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FINITE ELEMENT INVESTIGATION ON THE INTERACTION BETWEEN SHALLOW AND DEEP EXCAVATED TWIN TUNNELS

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ABSTRACT

In the twin tunnel, the spacing between tunnels or pillar width is an important issue for stability, because the mutual interference between tunnels depends on it during the construction sequence. It must be calculated with respect to tunnel size, soil condition, foundation type, construction method, and construction sequences. The tunnel and soil around it responses are also dependent on the clear distance between tunnels. Therefore, enough clear distance between tunnels must be maintained to ensure the tunnel stability. Sometimes, the surface movements and the interaction with existing foundations are required to be calculated. The shallow and deep twin tunnels in the present research are analyzed using PLAXIS finite element software. The analysis results obtained from finite elements are compared with experimental test results and analytical solutions obtained by other researchers. The present study show that the interaction between twin tunnels can be ignored for tunnel distances greater than the diameter of tunnel multiplied by 4.

Keywords: clay soil, deep and shallow, pillar width, settlement, soil -structure interaction, twin tunnels.

INTRODUCTION

The need for constructed tunnels in Arab countries, mainly for transportation purposes are increased in recent years. Sometimes, it is required to build new tunnel in close to existing constructed tunnels and the construction process has to be carried without causing any expected damages either to the existing buildings or to subsurface infrastructure. Therefore, it is required to predict possible interaction effects before reaching the design stage.

The surface soil settlements, S in the existing of a single tunnel built beneath in soft soil are assumed to obey an inverted Gaussian curve defined by Peck (1969) and examined by different site investigations and measurements [Mair *et al*. (1993)].
The proposed equations are given by:

$$S = S_{\max} \exp\left(-x^2 / 2i^2\right)$$
$$S_{\max} = \frac{V_s}{\sqrt{2\pi i}} = 1.252 \frac{V_L R^2}{i} \quad (1)$$

where x is the normal or perpendicular distance from the tunnel centerline axis, $S_{\max}$ is the maximum soil surface settlement (above the tunnel axis), , i is the settlement trough width, V_s is the volume loss, V_L is the percentage of ground loss if soil is incompressible ($V_L = V_s /(\pi \cdot R^2)$ and R is the tunnel radius) [Attewell and Farmer (1975)].

These settlements are developed due to the loss in volume which happens at the tunnel. It may be defined as the additional volume of excavated soil over the final lining volume. During excavation and as it proceeds, the soil around the tunnel face are unloaded and tend to move inwards. Losses may happen behind the tunnel face due to the nature or type of the tunnel shield. Many site or field studies have checked and confirmed that Equation 1 is acceptable for Green-field sites [Mair*et al.*(1993); Atkinson and Mair (1981)] but where building structures are present, as in cities, Equation 1 is assumed to be no longer valid.

For multiple installed tunnels, the settlements from each are determined by using Equation 1 and accumulated. This equation neglects the tunnel interaction during the installation or construction of each one. It is clear that the soil disturbance due to tunnel construction will change the surrounding soil properties, or redistribute the effect of a subsequent tunneling installation through that zone of soil.

Assuming multiple tunneling systems, with two parallel tunnels is considered. Due to installation of the second new tunnel, the first old tunnel and the soil surrounding moves as a rigid body. The redistribution of soil stresses develops "arching" around the new tunnel. This gives a gradual load removal from the tunnel. If the new or second tunnel is installed close to the first tunnel, the lining of first tunnel will distorted and has displacements. The minimum expected clear distance between the tunnels to prevent interaction effects depends on the position and soil properties.

Superposition method is proposed in case of multiple tunnels which is based on Gauss distribution as follows Mair *et al*. (1993)

$$S = S_{\max(1)} \exp\left[\frac{(x+T_s/2)^2}{2i_{(1)}^2}\right] + S_{\max(2)} \exp\left[\frac{(x-T_s/2)^2}{2i_{(2)}^2}\right] - S_{12} \quad (2)$$

