



EFFECT OF SOIL TYPE ON THE DEFORMATIONAL BEHAVIOR OF TWO ADJACENT TUNNELS

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ABSTRACT

With the increase in the claim for space-efficient transportation construction, the use of tunnels in urban subway construction are becoming extra popular. There are a lot of factors affecting the design of tunnels such as subsoil conditions and diameter of tunnel. In this paper the effect of type of soil and diameter of tunnel on the deformational behavior of two adjacent tunnels were studied. A parametric study on adjacent twin tunnels was carried out based on numerical analysis using PLAXIS 3D finite element analysis. The parametric study included the tunnel diameter and type of soil. The effect soil consistency for cohesion less and cohesive soils was investigated, with tunnel diameter (D) in the range of 6.00 to 15.00 m. The spacing between twin tunnel, and soil cover above the tunnel were taken as 1.5D. The investigated parameters are settlement of ground surface, tunnel vertical deformation in soil, deformation of tunnel and all-round soil stress were discussed and analysis. It was found that the effect of diameter on ground settlement is more significant than the tunnel spacing from D = 6 to 8 m, then with increase of tunnel diameter the increase in rate of ground settlement becomes negligible. On the other hand, after spacing (2-3)D the increase in rate of ground settlement becomes negligible. The tunnel vertical and lateral deformation increase in semi linear pattern with the increase of tunnel diameter for different soil consistencies. The elastic modulus has significant effect on the results of soft clay. Increasing the elastic modulus for soft clay from 5 to 25 MPa, decreased the tunnel crown deformation in soil by 11.46%. and also, surface settlement of soil by 54.93%.

KEYWORDS: Twin tunnel, circular, diameter. deformation, stability, cohesion, cohesion less, 3D.

تأثير نوع التربة علي سلوك التشوهات في نفقين متجاورين.

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الملخص :

نتيجة للتوسع العمراني أصبح من المهم زياده وسائل النقل في المناطق الحضرية . ومنها علي سبيل المثال مترو الانفاق المزودج . هناك الكثير من العوامل التي تؤثر علي تصميم الانفاق الدائريه منها علي سبيل المثال نوع التربه وقطر النفق. في هذا البحث تم دراسته تأثير نوع التربه وقطر النفق علي سلوك نفقين دائريين متجاورين . تم اجراء دراسته عدديه باستخدام برنامج Plaxis-3D علي نفقين دائريين متجاورين لخصائص مختلفه للتربه المتماسكه والتربه المفككه. وايضا دراسته تأثير معامل المرونه علي الطين اللين ، وتمت هذه الدراسة لقطر النفق في المدى من ٦ إلى ١٥ متر، مع أخذ التباعد بين النفقين الدائريين وكذلك غطاء التربة فوق النفق عند مقدار ثابت هو ١,٥ قطر النفق، مع تأثير هذه المعاملات علي الهبوط السطحي للتربه والازاحه العموديه والافقيه في التربه وإجهادات التربه ومناقشتها وتحليلها. ومن هذه الدراسة وجد ان هبوط سطح الارض يكون كبير بين النفقين في المسافه من ٦ إلى ٨ متر وبعد مسافه من (٢-٣) مرات القطر يصبح معدل الهبوط ضئيلا. من ناحية أخرى فإن زيادة قطر النفق ادي الي زياده الازاحه الرأسية عند تاج النفق وايضا زياده الازاحه الافقيه مع اختلاف نوع التربه في علاقة شبه خطية . وفي حالة التربه المتماسكه فإن إختيار قيمة معامل المرونه وبخاصة للتربه اللينه له تأثير كبير على الهبوط السطحي للتربه اللينه زياده معايير المرونه للتربه الطينيه اللينه من ٥ إلى ٢٥ ميجاباسكال ادي الي تقليل قيم التشكل الرأسي للنفق بنسبه ١١,٤٦٪، وكذلك قيم الهبوط السطحي للتربه بمقدار ٥٤,٩٣٪.

الكلمات المفتاحيه: نفقين مزدوجين ، دائري ، القطر ، التشكل، التماسك ، انعدام التماسك ، ثلاثي الابعاد.

1. INTRODUCTION

Urban tunnels, typically situated at shallow depths, are susceptible to substantial impact from nearby construction of new buildings or additional loading on the ground surface. Consequently, evaluating tunnel stability, ensuring lining safety, and assessing ground settlement become imperative after the imposition of surcharge loads. This surcharge has a direct effect on the tunnel crest. The effect of the surcharge may increase with the presence of the water table.

The effect of the material of the lining as reinforcement concrete was investigated on two adjacent tunnels in soft clay. Mohr-Coulomb model was used to simulate the nonlinear of the soft clay soil with modulus of elasticity (E_s) 500 to 1900 kN/m² and Poisson's ratio (μ_s) 0.4, 0.425, 0.45 and 0.49. The analysis indicated that, the horizontal distances between the tunnels slight effect on the internal forces and stresses [1]. Some studies found that the thickness of tunnel lining has minor effect on the tunnel deformational [2-5]

The maximum settlement of an existing tunnel crown decreases as the undercrossing angle increases, on the other hand, the vertical spacing between a newly constructed tunnel and an existing tunnel leads to an increase of the peak value of crown settlement [6]. They also found that, friction angle ϕ is the dominant parameter affecting crown deformation of the existing tunnel, while, the cohesion c is of less influential. During the process of route selection, it is suggested to keep the vertical spacing between new tunnel and the existing tunnel greater than the external diameter of the new tunnel discussed the various factor responsible for the stresses in tunnel lining in soft soil [7]. Also, give brief idea about the method of analysis and construction of tunnel developed in recent year.

The effects of overlying soil type on a tunnel excavated in soft ground has been studied on the stresses developing in the tunnel lining [8]. They found, depending on the thickness and location of the overlying stratum, the presence of a stiff or dense layer above the tunnel had a significant impact on the stresses developing in the tunnel lining. Large-diameter tunnels are underground structures in which the length is much larger than the cross-sectional dimension. Tunnels are dug in different types of geo-materials varying from soft clay to hard rock. The method of tunnel construction depends on such factors as the ground conditions, the ground water conditions, the length and diameter of the tunnel drive, the depth of the tunnel, the logistics of supporting the tunnel excavation, the final use and shape of the tunnel and appropriate risk management [9].

Performed a reduced-scale physical model testing to study the interaction between closely spaced twin tunnels in clay [10]. It was found that the displacement and moment interaction effects increase as the spacing between twin tunnels is reduced, and it is small when the distance between tunnels is more than 1.5D (D = diameter of tunnel). A significant effect was observed on surface settlement curve if the twin tunnels were built with a spacing of less than (3D) [4]. Investigated the effect of spacing of Istanbul Twin Metro Tunnels on the surface settlement [11]. For this purpose, the focus has been placed on the effect of transversal spacing between tunnels protecting method. (FLAC3D) was implemented to simulate the excavation sequence. According to the analysis, the amount of settlement by numerical approach was about 23.5 mm which was in good agreement with the field monitoring results that was 26.5 mm. Moreover, the interaction between twin tunnels by the increase in spacing between twin tunnels in the direction perpendicular to tunnel axis decreases and becomes less effective at the location about 3

times of the tunnel diameter. Similarly, the interaction between twin tunnels in the direction parallel to tunnel axis decreases as the spacing increases.

The relationship between twin tunnel distance and surface subsidence in soft ground has been introduced [12]. He presented a series of finite element analyses carried out for line 1 of Tabriz metro 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.

In the present study, the effect of soil type and clay elastic modulus; tunnel diameter on the ground settlement, vertical displacement and lateral deformation on the tunnel, besides, maximum stress in soil between the two tunnels were investigated. The twin tunnels spacing and soil cover above the tunnel were taken as $1.5D$ (where D is tunnel diameter). The tunnel diameter was in the range of 6.0m to 15.0 m. The numerical study was carried out using Plaxis 3D finite element program.

