

Stability Analysis of a Station-TBM Tunnel Intersection Applying Innovative Techniques



Mona A. Mansour, Amal N. Mohamed

Abstract: Tunnel construction using a tunnel boring machine TBM may encounter a coordination difficulty where the machine may reach the station site before the station completion. A construction solution for such a station-TBM intersection is vital. In the Cairo Metro Tunnel-Line 3, Heliopolis station, infrequent construction sequence was adapted, where the station transverse diaphragm walls were firstly installed to let the tunnel boring machine entering the station vicinity and erecting the tunnel lining within and after the station. Afterward, the longitudinal diaphragm walls of the station were installed parallel to the tunnel line. In view of that, the tunnel parts enclosed by the station were required to be safely demolished, followed by completing the remaining station elements. The process of removing the lining segments within the station involves a risk of instability of the existing tunnel because of excessive deformations. Therefore, innovative four construction techniques were suggested and numerically inspected to find an optimal sequence of executing such a hard construction condition. Numerical models, established by the 2-D finite element software, PLAXIS, were adopted in a staged analysis to simulate the construction phases till the critical phase of removing the tunnel segments, where the tunnel stability was considerably reduced. At that point, stability analysis was performed to examine the liability of the four demolishing scenarios. These scenarios include partial filling the tunnel with sand at the demolishing location, and/or using internal or external link members. Lastly, the optimal technique to remove the lining segments inside the station considering stability, economy and time-saving, was decided.

Keywords: Diaphragm wall, intersection, PLAXIS, station, stability analysis, TBM tunnel.

I. INTRODUCTION

The driving of tunnels using Tunnel Boring Machines (TBM) has proven itself as the most powerful approach as it achieved a substantial degree of success for a wide variety of tunneling conditions worldwide. Commonly, the underground stations are firstly constructed, then, the TBM excavates the tunnel lines which connecting the stations. Some researchers addressed different construction sequences due to uncommon

site conditions, [1, 2, 3]. A margin of safety against tunnel collapse and excessive soil deformations should be evaluated to assure the safety of the nearby structures and public lifeline facilities. Therefore, the stability of tunnels and the associated deformations that may occur during excavation, are the primary concern of engineers [4].

The current research deals with an infrequent procedure of a tunnel line construction when the TBM passes through an uncompleted station during execution of the Greater Cairo metro tunnel-Line 3. The tunnel was decided to be excavated prior to construction of the station, (Heliopolis station) because of time constraints. Then, the station was required to be completed in an intersection with the existing tunnel while removing the extra lining segments, [5, 6]. This construction sequence comprises demolishing the tunnel segments enclosed within the station diaphragm walls. Such a procedure involves a risk of instability of the existing tunnel due to excessive deformations that may occur because of losing the complete support of the surrounding soil. This research numerically investigates the tunneling system performance, while demolishing the tunnel lining segments within the station. The two-dimensional finite element software PLAXIS, [7] was implemented in the current study, where a staged analysis was conducted to simulate the in-situ construction phases. The soil behavior was represented using the Hardening Soil Model (HSM). Firstly, the traditional construction stages including tunnel excavation, diaphragm walls installation, sequential excavation and casting some of the station slabs, were analyzed through phases 1 to 9, [8]. The predicted deformations of the diaphragm walls were compared with the corresponding values monitored during the earlier construction stages, [8, 9]. Then, four different construction techniques were suggested and numerically investigated, by adopting the staged analysis procedure [10], to determine the optimum technique that would be followed to safely remove the lining segments and execute the remaining elements of the intersecting station.

These techniques include partial filling the tunnel with sand at the demolishing location, and/or using internal or external link members, or combining two procedures. To avoid collapse during demolishing the unwanted lining segments, a stability analysis was performed by detecting the safety factor variation at selected points within the surrounding soil, in the four proposed techniques.

Lastly, only filling the tunnel with sand was found to be the optimal technique to remove the lining segments inside the station without the risk of collapse during excavation.

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II. SITE DESCRIPTION AND TUNNEL-STATION CONFIGURATION

This research was concerned with simulating the construction procedure of a chosen underground station. Fig. 1 illustrates the general layout of Heliopolis station and the studying section position, which was instrumented by inclinometers. The station is 223 m in length and 20.5 m in width.

Fig. 2 shows a cross-section in the location considered in the current study including, the tunnel, the station diaphragm walls and slabs, struts, and the soil profile. The groundwater level was observed at (+18.50) m below ground surface, according to the boreholes and piezometers readings.

III. NUMERICAL MODELLING

Numerical analysis in the current research was conducted using the two-dimensional finite element program PLAXIS [7]. The different soil layers were modeled using fifteen-node triangular elements, and the tunnel lining was modeled using curved plate elements (shells) having three degrees of freedom. The diaphragm walls were also simulated using

plate elements. The interaction between the soil elements and the structural elements was represented in PLAXIS by an “Interface Element” defined by five pairs of nodes and had a zero thickness.

The connections between the slabs and the diaphragm walls were modeled in PLAXIS as fixed connections. As well as, the structural supports as struts and ties were modeled as (Node to Node anchors). The boundary conditions were adopted as follows: vertical boundaries have zero lateral movements, and the bottom horizontal boundary was restrained vertically and horizontally. The generated finite element mesh is shown in Fig. 3.

