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Analysis of Two Adjacent Circular Tunnels in Soft Clay Soil

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***Abstract*— The construction and use of tunnels can be considered one of the most important features of civilization in developed nations. However, it is difficult to construct tunnels in soft clay soil. So, the objectives of the present work are to study the followings: i) the analysis of two adjacent circular tunnels in soft clay soil. ii) the effect of varying the modulus of elasticity and Poisson's ratio for the soft clay soil on the behavior of tunnels. iii) the effect of varying the vertical distances between the two tunnels and the ground surface on the internal forces in the tunnel and the internal stresses as well as settlement in soft clay soil. iv) the effect of varying the horizontal distances between centerline of two tunnels on the internal forces in the tunnel and the internal stresses as well as settlement in soft clay soil. Numerical analysis using finite element software ADINA version 8.5 (a finite element computer program) is done. A numerical model is presented as a plane strain problem. Two dimensions triangle element of 3-node is used to present the soft clay soil and 2 -node beam element to simulate the lining of tunnels. The material of the lining is chosen as a reinforcement concrete. The Mohr-Coulomb model was used to simulate the nonlinear soft clay soil with different modulus of elasticity (E_s) 500, 1000, 1500 and 1900 kN/m^2 and different Poisson's ratio (µs) 0.4, 0.425, 0.45 and 0.49. The effect of changing the vertical distance (H) of (2r, 3r, 4r, 6r) and horizontal distance between the two tunnels (L) of (3r, 5r, 6r, 7r) on the internal forces, the displacement as well as the internal stresses were analyzed. The values of internal forces and displacement were investigated at the upper crown (Cr) and the spring (SL) points at the tunnel as well as internal stresses in the soft clay soil. The analysis shows that the internal forces and internal stresses for two adjacent circular tunnels at variable distances were slightly affected by the horizontal distances, however they are more affected by increasing the vertical distances. The internal forces for two adjacent circular tunnels increase up to 13% due to increasing vertical distances from 2r to 4r and slightly increases due to the increasing vertical distances from 4r to 6r. The numerical results show that the internal forces and internal stresses for two adjacent circular tunnels are more affected by the increasing (E_s) of soil. In addition, the bending moment, the shear force, the vertical displacement and the shear stresses for two adjacent circular tunnels decrease by about (77% to 96%) due to the increasing of the stiffness of soft clay soil, however the normal force and the horizontal stresses increases by about (18% to 52%).**

Keywords*— Modulus of Elasticity; Vertical Distance; Horizontal Distance; ADINA; Displacement

I. INTRODUCTION

The construction and use of tunnels can be considered one of the most important features of civilization in developed nations. Due to the development of engineering sciences and techniques, great depths of tunnels and mines can be reached. The depth of 1200 meters has been already reached in America and Russia. In South Africa, this figure has been increased to 2500 meters underground. Abdel Salam, S.S. (1979) investigated the factors affecting the stress distribution around two equal adjacent elliptical tunnels. The shape of tunnel openings, the inclination angel between the line joining the centroids of both tunnels as well as the distance apart between the centroids of the two tunnels and the ratio between the horizontal load and vertical load are some of the factors that affect the stress distribution around the tunnels. El Gammal, M.H.A. (1981) investigated the factors affecting the stress distribution around two unequal circular tunnels. The ratio between the horizontal load and vertical load, the distance between the centroids of both tunnels on the horizontal axis of symmetry and the diameter of left tunnel are some of the factors that affect the stress distribution. The relation between these variables and shear stresses was indicated. Akl, M. Y. (1989) presented an analysis for segmental tunnels. The finite element method was used in the analysis of the tunnel – soil model considering linear and nonlinear behavior of the reinforced concrete material of the tunnel. Intensive parametric study was made to investigate the effect of different parameters on the behavior of the segmental tunnel, such as, number of segments, location of joints between segments around the tunnel cross section, adjacent soil stiffness and tunnel wall thickness. A study case was presented for the rehabilitation and expansion of the Cairo waste water system project (zone number 3 from Souk El-Samak to Amiria pump station). Anter, E. (1992) used a nonlinear analysis of soil-tunnel interaction. Anter, E. developed a finite element analysis program in order to calculate the internal forces and stresses in lining, considering a nonlinear stress-strain relationship of soil. The obtained values were compared with an experimental method (photoelastic analysis). Eman, A.El-Shamy (1997) investigated the effect of distance between the two tunnels, crack location, crack-lining depth ratio, case of loading, height of the ground surface over the tunnels and type of soil. Test data was obtained and analyzed in order to obtain the internal forces in tunnels and the internal stresses in the soil medium based on the shear difference method. The experimental results were compared with the numerical results based on the finite element method. Abo.Elanwar, M. (2006) performed an analysis of circular tunnels embedded in soil. Abo.Elanwar,