2. MODELING CONFIGURATION

In the present study a model proposed for twin adjacent tunnels was developed and verified based on field case study by [4,7]. the results of the developed model were in fair agreement with those of the case study.

Plaxis 3D program was used to conduct a plane strain analysis for twin circular tunnels. The model boundaries were extended far from the twin tunnel to eliminate the boundary effect. The model configuration varies with the variation of tunnel diameter according to the boundary conditions.

The soil simulated according to the finite element in the present study, **Fig. 1** illustrates the geometry of the model that has been developed to examine the impact of variation of tunnel diameter from 6 to 15 m of tunnel (6m- 8m – 10m -12m and 15m) with constant soil type. Soil type was use investigated using sand as cohesion less soil with relative density varies from loose to dense, and clay as cohesive soil with consistency varies from soft to stiff.

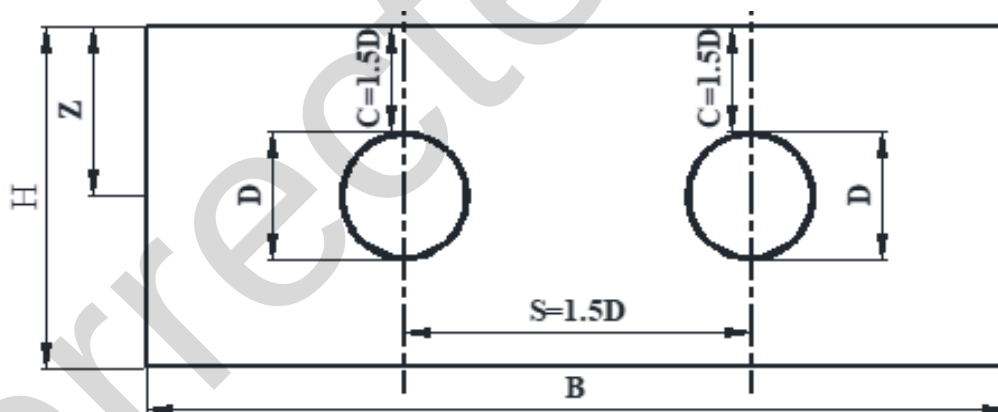


Fig. 1: Configuration twin circular tunnels model.

3.COHESION LESS SOIL.

In the effect of granular soils were investigated with consistency varies from loose to dense. The parameters used in this study are summarized in **Table. 1**.

Table 1: Parameters of cohesion less soil

Parameters of layer	Loose sand	Medium sand	Dense sand
Unit weight of soil (γ) kN/m ³ (1)	16	18	20
Angle of internal friction (ϕ) (2)	28°	33°	38
cohesion c	1	1	1
Poisson's ratio μ (1)	0.25	0.3	0.35
Elastic modulus E (MPa) (1)	20	40	100

[13] Bowles (1996), [14] Terzaghi and peck (1967), UFC_3_220.

The tunnel lining thickness was kept constant as 300mm with variation of circular tunnel diameter taking into consideration that, the thickness of tunnel lining has minor effect on the tunnel deformational [2-5].

3.1 Deformation of Ground Surface

Deformation of ground surface with variation of tunnel diameter from 6.00 to 15.00 m for loose, medium and dense sand is represented in Fig. 2-Fig. 4 and Table 2. Shown values of surface settlement with diameter of tunnel for loose, medium dense, and dense sandy soil.

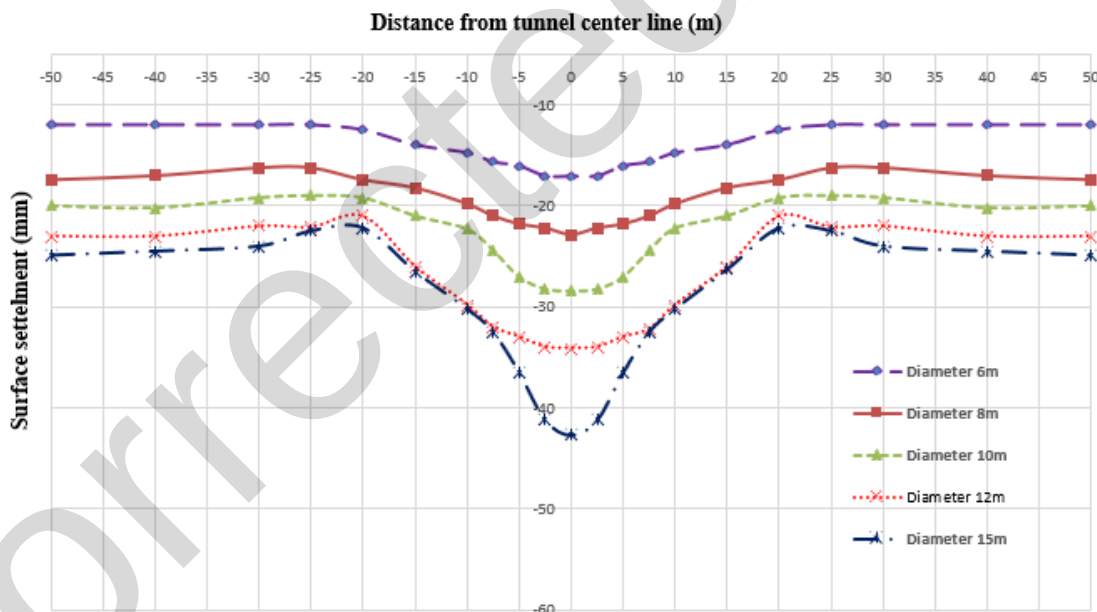


Fig. 2: Relationship between surface settlement and circular tunnel diameter loose sand.

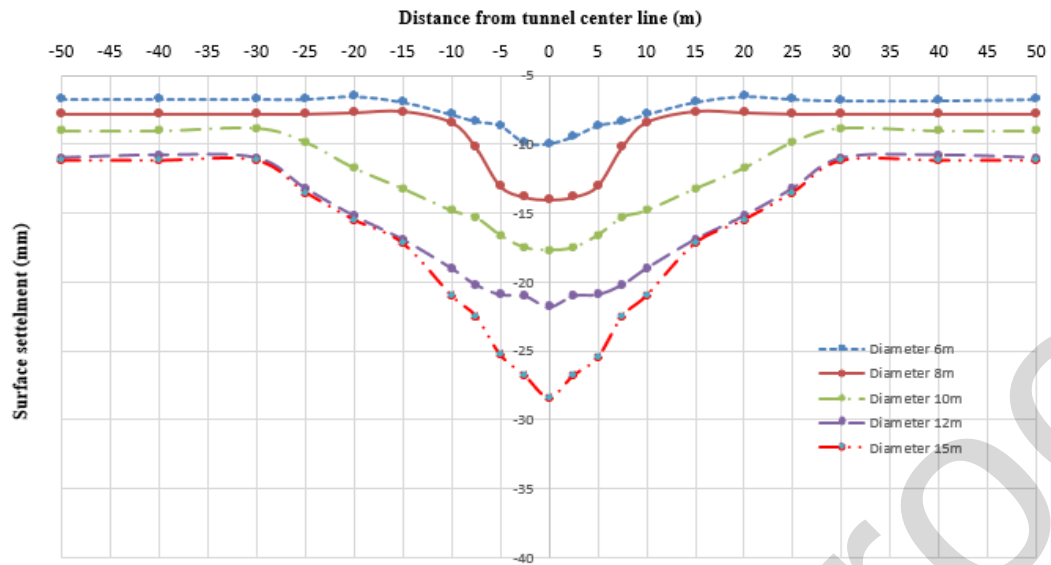


Fig. 3: Relationship between surface settlement and circular tunnel diameter for medium sand.

