Geomechanics and Engineering, *Vol. 9, No. 6 (2015) 775-791*
DOI: http://dx.doi.org/10.12989/gae.2015.9.6.775

Numerical modeling of two parallel tunnels interaction using three-dimensional Finite Elements Method

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(*Received Decembe 01, 2014, Revised January 13, 2015, Accepted November 05, 2015*)

Abstract. Due to the extension of communication ways (metro, highways, railways), hence, to improve traffic flow imposes often the difficult crossing that generally drive to the construction of underground works (tunnel, water conveyance tunnel...) plays a major role in the redevelopment of urban areas. This study is focused on the assessment of the interaction response of parallel tunnels, so this study uses the results from the simulation of two tunnels to illustrate a few observations that may aid in practical designs. In this article, simultaneous drilling of highway's twin tunnels is simulated by means of Finite Element Method (FEM) implemented in Plaxis program. So the treated subject appears in a setting of geotechnical where one can be to construct several tunnels sometimes in a ground of weak mechanical characteristics. The objective of this study is to simulate numerically the interaction effects caused by construction of two parallels tunnels. This is an important factor in the study of the total answer of the problem interaction between parallels underground works. The importance of the effects transmitted is function of several parameters as the type of the works, and the mechanical characteristics (tunnel size, depth, and the relative position between two tunnels, lining thickness...). This article describes numerical analyses of two parallels tunnels interaction. This study will be applied to a real case of a section tunnel T4 of the highway East-West (Algeria); the study presented below comprises a series of numerical simulations of two tunnels using the computer program Plaxis which is used in the analyses is based on Finite Element Method.

Keywords: interaction; tunnel; numerical; three-dimensional; Plaxis

1. Introduction

In Algeria, the rapid development of land has indirectly increased the congestion situation of the traffic in cities. As a result, network of highways, railroads... known significant development in recent years, and might have to be constructed to accommodate transportation system, communication and utility networks such as highway East-West 7000 km of length. This project imposes often the difficult crossing of the relief, as the mounts; which request of digging (construction the tunnels). Many tunneling projects have recently been constructed that involve the excavation of twin tunnels in close proximity to each other (Mroueh and Shahrour 2008). Even if in many cases, the new tunnel was excavated at close distance to an existing tunnel. Therefore, it is very important to understand in detail the interaction mechanism between two tunnels during their construction processes. Several works of research studied the interaction between tunnels at

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http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

Fig. 1 General view of the tunnel T4 at Twin-tubes

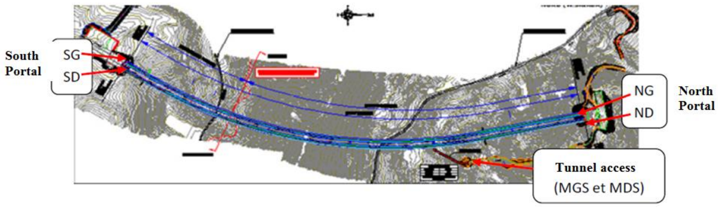

Fig. 2 Trace in plane of the Tunnel

various configurations. The tunnel T4 appears in the setting of the realization of the highway Unit of Maghreb about 7000 km of length (Mokhbi *et al*. 2014). The tunnel is part of the section 4 of this highway.

The highway tunnel consists of two tubes practically parallel with a total length of 2500 m (Fig. 1 and 2), (Mokhbi *et al*. 2014). This case includes evaluating the underground and surface displacements (settlements at surface and subsurface), the vertical and horizontal displacements of soil and the internal forces in the existing tunnel lining (constructs in first) before and after interaction with new adjacent tunnel (to construct in second) by the program Plaxis. The gotten results are exposing the effect of the second tunnel on the first tunnel structure behavior (interaction between two tunnels) and their answer, additionally ground reaction.

Addenbroke and Potts (1996) states that, excavation of new tunnels close to existing tunnels may be needed for construction activities like metro construction in crowded cities. New tunnels adjacent to existing tunnels may be excavated not only for the metro construction but also for an improvement of a network. For this reason, many authors (Hage Chehade and Shahrour 2007, Mroueh and Shahrour 2008, Hosseini *et al*. 2012, Tabbal *et al*. 2011, Karakus *et al*. 2007, etc.) suggested to investigate the interaction between the tunnels and ground response.

2. Presentation of Tunnel T4

The tunnel T4 behaves of an underground passage the crossing of the relief between the PK 229+220 and the PK 231+750 is going to be achieved with double tubes.

The conception of the tunnel at two tubes dictated the junction to the main axis of a second axis that takes birth in the PK 227+820, permitting the respect of the distance required between the axes of the 2 tubes of the tunnel. This second axis is projected of the West side of the main and continuous axis until the PK 232+811, 66 before joining the axis of the tracing of the freeway. The freeway tunnel understands two practically parallel tubes [PK: 229+226, 5 until 231+725, 0 for left tube and PK: 229+216, 5 until 231+743 for the right], they accommodate a traffic to unique sense on three see, the tubes separated by a spacing of 22 m. The measurements of the transverse section of every tube around the theoretical line of excavation are 17,9 m of width and 13 m of height. A tunnel of access of 320 m of length has been conceived and connected to the main tube to 811m the North Portal, its objective is to improve the advancement of works while opening two other fronts of attack in the middle of the tunnel while excavating toward the South Portal, it permits to conduct the digging on six (06) fronts of attacks: two (02) to the North Portal (NL and NR), two (02) in the middle of the southbound tunnel (MGS and MD) and two foreheads to the South Portal

