https://dx.doi.org/10.22161/ijaems.4.1.8 ISSN: 2454-1311

Rates of Soft Ground Tunneling in Vicinity of Existing Structures

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***Abstract*— *Soft ground tunneling in the vicinity of existing structures is a major challenge to tunneling engineers. Tunneling works cause inevitable ground movements that may lead to unrecoverable damages to adjacent structures. Tunneling rates significantly affect such risks. However, a guideline that determines appropriate tunneling rates and accounts for the effects of tunneling on the structures existing in the vicinity is not available. Tunneling records in terms of TBM advance speed (AS), utilization factor (U), and advance rate (AR) for tunnels constructed without causing significant risks on the existing structures are presented in the paper.These records are discussed for different types of existing structures.Ranges of these records for tunneling without causing detrimental effects on different types existing structures are recommended.Useful observations are also made on the variation of these records with the ground type and composition and the precautions to be adopted to mitigate the tunneling risks on existing structures.*

***Keywords*— Soft ground, mechanized tunneling, utilization factor, ground conditions, tunnel boring machine (TBM), productivity, advance speed, advance rate.**

I. INTRODUCTION

The term 'Hard Point' is used to describe the structures that exist in the vicinity oftunneling works. The hard points includefor instance buildings, footings of bridges and underground utilities such asshafts, sewer tunnels and electrical cables. Excavation by tunnel boring machines (TBMs) inevitably results in ground movements that may cause adjacent structures to deform, distort, and possibly sustain unrecoverable damages. A determination of the appropriate tunneling method that mitigates the tunneling risks on adjacent structures is a major challenge in soft ground tunneling. The difficulty stems from the many and critical factors involved in the process, such as the potential for ground loss because of tunneling, variable ground conditions under a hard point, and effect of tunneling on the integrity of existing structures. Tunneling advance rate, as a tunneling parameter, has been reported as a factor that affects the ground movements caused by TBM excavation (e.g., Toan and Hung 2007).

Tunnel construction duration is a critical factor in tunneling projects and is estimated on the basis of the tunneling advance rate as follows:

$$D = \frac{L}{AR} \quad (1)$$

where *D* (days) = construction duration, *L* (m) = length of tunnel, and *AR* (m/day) = advance rate of TBM and is defined as the distance of boring and ring erection divided by the total time (shift or day). *AR* is determined using the following expression

$$AR = \frac{AS \times U \times 60 \times 24}{100000} \quad (2)$$

where *AS* (mm/min) = advance speed of TBM and is defined as the stroke length of TBM into the ground divided by the operating time of excavation (i.e. the instantaneous penetration rate of TBM), and *U* (%) = utilization factor of TBM and is defined as the time of excavation by TBM divided by the total time. Therefore, accurate determination of *AR* or *AS* and *U* is necessary for the development of reliable tunnel construction time plans and cost estimate and control.

Management of tunneling works in the vicinity of hard points and the relevant risks necessitates determination of appropriate *AR* at the hard points. A guideline that determines *AR* in soft ground in the vicinity of hard points is not available.*AR* is usually determined on the basis of empiricism and experiences of practitioners. Little effort however has been made to establish a guideline that determines *AR* and accounts for the different types and conditions of hard points. Moreover, the literature lacks reported data on *AR*and the corresponding effects on hard points. The current paper presents field records of *AR*, *AS*, and *U* for tunnels actually constructed in Egypt in the vicinity of existing hard points. It also discusses these records for different types of hard points. The paper starts with an elaboration of the effects of tunneling works and rates on the conditions of existing structures in the vicinity of tunneling works. This is followed by a brief description of the project from which the records were obtained. Then, the records are presented and discussed.

https://dx.doi.org/10.22161/ijaems.4.1.8 ISSN: 2454-1311

II. EFFECT OF TUNNELING RATES ON CONDITION OF EXISTING STRUCTURES

Volumes of excavation larger than the volume of ground occupied by a tunnel are not uncommon in tunneling. Such differences in volumes, known as volume losses, inevitably result in ground movements. Toan and Hung (2007) reported that the net volume of surface settlement trough in most ground conditions is approximately equal to the volume loss because of tunneling. Such ground movements may cause adjacent structures to deform, rotate, distort, and possibly sustain unrecoverable damages (Zhang et al. 2012). Toan and Hung (2007) also indicated that the magnitude of volume loss depends on many different factors such as the tunneling method, tunneling advance rate, tunnel size, and ground type. The existence of structures in the vicinity of a constructed tunnel is therefore rated among the highrisk factors in tunneling in urban areas (Kovari 2004).

It has been reported that the tunneling induced ground movements and thus the risks on adjacent structures can be mitigated by adopting the following measures (e.g., Toan and Hung 2007; Goh et al. 2016; Sheng et al. 2016):

- Adopting appropriate tunneling advance rates to minimize the ground movements caused by the machine ground interaction.
- Adopting larger thrust forces to increase the depth of cutting and maintain the desired advance speed.
- Monitoring the lateral movement of tunnels to ensure that the generated drag forces have insignificant impact on the existing structures.
- The minimum pressure applied at the face should be slightly higher than the hydrostatic pressure, particularly when going below existing structures. This is done mainly by controlling the rotational speed of the screw and the amount of muck discharge at the outlet of the screw conveyor.
- Setting the cutterhead rotation to low revolutions so that any torque spikes that are indicative of obstructions encountered during the course of crossing sensitive structures are easily detected.
- Erecting the lining immediately after excavation and providing tight control of the tunneling process.
- Pre-planning for cutterhead interventions just before the TBMs go below existing structures for checking the cutterhead condition and making any necessary replacements of the cutting tools.