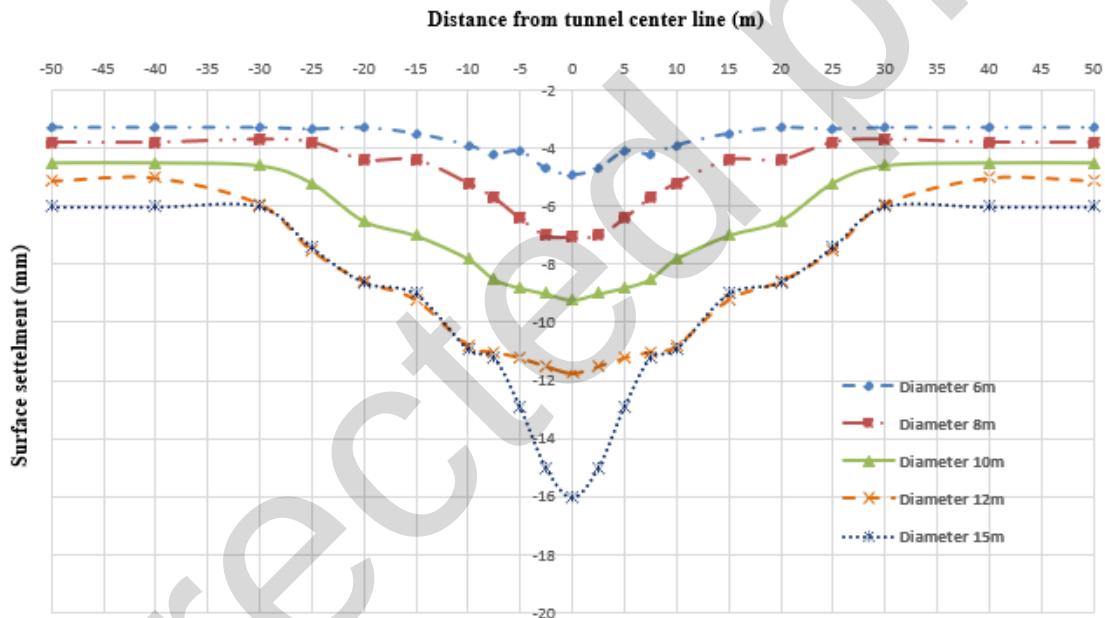


Fig. 4: Relationship between surface settlement and distance from circular tunnel diameter for dense sand.

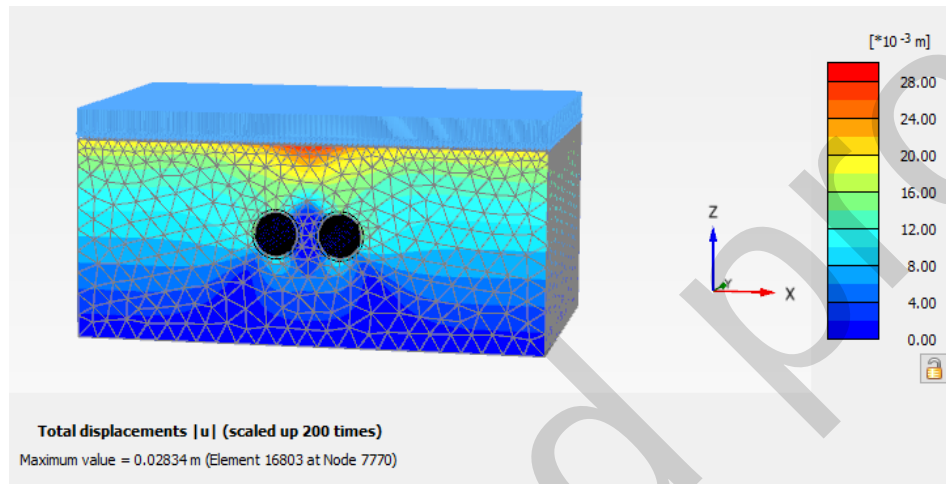
Table 2: Tunnel diameter and surface settlement for Sandy Soil with relative density

Tunnel (D) m	Loose Sand		Medium dense Sand		Dense Sand	
	Settlement (mm)	Increase in Rate (%)	Settlement (mm)	Increase in Rate (%)	Settlement (mm)	Increase in Rate (%)
6	17.1	---	9.84	---	4.94	---
8	22.82	33.45	14.11	43.39	7.03	42.30
10	28.28	65.38	18.43	87.30	9.21	86.44
12	34.12	99.53	23.09	134.65	11.74	137.65
15	42	145.61	28.2	186.59	16.02	224.29

From **Fig 2. to Fig 4.** it can be observed that, increasing circular tunnel diameter from 6.00 to 15.00 m had increased surface settlement by 220.4 % for dense sand, while for medium dense and loose values are observed in the order of 186.6% and 145.6% respectively on the other hand, tunnel diameter of 15.00 m has the higher order of ground at the mid-way between the two tunnels, and after 10 to 15 m its settlement pattern becomes nearly close to that of diameter = 12.00 m.

3.2 Tunnel Vertical Deformation

The tunnel vertical deformation for various relative density of sandy soil, with tunnel diameter from 6.00 to 15.00 m is plotted in **Fig 5.**



Max vertical deformation at crown of circular tunnel for diameter 10 m with loose sand.

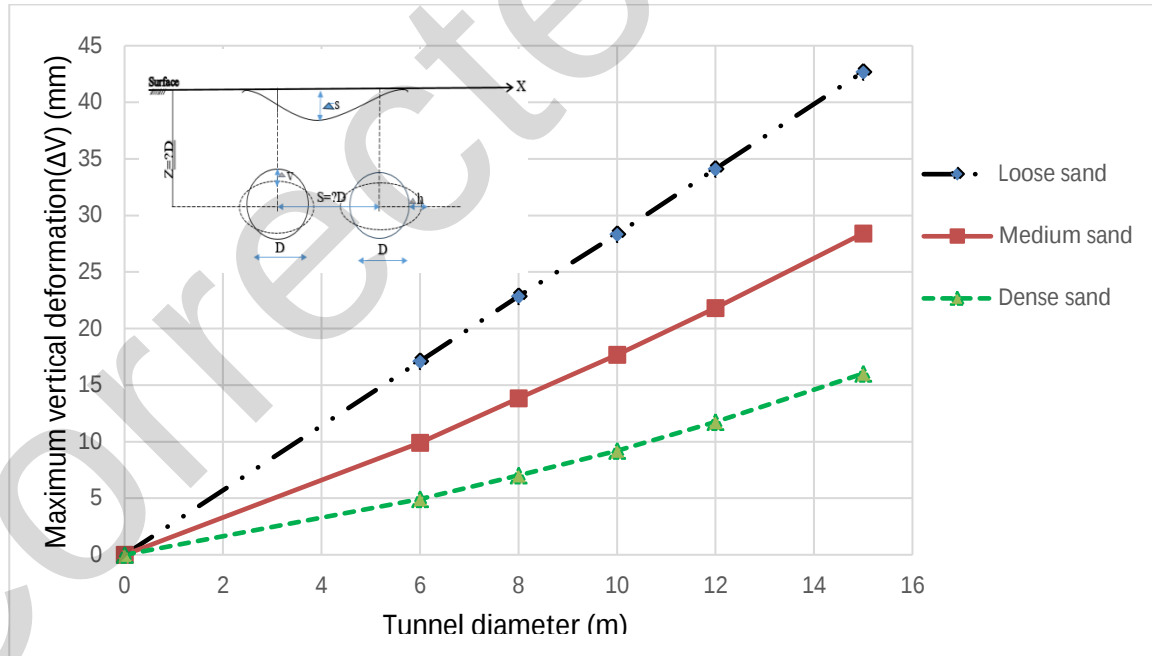


Fig. 5: Relationship between maximum vertical deformation and circular tunnel diameter for loose, medium and dense sandy soil.