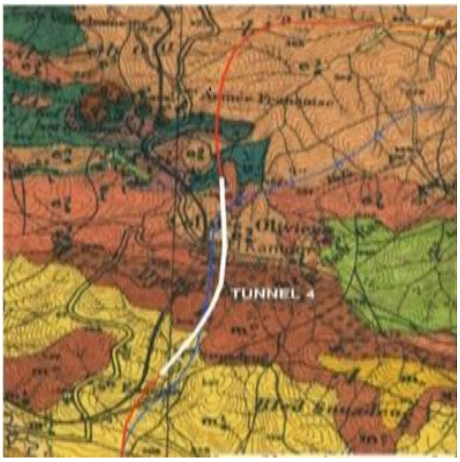

Fig. 3 Site of the tunnel T4 on the geological card of Smendou (Constantine-Algeria)

(SG and SD) [L: left, R: right] (Messast *et al*. 2014). The tracing of the tunnel is raised on the geological card of Smendou at 1/50.000th (Fig. 3).

3. Presentation of soil characteristics and displacements of tunnel T4

The tunnels will be constructed according to the "NATM" what characterizes it notably is the precocious application of the support in order to control the first deformation and to prevent all laxity to the tunnel front. For this study, we chose a circular section as a simplified model.

The stability analysis of the tunnel is studied in return for the finite element software Plaxis. Our objective in this part is to calculate numerically the kilometer point [231 + 253] that is at the left north portal (Zone of weak cover = 27 m) , The measures really done to the level of this point show that settlement Z1 reached 15cm after 10m excavation. Settlement stabilizes to 20 cm (Fig. 4).

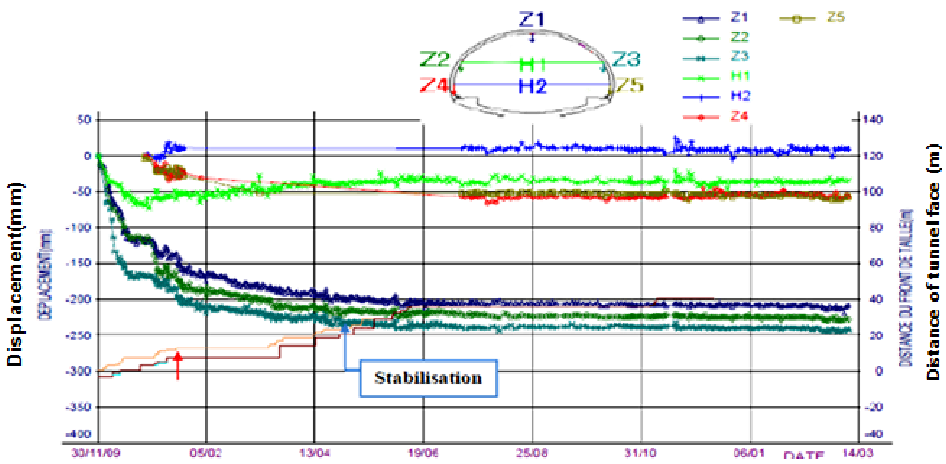

Fig. 4 Settlement & convergence of point (231+253) (Reference)

Table 1 Mechanical and geotechnical characteristics of soil used the Mohr Coulomb Model

Soil	Unit weight (kN/m^3)	Friction angle	Cohesion (kPa)	Elastic modulus (kPa)	Poisson's ratio
Clay Marly	17,50	27	5	30000	0.3

Table 2 Mechanical and geotechnical characteristics of soil used the Hardening Soil Model

Soil	E_{50} (kPa)	E_{oed} (kPa)	E_{ur} (kPa)	γ (kN/m3)	m	Φ°	v	c (kPa)	ψ/(°)	p^{ref} (kPa)
Clay marly	30000	30000	90000	17,50	1	27	0.3	5	0	100

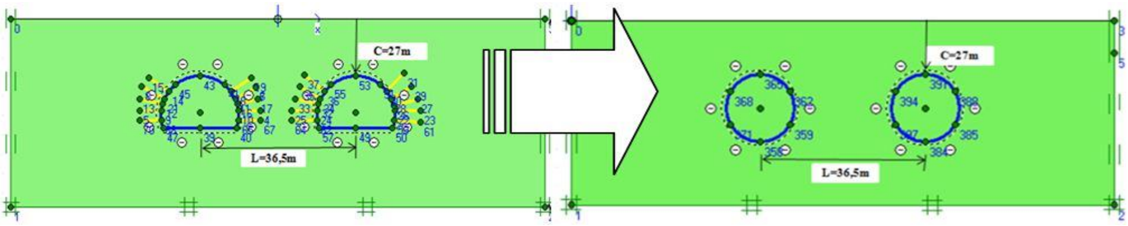

Fig. 5 The equivalent model (tunnel double tubes)

4. Numerical modeling of a tunnel section

The tunnel is composed of double tubes. The right tube is excavated in first, the left tube in continuation, in accordance with the method proposed of excavation. We excavate the totality of the section of the tunnel (We take an equivalent model; Fig. 5). In the present analysis, the two tunnels are circular in cross-section with 15.25 m outer diameter and 0.40 m of concrete lining thickness. The centers of the tunnels are to 2,27D below the surface of soil (D being the diameter of the tunnel).

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In this study, numerical simulations have been performed by means of the Plaxis program (Brinkgreve). The modeled domain was 100 m in length, 60 m in width and 50 m in depth.

