximum vertical settlement and maximum compressive normal force and maximum absolute value of bending moment of old underground structure as shown in Figures 61 to 63.

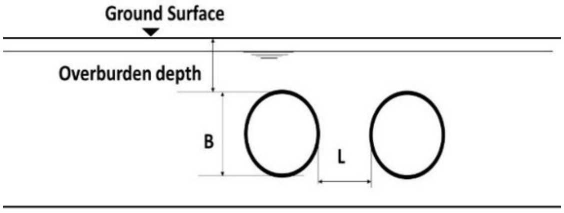

Figure 49: Two adjacent circular underground structures

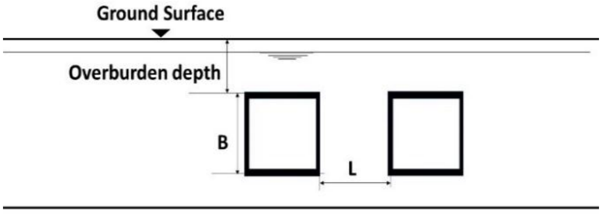

Figure 50: Two adjacent square underground structures

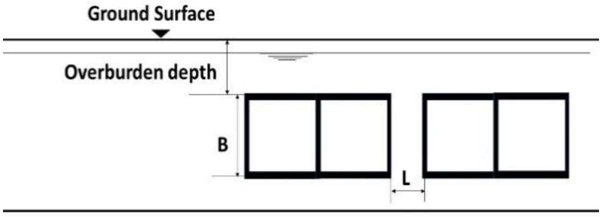

Figure 51: Two adjacent double-vent underground structures

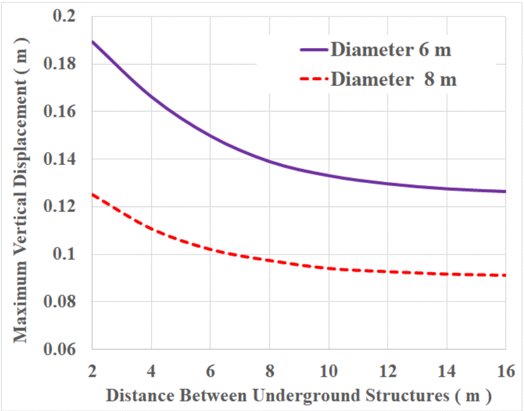

Figure 52: Maximum vertical settlement for circular underground Structures with overburden depth = 12 m

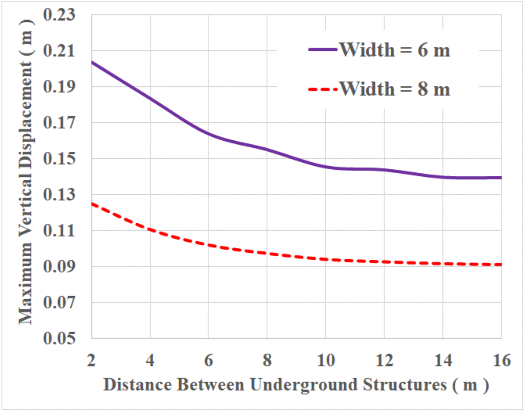

Figure 53: Maximum vertical settlement for square underground Structures with overburden depth = 12 m

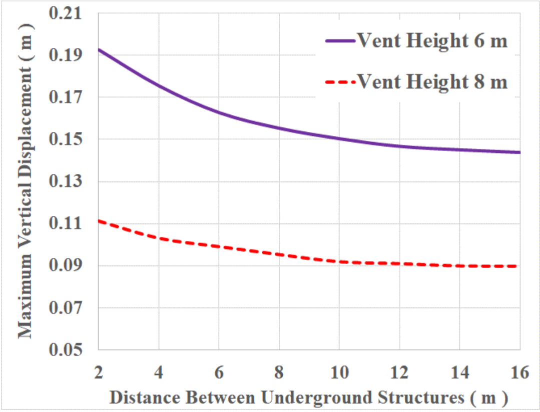

Figure 54: Maximum vertical settlement for double-vent underground Structures with overburden depth = 12 m