For: Equation

Loose sand $\Delta V = 2.843D + 0.0243$

Medium sand $\Delta V = 1.888D - 0.775$

Dense sand $\Delta V = 1.888D - 0.775$

$R^2 = 1$

$R^2 = 0.9955$

$R^2 = 0.9955$

Where

$D \neq 0$

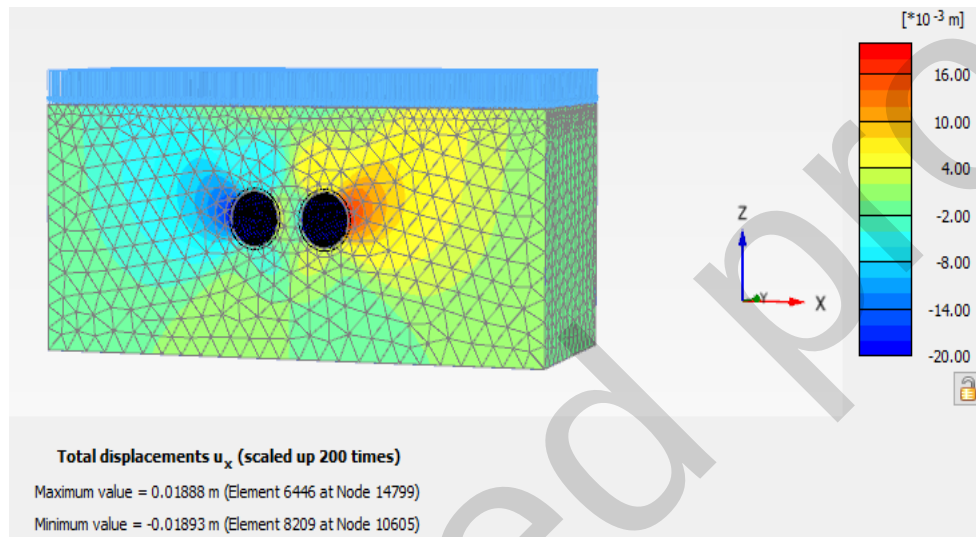
$D \neq 0$

$D \neq 0$

From **Fig. 5**, it can be observed that, with increase of circular tunnel diameter the vertical deformation increases in semi linear pattern, with the higher order for dense sand. On the other hand, increasing circular tunnel diameter from 6.00 to 15.00 m had increased the tunnel vertical deformation by about 224.29% for dense sand, while for medium sand and loose less values are observed in the order of 183.95% and 149.27% respectively.

3.3 Tunnel Lateral Deformation

The tunnel lateral deformation for loose, medium and dense sandy soil with variation of circular tunnel diameter from 6.00 to 15.00 m is represented in **Fig. 6**.



Maximum lateral deformation in soil at tunnel crown for (D=15) m, with spacing between two tunnels=1.5D, for medium dense sand.

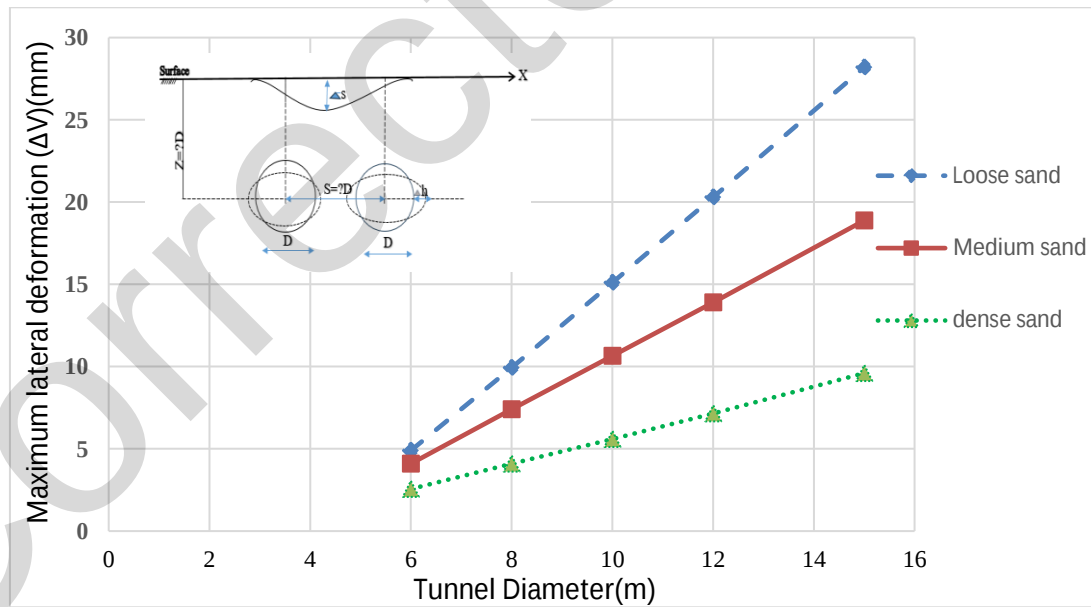


Fig. 6: Relationship between maximum lateral deformation of tunnel and circular diameter of tunnel with change soil type.

For Equation

Loose sand $\Delta h = 2.5902D - 10.735$
 Medium sand $\Delta h = 1.6396D - 5.7382$
 Dense sand $\Delta h = 0.7795D - 2.151$

$R^2 = 0.9999$

$R^2 = 1$

$R^2 = 0.9996$

Where $D \neq 0$

$D \neq 0$

$D \neq 0$

From **Fig. 6** it was found that, with the increasing circular tunnel diameter from 6.00m-15.00m the lateral deformation increased by 275% for dense sand, while for medium sand and loose high values are observed in the order of 360% and 475.3% respectively with increase of tunnel diameter. The tunnel lateral deformation is in inverse pattern to that of vertical deformation, where the higher order is for loose sand.

3.4 Maximum Stress in Soil Between the Two Tunnels

The effect of tunnel diameter on stresses induced between the two tunnels for different sandy soil states (loose- medium-dense) is presented in **Fig. 7**.

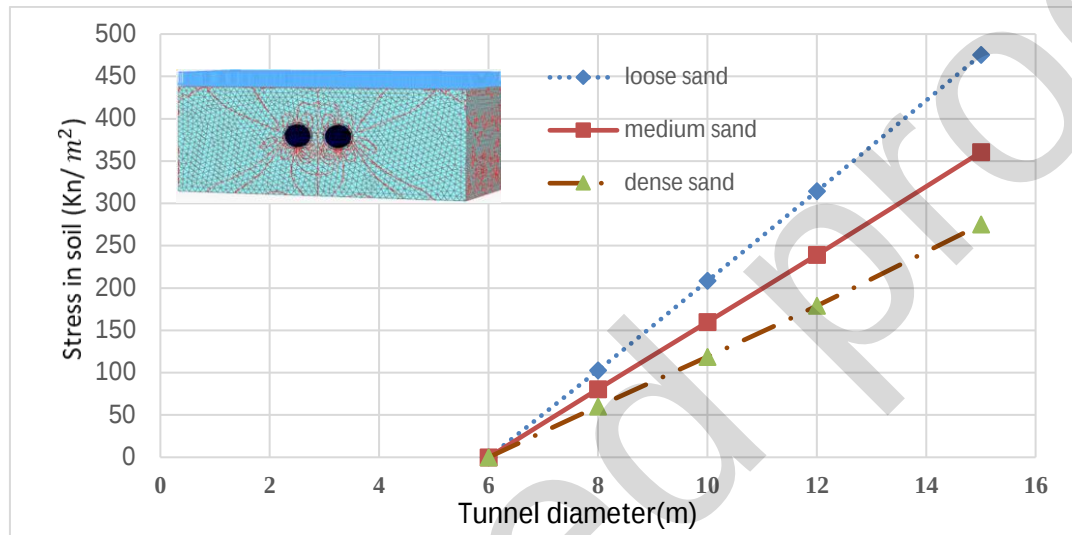


Fig. 7: Comparison between diameter of tunnel and soil type (loose- medium- dense) sand on induced maximum stresses in soil.

For equation:

Loose sand

$$\sigma = 52.862D - 319.07$$

Medium sand

$$\sigma = 39.991D - 239.96$$

Dense sand

$$\sigma = 30.45D - 184.03$$

Where

$D \neq 0$

$D \neq 0$

$D \neq 0$

From **Fig 7**. It can be observed that, stress in soil increases with the increase of circular tunnel diameter in linear relationship, with higher values for sand in dense state. Increasing the tunnel diameter from 6.00 to 15.00 m had increased the induced stresses between the tunnels by about 209.5% in case of dense state, while high values are observed for loose and medium by about 213.6% and 244.65% about respectively.