Figs. 7 and 8 show the 2D and 3D finite element mesh used in the numerical analysis. The two tubes are supposed constructed in a homogeneous soil. Also, the analyses carried out using elastic-

Table 3 Material properties of shotcrete

	E (MPa)	A (m^2)	I (m^4)	d	EA_{eq} (kN/m)	EI_{eq} ($kN.m^2/m$)	N	d_{eq} (m)
Lining	10^4	0,4	$5.33*10^{-3}$	1	$5,18*10^6$	$6,9*10^4$	0,15	0,4
Steel HEB200	2.10^5	$78.1*10^{-4}$	$0.569*10^{-4}$	1				

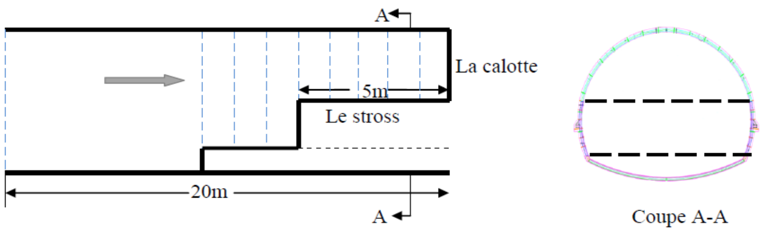


Fig. 6 Diagram of digging advancement

plastic model of Mohr-Coulomb yield criteria for soil and linear elastic model for tunnel lining.

5. Numerical simulation procedure

5.1 Simulation of excavation according to NATM Method

The excavation begins from kilometer point [231 + 253]; the modelling of the digging phasage has been conceived in accordance with the stages of digging really done, where the digging has been achieved by sections divided with a shift of (2 to 5 m). It means; we excavate 20 m; the shifting between the calotte and the stross is from 2 to 5 m (Dar Al-Handasah 2009).

5.1.1 Calculation phases according to NATM Method

Modeling of the construction of each tunnel process has been carried out in the following steps:

Phase 0: Initial Phase.

Phase 1: Excavation the 5 m of calotte, to activate shotcrete (& anchoring bolts).

Phase 2: Excavation the 5 m of calotte + 6 m of stross + 3 m of radier, to activate shotcrete (& anchoring bolts). We apply certain strength to the face (that to mean the 10 cm of lining that has been applied to the face.

Phase 3: Excavation the 5 m of calotte + 6 m of stross + 6 m of radier, to activate shotcrete (& Anchoring bolts).

Phase 4: Excavation the 5 m of calotte, to activate shotcrete (& anchoring bolts).

Phase 5: Excavation the 3 m of stross + 3 m of radier.

Phase 6: Excavation the 3 m of stross + 6 m of radier, to activate shotcrete (& anchoring bolts).

5.2 Simulation of excavation according to bored tunnel type

The available equivalent approaches, that allow the deconfinement process to be controlled, include the convergence confinement method (CCM) (Panet and Guenot 1982, Oreste 2003); the convergence confinement method is used as approach simplified of the analysis of the interaction between tunnel-soil; and the shape of the tunnel plays an important role in the convergence of the lining tunnel.

The main purpose of the present paper is to study the interaction mechanisms between tunnels due to the construction of new tunnel and to put in evidence the importance of excavation of the tunnels.

The convergence confinement method has been adopted in this study that the CCM allows the

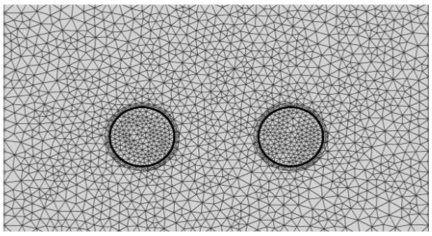


Fig. 7 Mesh used in 2D analysis

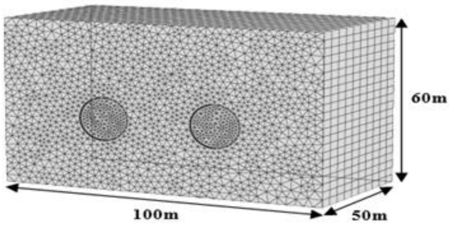


Fig. 8 Mesh used in 3D analysis

best agreement with experimental results, The process of the construction of the each tunnel has been modeled, we make use of an approaches stage by stage in 5 slices, in general, it has been modeled in two steps, in each slice for 10 m, the excavation process is consisted of: (i) a complete deactivation of soil elements situated in the section to be excavated; (ii) to active the lining tunnel and a full release of stresses in this section. The excavation of 2nd tunnel has been modeled after the completion of the 1st tunnel in the same manner method applied. This procedure includes numerically simulating the determination of vertical settlement, horizontal displacement, convergences, surface settlement and the internal efforts (M, N…) in the right tunnel lining before and after interaction with the second left tunnel.

6. Results

For multiple tunnels, settlements from each tunnel are calculated according to Eq. (1) and summed. This however ignores the interaction between tunnels during their construction. It is clear that the disturbance associated with tunnel construction must change the properties of the surrounding soil, and hence alter the effect of a subsequent tunneling operation through that zone of soil.

The surface settlements, S above a single tunnel constructed in soft ground are usually assumed to follow an inverted Gaussian curve, i.e.

