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Minimizing of tunneling effect on existing infrastructure in Egypt

Key words: tunneling, grouting, field measurements, Abaqus, Al-Azhar twin tunnel

Introduction

The construction of two closely distant tunnels under an existing tunnel can cause greater deformation for the existing tunnel and the ground due to the dual disturbances caused by the tunneling process (Jin, Yuan, Li & Zheng, 2018). Several studies have estimated the ground movements as well as the deformation has induced in the existing tunnels by the construction of a new tunnel (Fang, Zhang, Li & Wong, 2015; Zhang, Liu, Kang, Zhong & Chen, 2018; Lin, Chen, Wu & Cheng, 2019). Grout technology is widely used for strengthening the soil and protecting the existing structures in shield tunneling. Li, Zhang and Yuan (2013) presented the case of using jacking as the tunnel protection methodology in case of the tunnel excavation under the existing one. Kimpritis, Smon, Pandrea and Vukotic (2014) explained how jet grouting could be used as the integral part of the complex tunneling projects. They summarized the basic framework for the design and execution of jet-grouting in tunneling.

In this research, the case history of the intersection of Al-Azhar twin tunnel with the CWO sewer is idealized using the three-dimensional numerical model.

Consequently, in this study, a series of parametric studies are conducting by utilizing the verified model of the case history to evaluate the effect of other different protection techniques. The key part of this paper is to investigate the best configuration technique to minimize the tunneling effect on an adjacent structure.

Problem statement

Al-Azhar twin road tunnels were constructed to provide the fast link between the congested parts of downtown Cairo with the eastern parts of the city under the area of old Fatimid Cairo. The intersection of Al-Azhar Road Tunnels was with excavated diameters of 9.40 and 18.70 m spaced, and the CWO sewer 5 m external diameter at Port Said Street as shown in Figure 1. Table 1 summarizes the parameters of soil at the intersection point. According to El-Nahhas (1992), the sewer tunnel was constructed in 1988 with a bentonite slurry shield. Table 2 summarizes the parameters of the twin tunnels and the CWO sewer. Several measurements were conducted to the several sections of Al-Azhar road tunnels (Abu-Krisha, 2001; El-Sayed, 2001; Ezzeldine & Darrag, 2006). According to Campenon Bernard SGE report (1999), the groundwater table reported at 3.40 m below the ground surface.

Grouting techniques are highly evolved methods used in most tunneling projects as a stabilization method or as sealing to the structures. Before the launch of tunneling work, two slurry walls were injected to confine the sides of the CWO and the road tunnel. The characteristics of the grouted wall are summarized in Table 3. According to

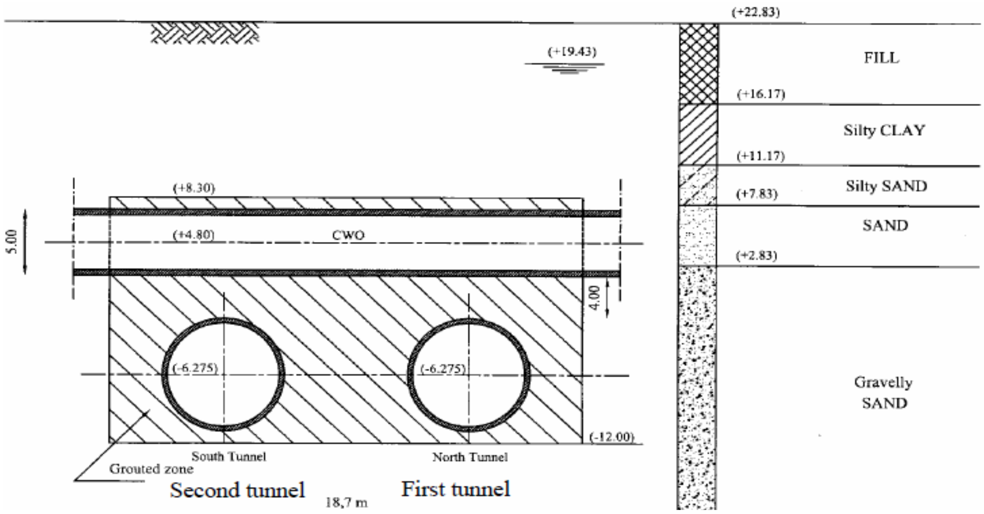

FIGURE 1. Subsurface conditions at the site of the intersection (El-Sayed, 2001)