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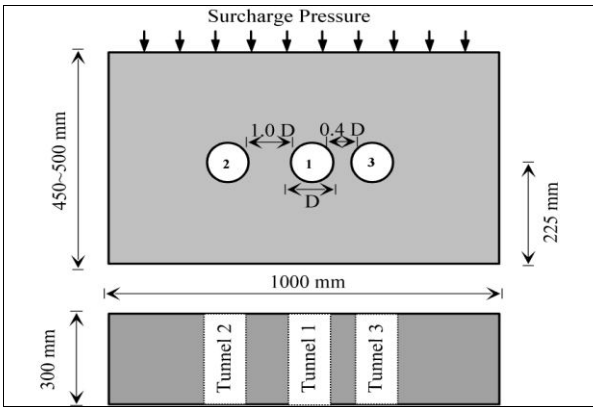
where S_{12}=0 for no interaction and T_s is the tunnels spacing. If the two tunnels have the same diameters and the ground loss, then $S_{\max(1)} = S_{\max(2)}$ and $i_{(1)} = i_{(2)}$. Finally the ground settlement is

$$S = S_{\max}\left\{\exp\left[\frac{(x+T_s/2)^2}{2i^2}\right] + S_{\max(2)}\exp\left[\frac{(x-T_s/2)^2}{2i^2}\right]\right\} \quad (3)$$

Previous researchers have been carried out the study using both experimental and finite element models to simulate the tunnel interaction. Ghaboussi and Ranken (1977) carried out analysis based on linear plane strain finite elements of multiple installed tunnels assuming the soil to be elastic. They showed that tunnel interaction effects were lesser for a clear space between the outside of two tunnels (pillar width) equals to tunnel diameter (1D). However, for a pillar width larger than 2D there was no significant tunnel interaction. Therefore the tunnels are considered as independent and settlements calculated accordingly.

Kim (1996) studied the effect of shield tunnel construction on the developed and induced displacements that are formed in the linings of existing close old tunnels through. The author carried out experimental model tests in which the tunnels were installed using a miniature shield tunneling machine. The experimental models were simulated with few number of two-dimensional plane finite elements. The adopted models are chosen to be similar to the models that mentioned by Ghaboussi and Ranken (1977). The difference was that special finite elements treatments were used to simulate the soil boundary movement related to tunnel installation. A set of five experiments have been made using kaolin clay samples consolidated in the tank with plane strain shown in Figure-1. In single clay soil sample, three tunnels were used and installed to carry out two interaction tests. One of these experiments was for a far tunnel (tunnel center-line spacing of 2.0D) and the other was for a near' tunnel (tunnel center-line spacing of 1.4D) where D is the tunnel diameter. The plane strain condition consisted of a rectangular tank with internal dimensions 1000 mm by 300 mm in plan and 600 mm in depth. Two 25 mm thick perspex walls were used having three holes (corresponding to the installation positions of the model tunnels).



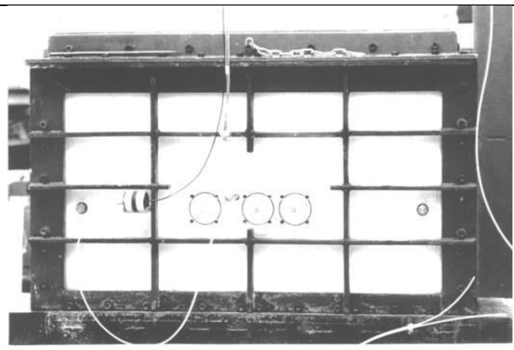


Figure-1. Layout of plane strain tank.

A set of additional experimental tests were carriedout by Kim (1996) in which the tunnels were put normal rather than parallel. A farther details and discussion of these tests are given by Kim (1996).

The soil properties and geometry of the plane strain experimental tests are specified in Table-1.

Table-1. Specification of the tests carried by Kim (1996).

Test	**H/D**	**Su** (kPa)	**OCR**	**t** (mm)	**Ps** (kPa)
PS1	3.36	23.4	1	0.254	88.5
PS2	3.39	24.3	2.9	0.254	38.4
PS3	3.94	20.7	1	0.356	88.5
PS3R	3.79	21.6	1	0.356	88.5
PS4	3.65	24.3	2.81	0.356	41.3

where su = Undrained shear strength of clay, Ps = Surcharge pressure, t = Liner thickness

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The clay soil samples were prepared by a kaolin slurry consolidation within the test rig itself. The used test soil samples were clay of either normally consolidated or over- consolidated with a value of approximately 3 for OCR. This value of OCR was chosen to represent real conditions in London Clay. All test samples had approximately the same shear strength of soil (about 20 kPa).

The 70 mm diameter plain steel tubes are used as tunnel liners. The tube thicknesses are selected to obtain the correct tunnel lining stiffness

FINIE ELELMENT ANALYSIS

The study of interaction problems between constructed tunnels is complicated and cannot be fully investigated through using prototype model testing because it is required many study parameters. The finite element modeling of such problems are carried out to check the obtained results, it is first necessary to develop realistic modeling procedures. The finite elements have also been used to investigate some of the modeling assumptions inherent in the physical tests. The analysis is limited to the case of the undrained condition to model interaction behavior immediately after tunnel construction. A plasticity soil model adopting Mohr-Coulomb yield criterion is used in the analysis of models. Fifteen node triangular continuum elements are used to simulate the soil and shell elements are used to model the tunnel liners. Figure-2 shows the used mesh in finite elements model analysis. The material properties of the lining and the soil are presented in Tables 2 and 3.