Sheng et al. 2016 reported a significant case history on the tunneling of the Downtown Line Stage 3 (DTL3) of Mass Rapid Transit (MRT) system across Singapore Island. The DTL3 alignment is overcrossing the existing North East Line (NEL) rail tunnel and undercrossing the existing North South Line (NSL) and Circle Line (CCL) with clear distance of less than one bored tunnel diameter, and overburden ranges from 20.0 to 45.0 m; the diameter of DTL3 is 6.35 m. DTL3 is located approximately 1.3 m above NEL tunnel, 8.7 m below NSL tunnel and 3.3 m below CCL tunnel. The ground consists mainly of siltstone with layers of mudstones and sandstone. They observed that the advance speed of the TBM was reduced to less than 5, 10 – 13, and 8 – 15 mm/min when overcrossing NEL, undercrossing NSL, and undercrossing CCL, respectively.

The aforementioned reveals that TBM tunneling in soft ground may cause significantly detrimental effects on existing structures in the vicinity. In addition, tunneling rate is an important factor that significantly affects the conditions of existing structures in the vicinity of tunneling. Therefore, appropriate tunneling rates should be determined to mitigate tunneling risks on adjacent structures.

III. PROJECT DESCRIPTION AND GROUND CONDITIONS

The network of the Greater Cairo metro consists of three lines (Lines 1 to 3) as shown in Fig. 1. Line 3 is approximately 47.87 km long and consists of 39 stations. The construction of the line has been divided into four main phases as indicated in Figs. 1 and 2 and summarized in Table 1. At the time of publishing this paper, the construction of Phases 1 and 2 has been completed, Phase 3 has been under study, and Phase 4 has beingconstructed. The types of TBMs used in the line are indicated in Fig. 2 and Table 1. Phases 1and 4A were fully excavated using slurry TBMs (TBM 1 and 2 for Phase1 and TBM 4 for Phase 4A) and constructed in 24 and 14 months, respectively. However, Phase 2 was fully excavated in 26 months using two different types of TBMs: Slurry and EPB TBMs.The tunnel segment extending from Abbasia station to Cairo Fair station (Lot 11-c) was fully excavated using TBM 2, while that extending from Cairo Fair station to Haroun station was fully excavated using EPB TBM (TBM 3).

Field records of the construction of Lot 11-c (Phase 2A), approximately 1,950 m in length, are used in the current paper. The records indicate that the construction of this phase progressed at a rate of 11.0 m per working day. A photo of the used TBM (TBM2) is shown in Fig. 3 and its general specifications are summarized in Table 2.In the construction of Lot 11-c, TBM 2 was excavating under many hard points which include different types of existing structure such as buildings, footings of Bridges, sewer tunnels, annexed structure and tunnel shafts. A general description of the hard points at the location of

https://dx.doi.org/10.22161/ijaems.4.1.8 ISSN: 2454-1311

Lot 11-c and their ground strata and distances from the tunnel are shown in Tables 3 to 6. Figure4 shows several existing structures and the vertical alignment of the tunnel at the location of Lot 11-c.

The general strata of ground as indicated by site investigations at the location of Lot 11-c consist of the following:

- Unit (1): It stands for recent man-made fill material.
- Unit (2): It includes all the sand formations in variable depths and are composed of following sub-layers:
  - Unit (2-a): for upper sand formation.
  - Unit (2-b): for middle sand formation.
  - Unit (2-b. G): for middle gravelly sand formation.
  - Unit (2-c): for lower cemented sand formation.
- Unit (3): It includes all the clay formations in different depths and are composed of the following sub- layers:
  - Unit (3-a): for upper clay formation.
  - Unit (3-b): for lower laminated clay formation.
- Unit (4): It is available only at the area of the Cairo Fair station and includes very weathered rock formation.

The estimated parameters of these strata are summarized in Table 7.

IV. FIELD RECORDS AND DISCUSSION

Figure 5-a shows a longitudinal section of ground through the tunnel alignment at the location of Lot 11-c. The figure also shows that the ground layers excavated by TBM 2 are the lower clay, middle sand, lower sand, and middle gravelly sand layers, which are designated in Table 7 as Units (3-b), (2-b), (2-c), and (2-b. G), respectively. Figures 5-b and 5-c show the variations of *AS* and cutterhead speed (*CHS*), respectively, with the number of rings erected during construction of Lot 11-c. The colored circles in Figs. 5-b and 5-c indicate the types and locations of the hard points at the location of Lot 11-c; the locations of hard points are shown at the corresponding rings of the tunnel. The TBM *AS*, *CHS*, penetration rate (*PR*), *U*, and *AR* at the locations of the hard points in Lot 11-c are summarized in Tables 8 to 11. The records of *AS*, *CHS*, and *PR* are obtained from the ring erection reports while those of *U* and *AR* are obtained from the machine daily reports. These records are shown in Tables 8 to 11 for the existing buildings, pile foundations of bridges, utility lines, and annexed structures, respectively. The general formations of ground excavated by TBM 2 below the hard points are indicated in Tables 3 to 6 and designated as Units (2-b), (2-c), (2-b. G), and (3-b).

Figure 5-a shows that TBM 2 experienced a clear mixed face ground at the location between rings 4,050 and 4,550 where it was excavating in the sand, gravel, and clay/silt-clay layers. At the location between rings 4,050 and 4,250, it is seen in Fig. 5-a that the thickness of the clay/silt-clay layer increases in the direction of tunnel advancement. Figure 5-b shows at the same location that *AS* decreases with the tunnel advancement. It is interesting to note at the location between rings 4,250 and 4,550 that a decrease in the thickness of the clay/silt-clay layer (Fig. 5-a) with tunnel advancement is corresponding to an increase in *AS* (Fig. 5-b). This implies that *AS* increases with the decrease of clay content or increase of sand content in the excavated ground. At the locations between rings 4,600 and 4,650 and at ring 5,016 where TBM 2 was cutting in the middle sand and gravelly sand layers, respectively, the highest values of *AS* (58 mm/min in Fig. 5-b) and cutter head speed (2.4 rpm in Fig. 5-c) were recorded. This is generally consistent with the above observation on the variation of *AS* with the type and composition of excavated ground. Figure 5 shows that these highest values were recorded at locations before and after the locations of the hard points.