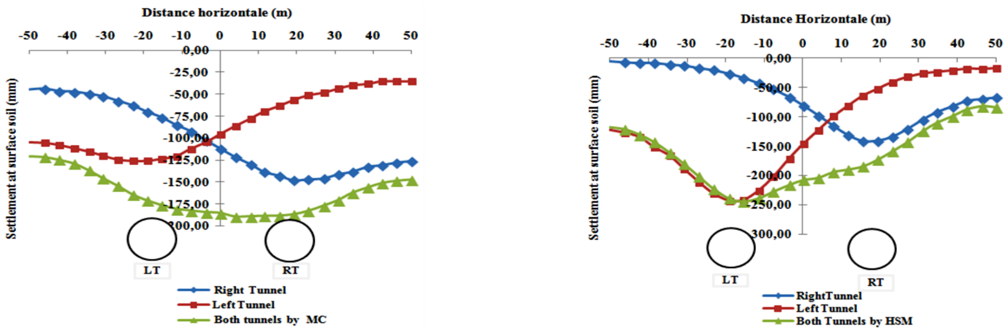
$$S = S\max \exp\left(-x^2/2i^2\right) \tag{1}$$

Where S_{max} is the maximum settlement (over the tunnel axis), x is the orthogonal distance from the tunnel axis and i is the width of the settlement trough (Attewell and Farmer 1975).

6.1 Prediction of the vertical movement of soil /*Settlement trough*)

We present here the results of analyses as the curves of settlement on three stages of digging mentioned (right tunnel, left tunnel, and the both tunnels) by the two models of behavior (MCM and HSM), in order to present a comparison between the results of our simulations by utilization of these behavior laws.

It can be seen from the Fig. 8 that the settlements profiles at surface soil in the transverse section for twin bored tunnels by the two models (we take only the vertical displacement of the last phase for the two models), calculated numerically by the software of Plaxis, are very different either of the point of view pace or maximal values for the two models of behavior, where the use of model of HSM gives more elevated results than the use of Mohr-coulomb model for the three



(a) (b)

Fig. 9 Settlements trough for two bored tunnels in the transverse section

cases distinguished of tunnel.

Suwansawat (2006) noted that the excavation of the two tunnels brings a variable shape settlement curve; however the excavation of single tunnel brings a symmetrical settlement curve is can be described while using the function of Gauss.

- The maximum settlement is to the level of the vertical axis of each tunnel. Scilicet; if we excavate the single right tunnel (RT), the maximal value of settlement is to the level of the axis of this tunnel with the two models, this value goes decreases when we move away of the axis of this tunnel. It is the same thing for the digging of single left tunnel (LT).
- Settlement at surface soil most elevated is recorded in the case of excavation the two tunnels (twin tunnel) with the two models. Scilicet; in case of we excavate the second left tunnel, settlement produces by the excavation of 1st tunnel goes increases.
- The maximum vertical displacement at the tunnel crown (S_{cmax}) and at the ground surface (S_{max}) corresponding to the vertical axis of the tunnel for the two models are given in the figure 04 after 50 m excavation (Last slice).

The most important displacements appear to the level of the tunnel crown (U_y = 194; 250; 281 mm) and they decrease until the surface (146; 130; 190 mm) in the three distinguished cases with the MC model.

The most important displacements appear to the level of the tunnel crown (U_y = 184; 280; 268 mm) and they decrease until the surface (142; 242; 244 mm) in the three distinguished cases with the MC model.

Table 4 Displacements at surface soil and at crown tunnel

Model	Mohr–Coulomb model			Hardening soil model		
Cases / Stt	Case 01 RT Excavation	Case 02 LT Excavation	Case 03 RT + LT Excavation	Case 01 RT Excavation	Case 02 LT Excavation	Case 03 RT + LT Excavation
S_{max}	146,17 mm	130,57 mm	190,00 mm	141,83 mm	242,43 mm	244,01 mm
S_{cmax}	194,39 mm	250,12 mm	281,00 mm	184,00 mm	280,00 mm	268,00 mm
S_{max}/S_c	75,19%	52,20%	67,61%	77,08%	86,58%	91,04%

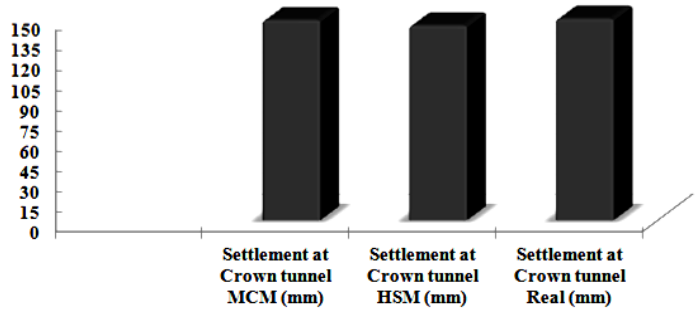


Fig. 10 Settlement at right tunnel crown

Generally the most values of settlements at the tunnel crown are appearing when use the MCM. Contrary the most important values of settlements at the ground surface are appearing when use the HSM.

Fig. 10 illustrates the measures done to the point situated at the right tunnel crown (S_c) shows that settlement reached (149 mm at MMC and 145 mm at HSM) after excavation of 10 m from origin, this value of settlement is approaching to the auscultation value calculated of the tunnel T4 that equals à 15 cm. (As a reference, Fig. 4).

6.2 Settlements according to the tunnels excavation

Fig. 11 presents the settlement profiles above the centerline of each tunnel and the middle distance along the longitudinal axes of the tunnels (i.e., the *Z* direction) for *L* = 2,33D. It can be seen that the settlement above the left tunnel (Section 3.3) is largest of settlement to his excavated on the right (Section 2.2). The profile of settlement to the middle distances between the two tunnels (Section 1.1) is farther to Sections 2.2 and 3.3. We can say that the comparison of settlement for the two tunnels put in evidence clearly that the excavation of 2nd tunnel duct an elevation of surface settlement; an effect of the 1st tunnel that excavated on the 2nd tunnel to excavate, it is the instability of the soil. This result is in good agreement with the results obtained in the Ng *et al*. (2004) study, which was also, performed using a 3D model ABAQUS.