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Vol. 5 Issue 04, April-2016

M. showed that the design of tunnel cross section depends on the values of internal forces and deformations induced in the lining. These values were influenced by many factors such as type of soil, method of construction and dimensions of the tunnel cross section. Abo.Elanwar, M. presented a numerical analysis using finite element software PLAXIS version 7.1.6.97 (a finite element code for soil and rock analyses). Akhaveissy, A.H. (2010) presented 2D numerical analysis of Sao Paulo tunnel. Non- linear finite element and serendipity eight node elements were used for determining of ground surface settlement due to tunneling. Linear element with elastic behavior was used for modeling of lining. Modified generalized plasticity model with non - associated flow rule was applied for analysis of a tunnel in Sao Paulo -Brazil. The tunnel had analyzed lades' model with 16 parameters. Akhaveissy, A.H. modified generalized plasticity with parameters. Also, Mohr- coulomb model was used to analysts the tunnel. The result showed a good agreement with observed of field data by modified generalized plasticity model than other models. The obtain result by Mohr-coulomb model showed less settlement than other model due to excavation. Saied Mohammad, et al (2012) introduced the relationship between twin tunnel distance and surface subsidence in soft ground. Saied Mohammad, et al presented a series of three-dimensional finite distinct element analyses carried out for line 1 of Tabriz metro tunnels. The Influence of the distance between twin tunnels on the surface subsidence, bending moment and axial forces in the segmental lining of the first tunnel had been investigated. Advancing of the second tunnel affects the surface subsidence, bending moment and internal forces in the lining of the first tunnel. These effects relate directly to the width of the pillar separating the twin tunnels. It was found that the location of the maximum subsidence was offset from the centerline of the first tunnel. The offset increased with decreased in the distance between the tunnels. Also, moment and axial forces of the first tunnel decreased by increasing the space between the tunnels. The interaction between the tunnels had been quantified and classified in accordance with various tunnel distances. Othman A. Shaalan, et al (2014) presented the effect of, closer spacing results in larger interaction, comparison between the different tunnels lining thickness for the different soil types indicates slight increase in the normalized internal forces due to increasing the thickness and changing the soil type from stiff clay to hard clays resulted in significant reductions in the heave during construction and the consequent settlement due to the tunnel operation, with hard clays giving minimal heave and settlement values. The soil domain is presented as a plane strain problem with porous media formulation for the soil domain, and 2-node beam element to simulate the lining of the circular tunnels. Elsamny, M.K., et al (2016) investigated the effect of change shape of tunnels, dimension of tunnels, thickness-radius ratio, properties of soil and cases of loading. Also, Mohr- coulomb model was used to analysts the tunnel. Mohamed Gouda presented a numerical analysis using finite element software ADINA version 8.5 (a finite element computer program).

II. MODEL DESCRIPTION

In the present work the shape of tunnel has been chosen as circular as shown in Fig. (1).

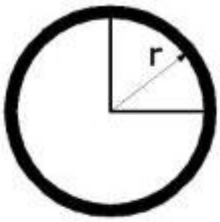

Fig. 1. Shape of tunnel

A. Properties of material for the cross section of the lining

The lining material of tunnels is chosen as a reinforced concrete. Its properties are chosen as follows:

Modules of elasticity (E) = (2.1 x107) kN /m^2.

Specific weight (γ) = 25 kN/m^3.

Poisson's ratio (ν) = 0.15

The lining weight (W) is specified by the program.

B. Boundary condition

There are two classes of boundary conditions: i). essential boundary conditions, such as prescribed displacement (and rotation) boundary conditions, and ii). natural boundary conditions, such as applied force and moment boundary conditions. For essential boundary conditions, roller supports are located at the side boundaries to allow the vertical displacement or settlement in Z- direction. However, roller supports are located in bottom of the model to prevent the displacement in Z- direction. In addition, applied force boundary conditions are located at top of the model describing the equivalent surcharging pressure of 100kN/m^2.

C. Description of twin parallel model

Fig. (2) shows a typical section of the two adjacent circular tunnels having diameter (D=10 m) with a modulus of elasticity (E=21* 〖10〗 ^6 kN/m^2), Poisson's ratio (ν =0.15), a lining thickness-radius ratio of (t/r= 0.2) where t= thickness of lining and r= radius of tunnel, and case of external loading only by equivalent discharge uniform load of 100 kN/m^2. The soft clay soil is taken as non-liner with parameters of modulus of elasticity (Es=500, 1000, 1500, 1900 kN/m^2) and Poisson's ratio (μs = 0.4, 0.425, 0.45, 0.49). Tunnels are assumed to be constructed in one layer of soil deposit of variable distances between them equal to (3r, 5r, 6r, and 7r where r= radius of tunnel) as well as variable distances between the ground surface and two tunnel equal to (2r, 3r, 4r, and 6r) as shown in Fig (2). Table (1) summarizes all previous parameters. Fig. (3) shows the finite element mesh used in the analysis for twin parallel circular tunnels at variable distances. Also, Fig. (2) shows the key plan of the tunnel where (sL) is left spring point, (cr) is the crown point and (sr) is the right spring point of the tunnel.

