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Impact of Tunneling Running Side-by-Side to An Existing Tunnel on Tunnel Performance using Non-linear Analysis

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ABSTRACT

During construction of twin tunnels running parallel side-by-side, there are Geotechnical concerns due to tunneling near annex structures. One of these concerns is occurred as a new tunnel is constructed side by side to an existing tunnel. The serious damage in the existing tunnel liner is predicted and the maximum radial displacement of the existing tunnel is also computed.

In the present study, the prediction of the tunnel system performance under the impact of the new constructed tunnel running side by side to the existing tunnel is highlighted and a model is proposed to study the soil structure interaction using a 2-D finite element analysis. The horizontal separation between the twin tunnels is also studied so as to ascertain the zones of influence. The study presents a case history along El-Azhar road tunnel to assess the accuracy of the proposed finite element model. Based on this case history, extensive study using the finite element model is conducted to predict the performance of the tunnel system under the twin tunnel construction. The constitutive model for this analysis contains elasto-plastic materials. A yielding function of the Mohr-Coulomb type and a plastic potential function of the Drucker-Prager type are employed. A linear constitutive model is employed to represent the tunnel liners.

At the case study, the study presents comparison of the results obtained by the field measurements and those obtained by the finite element analysis. There is a good agreement between computed and measured values. The tunnel system performance is expressed in terms of settlement and radial deformation in the existing tunnel under the twin tunnel construction. The study includes the prediction of the settlement, the relative movements, and the lining stress under construction processes. The horizontal separation between the twin tunnels is varied so as to determine the zones of influence. The horizontal separation between the twin tunnels has a significant effect on the

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existing tunnel movement due to the new tunnel construction parallel side by side to the existing tunnel.

Keywords: Tunnels, tunneling, settlement, numerical modeling and analysis, nonlinear displacement, design, deformations.

1. INTRODUCTION

Geotechnical problems were expected during the construction of the new tunnel running parallel side by side to the existing tunnel. The new constructed tunnel passes beside the existing tunnel, as shown in Fig. 1. The existing and the new tunnels lining are built of pre-cast reinforced concrete. The tunnel system performance under the impact of the new tunnel construction beside the existing tunnel is studied to determine the influence zone beyond which there is no impact due to the new tunnel construction on the existing tunnel performance.

This study is performed to understand the performance of the tunnel system due to construction of a new tunnel. The results show the estimated movement of the existing tunnel within the zone of influence. Modeling of such problem should include the details of tunnel construction phases and the associated stresses in and around the tunnels. To assess and predict the behavior of the tunnels due to construction of the new tunnel, 2-D finite element model is used. The study presents a case study along El-Azhar road tunnels to assesses the accuracy of the finite element model, as shown in Fig. 2. A nonlinear stress-strain constitutive model is adopted for the soil surrounding El-Azhar road tunnel at central Cairo City. A yield function of the Mohr-Coulomb type and a plastic potential function of the Drucker-Prager type are employed. In addition, linear elastic behavior is assumed for the tunnel linings.

The 2-D effects on the performance of the tunnel system are examined. The effects are expressed in terms of the settlement and radial displacement of the tunnel lining as well as the vertical displacement at different locations, when the new tunnel is constructed beside the existing tunnel.

2. FINITE ELEMENT MODEL

The finite element computer program (COSMOS/M) is used in this study. The finite element model takes into account the effects of the vertical overburden pressure, the lateral earth pressure, the nonlinear properties of the soils, and the linear properties of the tunnel lining. Figure 1 shows the configuration of the tunnels running parallel side-by-side. The soil, the tunnel lining, and the interface medium are simulated using appropriate finite elements. Numerical modeling of the tunnels reflects the ground continuum, the existing tunnel, and the new constructed tunnel. In addition, the compatibility and equilibrium condition at the interface between soil and the tunnel system are idealized in the numerical model. 2-D plane strain elements are used for modeling the soil media and 2-D beam elements for modeling the tunnel lining. Three-node triangle plane strain elements are adopted to simulate behavior of the soil media, as shown in Figs. 3 and 4.