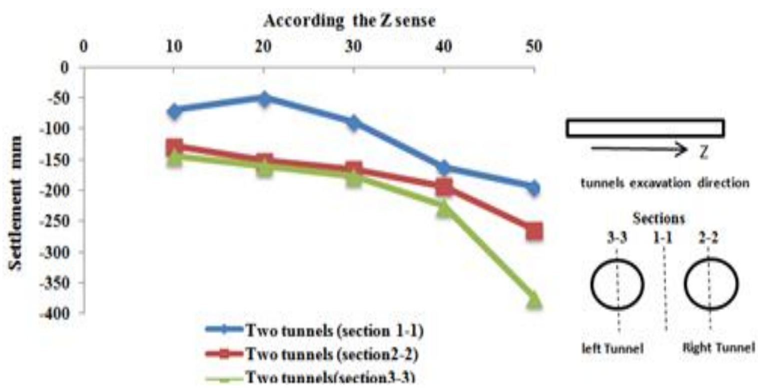
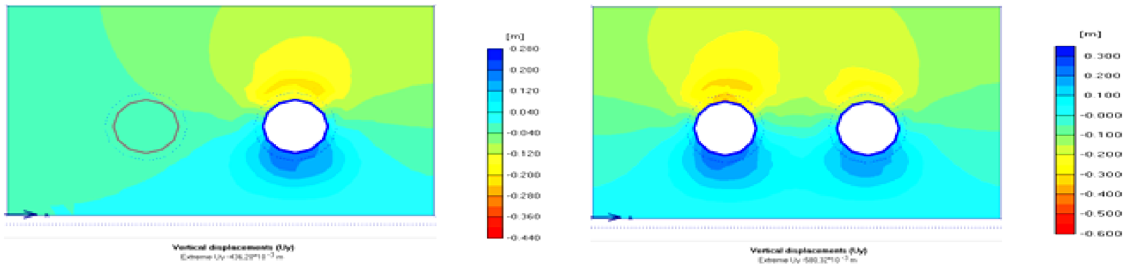
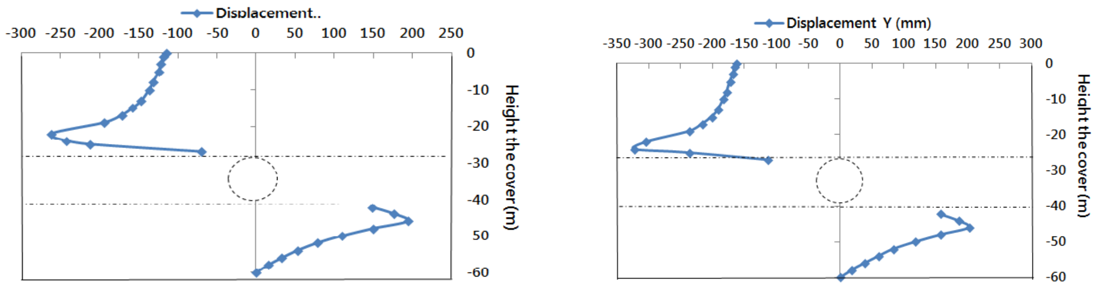


Fig. 11 Surface settlement at soil during to the different phases in the sense *Z*



(a) Single tunnel (b) Twin tunnels

Fig. 12 Vertical displacement (U_y)



(a) (b)

Fig. 13 Vertical displacements to the axis of the right tunnel

6.3 Vertical displacements

6.3.1 Around the tunnels

The profiles of the vertical displacements around the two tunnels (right & left) are given on the Fig. 12, we start in the first place with the excavation of the right tunnel, after, and we see the vertical displacement (U_y) provoked by the excavation of 1st tunnel around this tunnel. Then; we pass by the excavation of second left tunnel that gives the different value to the one given at first (interaction between two tunnels).

According to this figure, we determine the vertical displacements fields U_y induced by the excavation in virgin soil, the profile of the displacement due to the excavation of single right tunnel gives a value of (-436,20 mm), once in company of the left tunnel, the vertical displacement profile will exchange, it goes increases until a value of (-580,32 mm) Scilicet.; the profile of vertical displacement of the soil caused by the excavation of single right tunnel, will be change directly after the excavation of second tunnel; there is an interaction between the new and existing tunnel.

6.3.2 Axis of the tunnel

We are interested to the vertical displacements on the axis vertical pass by the center of the right tunnel (first tunnel). Fig. 13 presents the vertical displacements following the vertical axis of the right tunnel.