At the locations of the hard points in Lot 11-c, the ground is dominated by layers of sands and gravelly sands. However, Fig. 5 shows that the values of *AS* and *CHS* at the locations of the hard points are less than the highest values of 58 mm/min and 2.4 rpm, respectively. In this regard, it should be mentioned that when tunneling in the vicinity of hard points, *AS* is usually decreased to minimize the induced movements of ground. *CHS* is also decreased to minimize the wearing rate of the cutting tools of the cutterhead.

Though excavated in different ground layers and in the vicinity of different existing structures, the tunnel in Lot 11-c was constructed successfully without significant signs of distresses in the structures existing in the vicinity. Therefore, a documentation of the adopted tunneling records of *AS*, *CHS*, *PR*, *U* and *AR* will essentially represent a useful contribution to the practical database of tunneling works. The adopted records can be summarized as follows:

- The records in Table 8 for TBM 2 boring in the vicinity of existing buildings show that *AS*, *CHS*, *PR*, *U* and *AR* are in the ranges 42.55 – 50.55 mm/min, 1.91 – 2.06 rev/min, 22.27 – 24.50 mm/rev, 28.00 – 45.00%, and 20.00 – 29.00 m/day with average values of 48.43 mm/min, 2.03 rev/min, 23.82 mm/rev, 34.00%, and 24.88 m/day, respectively.
- The records in Table 9 for TBM 2 boring in the vicinity of existing pile foundations of bridges show

https://dx.doi.org/10.22161/ijaems.4.1.8 **ISSN: 2454-1311**

that *AS*, *CHS*, *PR*, *U* and *AR* are in the ranges 29.44 – 48.09 mm/min, 1.72 – 1.89 rev/min, 17.19 – 25.39 mm/rev, 33.00 – 42.00%, and 21.00 – 22.00 m/day with average values of 38.76 mm/min, 1.81 rev/min, 21.29 mm/rev, 38.00%, and 21.50 m/day, respectively. At the location between rings 5,180 and 5,295 TBM 2 was boring between two groups of the pile foundations of the existing 6th October Bridge western ramp and under sewer tunnels. The distance between the tunnel and one of the pile groups is approximately 1.68 m (see Fig. 6). This is the smallest distance between the tunnel and the hard points throughout the tunnel alignment. At this location, *AS* and *CHS* were significantly decreased to 29.44 mm/min and 1.72 rpm, respectively, and the corresponding *U* was 42.00%.

- The records in Table 10 for TBM 2 boring under existing utility tunnels of 1.00 – 2.25 m in diameter show that *AS*, *CHS*, *PR*, *U* and *AR* are in the ranges 30.26 – 40.32 mm/min, 1.69 – 1.93 rev/min, 16.96 – 20.86 mm/rev, 42.00 – 43.00%, and 21.00 – 23.00 m/day with average values of 34.29 mm/min, 1.77 rev/min, 19.31 mm/rev, 34.00%, and 22.50 m/day, respectively.
- The records in Table 11 for TBM 2 boring in diaphragm walls of existing annexed structures show that *AS*, *CHS*, *PR*, *U* and *AR* are in the ranges 9.80 – 12.70 mm/min, 2.03 – 2.31 rev/min, 5.00 – 6.00 mm/rev, 28.00 – 46.00%, and 5.00 – 6.00 m/day with average values of 11.25 mm/min, 2.17 rev/min, 5.50 mm/rev, 37.00%, and 5.50 m/day, respectively (see Fig. 7).

Figure 8 shows a representation of the average tunneling records of *AS*, *CHS* and *U* for the types of hard points existing in Lot 11-c.

It is worth mentioning that the relatively high values of *U* recorded during tunneling in the vicinity of the hard points in Lot 11-c are attributed to the following additional precautionary measures:

1. The rings were erected immediately after excavation. This contributed to the reduction of the delay times.
2. Hyperbaric interventions were routinely made before starting excavation in the vicinity of the hard points. This increases the cutting efficiency of the cutterhead in the ground and mitigates any residual risks.
3. Larger thrust forces were applied to increase the depth of cutting of the cutter tools and to maintain the advance speed.

A reduction in the delay and maintenance times contributes to the increase of *U*.

V. SUMMARY AND CONCLUSIONS

TBM tunneling in soft grounds inevitably results in ground movements that may cause unrecoverable damages to adjacent structures. The effects of TBM tunneling on adjacent structures are briefly reviewed in the paper. Management of tunneling works in the vicinity of existing structures (hard points) and the relevant risks necessitates determination of appropriate tunneling rates at the hard points. A guideline that determines appropriate rates of tunneling in the vicinity of hard points is not available. Moreover, the literature lacks reported data on tunneling rates and the corresponding effects on hard points. As a contribution to the database of tunneling works, the current paper presents field records of TBM tunneling advance speed (*AS*), utilization factor (*U*), and advance rate (*AR*) that are obtained from tunnels actually constructed in Egypt in the vicinity of hard points. It also discusses these records for different types of hard points: buildings, pile foundations, utility tunnels, and annexed structures. Ranges of *AS*, *U*, and *AR* for TBM tunneling without significant risks on the structures existing in the vicinity of tunneling works are also presented. In addition, observations and discussions on the variation of *AS*, *U*, and *AR* with the ground type and composition and precautions to be adopted to mitigate risks of tunneling on structures in the vicinity are presented in the paper.

REFERENCES

[1] Arshad, and Abdullah, R.A. (2016). "A review on selection of tunneling method and parameters affecting ground settlements," *Electronic Journal of Geotechnical Engineering*, Vol. 21, 4459–4475.

[2] Goh, K.H., Ng, S.S.G., and Wong, K.C. (2016). "Case histories of bored tunneling below buildings in Singapore downtown line," *International Journal of Geoengineering Case histories*, Vol. 3, 149–161.

[3] ITA (International Tunneling Assocation) (2000). "Mechanized tunneling, recommendations and guidelines for tunnel boring machines (TBMs),"*Working Group 14*, 1 – 118.