The Hardening Soil Model (HSM) was adopted to simulate the soil behavior. Table I presents the soil parameters implemented in the numerical analysis of the current study. In addition, Table II summarizes the stiffness parameters adopted in PLAXIS to simulate the structural behavior of concrete elements including the normal stiffness (EA) and the flexural rigidity (EI). The properties of the struts and the ties employed in the tunneling system are given in Table III.

Table I: Soil parameters adopted in the numerical analysis, [5].

Hardening Soil Model (HSM)	1	2	3	4
	FILL	SAND 1	CLAY	SAND2
Drainage Type	Drained	Drained	Drained	Drained
Soil unit weight above G.w- γ_{unsat} [kN/m ³]	18	19	19	21
Soil unit weight below G.w- γ_{sat} [kN/m ³]	18	19	19	21
Secant stiffness modulus - E_{50}^{ref} [kN/m ²]	10000	50000	30000	120000
Tangent stiffness modulus - E_{oed}^{ref} [kN/m ²]	8000	40000	24000	96000
Unloading - reloading stiffness modulus - E_{ur}^{ref} [kN/m ²]	12000	80000	48000	192000
Power - m [-]	0.5	0.5	1	0.5
Poisson's ratio- v [-]	0.3	0.3	0.45	0.3
Cohesion- c_{ref} [kN/m ²]	0	0	200	0
Friction angle- φ [°]	27	37	0	42
Dilatancy angle- ψ [°]	0	7	0	12
Interface strength- R_{inter} [-]	0.67	0.67	0.67	0.67

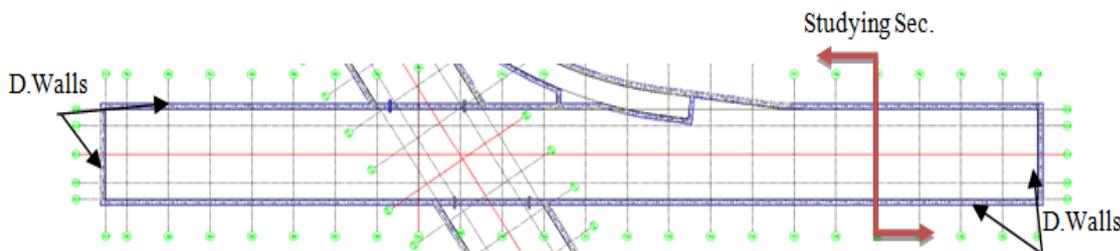


Fig. 1. The general layout of the tunnel-station Intersection (Heliopolis Station – Cairo Metro Tunnel – Line 3 [8,9].

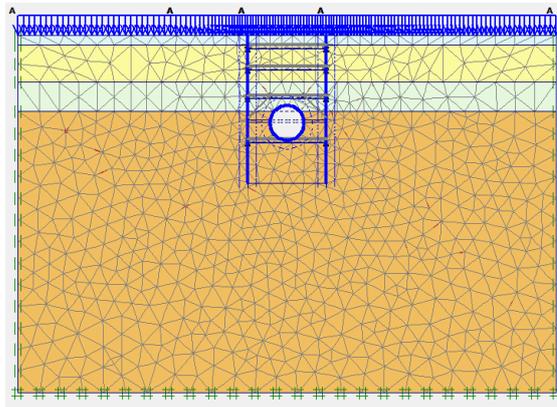


Fig. 3 Finite Element Mesh Generated by PLAXIS.

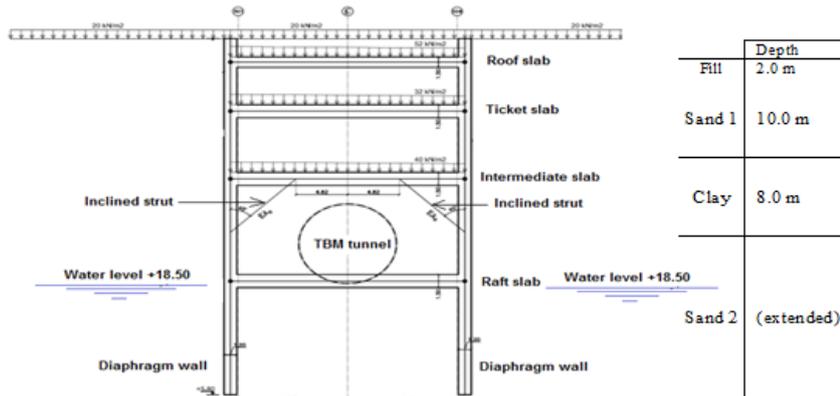


Fig. 2. Typical section at the station and the soil profile, [8, 9].

Table II. Parameters of structural concrete elements.