Fig. 14 presents the vertical displacements on the axis vertical pass by the center of the right

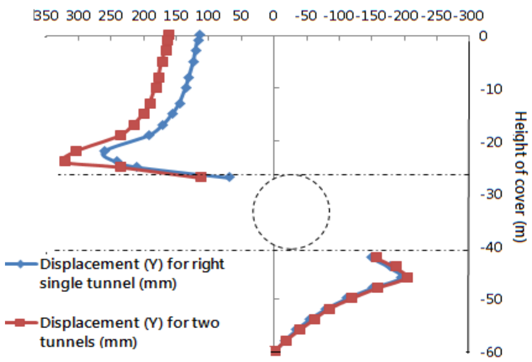


Fig. 14 Profile of the vertical displacements to the axis of the right tunnel (Accumulate case)

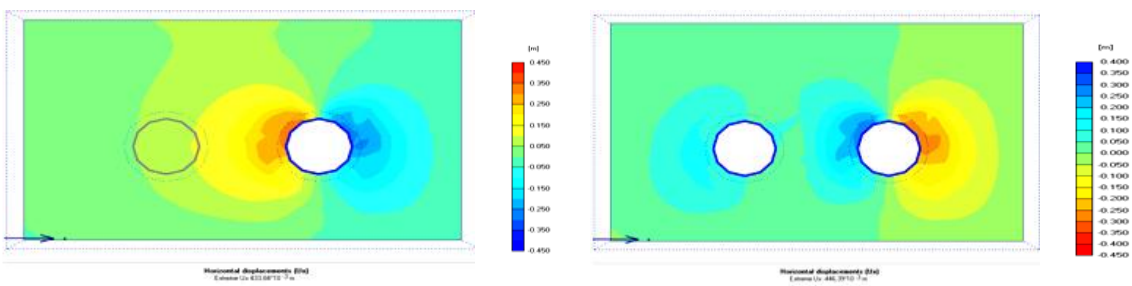
tunnel, these displacements are increase directly after the excavation of 2nd left tunnel (Case b) in relation to the vertical displacements along the same axis vertical pass by the center of the right tunnel (Case a), this gap is observed in a height attached between the surface and the clay of the right tunnel, it becomes important to a height of 24 m of cover; this increase of the vertical displacements can be explained by the interaction that produces between the 1st right tunnel with the 2nd left tunnel that excavate then, on the contrary, from a height of cover of 2,76D until 3.93D directly below the right tunnel the values of vertical displacements are nearly identical for the two distinguished cases. Therefore the effect of the interaction between the two tunnels is exposed practically in a height of 0 to 1,77D (surface - crown tunnel).

6.4 Horizontal displacement

6.4.1 Around the tunnels

The profiles of the horizontal displacements of soil due to the excavation of the two tunnels (right & left) are given in the Fig. 15, we start in the first place with the excavation of the right tunnel, after, one do see the displacement horizontal (U_x) of soil provoked by the excavation of single right tunnel (before interaction case); then one passes by the excavation of second left tunnel (after interaction case).

According to this figure, we determine the fields of horizontal displacements U_x induced by the excavation in virgin ground; at before interaction case, the profile of the displacement due to the



(a) Single tunnel (b) Twin tunnels

Fig. 15 Horizontal displacement (U_x) of soil due the excavation

excavation of the single right tunnel gives a value of (± 433 mm), once in company of the tunnel left, the profile of displacement horizontal will exchange, it goes increases until a value of (± 456 mm) i.e., the profile of displacement horizontal of the soil caused by the excavation of single tube, do change at the excavation of 2nd tube.

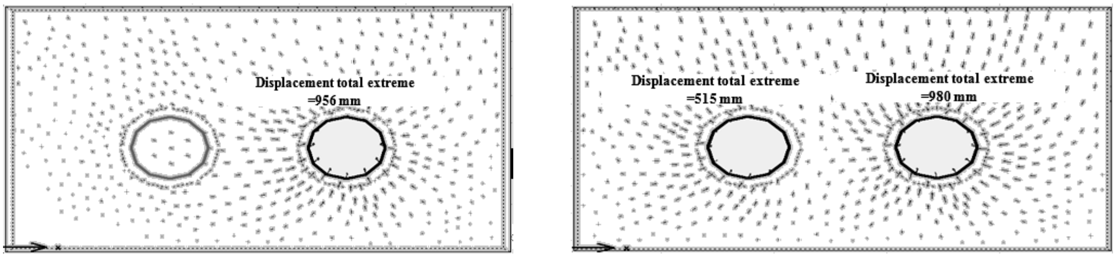
6.4.2 Axis of the tunnel

We are interested to the horizontal displacements on the axis vertical pass by the center of the right tunnel (first tunnel). Fig. 16 shows the horizontal displacements following the vertical axis of the right tunnel.

Fig. 16 presents the horizontal displacements on the axis vertical pass by the center of the right tunnel induced by the digging of a single right tunnel (Case a) and for the twin tunnels (Case b) in a height of 0 to 1,77D (surface - crown tunnel). The horizontal displacement profile due to the excavation of a single right tunnel h as some values positive of (+ 27,38 mm, maximal value to the surface of soil), on the contrary one finds negative values have the opposed signs of (-29,04 mm, maximal value to a height of 1,44D; once, we dig the 2nd left tunnel, these displacements are always on the same axis that passing in the center of the right tunnel; the horizontal displacement caused by the excavation of right tunnel, go change at the time we excavate the 2nd left tunnel (the

(a) Single right tunnel (b) Twin tunnels

Fig. 16 Horizontal displacements to the axis of the right tunnel



(a) Single tunnel (b) Twin tunnels

Fig. 17 Extreme total displacement vector for two tunnels during excavation change toward the values and the signs); therefore this change due to the effect of the interaction between the new left tunnel and the existing right tunnel.

6.5 Extreme total displacement

The extreme total displacements vectors (ETD) of the two parallel tubes tunnel (L = 35, 50 m) during each phase of excavation is given in the Fig. 17.

We start with the first tunnel (phase 1), one do seize the extreme total displacement induced by the excavation of 1st single right tunnel (before interaction), after one reduces by the second left tunnel (stage 2). The first remark of this figure, it is that the ETD is increased for the right tunnel after the excavation of second left tunnel. This case is explained per interaction between two tunnels effect.