[4] Kovari, K., and Ramoni, M. (2004)." Key note lecture at international congress on mechanized tunneling: challenging case histories," *Urban tunneling in soft ground using TBM's*, Politecnico di Torino, Italy, 16–19.

[5] Multi-Mode TBM. (2017). "TBM information," <https://www.herrenknecht.com/en/innovation/research-development/machinescomponents/multi-mode-tbm.html>(Aug. 20, 2017).

[6] NAT (National Authority for Tunnels) (2017)."Information of greater Cairo metro line-3," *Line-3*, <http://www.nat.org.eg/english/Line3.html> (Aug. 20, 2017).

https://dx.doi.org/10.22161/ijaems.4.1.8 ISSN: 2454-1311

[7] Ozfirat, M.K. (2015). "Selection of tunneling machines in soft ground by fuzzy analytic hierarchy process," DokuzEylul University, *Acta MontanisticaSlovaca*, Vol. 20, No. 2, 98–109.

[8] Sheng, E. S. Y., Chuan, J. Y. T., Ikhyung, H. K., Osborne, N. H., Boon, C. K., and Siew, R. (2016). " Tunneling undercrossing existing live MRT tunnels," *Tunneling and Underground Space Technology*, Vol. 57, 241–256.

[9] Shield Tunneling (2017). <http://helpiks.org/2-30162.html> (Aug. 20, 2017).

[10] Thomas, W.P. (2011)."Tunneling beneath open water, a practical guide for risk management and site investigations," *Professional Associate Finalist*, William Barclay Parsons Fellowship Program, Parsons Brinckerhoff, New York.

[11] Toan, D. N., Hung, L. X. (2007)."Some aspects of risk management and subsidence," Hanoi Metro Pilot Line Project, Report at the Meeting between ITA and ITST on Tunneling, Hanoi.

[12] Zhang, D., Fang, Q., Hou, Y. Li, P., and Yuen, W. L. (2012)."Protection of buildings against damages as a result of adjacent large-span tunneling in shallowly buried soft ground," *Journal of Geotechnical and Geo-Environmental Engineering*, Vol. 139, 903–13.

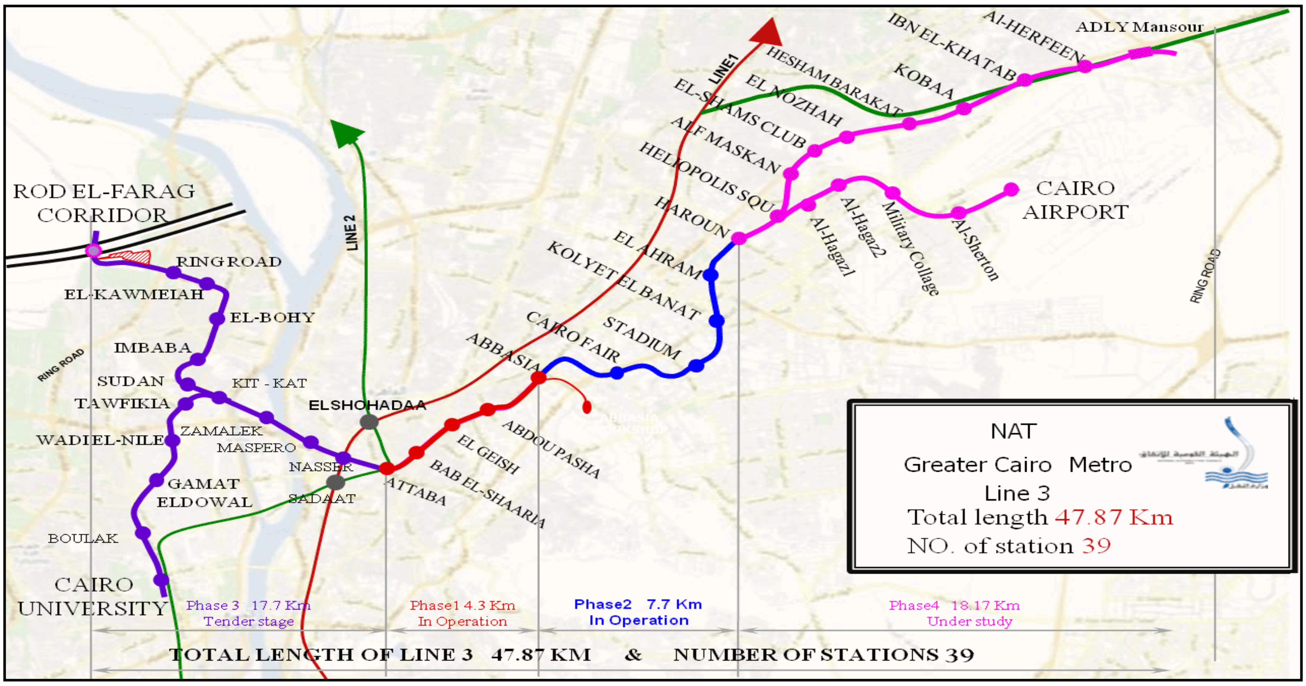


Fig. 1: Network of the Greater Cairo metro and route of Line 3 (NAT 2017).