The 2-D finite element mesh is shown in Figs. 3 and 4. The vertical boundaries of the 2-D finite element model are restrained by roller supports to prevent a movement normal to the boundaries. The horizontal plane at the bottom of the mesh represented a rigid bedrock layer and the movement at this plane is restrained in all directions. The movement at the upper horizontal plane is free to simulate a free ground surface.

The lining is composed of 40 cm thickness segments. The stiffness at the joint may be appreciable less than elsewhere. The segments joints are never aligned along the tunnel and the thickness reduction is not as local as it is simulated in the model, which is conservative. The computed normal forces and bending moment values must comply with the strength of the 40 cm thick reinforced segments and the 24 cm thick joints between segments.

The construction of the new tunnel running side-by-side the existing tunnels later caused the soil around the existing tunnel respond to unload. The nonlinear properties of soils, the horizontal separation between the existing and the new tunnels, and the confining pressure are included to study their effects on the settlement and radial displacement of the existing tunnels. In addition, the case study has been made with El-Azhar road tunnels, as it exists in the field at El-Azhar tunnel region. Different nonlinear properties of soil have been chosen to realistically simulate the behavior of the different soils along El-Azhar road tunnels (Ezzeldin, 1999; Mazek, 2003; Mazek et al., 2006; National Authority for Tunnels, 1999). Moreover, the soil-tunnel excavation and the construction of the new tunnel have been idealized using the yielding function of the Mohr-Coulomb type and the plastic potential function of the Drucker-Prager type.

3. PROPERTIES OF TUNNEL LINING AND SOIL

Since the existing tunnel is constructed before the construction of the new tunnel, further displacements would be induced in the existing tunnel after the construction of the new tunnel. The settlement and the additional radial displacement of the existing tunnels as well as the zone of influences due to the construction of the new tunnel have been calculated in this study.

The final diameters (D) for the twin tunnels are 8.35 m and the excavation diameter for both tunnels are 9.15 m. The circular tunnel lining consists of seven segments and one key. The length of the ring is 1.5 m. The characteristics of the tunnels are tabulated in Table 1.

The project area under analysis lies within the alluvial plain, which covers the major area of the low land portion of the Nile valley in Cairo vicinity (Campo and Richards, 1998; El-Nahhass et al., 1994; Mazek et al., 2001; National Authority for tunnels, 1993, 1999). Site investigations along the project alignment have indicated that the soil profile consists of a relatively thin surficial fill layer ranging from two to four metres in thickness. A natural deposit of stiff, overconsolidated silty clay underlies the fill. This deposit includes occasional sand and silt partings of thickness from four to ten metres. Beneath the clay layer, there is a thick alluvial sand that extends down to bedrock, which is well below El-Azhar road tunnels. The watertable varies between two meters to four meters from the ground surface. The upper few metres of this alluvial sand are parts of a transition layer of highly interbedded clay silt and fine sand. Below the transition layer, the alluvial sand layer is more uniform with coarse to fine sand, which occasionally contains layers of silt to clayey silt that varies in thickness from a few centimetres to several decimetres. Lenses of gravel and cobbles, up to several metres thick, may also be present at depths of 25 to 80 metres. Soil parameters are presented in Table 2.

Since soil behavior is generally inelastic, the constitutive relationship adopted in the analysis is an elasto-plastic model. The Mohr-Coulomb criterion is adopted. Excavations of the existing and the new tunnels have been simulated by removing elements from the excavated boundary. The friction angles (ϕ) adopted for the layers have been obtained using laboratory test results from reconstituted samples. The vertical initial drained modulus (E_v) is related to the effective pressure based on Janbu empirical equation (Janbu, 1963), which is given by Eq. 1

$$E_v = mp_a\left(\frac{\sigma_3}{p_a}\right)^n \qquad (1)$$

In which, the modulus number (m) and the exponent number (n) are both pure number and (p_a) is the value of the atmospheric pressure expressed in appropriate units.