7. Analysis of numerical results

Ngoc Anh Do and Daniel Dias studied a considerable influence of the tunnel distance on the bending moment induced in both jointed and continuous linings of the first tunnel. In this study two cases have been distinguished: The first consists to construct the right tunnel by slices (Slices; excavation after 10, 20, 30, 40 m, and excavation complete), before interaction case with the second left tunnel. The second consists in digging the left tunnel by the same phases, after interaction case between the two tunnels. The profiles of the convergences (diametrical shrinking of a tunnel section), and the internal efforts (axial and shear force; bending moments) in the 1st right tunnel lining before and after interaction are given on the Figs. 18 and 19.

In first report it is that the value of the convergence of the right tunnel at first slice (after 10 m excavation) is the same value measured of the tunnel T4 that equals to (- 60 mm; to see Fig. 4).

As we note that the values of the convergence , and the internal efforts (axial force, bending moments and shear force) induced in the right tunnel lining before and after interaction are enlarged during excavation following different slices (advancement of excavation), once one

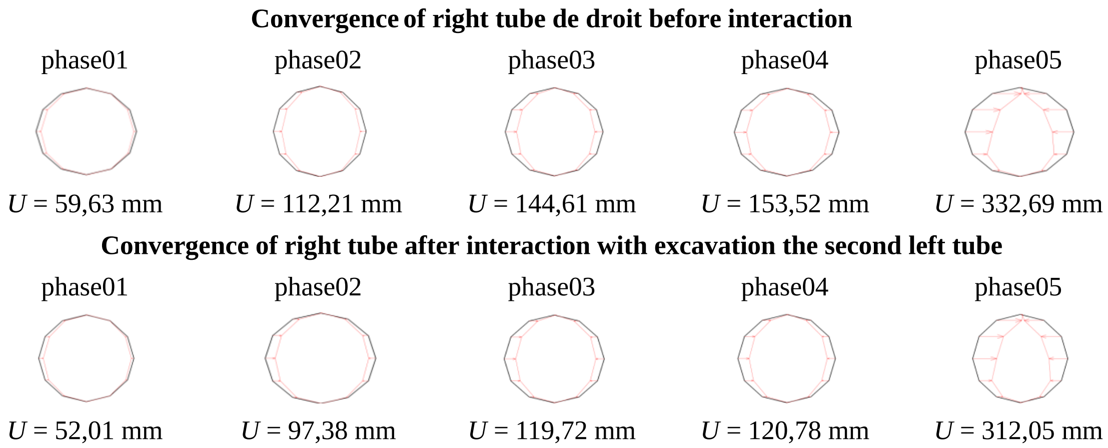
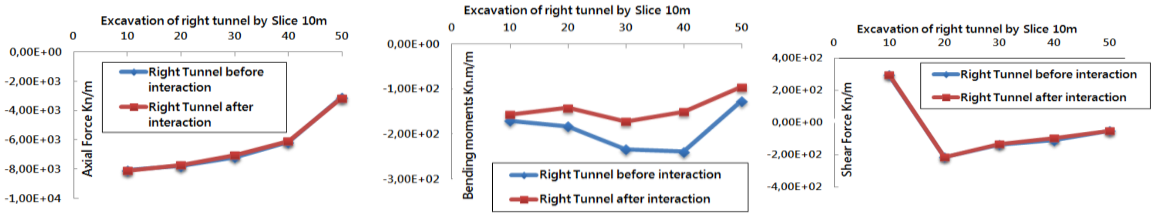


Fig. 18 Convergence in right tunnel lining (before and after interaction with new left tunnel)



(a) Axial force profile (b) Bending moments profile (c) Shear force profile

Fig. 19 The internal efforts induced in the lining right tunnel (before and after interaction with the new left tunnel) following the sense *Z*

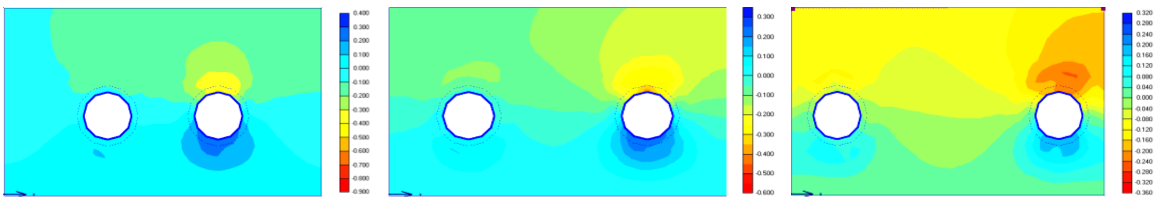
advances the excavation in the sense *Z* by the increment been taken like 10 m in 1st right tunnel, there is an increase of the convergences in the 1st tunnel lining within the two cases of before and after interaction. A comparison between the values of two cases (before and after interaction) addresses that these last are decreased in the case the excavation of 2nd tunnel; scilicet, after the interaction between the two tunnels (Fig. 18). As can be seen clearly from (Fig. 19) a good concordance between these results of the axial force and bending moment decides either of the point of view shape or maximal values in the two cases (after and before interaction), scilicet there is a little influence of excavation the 2nd tunnel (new) on the 1st tunnel (existing) (the insignificant interaction between the two tunnels), contrary the bending moment curves, one mentions that the two curves possessing the same tracing of the point of view shape, but the values are separated in every slice, these is a influence excavation of 2nd tunnel on 1st tunnel belong the values, therefore an interaction exists between the two tunnels.