TABLE 1. Soil properties (Abu-Krisha, 2001)

Layer	Thickness [m]	γ [kN·m^{-3}]	φ [°]	C [kPa]	E [kN·m^{-2}]	ν	Ψ [°]
Fill	6.70	16.50–6.50	23	0.20	8 300	0.40	0
Silty clay	5.00	8.00	15	10.50	11 000	0.35	0
Silty sand	3.40	9.00	30	–	50 000	0.35	0
Sand	5.50	9.50	35	–	75 000	0.30	5
Gravelly sand	extend	9.50	41	–	80 000	0.30	11

Campenon Bernard SGE report (1999), the required instrumentation to evaluate the tunnel effect on the adjacent CWO sewer shown in Figure 2.

TABLE 2. Twin tunnel and CWO sewer properties (Abu-Krisha, 2001)

Twin tunnel	geometry	outer diameter	9.40 m	shield thickness	50 mm
		inner diameter	8.35 m	gap thickness	75 mm
		lining thickness	0.40 m	grouting thickness	125 mm
	mechanical properties	type	E [kN·m^{-2}]	ν	γ [kN·m^{-3}]
		lining	$1.4 \cdot 10^{7}$	0.15	25
		shield	$2.1 \cdot 10^{8}$	0.3	78
		gap	1 000	0.3	–
		grouting	vary	0.15	25
CWO sewer	geometry	outer diameter	5.00 m	limning thickness	32.80 cm
		inner diameter	4.15 m	grouting thickness	26.20 mm
	mechanical properties	type	E [kN·m^{-2}]	ν	γ [kN·m^{-3}]
		lining	$1.4 \cdot 10^{7}$	0.20	25
		grouting	$1 \cdot 10^{5}$	0.15	25

TABLE 3. Grouted walls geometry and properties (Abu-Krisha, 2001)

Height = 20.30 m	Length = 38.50 m	Thickness = 2.00 m	ν = 0.23
$E = 250 \cdot 10^{3}$ kN·m^{-2}	$C = 100$ kN·m^{-2}	$\varphi = 35°$	q_c = 1.5 MPa

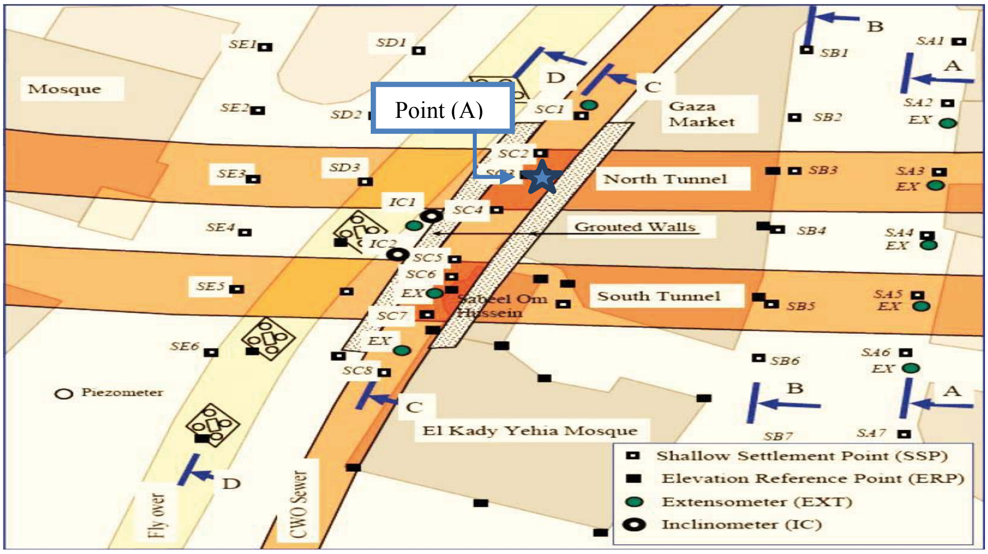

FIGURE 2. Instrumentation layout (Ezzeldine & Darrag, 2006)

Numerical model

To investigate the tunneling effect on the induced ground response, a three--dimensional model with a circular twin-tunnel configuration was developed by using the general-purpose finite element suite Abaqus/CAE (Dassault Systèmes Simulia, 2016).