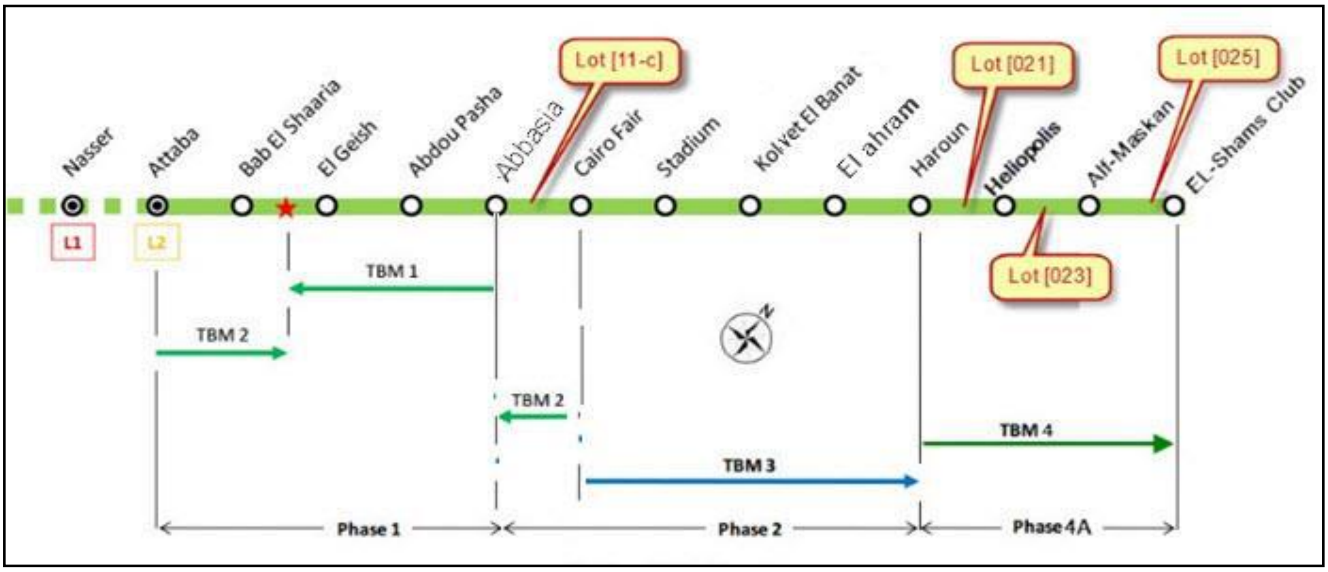


Fig. 2: Construction phases of Line 3 and the used TBMs.

https://dx.doi.org/10.22161/ijaems.4.1.8 *ISSN: 2454-1311*

Fig. 3: The slurry TBM used in Line 3, Lot 11-c (Phase 2A), of the Greater Cairo metro (NAT 2017).

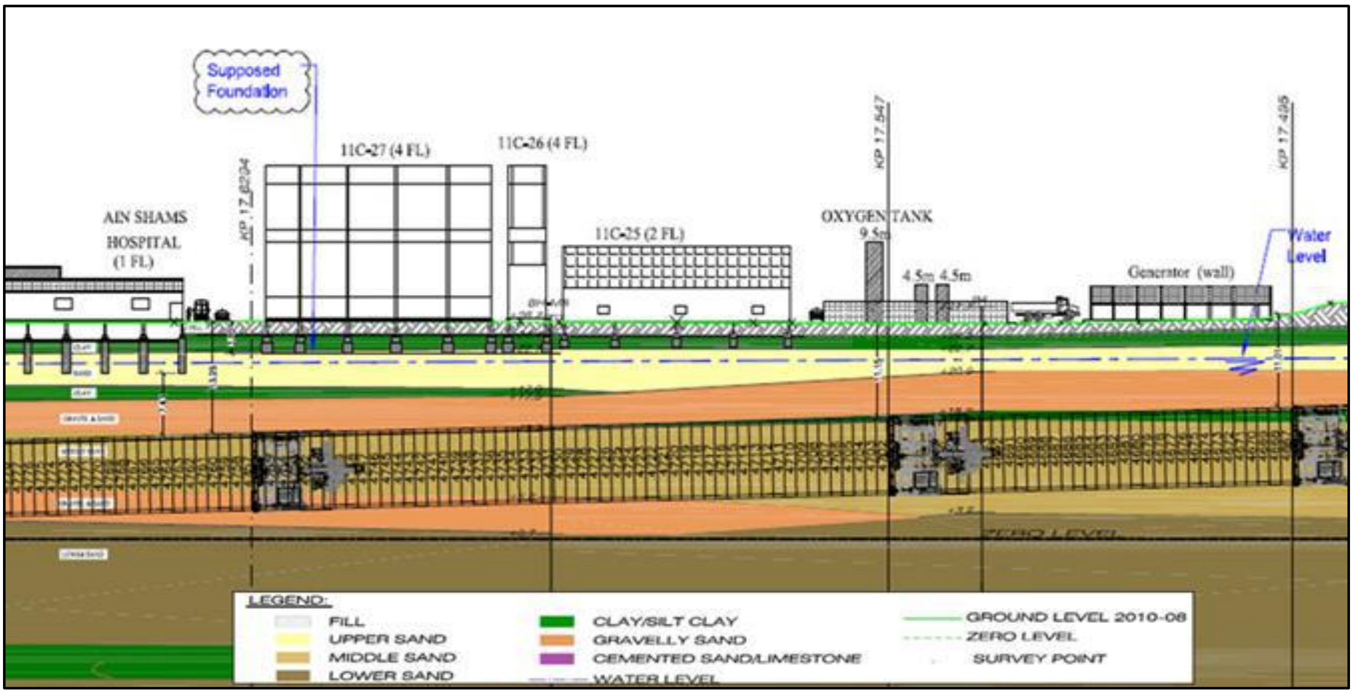
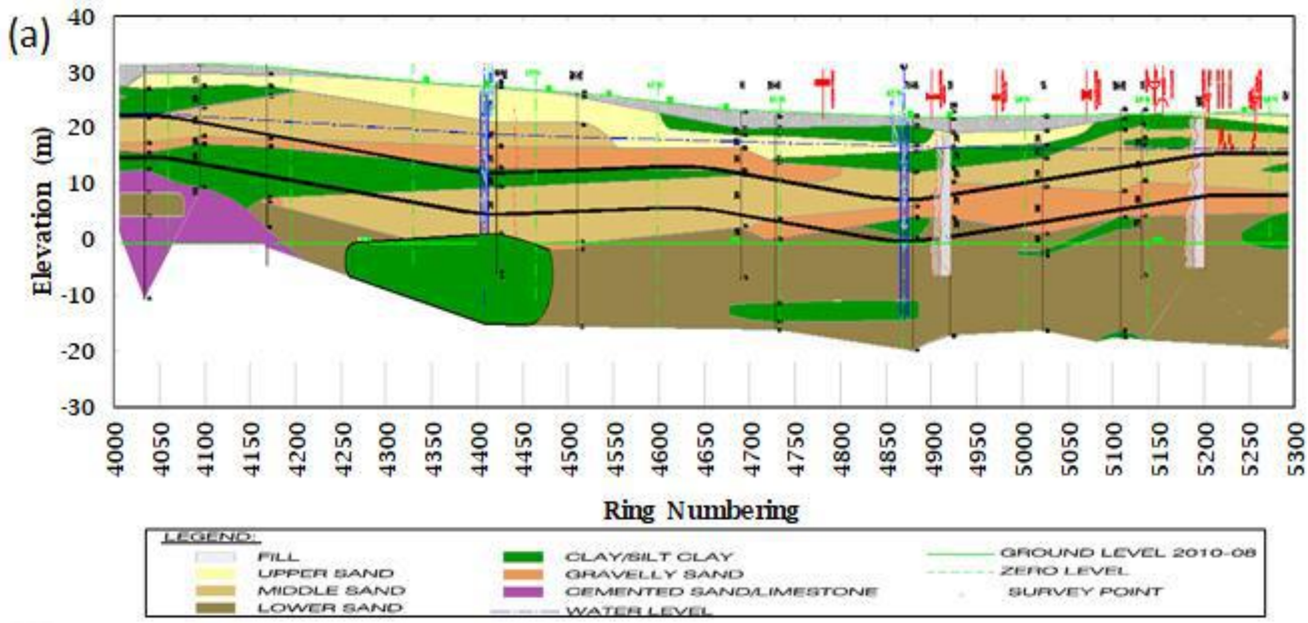