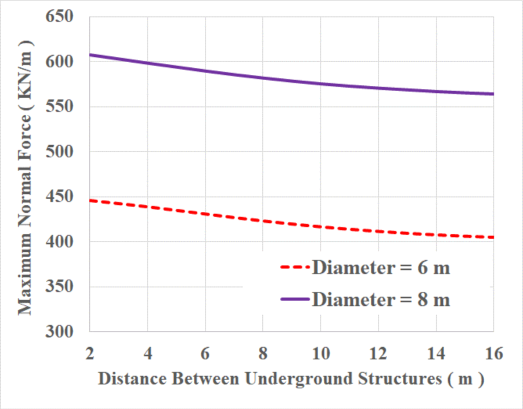

Figure 55: Maximum compressive normal force for circular underground Structures with overburden depth = 12 m

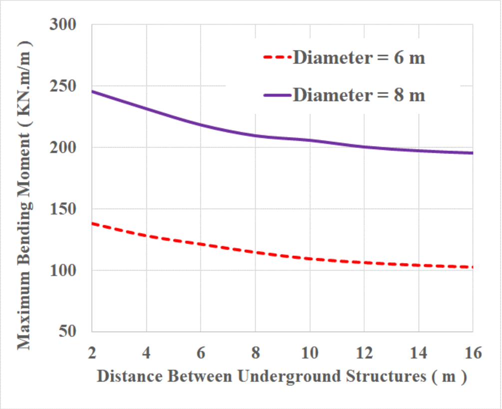

Figure 58: Maximum absolute value of bending moment for circular underground Structures with overburden depth = 12 m

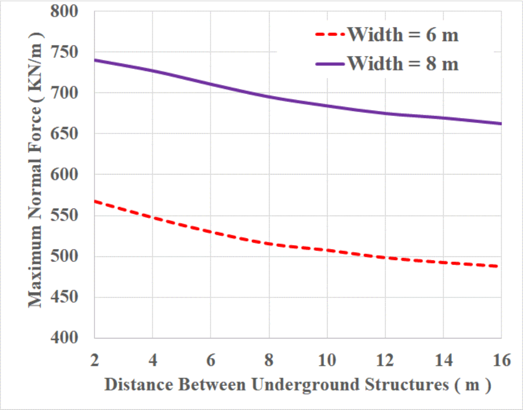

Figure 56: Maximum compressive normal force for square underground Structures with overburden depth = 12 m

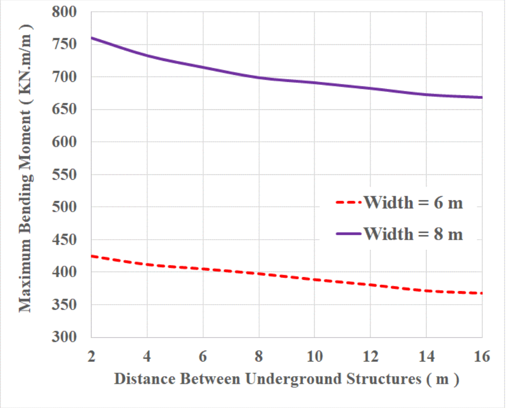

Figure 59: Maximum absolute value of bending moment for square underground Structures with overburden depth = 12 m

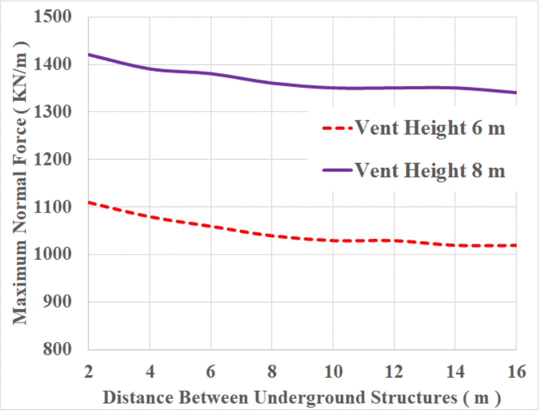

Figure 57: Maximum compressive normal force for double-vent underground Structures with overburden depth = 12 m

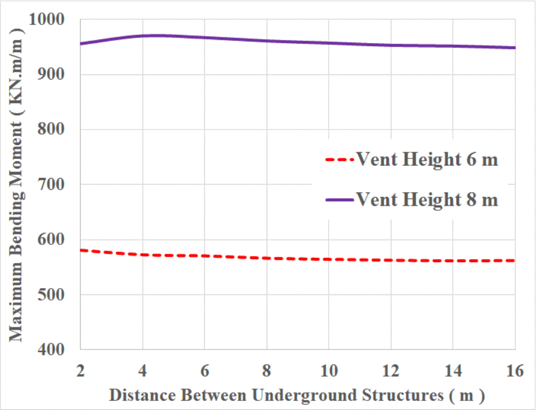

Figure 60: Maximum absolute value of bending moment for double-vent underground Structures with overburden depth = 12 m