Soil section with five distinct layers and grout components modeled as solid element, the material utilized in this model is employing elastic-perfectly plastic (the Mohr–Coulomb criterion), while lining, grouting, gap, shield and CWO elements are modeled as solid element by adopting elastic material.

The choice of sufficient mesh dimensions should not affect the tunneling process Moller (2006). Accordingly, the scope of the model was chosen to be in the transverse direction is 100 m, 76 m in the longitudinal direction, and 60 m in the depth. Figure 3 shows the three--dimensional model for the numerical analysis considered in this study.

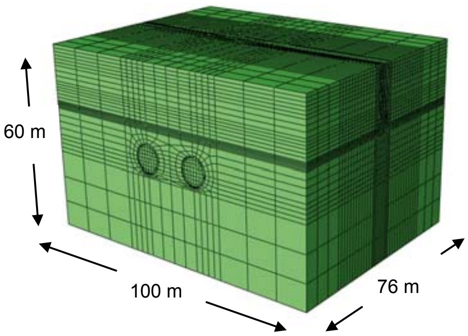

FIGURE 3. The three-dimensional finite element model for the intersection point

The typical excavation of tunneling activities is simulated step by step by taking into consideration the rate of tunnel advancement as 0.5 to 1.5 $m \cdot h^{-1}$. This simultaneousness of tunneling is as following:

- Removing the length of soil equal to 1.5 m per step, conducting TBM shield with surrounding gap and applying excess face pressure 160 kPa to sustain the shield length of 9 m.
- Deactivating the TBM shield with surrounding gap element and the face pressure.
- Activating lining and grout elements with pressure of 300 kPa taking into consideration the setting time of the grout. The initial stiffness of the grout is 1,000 kPa. This stiffness increases with the rate which is depending on the time from the liquid state to the harding state. It is also relating to the compression strength by the developed empirical formula (Eq. 1), according to ACI 318-11 Building Code (American Concrete Institute [ACI], 2011).

$$E = 4730\sqrt{(f_c)}[kPa] \quad (1)$$

Numerical model results

Results from the finite element study were compared with the field monitoring data to evaluate the capability of the proposed model to simulate the complex between the soil – CWO sewer – tunneling interaction.

Prediction of deformation field

The observed deformation trend of the soil was well depicted by the Abaqus model after the execution of the north tunnel and after the respective execution of both tunnels as shown in Figures 4 and 5.

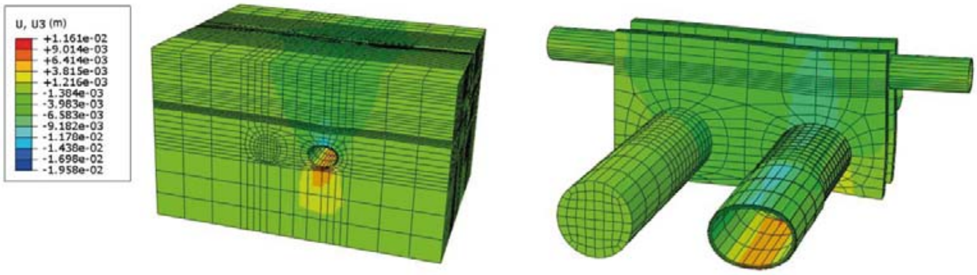

FIGURE 4. Vertical deformation after the execution of the north tunnel

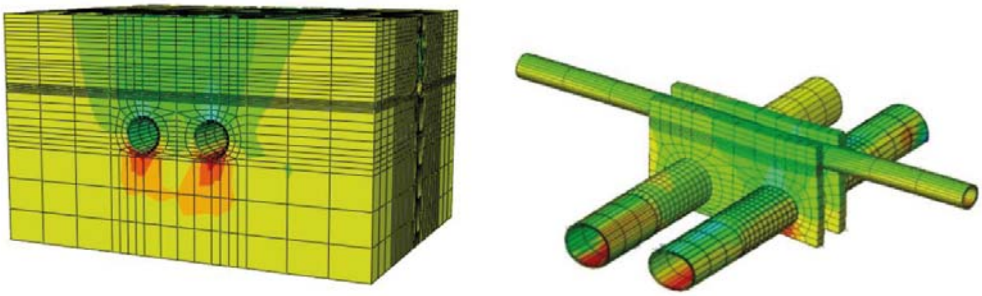

FIGURE 5. Vertical deformation after the execution of south tunnel

It can be noted that the soil deformation increases towards the tunnel vicinity as a result of tunnel cutting over.