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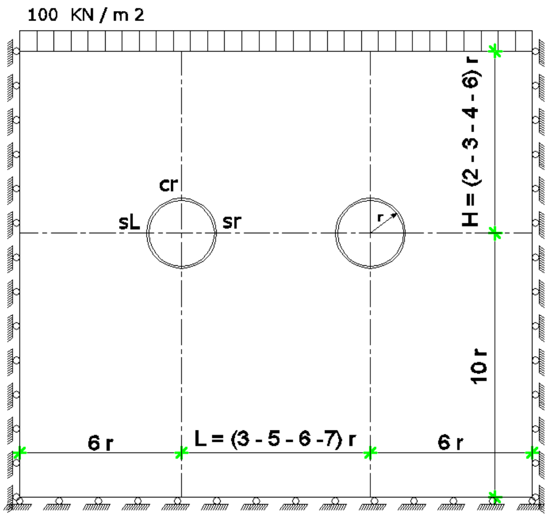

Fig. 2. Boundary conditions for twin parallel circular tunnel

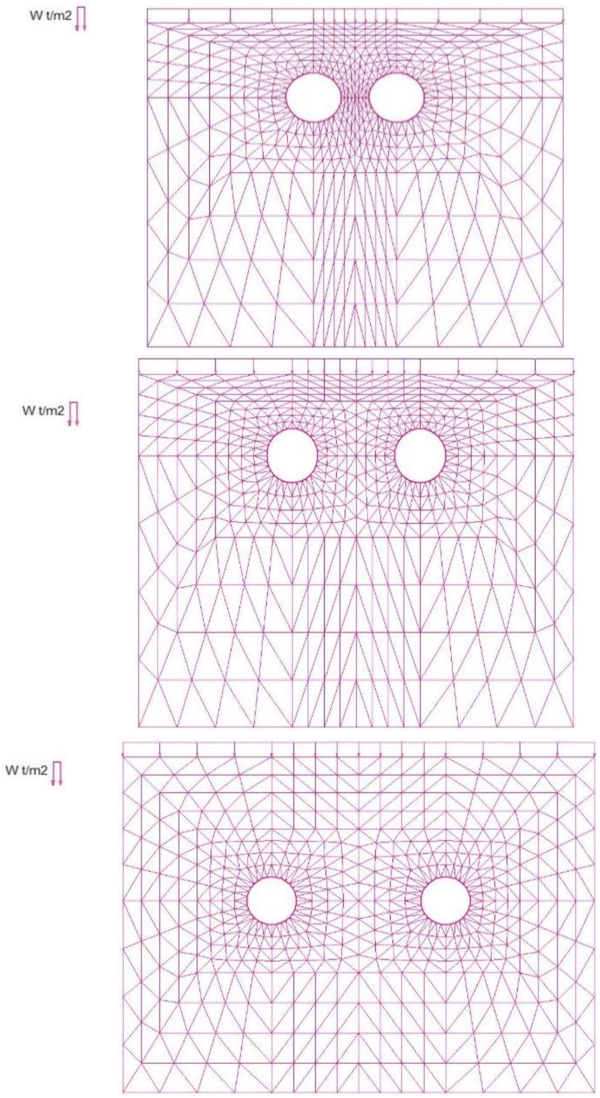

Fig. 3. Finite element mesh for twin parallel circular tunnels

TABLE I. THE VALUES OF UTILIZED CONSTANTS AND VARIABLES USED IN THE STUDY

No.	Parameters	Status	Value/Values
1	External load	Constant	100(kN/m^2)
2	Tunnel depth (H)	Variable	(2r, 3r, 4r, 6r) (m)
3	L (distance between centerline of tunnels)	Variable	(3r, 5r, 6r, 7r) (m)
4	Shape of tunnel	Constant	Circular
5	Modulus of elasticity for tunnel (Es)	Constant	21* 〖10〗 ^6 (kN/m^2)
6	Circular diameter (D)	Constant	10 (m)
7	Thickness radius ratio(t/r)	Constant	0.2
8	Case of loading	Constant	External load = 100(kN/m^2)
9	Native soil properties (Es)	Variable	500, 1000, 1500, 1900(kN/m^2)
10	Poisson’s ratio (µs)	Variable	0.4, 0.425, 0.45, 0.49

III. THE PARAMETRIC STUDY

A. Properties of soil

The soft clay soil used in this study has different four values of modulus of elasticity (Es=500, 1000, 1500, 1900 kN/m^2) and Poisson's ratio (µs = 0.4, 0.425, 0.45, 0.49). The values of (Es, µ) are given in tables (2), (3).