Fig. 4: Tunnel alignment under existing structures at location of Lot 11-c (Phase 2A); TBMs are shown for illustration.



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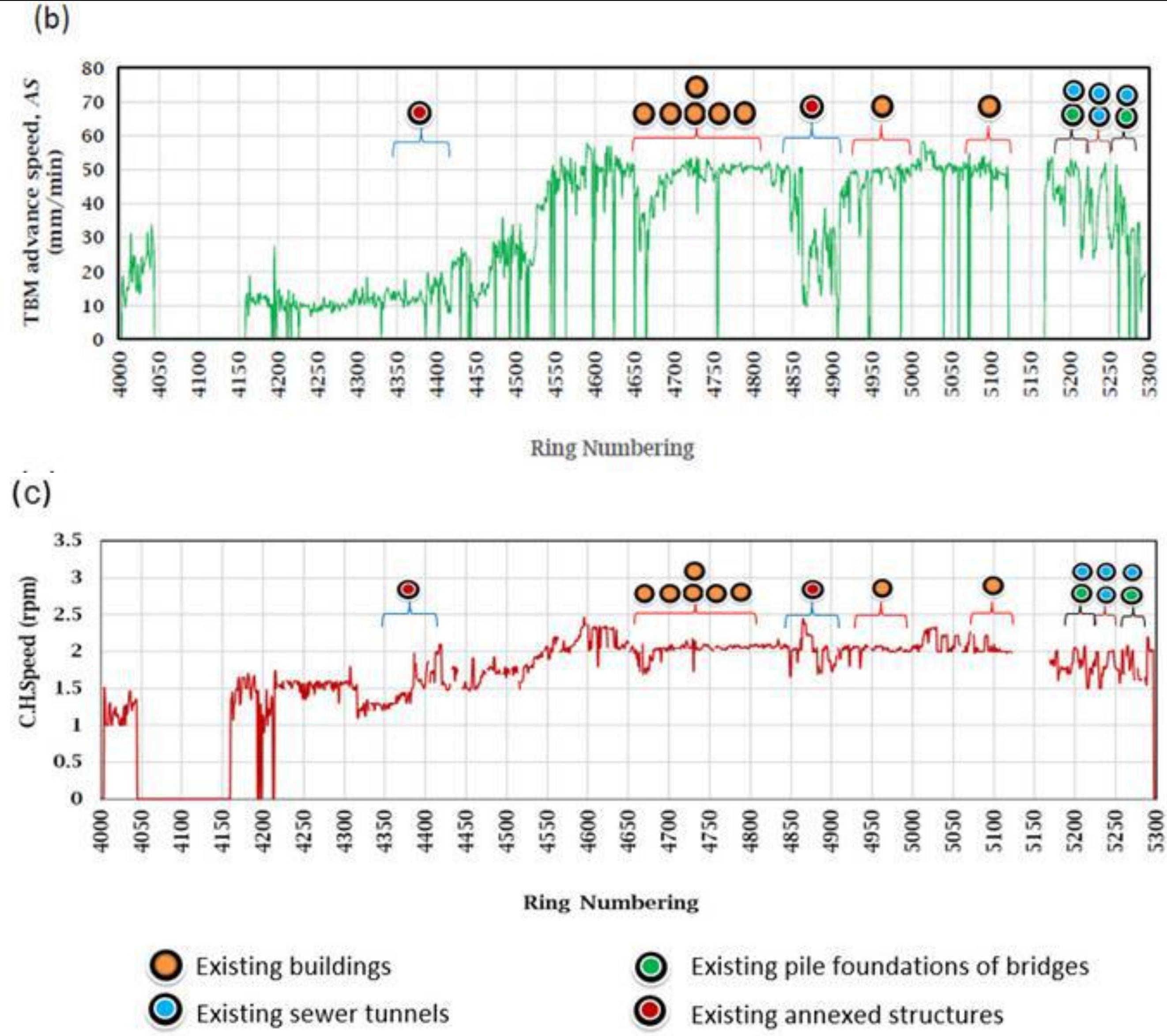

Fig. 5: Ground profile and TBM records at the location of Lot 11-c: (a) ground profile; (b) AS; (c) CH