Geotechnical parameters have been presented in National Authority for Tunnels (NAT) documents (National Authority for Tunnels, 1993 and 1999). The soil parameters used for elasto-plastic finite element analysis for different types of the soil are presented in Table 3 (Mazek et al., 2006; National Authority for Tunnels, 1993 and 1999).

The finite element analysis of the tunnel is carried out to simulate the construction of both the existing tunnels and the new tunnel. The construction of the existing tunnel was under the initial in-situ stress condition. The excavation of the new tunnel causes the soil around the existing tunnel system to respond in an unloading manner, and unload moduli is appropriate during this stage. Under the unload-reload condition, Duncan et al. (1980) found that unload and reload modulus (E_{ur}) are similar and are 1.2-3 times the vertical drained modulus (E_v). Byrne et al. (1987), based on tests on granular soils, found E_{ur}/ E_v in the range 2-4. A shear modulus (G_{vh}) is used in the finite element analysis. The ratio of the shear modulus to the vertical modulus G_{vh}/E_v is about 0.35 in initial loading condition for sand. In unloading condition, the G_{vh}/E_v ratio is about 0.25 for sand. Effective stress is used in the finite element analysis, as the existing and the new tunnels are located in sand.

4. STRESSES IN SOIL

The stresses in the soil have undergone two stages of change. The first stage corresponds to the construction of the existing tunnel (old tunnel) and the second stage to the construction of the new tunnel.

At the first stage, the loading steps of the tunnel construction have been simulated using the 2-D finite element analysis. First, the initial principal stresses are computed with the absence of the existing tunnel. Second, the excavation of the existing tunnel is modeled by means of the finite element method. The excavation has been simulated by the removal of those elements inside the boundary of the existing tunnel surface to be exposed by the excavation. Third, the movement and stress changes induced in soil media are calculated. Fourth, the calculated changes in stresses are then added to the initial principal stresses computed from the first step to determine the final principal stresses resulting from the existing tunnel construction. These final induced principal stresses are considered as the initial principal stresses for the second stage (Stage 1).

At the second stage, the loading steps of the new tunnel construction are also simulated using the 2-D finite element analysis. First, the initial principal stresses for this stage have been computed as mentioned above (Stage 1). Second, the excavation has been simulated by the removal of those elements inside the boundary of the new tunnel surface to be exposed by the excavation. Third, the movement and stress changes induced in the soil media are calculated. Fourth, the final stresses due to the construction of the new tunnel are computed.

5. 2-D FINITE ELEMENT MODEL VERFICATION (CASE HISTORY)

This case study is located along El-Azhar road tunnels, as shown in Fig. 2. The 2-D finite element model is proposed to predict the performance of El-Azhar road tunnels. The computed surface settlement obtained by the finite element analysis is compared with those obtained by the field measurements so as to understand the behavior of El-Azhar road tunnels. This comparison is used to assess the accuracy of the proposed numerical model, as shown in Fig. 5. The comparison shows that there is good agreement between the computed and measured readings.

Based on the good agreement between the computed and measured values, one can proceed to use the 2-D numerical model to explore other beneficial aspects of the tunnel system performance under the new tunnel construction beside the existing tunnel. In fact, the proposed model can help to predict the tunnel system performance under new tunnel construction.

6. EFFECT OF NEW TUNNEL CONSTRUCTION ON EXISTING TUNNEL RUNNEING SIDE-BY-SIDE

With different horizontal separation between the twin tunnels, the finite element analysis is conducted so as to determine the influence zones. The geotechnical properties of the soil for this part of the study have been listed in Table 3. The numerical analysis is carried out under the unload reload modulus (E_{urn}) for the soil based on Janbu's equation [Equation 1] applying different nonlinear soil parameters.