TABLE II. E_s FOR DIFFERENT SOILS

Soil Type	Classification	Es (MN/m2)
Clay	Soft	0.50 – 2.0
	Medium Stiff	1.50 – 6.0
	Stiff	2.50 – 10.0
	Very Stiff	5.0 – 20.0
	Hard	10.0 – 40.0
Silt		3.0 – 30.0
Sand	Loose	10.0 – 25.0
	Medium Dense	25.0 – 75.0
	Dense	75.0 – 150.0
	Very Dense	150.0 – 400.0
Gravel		100.0 – 400.0
Organic		0.50 – 2.0

International Journal of Engineering Research & Technology (IJERT)
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TABLE III. μ_S FOR DIFFERENT SOILS

Soil Type	Passion's ration, μs
Coarse Sand	0.15-0.12
Medium loose sand	0.20-0.25
Fine Sand	0.25-0.30
Sandy silt and silt	0.30-0.35
Saturated clay (undrained)	0.50
Saturated clay-lightly over consolidated (Drained)	0.2-0.4

B. Vertical distance

Vertical distance between centerline of two tunnel and ground surface (H) is presented to be (2r, 3r, 4r, and 6r).

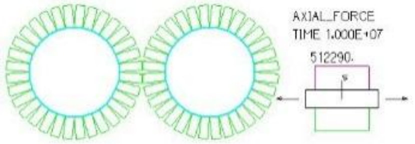
C. Horizontal distance

Horizontal distance from centerline of each tunnel (L) is presented to be (3r, 5r, 6r, and 7r).

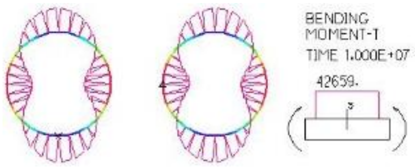
IV. NUMERICAL RESULTS

ADINA program was used to calculate the internal forces [{moment (M)}, {normal (N)}, {shear (Q)}], the internal stresses {vertical stresses (σ_z)}, {horizontal stresses (σ_y)}, {shear stresses (τ_{zy})} and the vertical displacement (dz) in soft clay soil. Analysis in ADINA program included the effect of varying of native soil Es on the internal forces of lining, internal stresses and displacement on soil surrounding tunnel due to change vertical and horizontal distances.

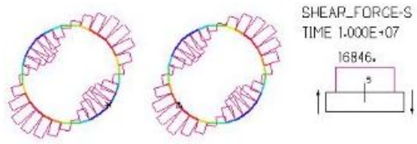
Fig. (4) shows the distribution of the normal force, bending moment and shear force through the two adjacent circular tunnels lining at vertical distance (H)= 2r, horizontal distance (L)= 3r and modulus of elasticity (Es) =1900kN/m^2. Fig (5) and fig (6) show the distribution of the internal stresses and the displacement in the soft clay soil which surrounding the two adjacent circular tunnels at vertical distance H=2r, horizontal distance L=3r and the modulus of elasticity (Es) =1900kN/m^2.



Normal force

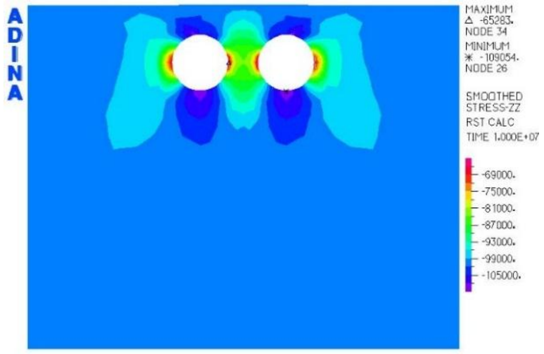


Bending moment

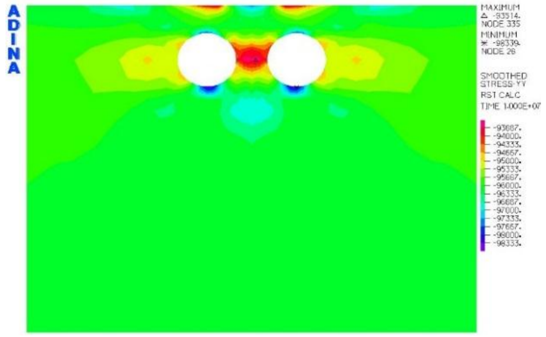


Shear force

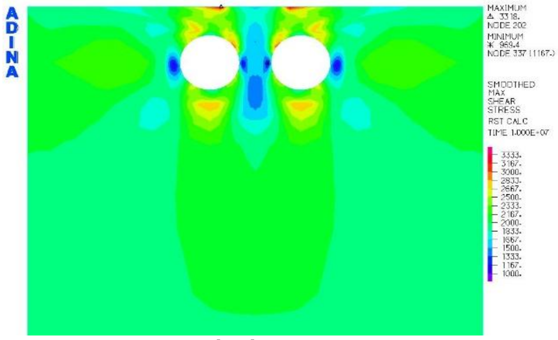
Fig. 4. Internal forces in the circular lining tunnel at H=2r, L=3r, Es=1900kN/m^2