Settlement trough

Figure 6 shows that the surface settlement was estimated in the region of the untreated zone after running the north tunnel. The results indicated that the computed ground surface displacement was about 14% more than that of field displacement.

Also, the ordinate of surface settlement trough was not symmetrical about the tunnel vicinity due to the existence of CWO in the global interaction system.

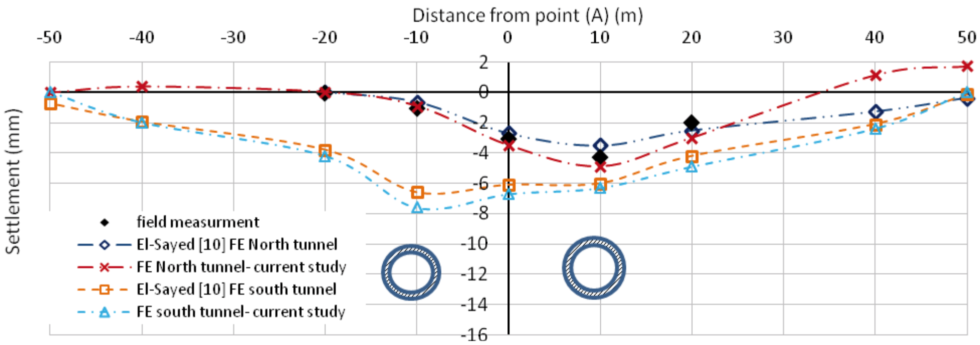

FIGURE 6. Surface settlement trough of the untreated ground

Generally, the comparison indicated the good signs of the agreement between the computed ordinates and the measured values. However, the idealization of the second tunnel after setting up the final field of the ground movements associated with the construction of the first tunnel as shown in Figure 5. Also, the settlement through has estimated and represented in the same figure from another numerical model adopted by El--Sayed (2001).

It can be noticed that the through has reported the maximum settlement of approximately 8 mm as it was compared with the estimated one by El-Sayed (2001). The general trend of the displacement curve appears to agree with the other finite element model simulation conducted by El-Sayed (2001) about 15%. Furthermore, the maximum computed settlement is 24% less than the allowable settlement documented by the Campenon Bernard SGE report (1999) as no more than 8 mm.

Parametric study

A series of parametric studies were carried out to investigate the most effective technique in reducing the tunneling effect, as an alternative technique instead of using the two grouted wall method. Table 4 summarized all cases of the protection techniques conducted in the parametric studies to reduce the tunneling effects.

Analysis 1 is the reference case that is developed without any protection method which indicates efficiency of all other techniques used to minimize the tunneling effect.

TABLE 4. The protection techniques used in parametric studies

Analysis	Protection technique
1	No protective method
2	Two grouted walls (executed case)
3	Slurry piles
4	Secant piles wall
5	Grouted block of slurry beneath the CWO sewer

Analysis 2 investigates the effect of using two grouted walls. The development of the two grouted wall is based on the case study, as shown in Figure 7.

Figure 8 illustrates the protection method of the third analysis by using 38 adjacent slurry piles of diameter 1.0 m distributed in two rows around CWO sewer with length of 35 m from the ground level. The distance between piles C.L. to C.L. is about 2.00 m. The slurry piles are modeled by adopting Mohr––Coulomb with $E = 7.9 \cdot 10^5$ kN·m^{-2}, $\nu = 0.26$, $C = 780$ kPa, and $\varphi = 30°$.

Analysis 4 investigates the effect of using a total 34 reinforced concrete piles with slurry piles (secant piles) with length of 24 m. The distance between piles C.L. to C.L. is about 2.00 m with a diameter of 1.00 m. The pile's tip level is approximately 0.5 m above the tunnel crown to avoid the damage of the piles when TBM advance. The concrete piles are modeled as an elastic material with $E = 140 \cdot 105$ kN·m^{-2}, $\nu = 0.15$. The slurry piles modeled like (Analysis 3) as shown in Figure 9.