4.COHESSIVE SOIL

The effect of cohesive soil on the deformations of ground surface, tunnel, and stresses in soil were investigated for cohesive soil with consistency varies from soft to stiff. The parameters used in the numerical study are summarized in **Table 3**.

Table 3: Parameters of cohesive soil.

Parameters of layer	Soft clay	Medium clay	Stiff clay
Unit weight of soil γ kN/m ³ ⁽¹⁾	16	17	18
Angle of internal friction ϕ ⁽²⁾	20°	21°	22°
Cohesion c ⁽²⁾	10	20	30
Poisson's ratio μ ⁽¹⁾	0.2	0.2	0.3
Elastic modulus E mPa ⁽³⁾	10	20	60

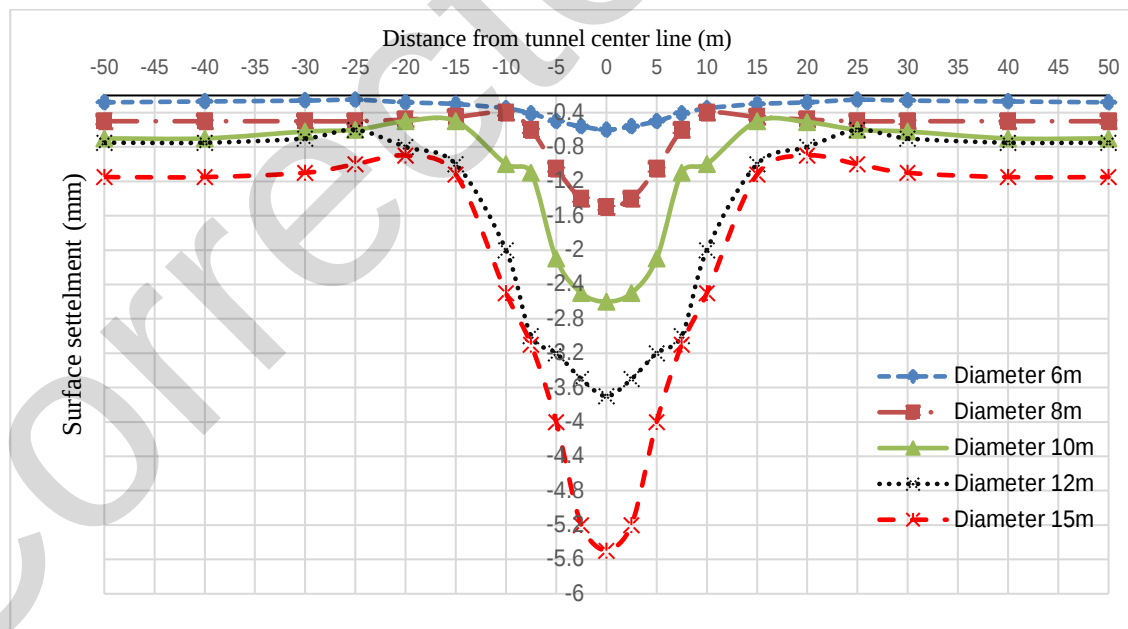
[13].Bowles (1996), [14].Terzaghi and peck (1967), UFC_3_220. [15].Narunat, .et.al (2018).

4.1 Deformation of Ground Surface

The deformation of ground surface with variation of tunnel diameter from 6.00 to 15.00 m for soft, medium and stiff clayey soil is represented in **Figs. 9 -Fig. 10**. The ground settlements with variation of tunnel diameter are listed in **Table 4**.

Table 4: Tunnel diameter and surface settlement for soft, medium, and stiff clayey soil.

Tunnel (D) m	Soft Clay		Medium Stiff Clay		Stiff Clay	
	Settlement (mm)	Increase in Rate (%)	Settlement (mm)	Increase in Rate (%)	Settlement (mm)	Increase in Rate (%)
6	0.8	---	0.6	---	0.43	---
8	1.76	120.0	0.98	63.33	0.92	11395
10	2.6	225.0	1.82	203.33	1.88	337.20
12	3.7	362.5	2.4	300.00	2.5	481.39
15	5.5	587.5	4.3	616.67	3.7	760.47