The vertical stresses



The horizontal stresses



The shear stresses

Fig. 5. The distribution of internal stresses in the soft clay soil at H=2r, L=3r, Es=1900kN/m^2

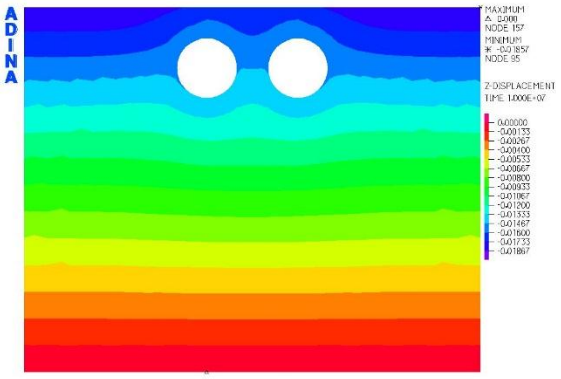


Fig. 6. The distribution of displacement in the soft clay soil at H=2r, L=3r, Es=1900kN/m^2

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 04, April-2016

A. *Effect of the change in the stiffness of soft clay soil (Es) on the behavior of twin circular tunnels at variable distances*

The effect of change in the modulus of elasticity (Es)= (500, 1000, 1500, 1900 kN/m^2) and poison ratio (μs) = (0.4, 0.425, 0.45, 0.49) on the internal forces, the displacement of tunnel and internal stresses in soil domain for two adjacent circular tunnels due to the changing in the vertical distances (H)= (2r, 3r, 4r, 6r) and the horizontal distances (L)= (3r, 5r, 6r, 7r) has been investigated.

Fig. (7) and Fig. (8) show the bending moment and the shear force of two adjacent circular tunnels with the increasing of the stiffness of soft clay soil. From these figures it can be seen that bending moment and shear forces decrease up to 77% due to increasing Es. However, Fig. (9) shows that the normal force increases up to 18% due to the increasing of the stiffness of soft clay soil.

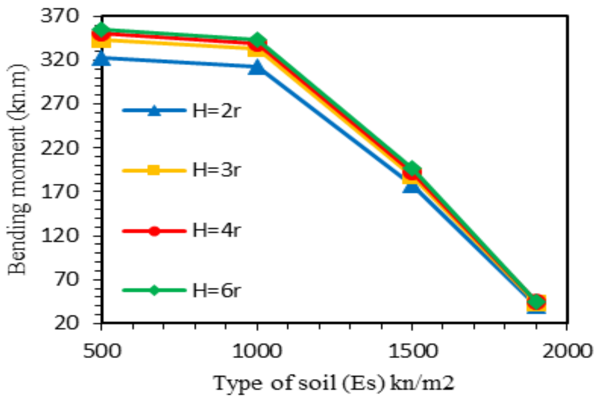


Fig. 7. Effect of the change in the soft clay soil (Es) on the bending moment of circular tunnel

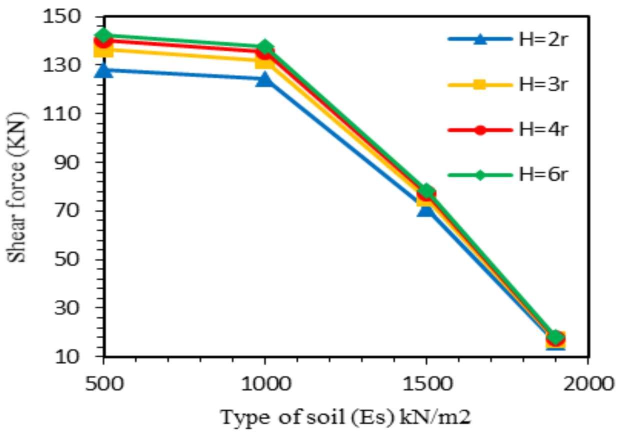


Fig. 8. Effect of the change in the soft clay soil (Es) on the shear force of circular tunnel