Identification	Thick. (m)	EA [kN/m]	EI [kNm ² /m]	weight [kN/m/m]	v [-]
Diaphragm walls	1.2	2.39E+07	2.87E+06	30	0.2
Roof & ticket & intermediate slabs	1.5	3.50E+07	6.56E+06	37.5	0.2
Raft slab	1.5	3.50E+07	6.56E+06	37.5	0.2
Tunnel lining	0.4	1.03E+07	1.37E+05	10	0.2

Table III. Properties of the link members

Horizontal strut		
A	m ²	0.052
E	Kpa	2.00E+08
Spacing	m ²	3.4
EA0	Kn/m	3.07E+06
EA=A*E/S		

A. Sequential Construction Simulation

Execution of the tunneling system was numerically investigated, considering sequential construction steps to simulate activation and/or deactivation of some elements, according to the analyzed phase. The results of analysis of each phase were considered the initial condition for the next phase. Beginning with the initial state, construction phases before demolishing the extra tunnel part enclosed by the station (Phases 1 to 10), are described as follows:

- Phase 1: Activation of the initial soil stresses and applying the nearby building loads.
- Phase 2: Tunnel activation, where the TBM cutting the short side of the diaphragm box, which is locally reinforced with glass-fiber (GFR) bars, and erecting the

tunnel. This phase presents the default plane strain behavior of the tunnel inside and outside the station.

- Phase 3: This phase presents the activation of the longitudinal diaphragm walls (D.W) parallel to the tunnel.
- Phase 4: Excavation to the roof slab level was carried out after installing of the longitudinal diaphragm walls.
- Phase 5: Casting the Roof slab on the soil by adding its own weight. The roof slab has been cast with a temporary opening to install machines for excavation below the roof to reach the level of the next slab.
- Phase 6, 7, 8, 9: The Roof slab was activated and connected to the diaphragm walls with fixed supports. Then, excavation to the next Ticket slab. Sequentially, these construction phases were repeated for ticket and intermediate slabs, as shown in Fig. 4.
- Phase 10: Activation of the intermediate slab and excavation to the tunnel by removing the clayey soil above, the first part of the tunnel had been exposed as shown in Fig. 5.

At this stage, the tunnel segments inside the station are needed to be removed safely. Therefore, a demolishing technique of the tunnel was needed to assure the safety of the constructed items against collapse. The following Four different possible techniques were proposed and numerically examined.

B. Proposed Demolishing Construction Techniques

▪ **Technique 1:** *Filling the tunnel with sand,*

The stability of the tunnel can be maintained by filling the tunnel with sand and removing its segments sequentially, beginning with the upper two segments, (Phase 10- Tech.1). Then, removing the second two segments and excavate to half of the tunnel safely, (Phase 11- Tech.1). The main concept is to reduce the soil heave below the tunnel at the middle of the lining, as it was the most critical point.

▪ **Technique 2:** *Installing struts inside the tunnel,*

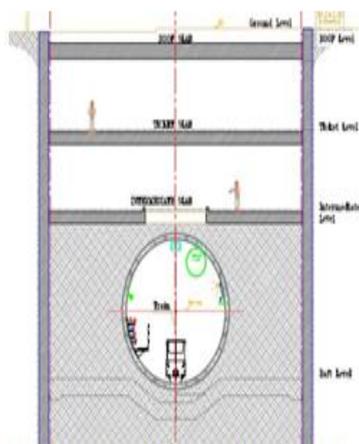


Fig. 4. Casting intermediate slab with temporary opening, [6].

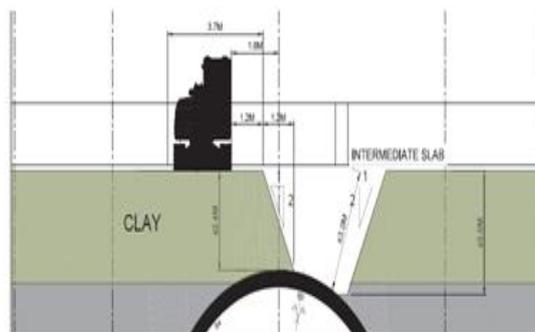


Fig. 5. Activate intermediate slab and excavate to tunnel lining, [6]

▪ **Technique 3:** *Providing two link members between the tunnel and the diaphragm walls,*

Similar to Technique 2, a row of link members, 3.4 m spacing, are provided at both sides of the tunnel to connect the segments with the diaphragm walls during the soil removal. Then the first exposed two segments were removed, (Phase 10- Tech.3). This process was repeated with the next two segments, as well as excavating to half of the tunnel safely (Phase 11- Tech.3). The idea of this technique was to reduce mainly the horizontal displacements of the tunnel during excavation of the surrounding soil.

▪ **Technique 4:** *Filling the tunnel with sand and installing struts inside the tunnel,*