**Fig. 8: Surface settlement in soft clayey soil.**

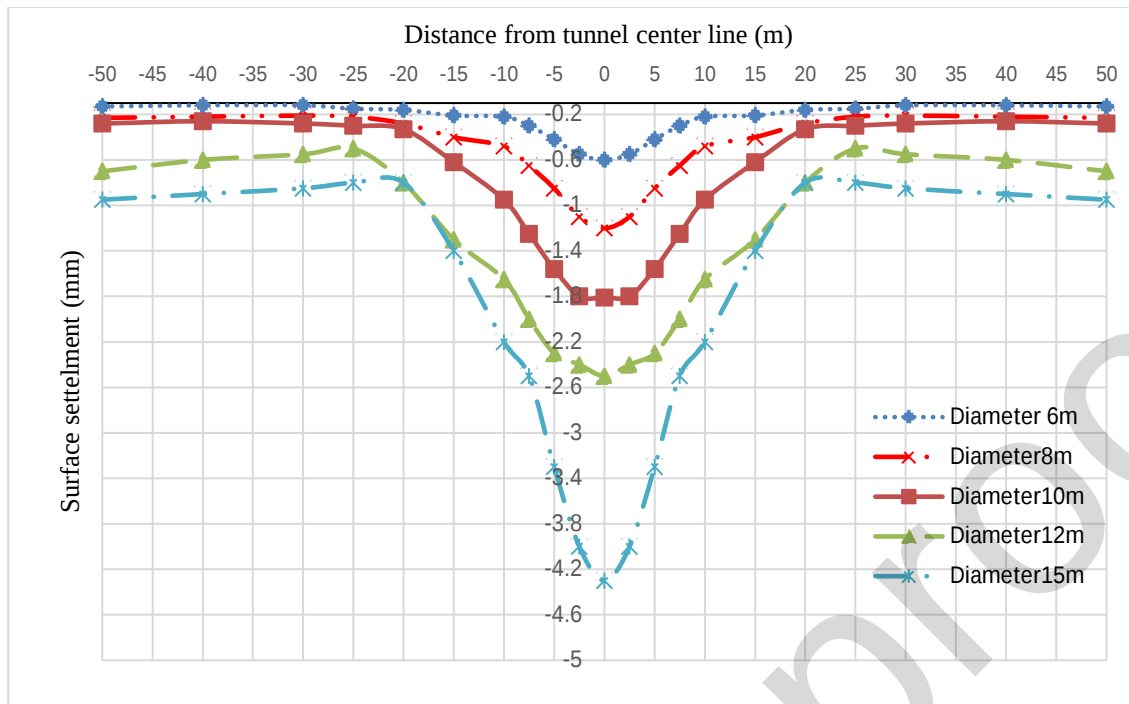


Fig. 9: Surface settlement in medium stiff clayey soil

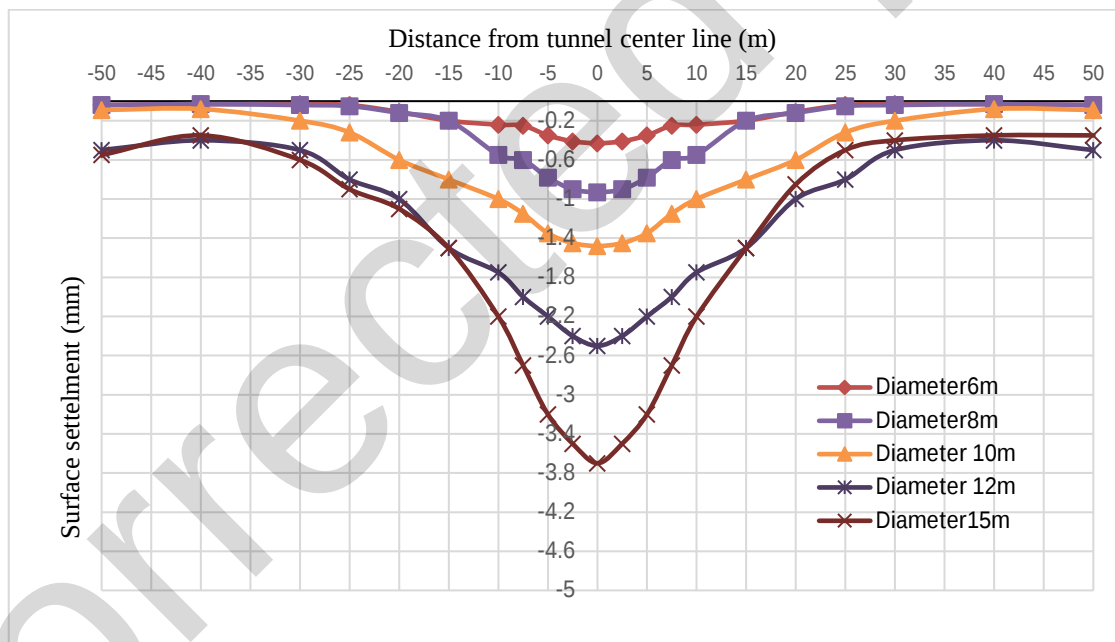
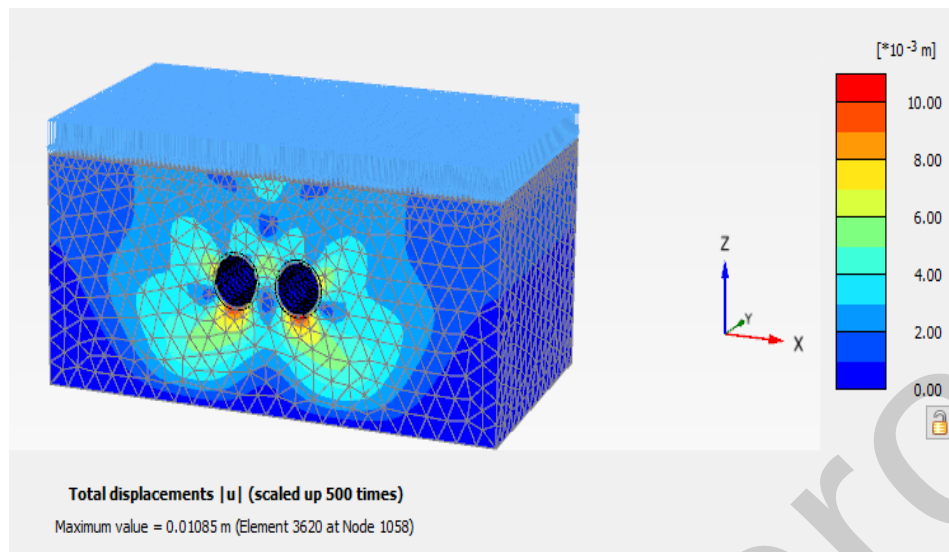


Fig. 10: Surface settlement in stiff clayey soil.

From Fig 8. to Fig 10. it can be observed that, increasing tunnel diameter from 6.00 to 15.00 m had increased surface settlement by 760% for stiff clay, while for medium and soft clay less values are observed to be in the order of 616,6% and 587.5% respectively. On the other hand, circular tunnel diameter of 15.00 m has the higher order of ground at the mid-way between the two tunnels, and in case of medium stiff to stiff clay after about 10 m its settlement pattern becomes nearly close to that of diameter = 12.00 m, while in case of soft clay this pattern is observed after about 7.5 0 m.

4.2. Tunnel Vertical Deformation



Max vertical deformation at crown of tunnel for diameter 12m in soft clay.

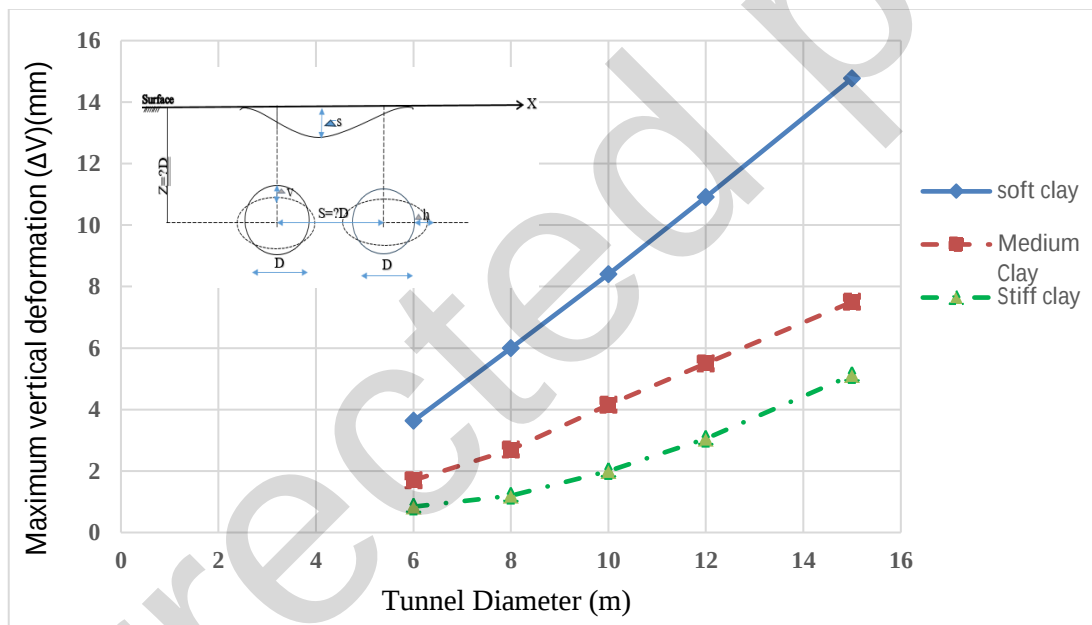


Fig. 11: Maximum tunnel vertical deformation at crown in soft, medium stiff and stiff clayey soil

For Equation

Soft clay

$$\Delta V = 1.2379D - 3.8843 \quad R^2 = 0.9996 \quad \text{Where } D \neq 0$$

Medium clay

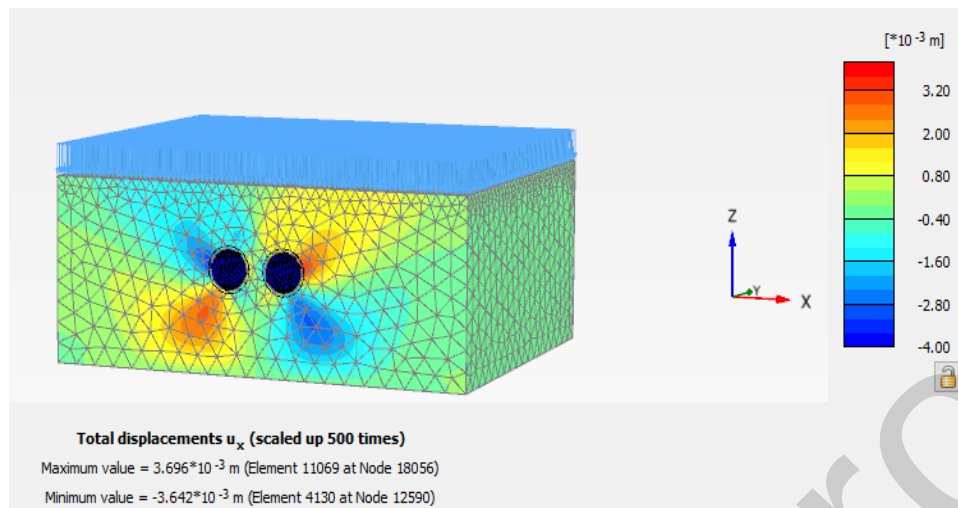
$$\Delta V = 0.6555D - 2.3764 \quad R^2 = 0.9975 \quad D \neq 0$$

Stiff clay

$$\Delta V = 0.4815D - 2.4695 \quad R^2 = 0.9552 \quad D \neq 0$$

From Fig. 11 it can be observed that, the circular tunnel vertical deformation increases with the increase of tunnel diameter in semi linear relationship, with higher values in case of soft clay state. Increasing tunnel diameter from 6.00 to 15.00 m had increased vertical deformation by 509.8% for stiff clay, while for medium clay and soft clay less values are observed in the order of 341.17% and 306.8% respectively, after tunnel diameter of 12.00 m, the linear rate of increase in vertical deformation is in higher order compared to that for diameter from 6.00 to 12.00 m.