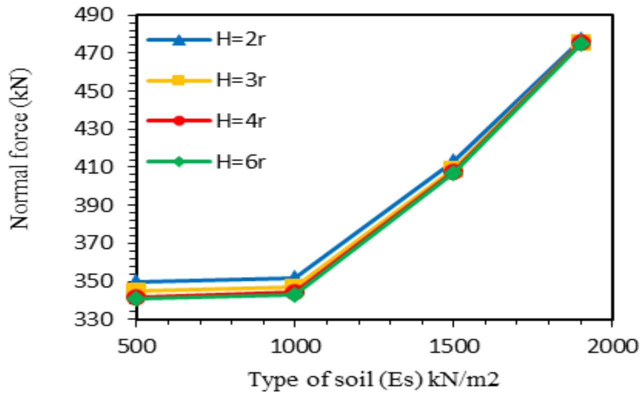


Fig. 9. Effect of the change in the soft clay soil (Es) on the normal force of circular tunnel

Fig. (10) and Fig. (11) show the vertical stresses and the shear stresses in the soft clay soil surrounding the two adjacent circular tunnels which show decrease by about 15% and 78% respectively due to the increasing of the stiffness of soft clay soil. However, Fig. (12) shows that the horizontal stresses increase up to 52% due to increasing of the stiffness of soft clay soil.

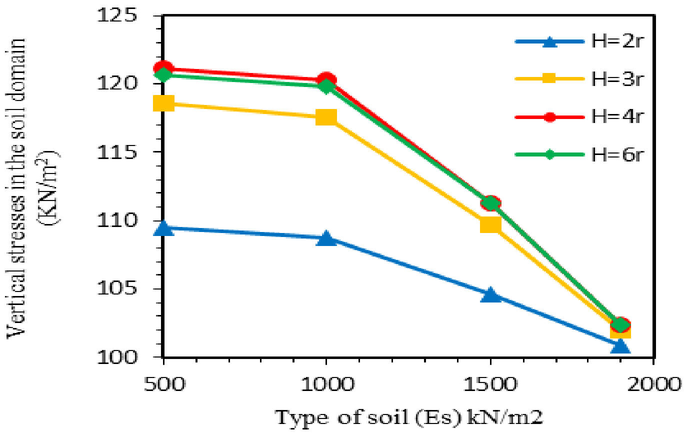


Fig. 10. Effect of the change in the soft clay soil (Es) on the vertical stresses

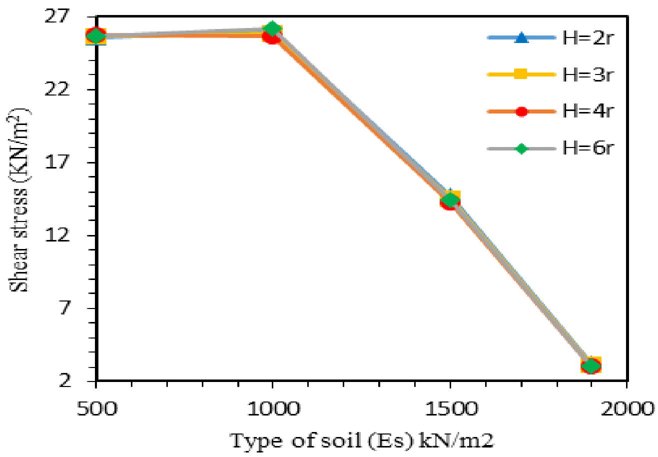


Fig. 11. Effect of the change in the soft clay soil (Es) on the shear stresses

International Journal of Engineering Research & Technology (IJERT)
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Vol. 5 Issue 04, April-2016

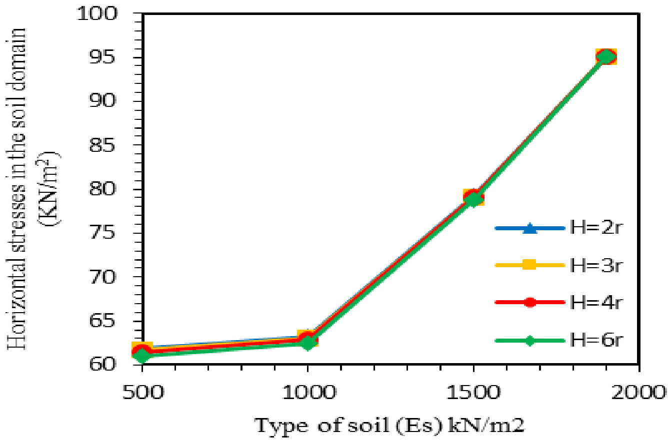

Fig. 12. Effect of the change in the soft clay soil (Es) on the horizontal stresses

Fig. (13) shows the vertical displacement at upper crown point of the circular tunnel which decreases up to 96% due to the increasing of the stiffness of soft clay soil.