The analysis is performed through main stages as follows. The loading of the first stage includes: (1) initial soil condition before the construction of the old tunnel; (2) removal of the soil inside the boundary of the old tunnel surface; and (3) construction of the old tunnel liners (Stage 1). The loading of the second stage includes: (1) initial soil condition before construction of the new tunnel (Stage 1); (2) removal of the soil inside the boundary of the new tunnel surface (Stage 2); and (3) construction of the new tunnel liners (Stage 3).

The horizontal separation between the twin tunnels changes from 0.5D to 3D, as shown in Fig 1. At the different horizontal separation, the final vertical displacement at different levels and locations around the tunnel system is discussed. The final vertical displacement along centerline of the twin tunnel at different levels with one-diameter horizontal separation is presented in Fig. 6. The final vertical displacement along centerline of the twin tunnel at different levels with three-diameter horizontal separation is also presented in Fig. 7. The calculated maximum settlement at ground surface is shown in Fig. 7. The Calculated maximum heave at invert of the new tunnel is also shown in Fig. 7. The calculated maximum settlement at ground surface against different horizontal separations (new tunnel running side-by-side to old tunnel) is shown in Fig. 8.

The results show that the soil above the crown of the twin tunnels moves down and the soil under the invert of the twin tunnels heaves. The study also demonstrates that the old tunnel also moves due to the construction of the new tunnel. The results show that the maximum displacement at the surface and the crown of the twin tunnels decreases with an increase of the horizontal separation. The results show that the maximum heave at the invert of the twin tunnel decreases with an increase of the horizontal separation. The displacement at the surface and the crown of the twin tunnels decreases with increases the horizontal separation between two tunnels until the horizontal separation reaches to the critical separation beyond which there is a little impact on the old tunnel performance due to the construction the new tunnel.

When the horizontal separation reaches 3 D, there is no effect due to the construction of new tunnel on the old tunnel performance. Generally, there is little impact on the old tunnel lining when the horizontal separation between twin tunnels is greater than three times of the tunnel diameter.

7. CONCLUSIONS

A 2-D nonlinear finite element analysis has been used to study the construction of a new tunnel running side-by-side to the existing tunnel. The analysis takes into account the changes in stress, the non-linear behavior of the soil, and the construction progress, etc. The following conclusions can be drawn regarding the performance of the tunnel under the effects of different factors.

- The proposed 2-D numerical model is applicable to predict the performance of the tunnel system under the shadow of the case history.
- The 2-D finite element model can be adopted to analyze and predict the performance of the tunnel system under the new tunnel construction effect.
- The 2-D finite element model can be used to determine the zone of the influences due to the new tunnel construction beside the existing tunnel.
- The critical horizontal separation (zone of the influence) between the twin tunnels is determined to be three times of the twin tunnel diameter beyond which there is a little impact on the existing tunnel performance due to the construction of the new tunnel running side-by-side to the existing tunnel.

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Table 1: Characteristics of the road tunnel lining

ν	E_b (t/m^2)	(t) cm	f_c (t/m^2)
0.2	2.1×10^6	40	4000

In Table 1, ν is Poisson's ratio of tunnel liner, E_b is the elastic modulus of the tunnel lining, t is the thickness of tunnel lining, and f_c is the compressive strength of concrete.

Table 2: Geotechnical properties

Soil parameter	Fill	Silty clay (drained condition)	Sand
γ_b (t/m^3)	1.8	1.9	2.0
k_o	0.58	0.8	0.37
υ_s	0.4	0.35	0.30
ϕ (Degree)	25	26	40
C (t/m^2)	1.0	0	0
Depth (m)	0.0 to 4.0	4.0 to 10.0	10.0 to end

In Table 2, γ_b is bulk density, k_o is coefficient of lateral earth pressure, υ_s is Poisson's ratio, ϕ is the angle of internal friction for the soil, and C is cohesion.