4.3 Tunnel Lateral Deformation



Maximum lateral deformation in soil at crown of tunnel for (D=10) m, with spacing between two tunnels=1.5D, for soft clay.

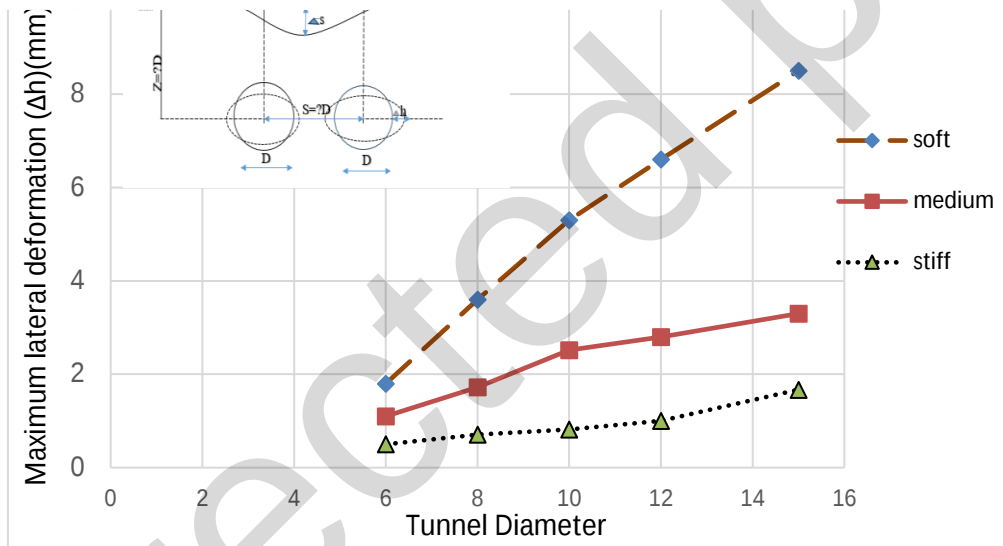


Fig. 12: Circular tunnel diameter and maximum lateral deformation in soft, medium stiff and stiff clayey soil

For equation

Soft clay	$\Delta h = 0.7406D - 2.3939$	$R^2 = 0.9923$	Where $D \neq 0$
Medium clay	$\Delta h = 0.2453D - 0.2143$	$R^2 = 0.9554$	$D \neq 0$
Stiff clay	$\Delta h = 0.2453D - 0.2143$	$R^2 = 0.9554$	$D \neq 0$

The presentation of **Fig. 12.** shows that, with the increasing circular tunnel diameter from 6.00m-15.00m the lateral deformation increased by 234% for stiff clay, while for medium sand and soft clay high values are observed in the order of 236.6% and 236% respectively with increase of tunnel diameter.

4.4 Tunnel Lateral Deformation

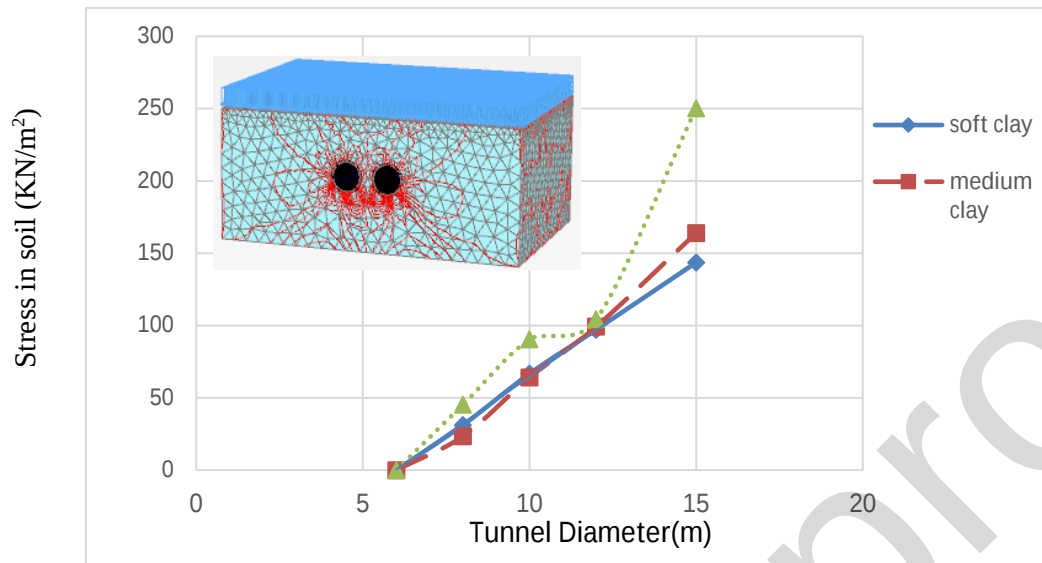


Fig. 13: Circular tunnel diameter and soil induced stresses in soft, medium stiff, and stiff clayey soil

For equation

Soft clay

$$\sigma = 16.029D - 95.808$$

Where $D \neq 0$

Medium clay

$$\sigma = 18.469D - 118.26$$

$D \neq 0$

Stiff clay

$$\sigma = 26.055xD - 167.77$$

$D \neq 0$

From Fig. 13 it can be observed that Stress in soil increasing with increased diameter of tunnel from (6m-15m) the stress in soil by 250 % for stiff clay, while for medium clay and soft clay less values are observed in the order of 163.9% and 143.56% respectively. with the increase of tunnel diameter, the stress in soil linearly increased.

5. EFFECT OF SOFT CLAY ELASTIC MODULUS

The effect of variation of the elastic modulus for soft in the range of (5 to 25) MPa on ground settlement and tunnel deformations are presented Fig. 14 - Fig. 16.

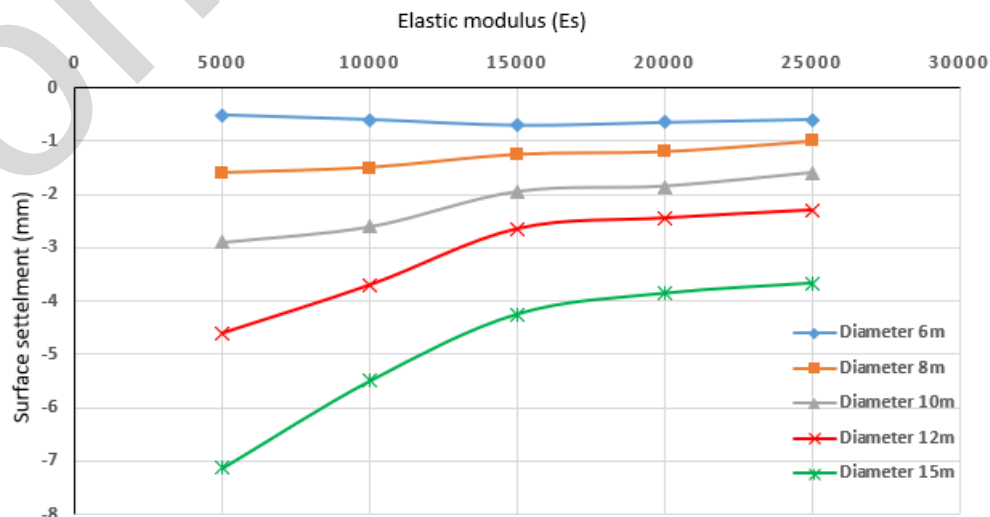


Fig. 14: Elastic modulus of soft clay settlement of ground surface

It is clear from **Fig. 14** that with increase of soft clay elastic modulus, the surface settlement decreases up to tunnel diameter of 6m, after which the rate in decrease in surface settlement becomes negligible.