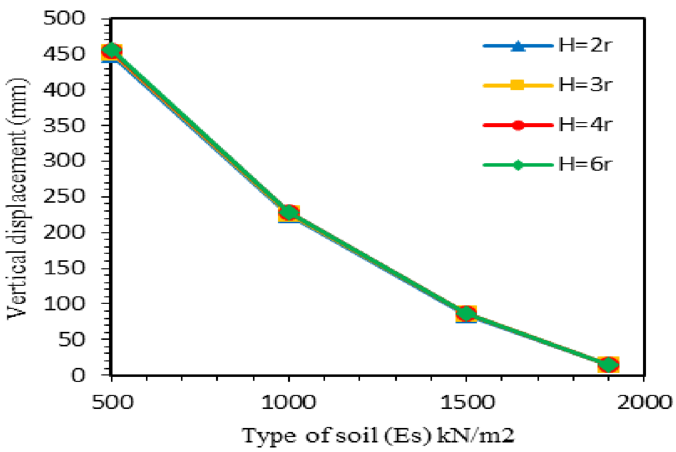

Fig. 13. Effect of the change in the soft clay soil (Es) on the vertical displacement

B. *Effect of change of vertical and horizontal distances on two adjacent circular tunnels*

The effect of change in the vertical distance (H)= (2r, 4r, and 6r) and the effect of change in the horizontal distance (L)= (3r, 5r, 6r, and 7r) on the internal forces of tunnel, the displacement and the internal stresses in soil has been investigated.

Fig. (14) and Fig. (15) show the bending moment and the shear force of two adjacent circular tunnels which increase up to 13% due to increasing of vertical distance from H=2r to 4r. However, they are slightly affected by increasing of vertical distance from H=4r to 6r. In addition, Fig. (16) shows that the normal force slightly decreases due to increasing of vertical distance from H=2r to 6r.