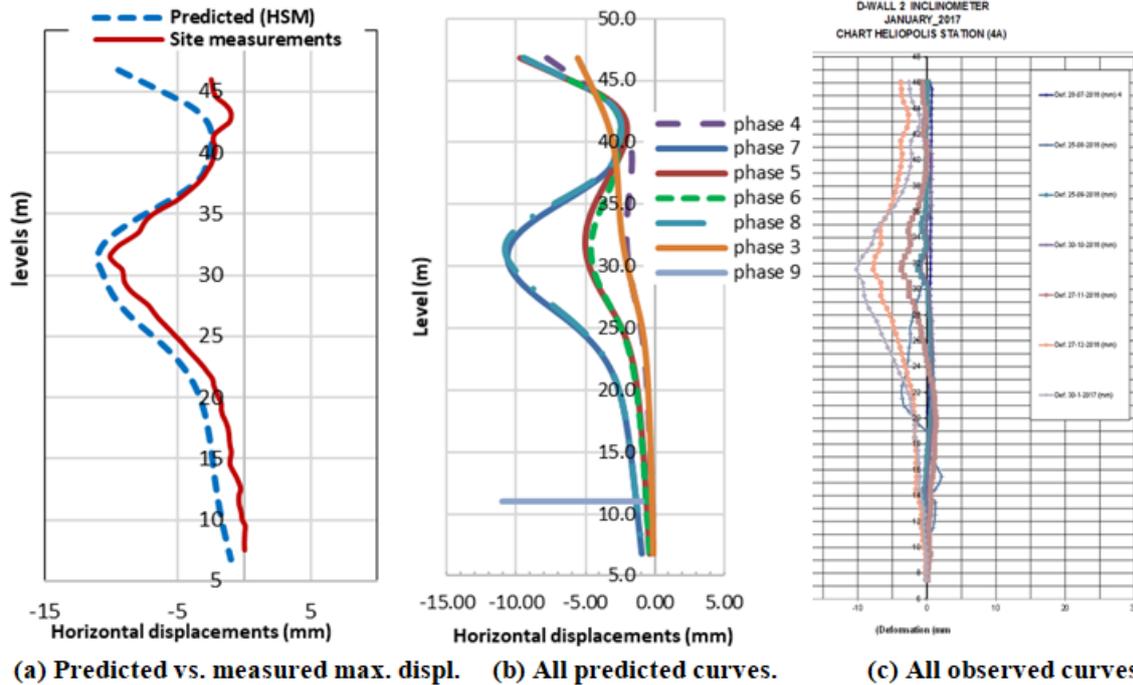
This technique was generated after studying the results of the three previous techniques, by adapting a combination of techniques 1 and 2. While filling the tunnel with sand to decrease the vertical heave, struts inside the tunnel are provided to decrease the horizontal movements, (Phase 10- Tech.4). Construction of (Phase 11- Tech.4) involves excavation to half of the tunnel and installation of the second

This technique involves providing a row of struts, 3.4 m spacing, between the second two segments during the soil removal around the tunnel till the strut level, (Phase 10- Tech.2). These struts are extended within the station vicinity. Then, installing the second strut row inside the tunnel, in the middle of its section, and removing the second two segments, (Phase 11- Tech.2). This process is then repeated for the next two segments until totally removing the tunnel. This technique is expected to minimize the horizontal displacements of the tunnel.

strut row inside the tunnel, followed by removing the second two segments. This technique was expected to be the most effective technique to save the tunnel stability during demolishing the segments, as well as, to reach the most factor of safety during excavation.

The previously described phase 10 before demolishing the tunnel (collapsed case), was to be modified to include the actions suggested by each of the four techniques for removal of the upper two lining segments. Whereas, in Phase 11, the second two segments are removed, as well as, excavating to half of the tunnel and activating the temporary inclined struts to support the diaphragm until casting the raft slab, are performed.

The Excavation to half of the tunnel and demolishing the upper segments safely is extremely important to reach a safe stage of demolishing the rest of the tunnel segments simply. This phase is considered the most critical phase regarding stability.



(a) Predicted vs. measured max. displ. (b) All predicted curves. (c) All observed curves
Fig. 6. Comparison between predicted and observed horizontal deformations of the diaphragm wall

IV. RESULTS AND ANALYSIS

Ground deformation due to tunneling is one of the major parameters that control the selection of the excavation and supporting methods. Therefore, reliable numerical models are widely implemented to predict the expected deformations during tunnel construction. Safety during tunneling is of major concern for the surface structures and, also for the underground vicinity of the tunnel and station construction.

In the following sections, deformations and stability of the tunneling system during construction phases and that occurred when applying the four different techniques to demolish the tunnel inside the station were compared to find the optimum solution.

A. Verification of the Numerical Model

Verification of the numerical models implemented in this research was conducted by comparing the predicted deformations of the diaphragm wall with the corresponding field monitored values, [6]. Fig. 7 delineates exceptional compatibility between the predicted and the measured deformation curves of the diaphragm wall, concerning both the trend and the values.

The maximum wall deformation was detected at about 16m depth, with values of 11.05 mm and 10.14 mm, for both predicted and measured methods, respectively.

B. Deformations of the Tunnel Within the Station

The numerically predicted deformations of the tunnel lining at the construction phases from 2 to 9 are presented in Table IV.

Table IV: Max horizontal and vertical displacement with construction phases

Phase	Max. Hz. dis. U_x (mm)	Max. Vl.dis. U_y (mm)
1	-	-
2	2.43	4.61
3	2.31	6.08
4	1.58	3.2
5	1.91	4.5
6	0.251	3.54
7	0.47185	3.04
8	0.469	12.4
9	4.42	10.95
10	15.25	9.85

Construction phase 10 (activate the intermediate slab and excavate to the tunnel without any precautions), was the most critical phase at which undesirable high vertical deformation values occurred. Therefore, the risk of removing the soil surrounding and above the tunnel, without applying an adequate technique, may cause instability and collapse may occur as shown in Fig. 7 (a).