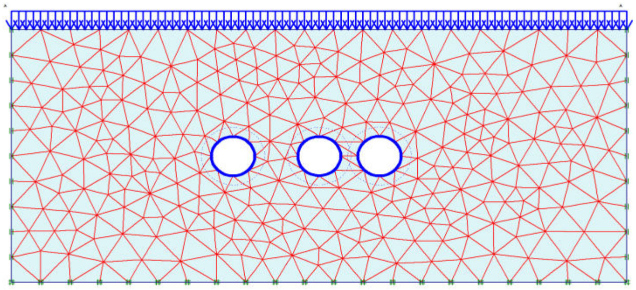


Figure-2. Finite element mesh.

Table-2. Material properties of the lining.

Parameters	Name	Value	Unit
Norma stiffness	EA	50800	N/mm
Flexural rigidity	EI	300	$N/mm^2/mm$
Thickness	d	0.254	mm
Poisson's ratio	ν	0.3	-

Table-3. Material properties of the soil.

Parameters	Name	Value	Unit
Dry soil weight	γ_{dry}	15e-6	N/mm^2
Wet soil weight	γ_{sat}	18e-6	N/mm^2
Permeability	k	0.1	mm/day
Young's modulus	E_s	6.8	N/mm^2
Poisson's ratio	ν_s	0.3	
Cohesion	c	0.02	N/mm^2
Friction angle	ϕ	0.0	
Dilatancy angle	ψ	0.0	
Effective stress ratio	K_o	0.64	

The tunnel excavation was modeled numerically through deactivating the soil elements inside the tunnel [Augarde *et al.* (1995)]. In these analyses, it was important to simulate the void between the soil and tunnel liner as a result of the tunnel overcutting. This was done by applying to the inside of the tunnel liner a suitable hydrostatic suction in order to reduce its circumference. This method or procedure is expected to produce varying hoop force or stress values.

The following procedures were used for modeling the construction of each tunnel in the analyses.

a) Apply initial stresses to soil with tunnel shell elements deactivated. The expression $0.64\sqrt{OCR}$ is assumed to give K_o value.

b) Remove excavated soil elements inside the tunnel.

c) Activate tunnel shell elements to model tunnel liner in tunnel position to be installed.

d) Apply internal pressure to simulate ground loss.

Three separate calculation procedures were adopted for comparison with experimental work as given below.

a) Single tunnel installation or construction in position 1.

b) After installation or construction of tunnel in position 1, the tunnel at position 2 is installed.

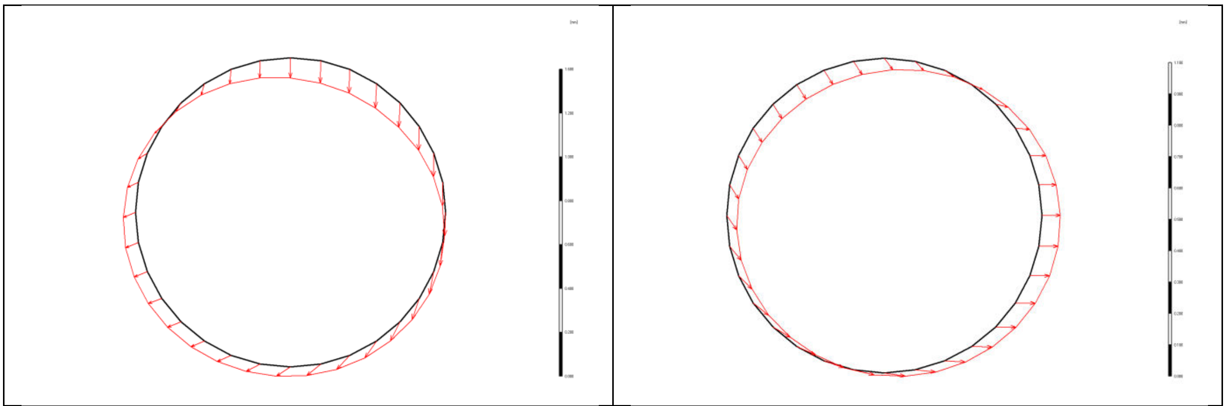
c) Tunnel installation or construction in position 3 after tunnels are constructed or installed at positions 1 and 2.