Table 3: Soil parameters

Material	m	n	C_u (kPa)	C (kPa)	ϕ_u	ϕ	υ_u	υ
Fill	300	0.74	50	10	20	25	0.4	0.4
Silty Clay	350	0.60	75	0	0	26	0.45	0.35
Sand	400-600	0.5-0.6	0	0	-	40	-	0.3

In Table 3, C_u is the undrained cohesion, C the effective cohesion (drained), ϕ_u is angle of internal friction in terms of total stress (for unsaturated fill $\phi_u = 20^{\circ}$), ϕ is the effective angle of internal friction (drained), υ_u is the undrained Poisson's ratio, and υ is the drained Poisson's ratio.

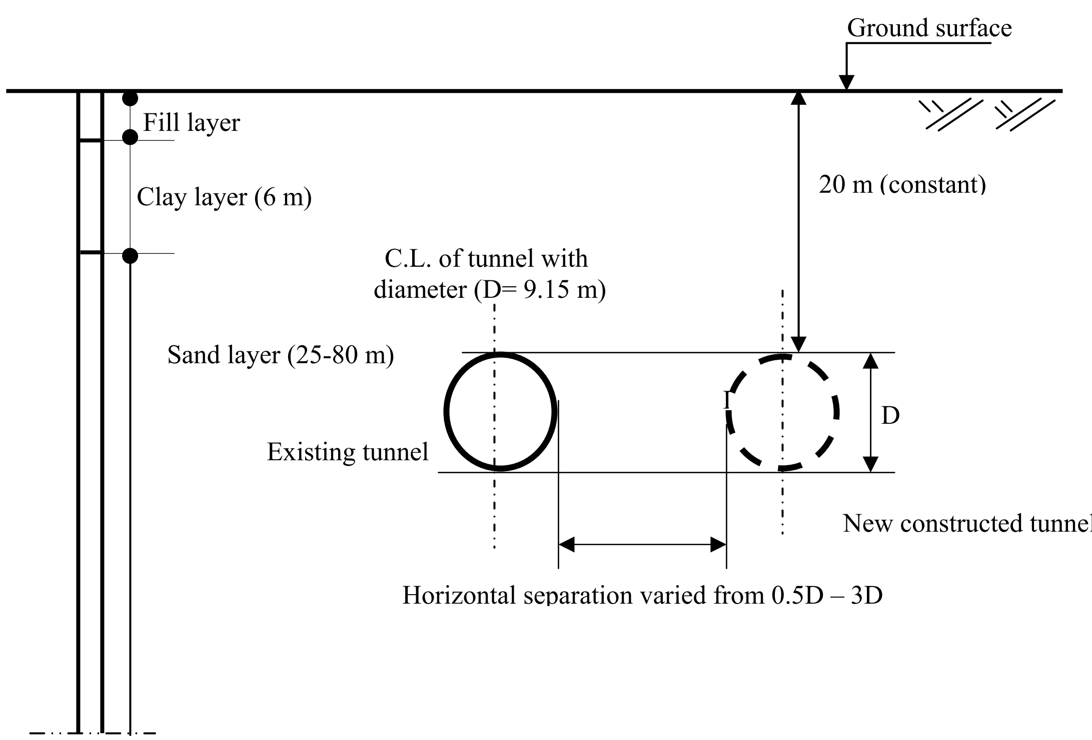
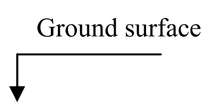


Fig. 1: Cross section showing the twin tunnels (parallel side-by-side)