Fig. 7 (b) shows a comparison between the four techniques at the phases of removing the tunnel, the minimum horizontal displacement was detected in technique 4 then 1 as the two models had the soil inside the tunnel to resist the lateral earth pressure. On the other hand, Fig. 8 (a) shows that, the vertical heave increases with removing the soil load and decreases when casting the slabs due to adding its own weight during excavation till phase 8 (excavate to intermediate slab). Also, the minimum vertical displacement was in technique 4 then technique 1, where the soil weight inside the tunnel resisted the vertical heave as shown in Fig. 8 (b).

$$\sum Msf = \frac{\tan \phi_{input}}{\tan \phi_{reduced}} = \frac{C_{input}}{C_{reduced}}$$



C. Ground surface settlement

During construction process from TBM activation till demolishing the tunnel part within the station, the soil beside the diaphragm walls was affected. Fig. 9 (a) shows the change of the ground surface settlement with construction phases. The comparison between the four techniques involving construction phases of removing the tunnel segments, phase 10 and 11, is presented in Fig. 9 (b).

As shown in the figure, the ground surface settlements have almost the same narrow range at all techniques, (3.7 mm to 4.5 mm). Indicating that, these techniques have no considerable effect on the soil outside the station which mainly affected by the diaphragm wall deformations.

D. Stability Analysis

The tunnel stability has been checked by adopting the ϕ -c reduction approach integrated into PLAXIS [7], for the computation of global safety factors. In this approach, the soil shear strength parameters, c and $\tan(\phi)$ are reduced, then measuring the corresponding displacement at several points. Failure was assumed to occur when a very small variation of c and/or ϕ entails a big variation in the calculated displacement. The cohesion and the tangent of the friction angle are reduced in the same proportion. The reduction of these strength parameters is controlled by a total multiplier (ΣMsf), defined as the quotient of the original strength parameters and the reduced strength parameters according to (1):

$$(1)$$

The total multiplier ΣMsf was set to 1.0 at the start of a calculation to set all material strengths to their unreduced values. Then, ΣMsf is increased in a step-by-step procedure until failure occurs. The safety factor is then defined as the value of ΣMsf at failure, (2):

$$F.O.S = \text{available strength} / \text{strength at failure} = \Sigma Msf \text{ at failure} \quad (2)$$

The safety analysis was performed for the four techniques at phases 10 and 11, to check the stability of the tunnel during the demolishing process for removing the segments safely. To achieve such a process, defining the plastic points which are the stress points reached the plastic-state, is important to

emphasize the highest stressed points nominated to failure in conducting the stability analysis. Fig. 10 shows the development of the plastic zone in the vicinity of construction, either around the tunnel or at the areas affected by the construction process, considering the four suggested demolishing techniques. It can be noticed that, although the plastic zone has a similar trend and extension outside the diaphragm walls, it propagates below the tunnel slightly more when using techniques 2 and 3. Fig. 11 shows the most critical points around the tunnel (A, B, C, D) to be considered in safety analysis.

Fig. 12 and Fig. 13 (a to h) exhibit the safety factor against displacements for phase 9 and phases 10 & 11 associated with the four suggested techniques, respectively. The figures delineate that, any of the selected points is affected according to its location with respect to the tunnel. The most stable point was point (A) located beneath the tunnel, whereas, point (D), located near to the excavation and region of removing the segments, displaces more to reach its stability.

Safety analysis for phase 9 showed that the structure was extremely safe during excavation till demolishing phases, with a safety factor (F.O.S) of 4.6. Thereafter, in applying any of the four suggested techniques, the safety factor considerably reduced as shown in Fig. 13. Technique 4 attained the higher safety factor of 3.12, followed by technique 1, with a F.O.S of 2.548. Then, techniques 2 and 3 produced lower F.O.S. values of 2.483 and 2.106, respectively.

Ultimately, after performing the safety analysis and recording the factor of safety at the critical demolishing phases, Technique 4 was found to be the optimum solution that attained the higher safety factors against the risk of excessive deformations or collapse. Alternatively, results of technique 1 were found to be so close to that of technique 4, without the addition of the struts inside the tunnel.

Therefore, technique 1 can be nominated as the most practical and beneficial technique that attains safety, economy and time-saving.

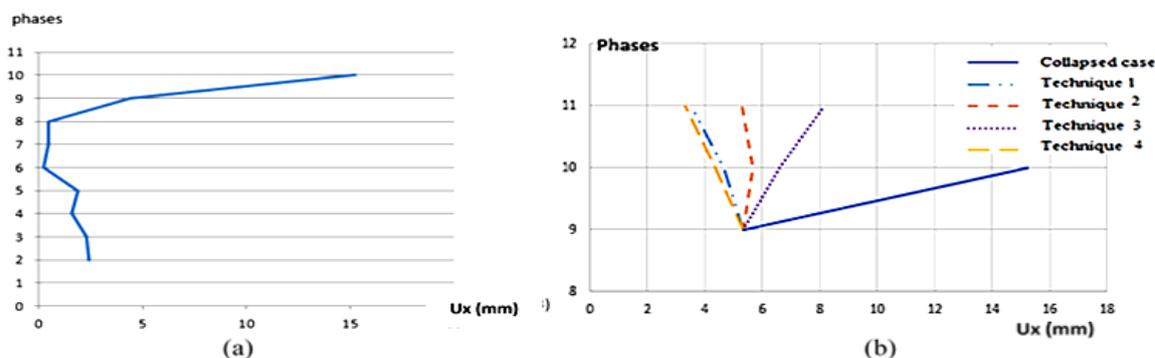


Fig. 7: Variation of the horizontal displacement at the springline: (a) at construction phases 1 to 9 & (b) comparing the four techniques.