Cases 1,2 and 3 were intended to represent the procedures adopted in the experimental model tests carried by Kim (1996)

VERFICATION WITH PREVIOUS TEST RESULTS

The results presented in this article are concerned with the comparison between the test results of PS3 sample that was carried by Kim (1996) and the present study finite elements. In general, the results of the experimental model tests show that tunnel interaction effects are larger for the pillar spring-line and old tunnel crown.

Figure-3[a] and [b] show typical displacement results of the old tunnel liner due to the addition of two new twin tunnels in positions 2 and 3 for the Kim (1996) experimental model and the present study numerical model. The obtained finite elements results show acceptable agreement with the data obtained from experimental model tests. The results show also that greater outward displacements of the pillar spring-line occurred if a new tunnel was added. In each case the tunnel crown displaced downwards; however movement of the invert was negligible. Similar general displacement pattern for tunnels installed at distance of 2.0D and 1.4D (from each other) is obtained with greater magnitudes for the near tunnel.



[a] Tunnel installed at position 2 (Spacing =2.0 D)	[b] Tunnel installed at position 3 (Spacing =1.4 D)

Figure-3. Additional displacement of the existing or old tunnel liner for PS3.

The tunnel deformations are shown through the values of horizontal diameter change at spring-line level and vertical diameter change. The existing tunnel immediate diameter changes after the construction of the new tunnels is drawn together with the tunnel spacing and shown in Figure-4. This figure shows the previous experimental results are plotted together with the present numerical analysis results. Figure-4 indicates acceptable agreement between the results obtained from physical and numerical models. These results show that the tunnels interaction effects are small for tunnel spacing exceeds 4 D.

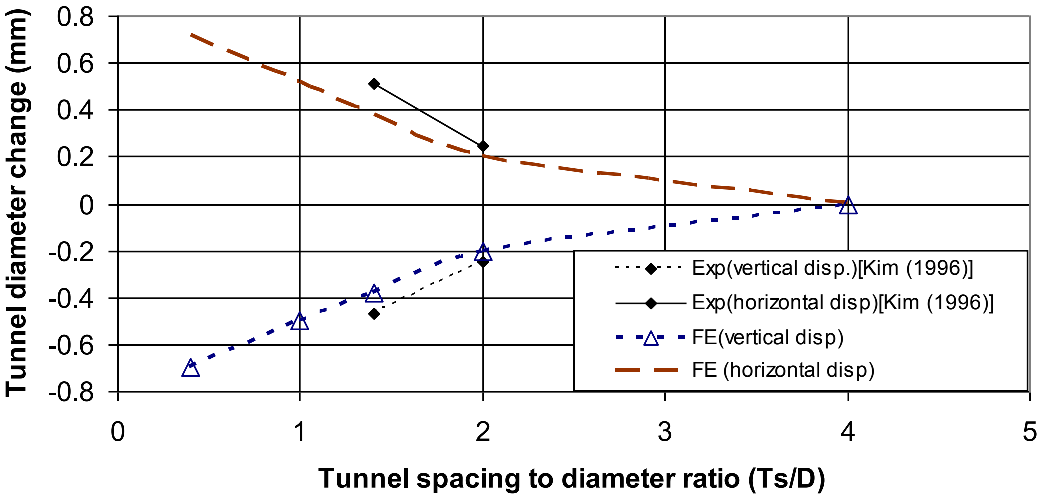


Figure-4. Tunnel diameter change against Tunnel spacing for PS3.

Figures 5 and 6 show the bending moments at each increment developed in the instrumented liner due to the existing of the 2nd and 3rd tunnels. In these figures M is the moment at each increment obtained in the installed tunnel after constructing the additional tunnels. The values obtained from the present study analysis and measured by

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Kim (1996) are drawn in these figures. The results show that significant values of bending moments were developed in the installed tunnel due to the installation of the new tunnels. Through the two used methods (the numerical and experimental tested model) the results is found to be agreed. As, the new tunnels are constructed close to an existing or tunnel, the increment in the moment developed at the pillar spring-line of the existing or old tunnel liner become larger.