8. Investigating of the effect of tunnels spacing on interaction

Chakeri *et al*. (2011) investigated the effect of the horizontal spacing between the Tohid Tunnels on the stability of both these tunnels and the metro tunnel (Line 4). And Salim (2013) studied the effect of position of new tunnel on the existing tunnel.

The effect of the horizontal spacing between the centers of the two tunnels on the stability of both these tunnels has been investigated using three different tunnel spacing (1, 1.5 and 2) L; where L is the distance between the centers of the tunnels.

Fig. 20 presents vertical (*y*) displacement contours for the different horizontal spacing between the twin tunnels. It can be seen that both the *Z* displacement significantly affected by the horizontal



(a) Spacing's L (b) Spacing's 1.5L (c) Spacing's 2L

Fig. 20 Vertical displacement for spacing's L, 1.5 L, 2 L horizontal distance between the tunnels. As expected, an increase in the distance between tunnels decreases the *y*-displacement leading to a reduction in the displacement contours above each tunnel. By other term the distance between the tunnels decreases, there is an increase of the vertical constraints and a reduction of the horizontal constraints in the space separate the two tunnels and that is the reason of the increase of settlement.

8. Influence of lining thickness

Hefny *et al*. (2004) studied the influence of lining of both the new and existing on the value of the induced bending moment after interaction.

In this study, three values of lining thickness were adopted for the first tunnel, i.e., 150 mm in thickness (represents very flexible lining), 400 mm (represents relatively stiff lining), and 900 mm (represents very stiff lining). For each value of lining thickness of the first tunnel, the lining thickness of the new tunnel (second) was varied from 150 mm to 900 mm and the effect on the bending moment induced in the first tunnel was studied. Fig. 21 shows the moment coefficient as a function of the flexibility ratio. The dimensionless flexibility ratio and the moment coefficient are defined by the following equations:

Flexibility ratio = $\dfrac{\frac{Es}{/1+\vartheta s)}}{\frac{6EI}{(1-\vartheta^2)}\ \frac{1}{R^3}}$

Moment coefficient = $\dfrac{M}{\gamma H R^2}$.

Where: I: is the moment of inertia of the lining per unit length.
M: is the maximum bending moment induced in the lining

It can be seen from Fig. 21 that for a first tunnel of very flexible lining, the interaction between the first tunnel and the second adjacent tunnel has negligible influence on the bending moment induced in the first tunnel. For cases of a first tunnel of stiffer lining, the moment coefficient decreases as the flexibility ratio decreases (reduction of the values of the flexibility ratio correspond the elevation of the lining thickness). The change in moment coefficient is insignificant once the flexibility ratio is greater than 2.50; (This implies that the lining more than 600 mm) behaves as a flexible lining.

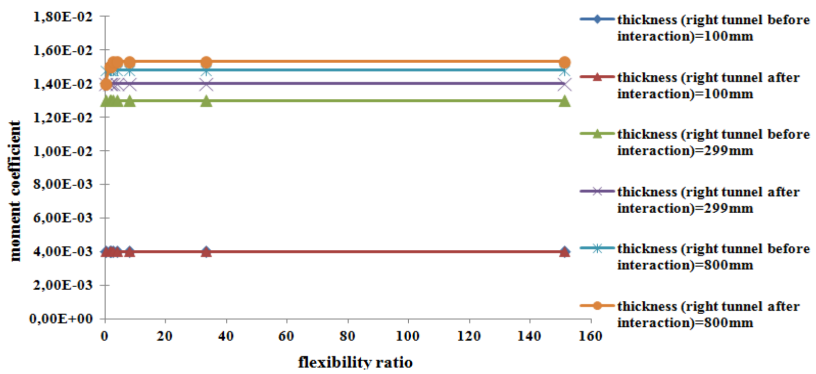


Fig. 21 Variation of maximum bending moment induced in the lining (first right tunnel after interaction) with lining thickness (Second left tunnel)

9. Conclusions

In this research, Three-dimensional Finite Elements Method using Plaxis program has been used to predict the behavior of an existing tunnel under the effect of a new nearby tunnel to excavate, and also to study numerically the interaction mechanism between two parallel tunnels, the similar as the tunnel T4 double-tubes. After we go to change several geometrical and geotechnical parameters in order to study their influences on settlement at soil surface. The following conclusions can be drawn from this numerical study:

- The procedures of construction affect settlement, displacement and the internal efforts in the tunnels.
- For two parallel horizontally tunnels for more of stability of the ground it will be necessary to consider the excavation of the 1st tunnel then the second, although this procedure will require in most cases a structural reinforcement of the 1st tunnel (definitive lining).
- The settlement trough at the shapes variable they can be symmetrical as they can be asymmetric.
- After the excavation of the 2nd tunnel, we note an increase of settlement that can be due to the change of the soil rigidity due to its weakening in the neighborhood of this last provoked by the 1st excavation and that is an important factor in the movement of ground that occurs. Even for the displacements of subsurface and the internal efforts in the first tunnel lining, we notice an increase after the interaction with the second tunnel.
- Once the distance between the two tunnels to enlarge, the vertical displacement goes decreases, the behavior of the 1st tunnel in presence of 2nd tunnel is similar to the one of the tunnel constructs alone in a virgin ground.
- The study indicates that there is significant effect of position of new tunnel on the existing tunnel.

Finally, we can say that this study put in evidence clearly the interaction between two tunnels, and the numerical modeling considers itself in general resembling a prevision method for more stability of ground it will be unavoidable to distant the tunnels one of the other.

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