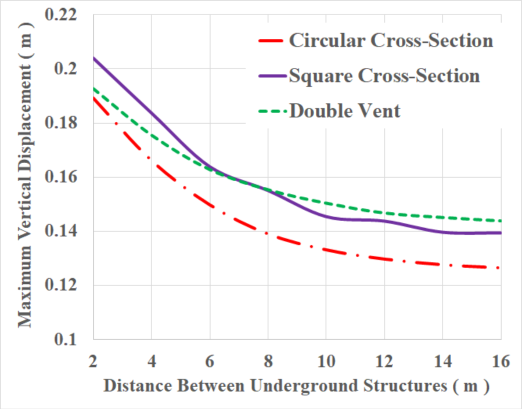

Figure 61: Maximum vertical settlement for circular, square and double-vent underground structures of width = 6m with overburden depth = 12 m

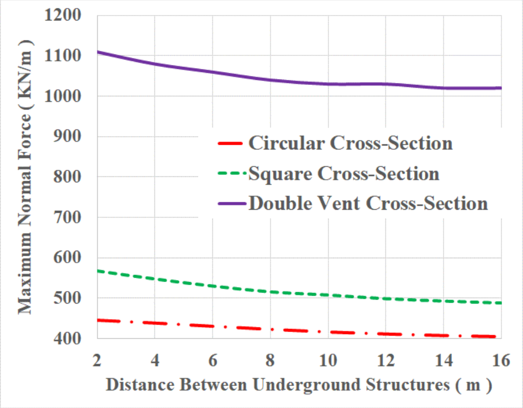

Figure 62: Maximum compressive normal force for circular, square and double-vent underground Structures of width = 6m with overburden depth = 12 m

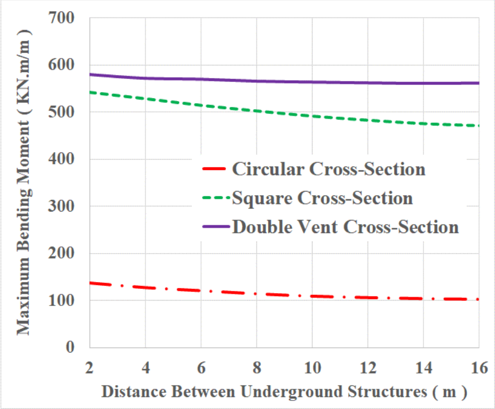

Figure 63: Maximum absolute value of bending moment for circular, square and double-vent underground Structures of width = 6m with overburden depth = 12 m

8 CONCLUSIONS

This paper presents the behavior of underground structures in weak soil in different conditions. The East Port Said zone soil profile was taken as the soil case of study. 2D analysis was performed using Plaxis 2D program. The model dimensions are 300 m x 62 m. The circular, square, double-vent cross-sections are considered for underground structures in this study. The key results also the design guidelines obtained from this study can be summarized as follows:

- It is recommended to construct underground structures with overburden depth more than 32 m in such soil profile as the underground structures get into the stiff sand soil layer and the change in the value of the maximum total vertical settlement is too small with values less than 0.035 m which is less than the required values in most of design codes also at these depths the effect of construction of surface structure with piles disappears.
- In case of construction of any surface structure near the underground one, it is recommended that the horizontal distance between them is equal to 3.5 times the underground structure width or more as the effect of the construction of the surface structure disappears due to the distribution of the load caused by it.
- The circular cross-section is the best choice for underground structures as it has the lowest value of bending moment compared to square and double-vent cross-sections as the shape effect which converts part of the bending moment to a normal force.
- In case of construction of a new underground structure beside an old one, it is recommended that the horizontal distance between them is equal to or more than 1.5 times the underground structure width as the effect of construction of the new underground structure decrease with the increase of the horizontal distance between them and at this distance, the change in the values the maximum vertical settlement, maximum compressive normal force and maximum absolute value of the bending moment of the old underground structure is too small as the effect of construction of the new underground structure almost disappears.
- The bigger the underground structure width, the lower the maximum vertical displacement and the higher the maximum compressive normal force and bending moment for the same overburden depth of soil.
- No surface structure with more than one floor can be constructed in such soil profile without piles as the soil body collapses.
- Increasing the number of floors of the constructed surface structure with piles near the underground structure has slight effect on the maximum compressive normal forces and the maximum bending moments induced in the underground structure.

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