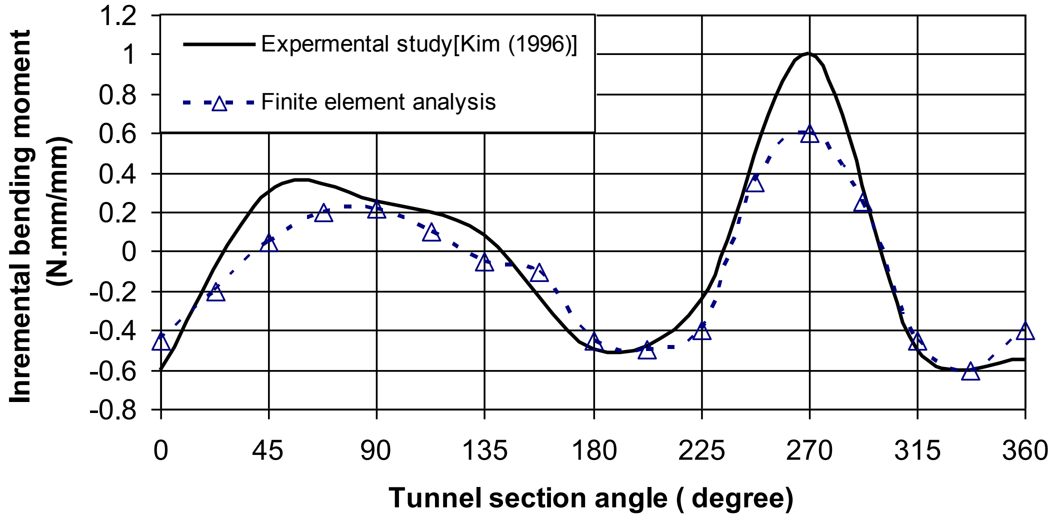

Figure-5. Additional Bending Moments (PS3) due to Tunnel installation at position 2 (Spacing=2.0 D).

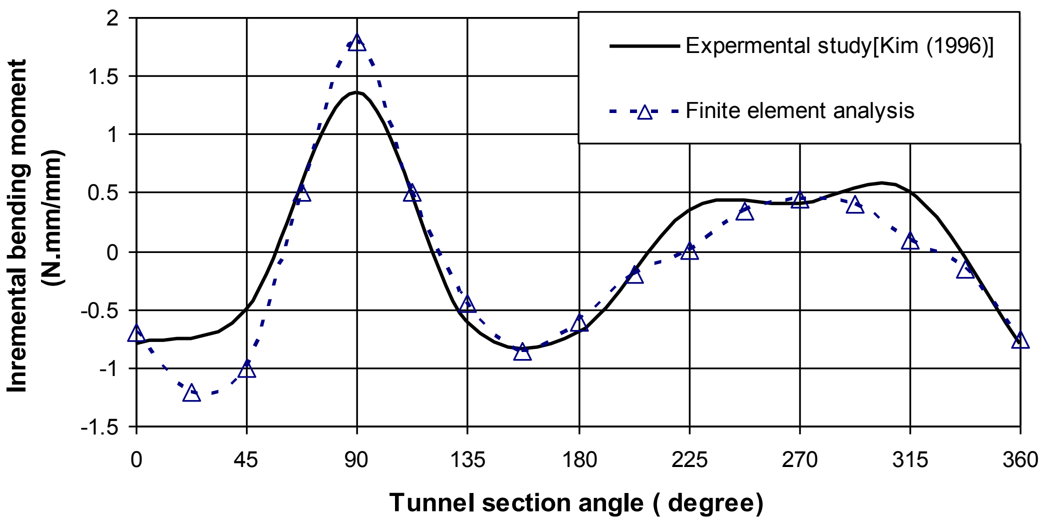

Figure-6. Additional Bending Moments (PS3) due to Tunnel installation at position 3 (Spacing=1.4 D).

SETTLEMENT DUE TO TUNNEL INTERACTION

This numerical study gives guidance on the possible ground settlement induced by one and two twin tunnels. The interaction and tunnel depth are studied as variable parameters. As shown in Figure-7, a finite element analysis model is used for solving the problem using the material properties and model dimensions for (PS1) problem. The effect of ground loading (surcharge) and water table are neglected here.

In general before excavation of the tunnels the soil system was in equilibrium. When the tunnels are excavated in soil, the soil equilibrium is disturbed and the soil moves to the boundaries of the tunnel.

Figures 8 and 9 compare surface settlement induced by one tunnel and two tunnels. Superposition method (equation 3) without interaction is also plotted for comparison. For one and two tunnels the numerical results agrees with the analytical solution obtained by Mair *et al* (1993) with a percentage of 3%.