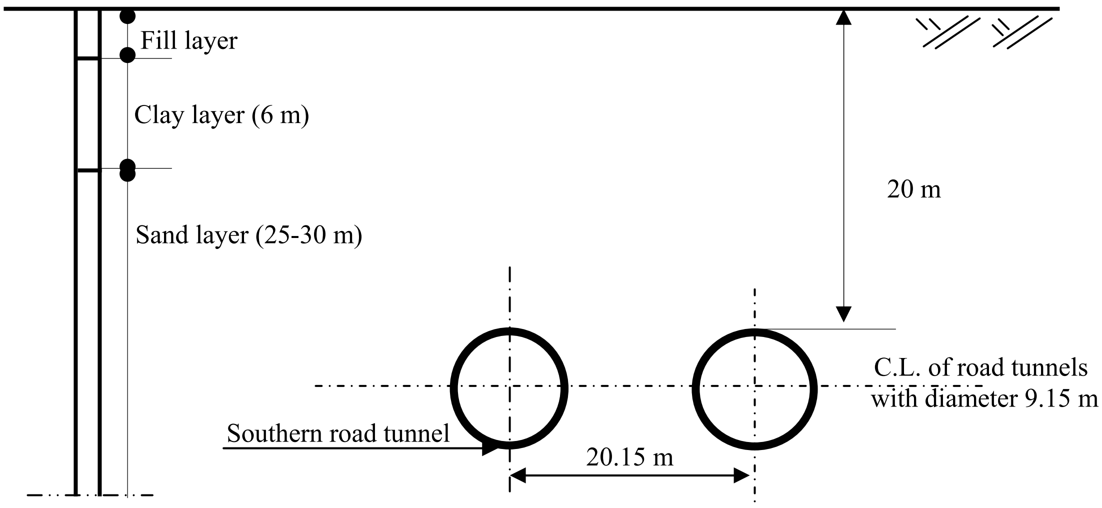


Fig. 2: Cross section along El-Azhar road tunnel (Case study)

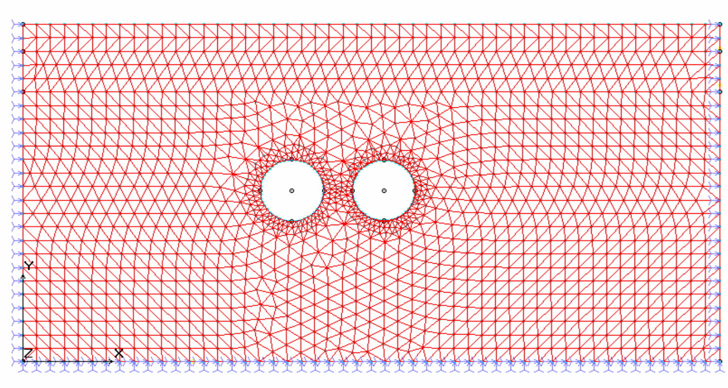


Fig. 3: 2-D finite element model of tunnel (new tunnel running side by side to existing tunnel)

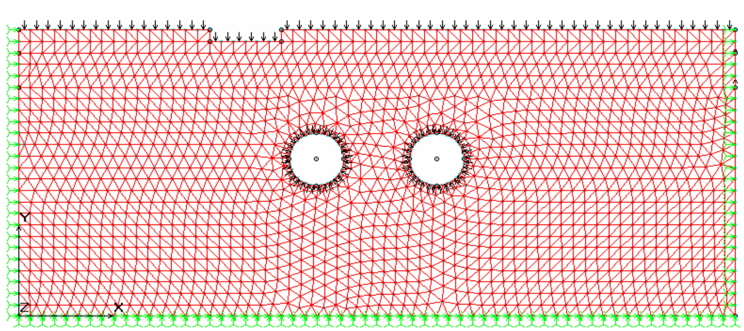


Fig. 4: 2-D finite element model of tunnel (case history- side by side)