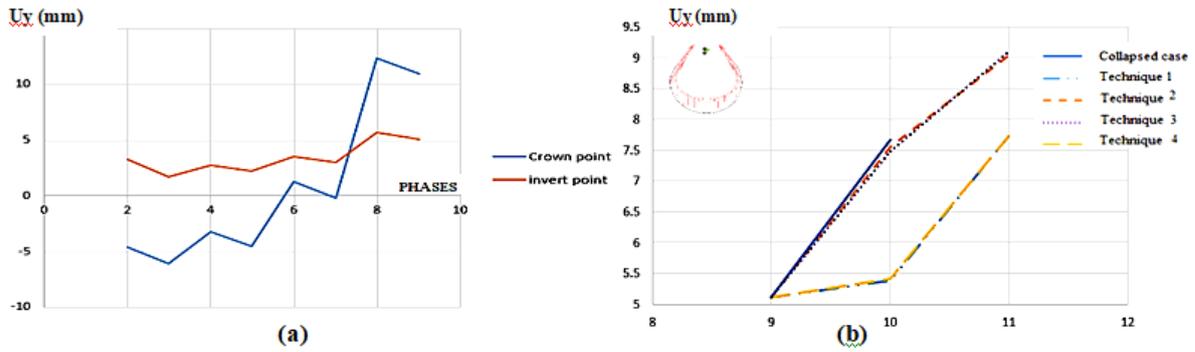


Fig. 8: Variation of the maximum vertical displacements: (a) with construction phases 1 to 9 at the crown and invert & (b) comparing the four techniques, for the invert.

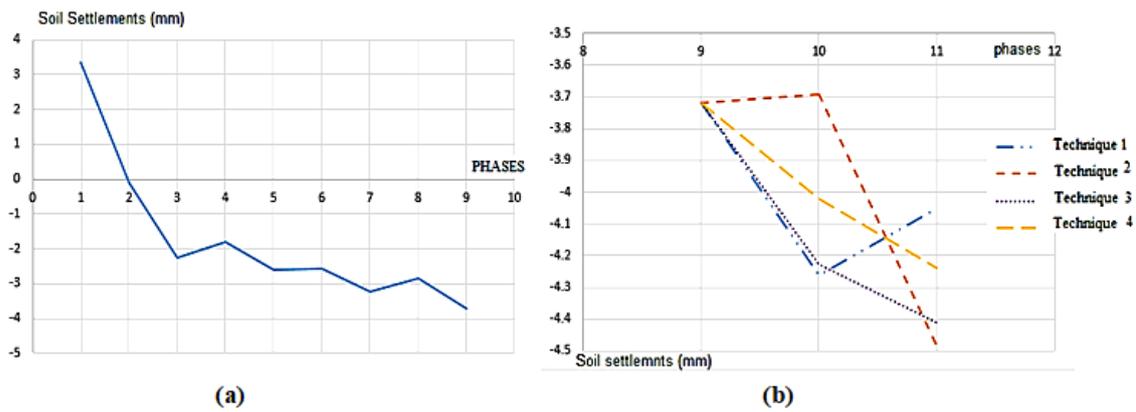


Fig. 9. Variation of the ground surface settlements: (a) at construction phases 1 to 9 & (b) comparing the four techniques.

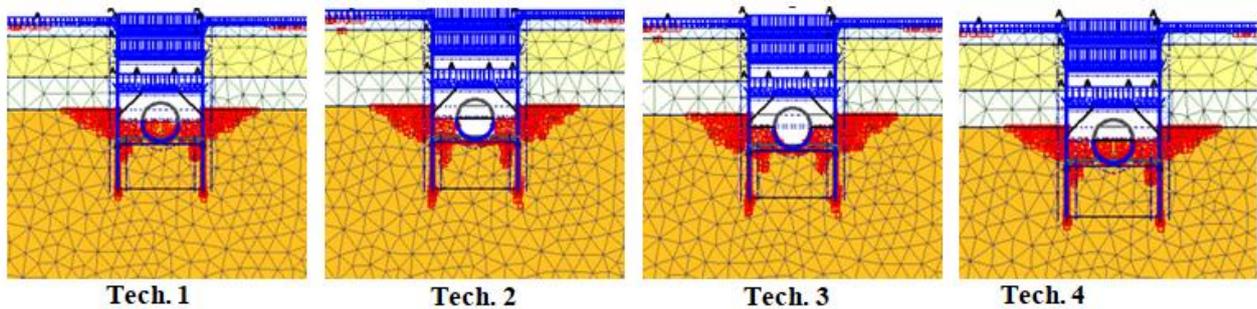


Fig. 10. Plastic zone developed at the for techniques (Phase 11)