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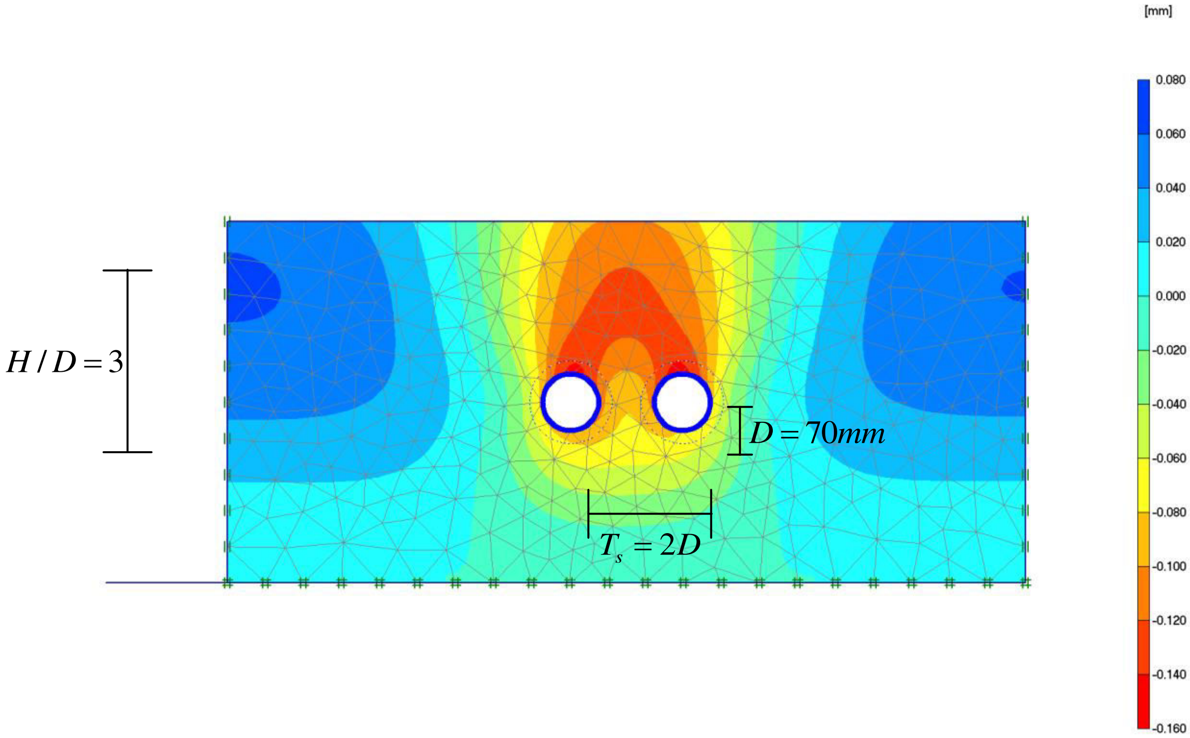

Figure-7. Tunnel model for finite element analysis.

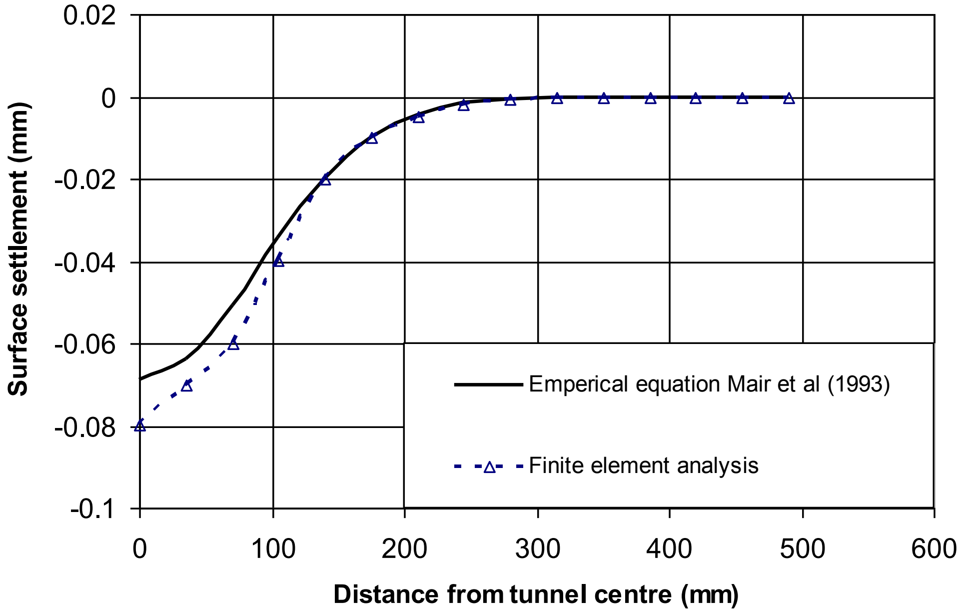

Figure-8. Comparison of surface settlement for one tunnel.