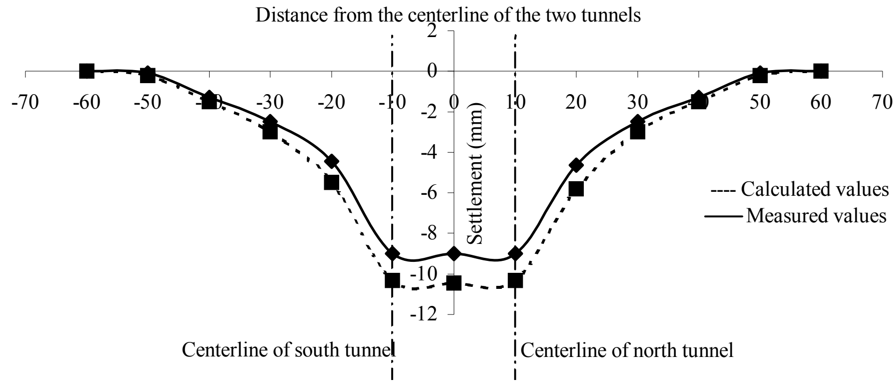


Fig. 5: Vertical displacement of soil at the ground surface after achievement of El-Azhar road tunnels construction (Case history)

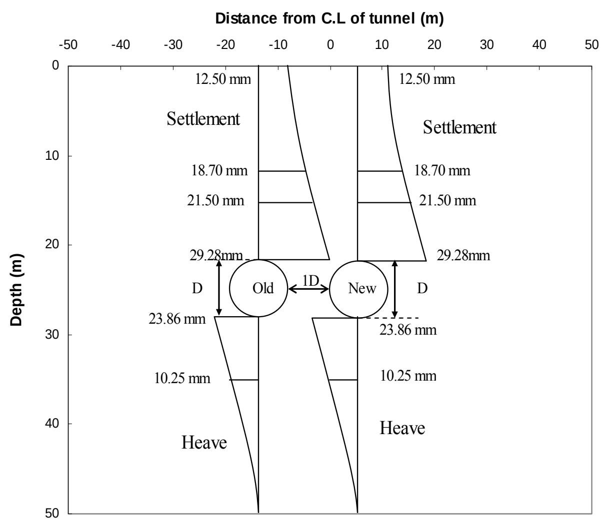


Fig. 6: Vertical displacement at different levels along centerline of twin tunnel with one-diameter horizontal separation

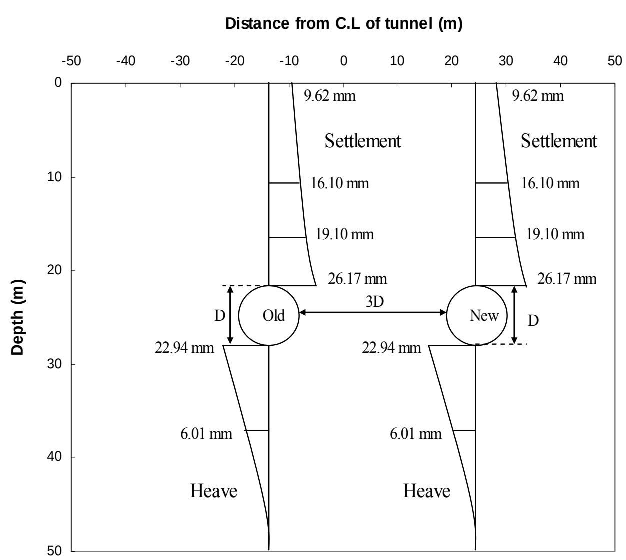


Fig. 7: Vertical displacement at different levels along centerline of twin tunnel with three-diameter horizontal separation

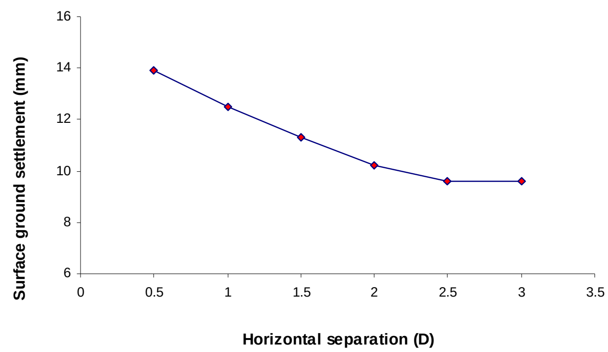


Fig. 8: Calculated settlement at ground surface with different horizontal separations (new tunnel running side-by-side old tunnel)