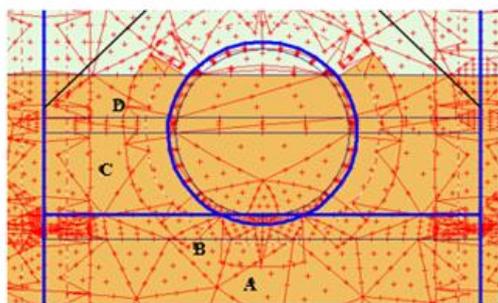


Fig. 11. Critical points around the tunnel

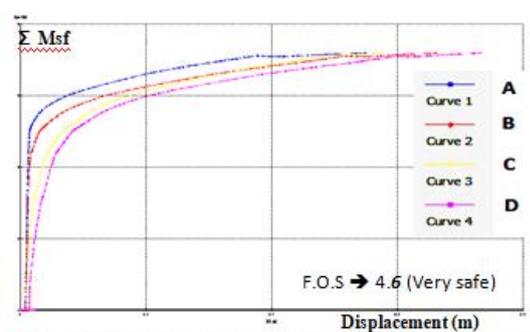


Fig. 12. Relation between the displacement and ΣM_{sf} at phase 9

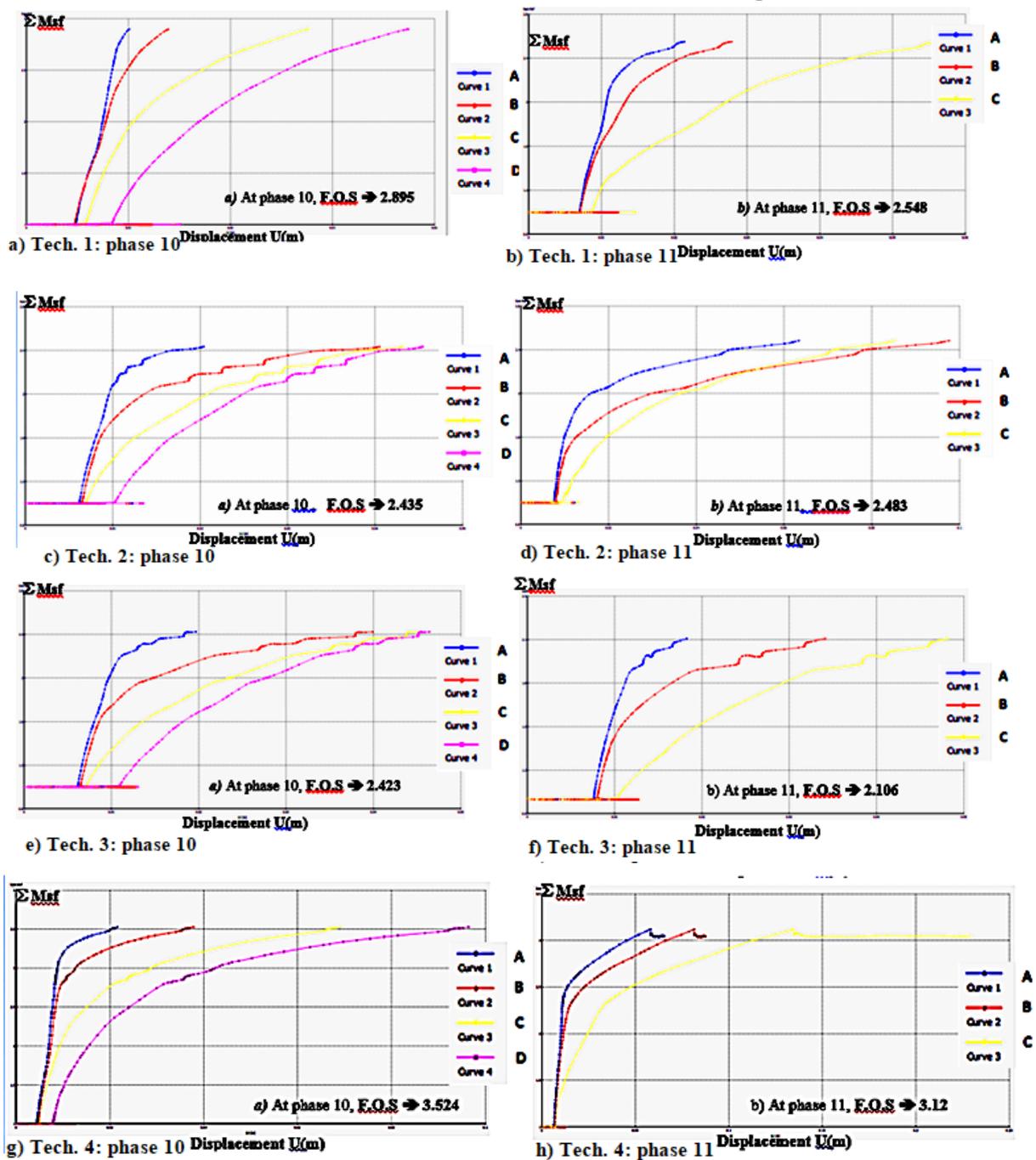


Fig. 13. Relationship between the displacement and ΣM_{sf} for the four Techniques