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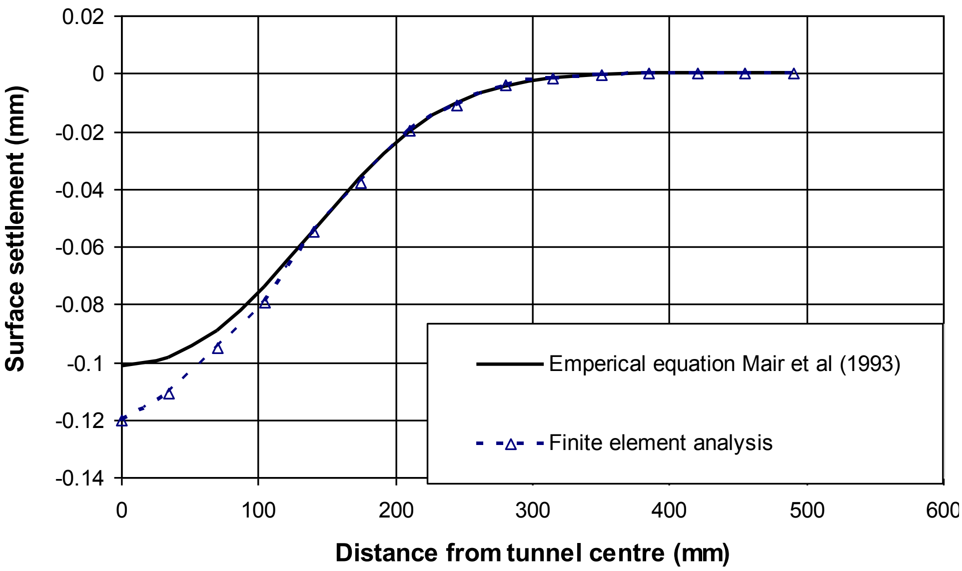

Figure-9. Comparison of surface settlement for two tunnels.

Figure-10 shows the interaction is an important index to the surface settlement. When the distance between tunnels spacing is greater than 4D, the interaction effect can be ignored and reduced values of surface settlement are obtained.

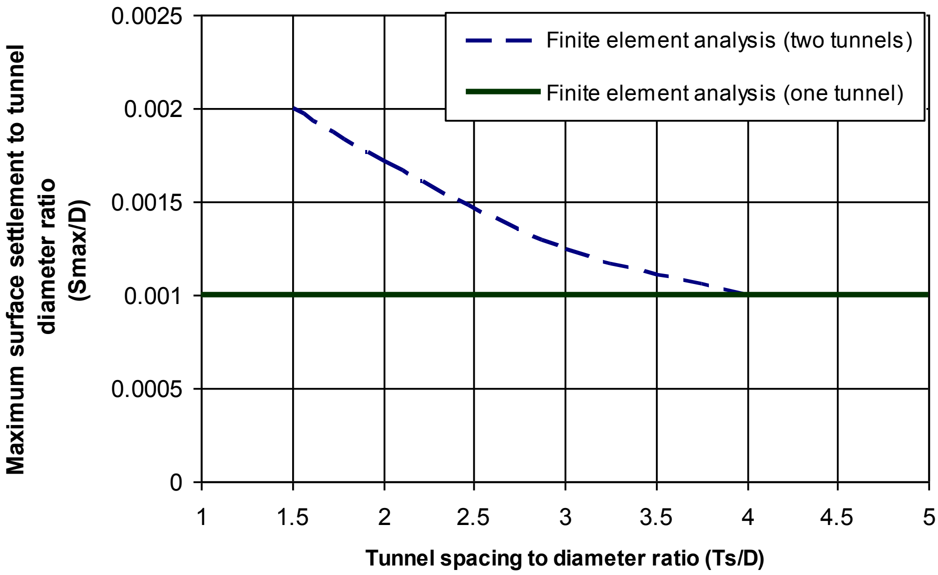

Figure-10. Effect of tunnel spacing on the maximum surface settlement (H/D=3).

Figure-11 shows the effect of tunnel depth is a major factor on the surface settlement. When the depth of tunnel is large, the surface settlement value is reduced.