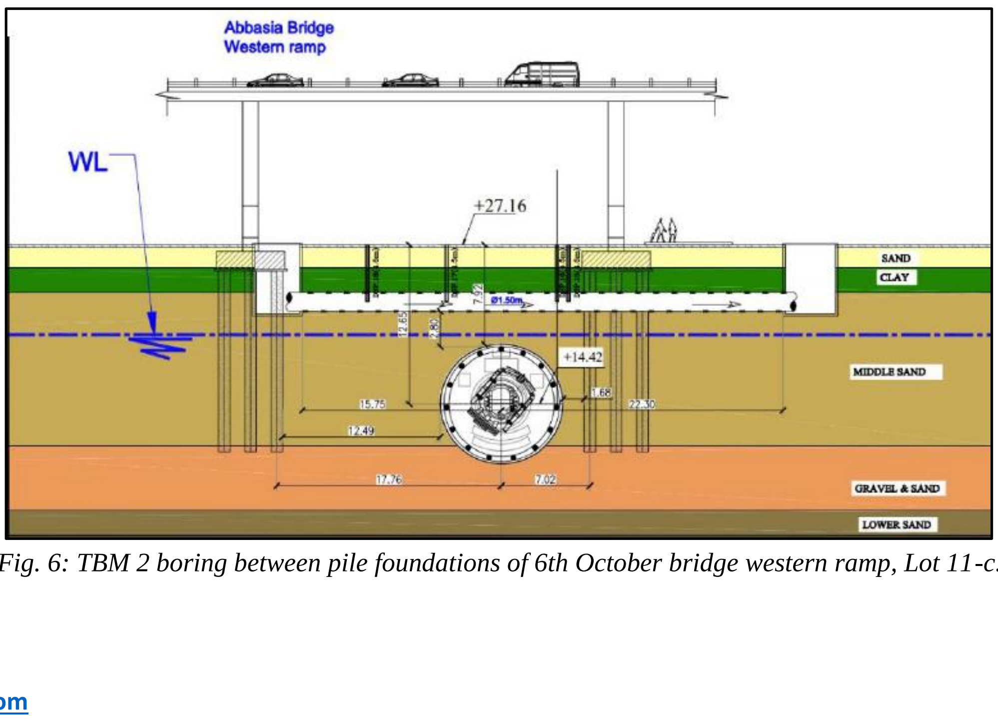

Fig. 6: TBM 2 boring between pile foundations of 6th October bridge western ramp, Lot 11-c.

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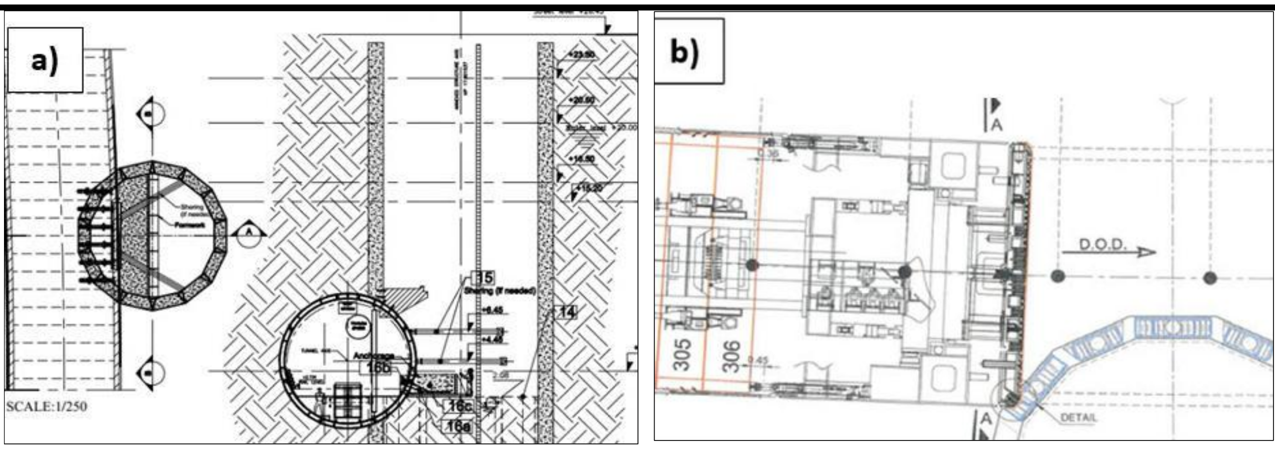

Fig.7: TBM 2 crossing annexed structure 11-B, Lot 11-c: (a) vertical section; (b) plan view.