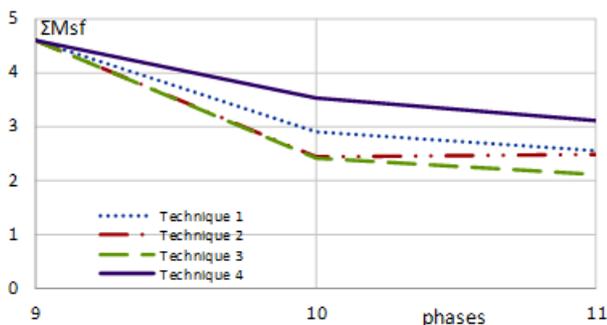


Fig. 14. Comparison between factor of safety for the four techniques

V. IN-SITU IMPLEMENTATION OF TECHNIQUE 1

Implementation of technique 1 in the station site required, firstly, installing the longitudinal diaphragm walls. Then, excavation from top to bottom while casting the station slabs sequentially, the roof, the ticket and the intermediate slabs. A temporary opening was developed in each slab to install a small machine excavating below the slab.

The excavation was continued till the crown of the tunnel, where Technique 1 was commenced by creating two small openings at the crown to fill the tunnel with sand at these demolishing points, as shown in Fig. 15.

As shown in Fig. 16, removing the tunnel segments safely while excavation till half of the tunnel was performed in sequential construction steps. Then, excavation till raft and

removing the remaining tunnel parts easily, in such a manner that collapse could be controlled.

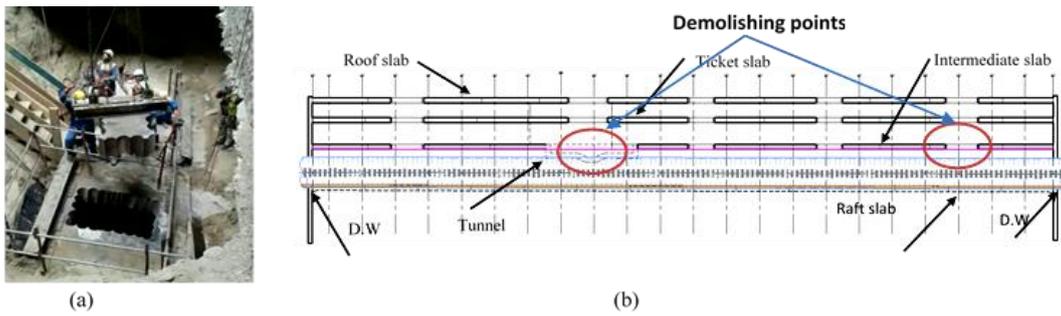


Fig. 15. (a) Making a small opening in the tunnel, (b) Sectional elevation at the station and the tunnel demolishing part.



Fig. 16. Excavate to half of the tunnel and removing the tunnel segments, [6]

Technique 1 gave great efficiency to reduce the heave of soil under the tunnel and to balance the earth pressure beside the tunnel in order to keep segmental lining under control during dismantling. Therefore, the application of technique 1 was nominated to be the most adequate and cost-effective without any risks of collapse inside or above the tunnel.

VI. CONCLUSIONS

The objective of this research was to numerically investigate the effect of casting an underground metro station in Cairo, Heliopolis station, using an uncommon sequence. Numerical analysis was performed by adopting PLAXIS -2D to simulate the construction phases of casting the structural elements until starting to remove the tunnel segments inside the station. At this last phase, the tunnel stability was considerably reduced, and the system was numerically collapsed.

The diaphragm wall deformations predicted using numerical modeling were compared with the corresponding monitored values to verify the adequacy of the numerical model. Good agreement was noticed between the finite element results, and the field monitored displacement values. The maximum displacement predicted by PLAXIS where the soil was modeled using the (HSM), was found to be slightly higher, by about 9%, than the corresponding measured value, at the level of 16 m from the top, that represents the maximum deformation zone.

Then, four numerical models have been created to simulate different techniques of demolishing the tunnel part inside the

station and completing the station construction. The results of the four suggested techniques to remove the tunnel segments enclosed by the station walls; including deformations and stability analysis, were compared. Technique 4 was

recommended as the most optimum solution that attains the higher safety factors against the risk of excessive deformations or sudden collapse. Alternatively, the results of technique 1 were found to be so close to that of technique 4, where the tunnel was filled with sand before removing the unwanted tunnel part without adding struts inside the tunnel as in technique 4. Technique 1 gave great efficiency to reduce the heave of soil under the tunnel by filling the tunnel with sand, and to resist the earth pressure beside the tunnel. So, filling the tunnel with sand has balanced the loads from outside the tunnel and kept lining segments under control during dismantling.

Therefore, from the economic point of view, technique 1 can be considered the most practical and beneficial technique that attains safety, economy and construction time-saving. The implementation of technique 1 in demolishing the tunnel part, was very simple and gave a great performance in the site where there was no impact on the diaphragm walls and the surrounding soil.

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