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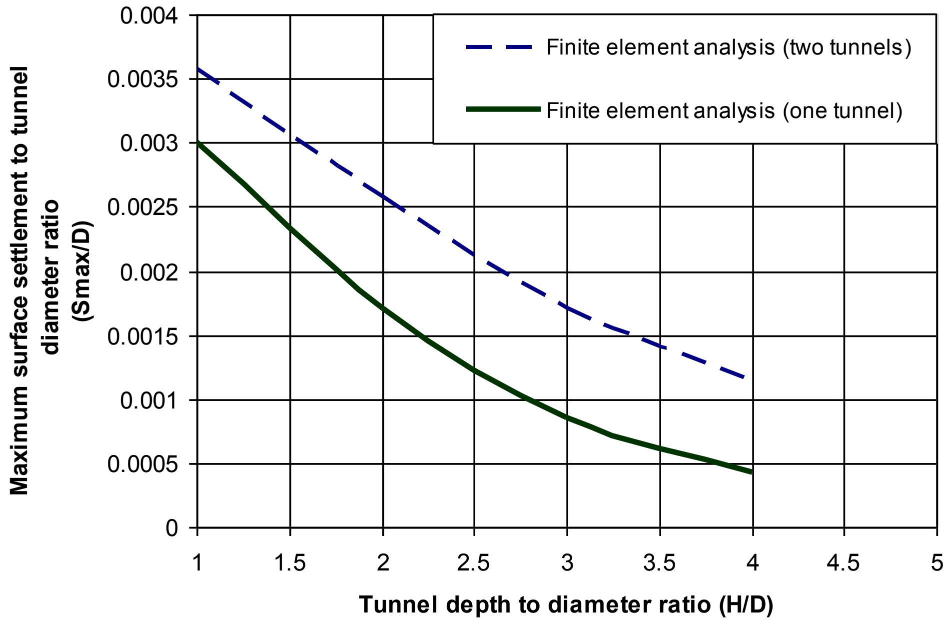

Figure-11. Effect of tunnel depth on the maximum surface settlement (Ts/D=2).

Figure-12 shows the effect of tunnel thickness on ground surface and tunnel settlements. As the tunnel thickness increased, the soil surface and tunnel settlements decreased. The effect was found to be greater on surface settlement.

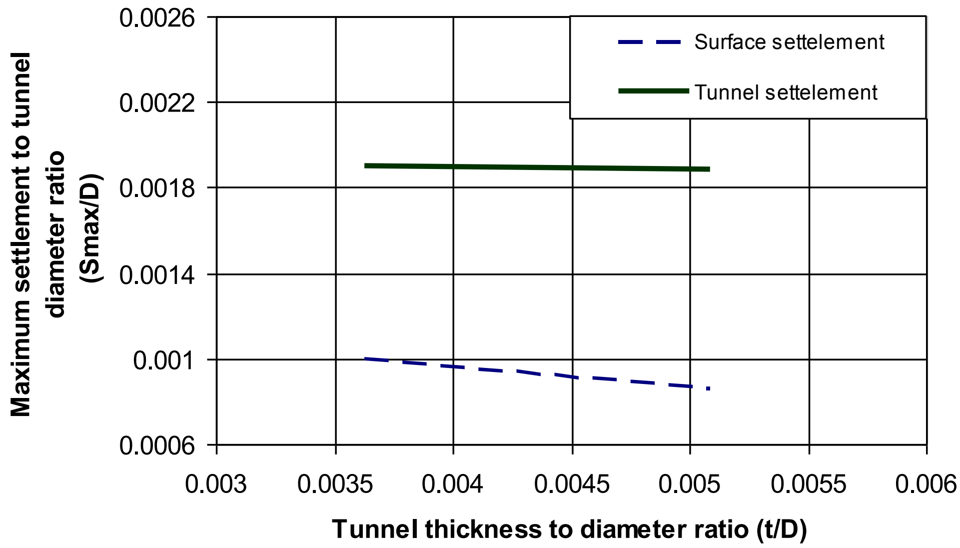

Figure-12. Effect of tunnel thickness on the maximum for single tunnel.

CONCLUSIONS

The numerical analysis through finite elements shows that for tunnels spaced closely, the settlements and moments of tunnels are considered to be important. The main conclusions obtained from the present research are as follows:

a) Finite element analysis gives results that in acceptable agreement with the previous model tests results carried out by Kim (1996) and the previous closed form solutions.

b) It is obvious that the tunnels interaction is neglected for the distance between the tunnel centers is less than or equal to the value of tunnel diameter multiplied by 4.

c) The effect of tunnel depth is a major factor on the surface settlement. When the depth of tunnel is large (the tunnel diameter multiplied by 4), the surface settlement value is reduced.

d) When the tunnel thickness increased, the surface of soil settlement and also tunnel settlement are decreased. The obtained effect was greater on surface settlement.

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