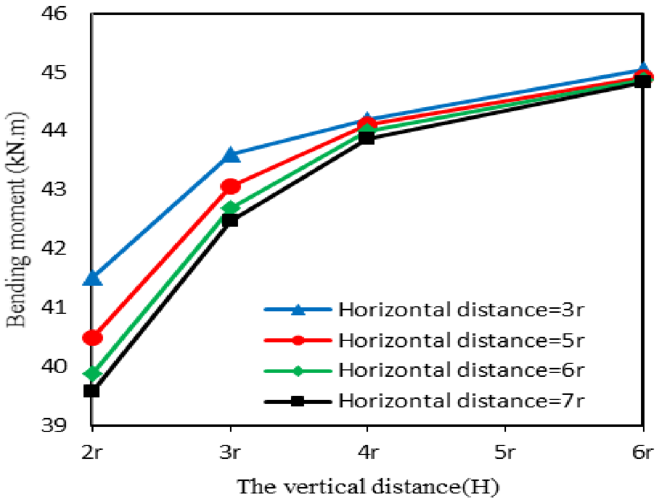

Fig. 14. Effect of the change in the vertical distance on the bending moment

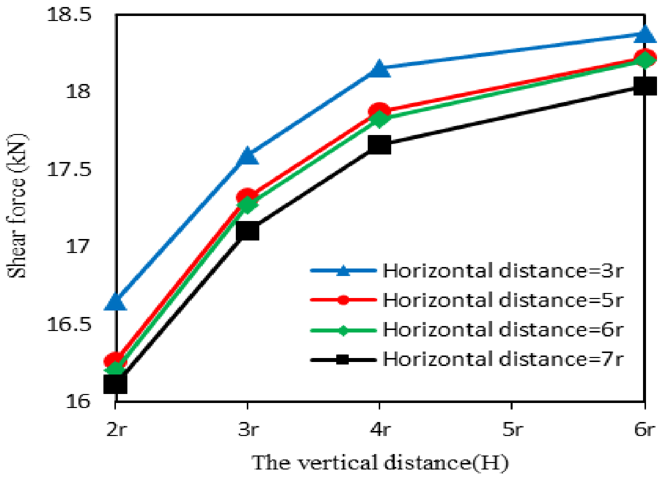

Fig. 15. Effect of the change in the vertical distance on the shear force

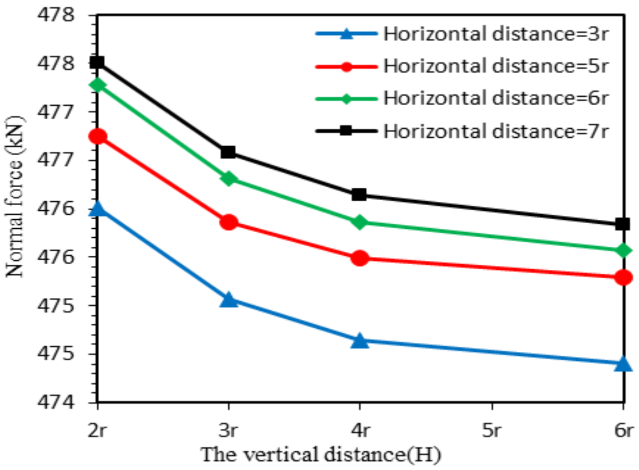

Fig. 16. Effect of the change in the vertical distance on the normal force

Fig. (17) shows that the vertical stresses in the soft clay soil surrounding the two adjacent circular tunnels increase up to 1.5% due to increasing of vertical distance from H=2r to 4r. However, they are slightly affected by increasing of vertical distance from H=4r to 6r. In addition, Fig. (18) shows that the horizontal stresses slightly decrease due to increasing of vertical distance from H=2r to 6r.

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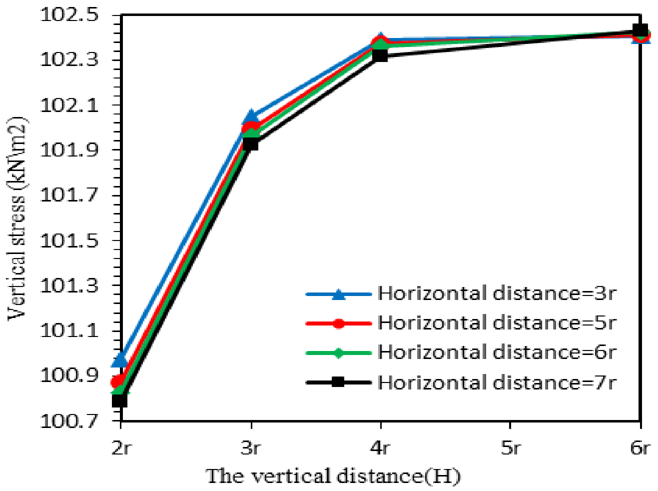

Fig. 17. Effect of the change in the vertical distance on the vertical stresses in the soft clay soil surrounding the circular tunnel

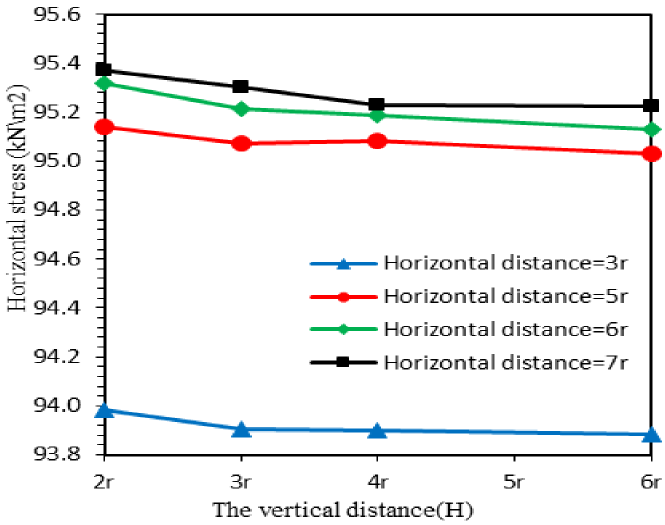

Fig. 18. Effect of the change in the vertical distance on the horizontal stresses in the soft clay soil surrounding the circular tunnel

V. CONCLUSIONS

Based on the results of the research, the following conclusions are drawn:

- There is no effect on the internal stresses when the horizontal and vertical distances are more than 6r.
- The internal stresses for two adjacent circular tunnels are slightly affected by the horizontal distances between two adjacent tunnels, but they are more affected by increasing vertical distances.
- The bending moment at upper crown and left spring point for two adjacent circular tunnels increases up to 13% due to increasing vertical distance from H=2r to 4r.
- Increasing vertical distance from H=2r to 4r increases the vertical displacement at upper crown of the two adjacent circular tunnels up to 1.5% and increases the horizontal displacement at left spring up to 51%.
- Increasing vertical distance from H=4r to 6r has slight effect on the internal forces, internal stresses and displacement of two adjacent circular tunnels.
- The internal stresses for two adjacent circular tunnels are slightly affected by the variable distances, but they are more affected by increasing properties of soft clay soil (Es).
- The bending moment and the shear force for two adjacent circular tunnels decrease up to 77% due to the increasing of the stiffness of soft clay soil. However, the normal force increases up to 18%.
- The vertical stresses and the shear stresses in the soft clay soil surrounding circular tunnels decrease by about 15% and 78% respectively due to increasing stiffness of soft clay soil. However, the horizontal stresses increase up to 52%.
- The vertical displacement at upper crown point for two adjacent circular tunnels decreases up to 96% due to increasing stiffness of soft clay soil.

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