Analysis 5 demonstrates the use of the grouted block. It confines the twin tunnels with the following dimension 38.50 × 14.50 × 9.00 m. The grouted block is modeled as elastic perfectly plastic Mohr–Coulomb material like the two grouted walls as shown in Figure 10.

Results of numerical models and discussion

The results of numerical models clarified the effect of the different protection technique on the surficial settlement, CWO sewer settlement, CWO sewer cross-section, longitudinal deformations, principles stresses, bending moment developed on CWO sewer.

Surficial settlement

Figure 11 illustrates the induced maximum surficial settlement curves which are presented for different protection configurations. The figure indicates that using a deep grouted wall or grouted block had almost the same effect on the surficial ground settlement. Also, the induced surface settlement in the case of (Analysis 4) is less than that induced in (Analysis 1) by about 60%. This may be due to the upper portion of the tunnel. It has a larger over-cutting than that of the lower portion. The restraining effect takes place at the lower portion by the restrained secant piles.

Figure 12 demonstrates a comparison between the induced surficial settlements in different analyses associated with the tunnel advancement at the location of the points (A). The maximum settlement is detected after the TBM has passed the point A by the distance of 22.5 m. Also, the results indicate that the ground surface vertical movements measured at the point A start to take place when the TBM ap-

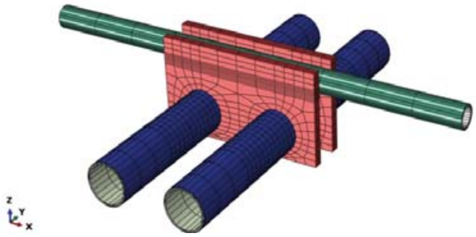

FIGURE 7. Analysis 2

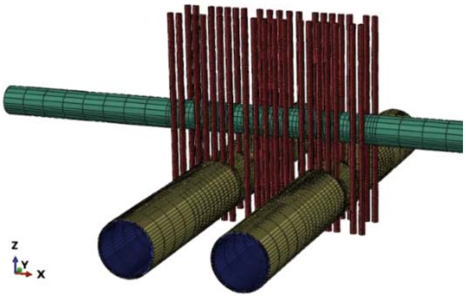

FIGURE 8. Analysis 3

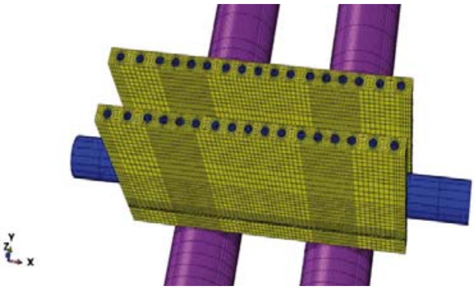

FIGURE 9. Analysis 4

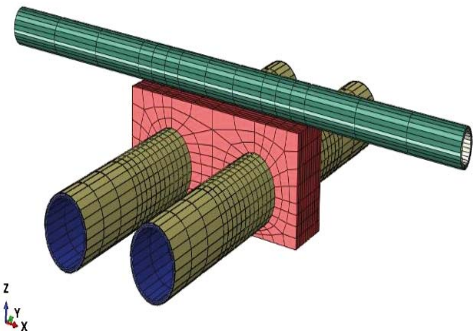

FIGURE 10. Analysis 5

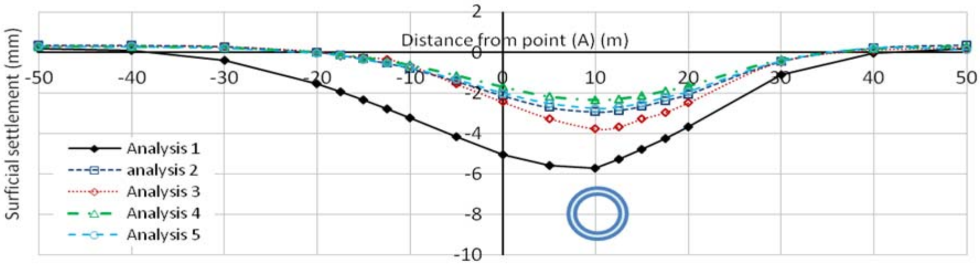

FIGURE 11. Induced surficial settlement relative to different protection configuration