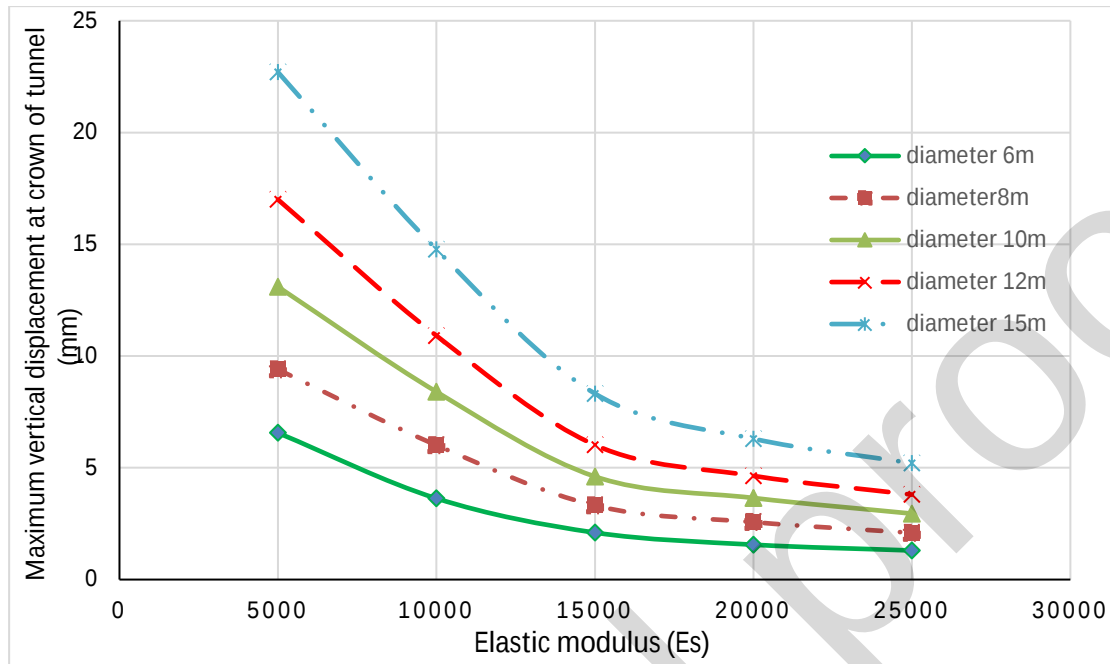


Fig. 15. Elastic modulus of soft clay maximum vertical deformation.

From **Fig. 15**: it can be observed that, increase elastic modulus from 5 MPa to 25 MPa decreased the vertical displacement in soil by about 11.46%.

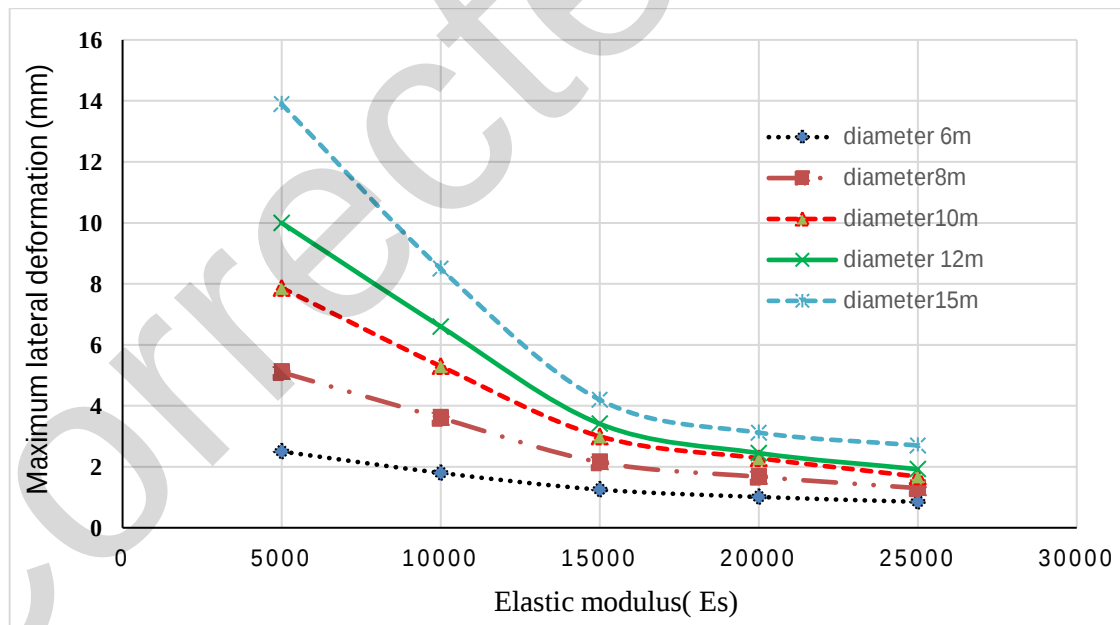


Fig. 16: Relation between maximum lateral deformation of tunnel and diameter of tunnel with change elastic modulus (E) (5000-25000) KPa. for soft clay.

From **Fig. 16** it can be observed that, increase elastic modulus for (5- 25) MPa decreased lateral deformation of tunnel by 6.48%. for diameter 6m values of lateral deformation negligible.

CONCLUSIONS

From the present study, the following conclusions are obtained:

- 1) Increasing circular tunnel diameter from 6.00 to 15.00 m had increased ground surface settlement by 220.4 % for dense sand, while for medium dense and loose less values are observed in the order of 186.6% and 145.6% respectively.
- 2) The tunnel vertical deformation increases with increase of tunnel diameter in semi linear pattern. Increasing tunnel diameter from 6.00 to 15.00 m had increased the tunnel vertical deformation by about 224.29% for dense sand, while for medium sand and loose less values are observed in the order of 183.95% and 149.27% respectively.
- 3) The tunnel lateral deformation increased by 275% for dense sand, while for medium sand and loose high values are observed in the order of 360% and 475.3% respectively with increase of tunnel diameter. The tunnel lateral deformation is in inverse pattern to that of vertical deformation, where the higher order is for loose sand compared with that for dense sand
- 4) Stress in soil increases with the increase of circular tunnel diameter in linear relationship, with higher values for sand in dense state. Increasing the tunnel diameter from 6.00 to 15.00 m had increased the induced stresses between the tunnels by about 209.5% in case of dense state, while high values are observed for loose and medium by about 213.6% and 244.65% about respectively.
- 5) In clay, increasing circular tunnel diameter from 6.00 to 15.00 m had increased ground surface settlement by 760% for stiff clay, while for medium and soft clay less values are observed to be in the order of 616.6% and 587.5% respectively.
- 6) In case of stiff clay, stress in soil increased by about 250% with increase of tunnel diameter from 6 to 15 m, while for medium clay and soft clay less values are observed in the order of 163.9% and 143.56% respectively.
- 7) Increasing elastic modulus of soft clay decreased surface settlement for diameter 6m is negligible settlement, increase diameter of tunnel increasing surface settlement.
- 8) Settlement of ground surface due to tunneling in loose or medium dense sand with diameter of 10.00 m is much higher than that in soft or medium stiff clay in the order of about 9 times, while in dense sand it becomes about 4 times that on stiff clay.

CONFLICT OF INTEREST

The authors have no financial interest to declare in relation to the content of this article.

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