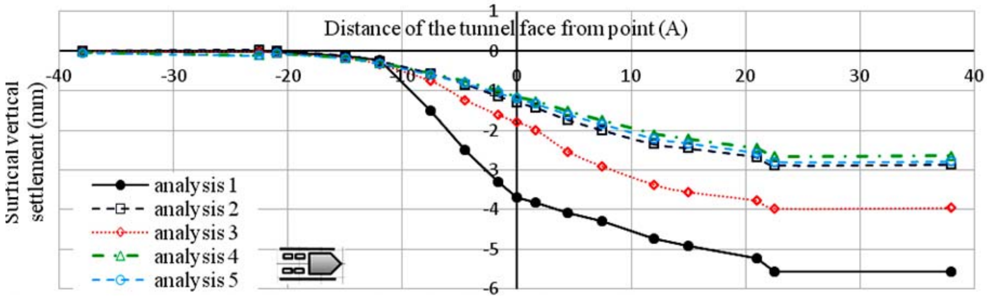

FIGURE 12. Induced vertical settlement at point A for all protection techniques

proaches before point A by the distance of about 1.2 times tunnel diameter, after that the rate increases up to distance 1.2 times tunnel diameter. However, after the distance of 2 times tunnel diameter, there is no increase in the rate of settlement associated with the tunnel advancement.

CWO sewer settlement

Determining the displacement induced from the tunnel is an important parameter to evaluate the construction quality and the structural stability of the CWO sewer. Figure 13 shows the induced settlement at the level of the crown of CWO at point A, as shown in Figure 2 after the excavation of the north tunnel.

Using the secant piles and the grouted block (Analyses 4 and 5) are more effective method in reducing the CWO sewer settlement by approximately 63% more than that induced in Analysis 1. Generally using any protection methods reduce the CWO settlement less than the allow-

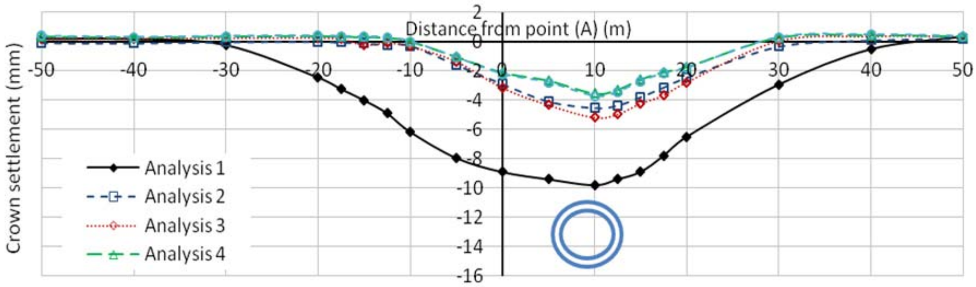

FIGURE 13. Induced CWO sewer settlement after excavation of north tunnel at section C–C

able settlement (8 cm). According to the economic view, using the adjacent slurry pile (Analysis 3) is saving time and cost regardless the settlement.

CWO sewer cross section deformation

Figure 14 shows the crown, invert, and spring line deformations. Realistically, the shape of CWO oval due to the effect of the soil own weight. Away from the CWO shape, the tunneling process causes additional displacement in the CWO sewer. The maximum offset of the CWO sewer is pushed in the diagonal axis which is detected when the tunnel face advancement is ahead of the point A by approximately 24 m or 39 m behind the tunnel. The observed trend of the CWO deformation matched with the documented by Jin, Yuan, Li and Zheng (2018).

Also, there is a difference between the left and right springline deformation caused by the effect of the tunnel face pressure pushing the CWO sewer away from the tunnel. This pushing force causes left springline moves laterally more than the right springline. This can be attributed to the restraining effect of soil against the right springline movement.

The invert deformation of CWO is heave when the TBM head is behind the CWO by 15 m. Then the invert deformation changes from the inward to the outward deformation as the tunnel excavation proceeded. This change in deformation is due to the soil losses resulted from the TBM over-cutting.

Vertical and lateral stresses developed on CWO sewer

Figure 15 sheds light on all changes in the vertical and lateral stresses induced after the tunneling process concerning (Analysis 1). By comparing, the induced lateral and vertical stresses developed in the crown, invert, and springline by that are developed in the un protected case, it can be detected that the maximum reduction about 33% is developed in crown vertical in case of employing the grouted bock (Analysis 5). While conducting adjacent slurry piles (Analysis 3) cause an increase in crown stress about 104%. This change in crown stress can be attributed to the rigidity of the confining method around either tunnel vicinity or CWO.

On the other hand, conducting secant pile is more effective technique in reducing the lateral stress induced along crown, invert, and springline by approximately 15%, 15%, and 19% of that developed in Analysis 1. While utilizing other methods causes an increase in spring line lateral stresses. This can be attributed to the decrease in crown force, which is transferred by arch action to spring line.

Summary and conclusions

The effects of tunneling on the infrastructure have great concern of this research by developing a 3-D numerical model using the finite element program Abaqus (ver. 6.16).

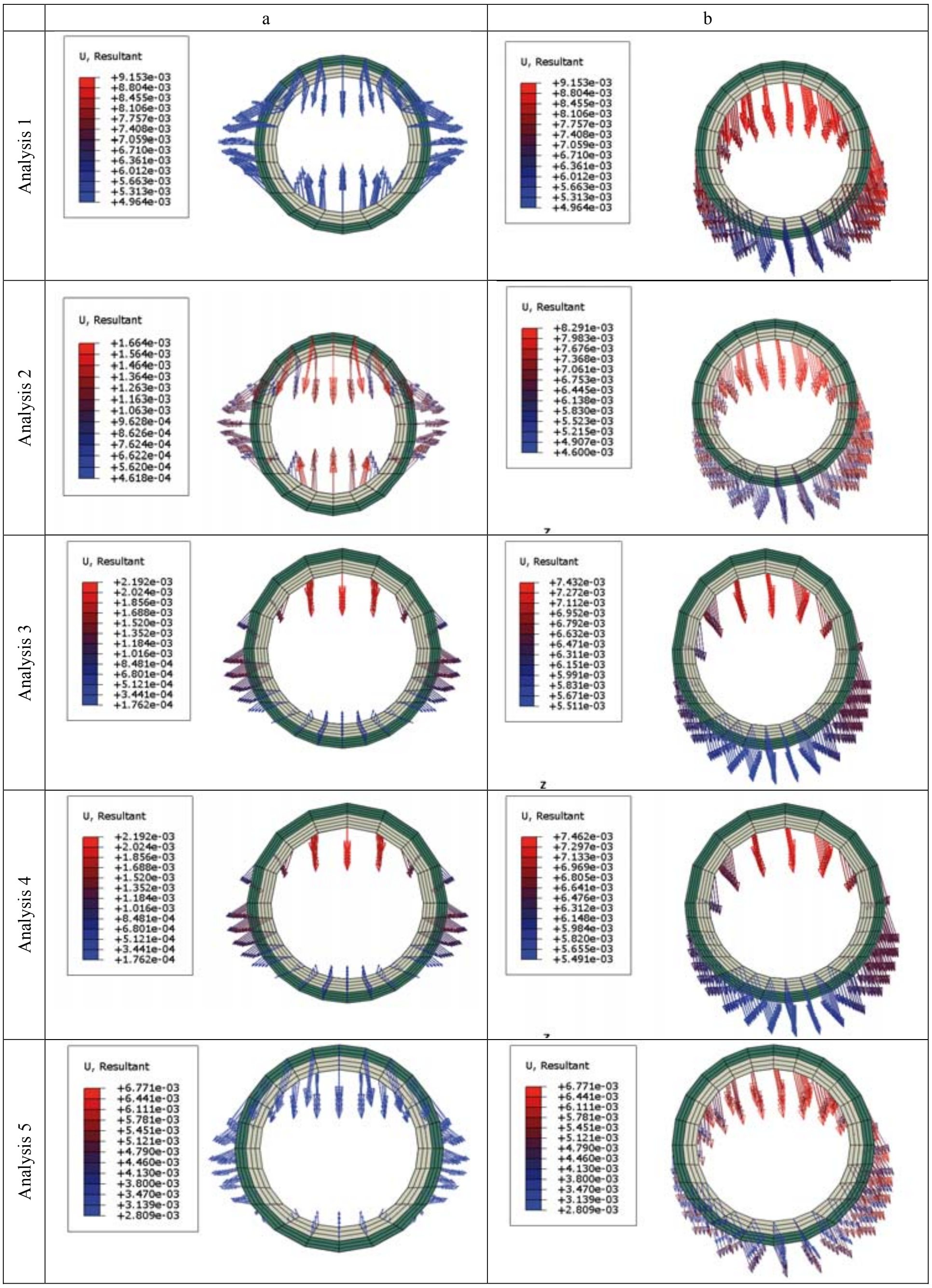

FIGURE 14. Deformation of the CWO sewer at the intersection with the north tunnel: a – before tunneling process; b – after executing of the north tunnel

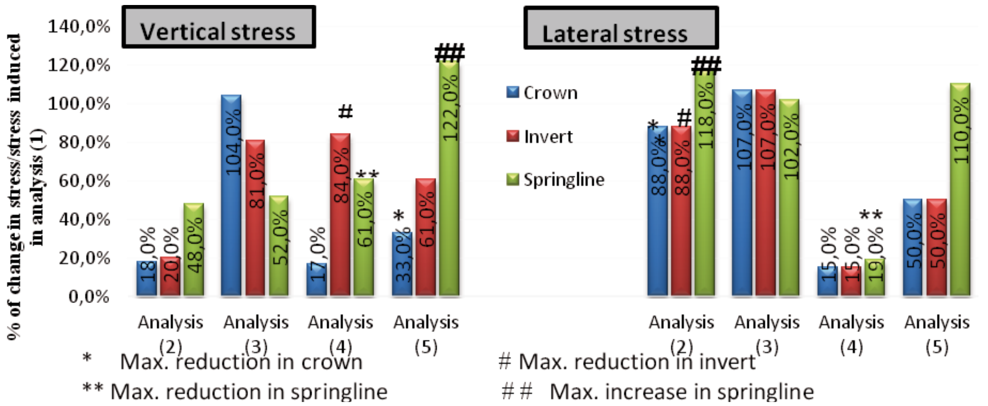

FIGURE 15. The percentage of vertical stress and lateral stresses induced on CWO sewer with respect to Analysis 1

1. The gained surficial settlement from the numerical model fairly agree with field data obtained from monitoring the advanced Al-Azhar twin tunnel during crossing the main sewer of Cairo.
2. Modeling such complicated interaction features is a typical 4D problem

A set of parametric studies is conducting with the same model of the verified case to investigate the effective sealing method of the CWO sewer from the tunneling effect regarding the sealing configuration. 4-different types of mitigation methods were adopted to seal the CWO sewer from the tunneling effect. Based on the results of parametric studies the following may be concluded:

– By comparing the displacement resulted in (Analyses 2 and 3), it can be demonstrated that using the slurry piles (Analysis 3) increases the developed CWO displacements at the crown and invert by 2%, and 34% respectively of that are recorded in (Analysis 2). However, all protection methods are effective in reducing the CWO settlement less than that are developed in Analysis (1) by 50%, 35%, 60%, 25% in the crown, invert, springline right, and springline left respectively.
– The comparative analyses of the CWO stresses show that using the slurry piles as protection technique reduces the invert stress by 81% of that are induced in the (Analysis 1). While the TBM face pressure, as well as grouted pressure is transferred by the arch action to the CWO crown causing an increase in stresses by 104% of that is induced in Analysis 1.
– Using of the adjacent slurry pile to reduce the tunneling may be considered an effective method in reducing the tunneling effect by the careful selection of the shield. In addition, from an economic view, it is considered that the most sophisticated method (regarding saving time and cost) as the CWO deformation does not exceeded the permissible value.
– Using the grouted block and secant pile (Analyses 4 and 5) are the most effective technique in reducing the

tunneling effect regarding the CWO displacement and stresses.

- The only negative result of using the grouted block below the CWO is increasing spring line vertical and lateral stress by 122% and 110% respectively of that induced in Analysis 1.
- The induced axial stress in the CWO sewer is unexpectedly large in the crown than that induced in the invert. The tensile stress is developed in invert is due to hanging and sagging moments. However, the rigid lining face support can resist the separation force.

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Summary

Minimizing of tunneling effect on existing infrastructure in Egypt. A set of parametric studies by using the Abaqus software is conducting to investigate the effective method to seal the CWO sewer from the tunneling process. These methods include: (i) two deep grouted walls, (ii) adjacent slurry piles, (iii) bored reinforced concrete piles assisted with slurry piles, and (iv) grouted block confining the twin tunnel wall. Based on the results of parametric studies. Most of the protective studied technique was effective on reducing the tunneling effect on the ground movements.

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