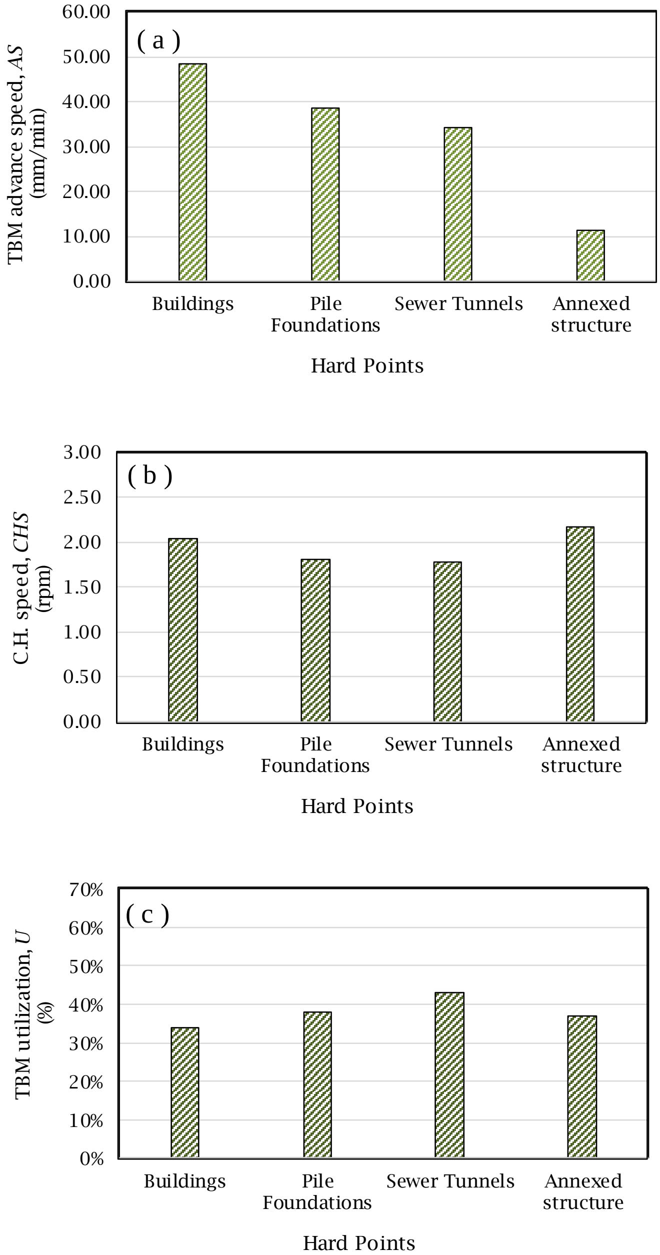

Fig.8: Average production records of TBM 2 for different types of hard points in the vicinity of tunneling works: (a) AS; (b) CHS; (c) U.

Table.1: Construction phases and types of TBMs used in Line 3 of the Greater Cairo metro.

Phase #	Stage #	Tunnel Path	Stage Length (km)	TBM Type	TBM No.
1	-	From Attaba station to Abbasia station	4.3	Slurry TBM	TBMs 1 & 2
2	A	From Abbasia station to Cairo Fair station	1.95	Slurry TBM	TBM 2
	B	From Cairo Fair station to Haroun station	5.75	EPBM	TBM 3
3	A	From Attaba station to Kit Kat station	4.00	---	Under study
	B	From Kit Kat station to Rod EL-Farag station	6.60	---	Under study
	C	From Kit Kat station to Cairo University station	7.20	---	Under study
4	A	From Haroun station to El-Shams Club station	5.15	Slurry	TBM 4
	B	From El-Shams Clubstation to Adly Mansour station	6.37	-----	Surface path
	C	From Helipolis station to Cairo Airport station	6.65	---	Under study

Table.2: General specifications of slurry TBM (TBM 2) used in Lot 11-c (Phase 2A) of Line 3.

Specification	TBM 2
Shield diameter (m)	9.46
Shield length (m)	11.3
Max. advance speed (mm/min)	80
Max. rotational speed (rpm)	3
Max. thrust force (ton)	5500
Stroke length (m)	2
Max. torque of cutter head (ton.m)	2000
Cutting tools type: disc cutter, rippers, scrapers (no.)	22, 8, 168

Table.3: Existing buildings and their ground strata and distances from the tunnel at the location of Lot 11-c.

Building	No. of Floors	Ground Formation	Vertical Distance to Tunnel Crown (m)	Horizontal Distance to Tunnel Axis (m)
11-c-31	1	Middle sandand clay	11.01	9.25
Oxygen Station	1	Middle sand	11.15	0
11-c-25	2	Middle sand	9.44	0
11-c-26	4	Middle sand	9.44	11
11-c-27	4	Middle sand	9.44	0
Ain Shams Hospital	1	Middle sand andgravelly sand	9.45	0
Faculty of Arts	7	Gravelly sand	12.6	0
Ain Shams Information Center-11-c-06	3	Gravelly sand andmiddle sand	8.61	8.35

Table.4: Existing pile foundations of bridges and their ground strata and distances from the tunnel at the location of Lot 11-c.

Pile Foundation	Status	Ground Formation	Vertical Distance to Tunnel Crown (m)	Horizontal Distance to Tunnel Axis (m)
Foundation of 6th October Bridge Western Ramp	Crossing between two groups of pile foundations	Middle sand and gravelly Sand	8.50	6.18
Foundation of 6th October Bridge Eastern Ramp	Crossing between two groups of pile foundations	Middle sand andgravelly sand	8.70	7.00

https://dx.doi.org/10.22161/ijaems.4.1.8 ISSN: 2454-1311

Table.5: Existing utility tunnels and their ground strata and distances from the tunnel at the location of Lot 11-c.

Sewer (Utility) Tunnel	Status	Ground Formation	Vertical Distance to Tunnel Crown (m)	Horizontal Distance to Tunnel Axis (m)
Sewer tunnel, Diameter (1.00 m)	TBM crossing between 2-pile group and sewer tunnel	Middle sand andgravelly sand	4.90	0.00
Sewer tunnel, Diameter (2.25 m)	Normal case "TBM crossing Sewer tunnel only"	Middle sand andgravelly sand	2.90	0.00
Sewer tunnel, Diameter (1.80 m)	Normal case "TBM crossing Sewer tunnel only"	Middle sand andgravelly sand	2.10	0.00
Sewer tunnel, Diameter (1.50 m)	TBM crossing between 2-pile group and sewer tunnel	Middle sand andgravelly sand	2.80	0.00

Table.6: Existing annexed structures and their ground strata and distances from the tunnel at the location of Lot 11-c.

Annexed Structure	Status	Ground Formation	Vertical Distance to Tunnel Crown (m)	Horizontal Distance to Tunnel Axis (m)
Structure 11-A	TBM crossing and cutting in diaphragm wall of annexed structure	Middle sand, gravelly sand and clay	0.00	0.00
Structure 11-B	TBM crossing and cutting in diaphragm wall of annexed structure	Middle sandand clay	0.00	0.00

Table.7: General ground strata at location of Lot 11-cand estimated ground parameters.

Stratum	Material Code	Depth (m)	SPT N	Dr (%)	K_0	γ_b (Mg/m^3)	C_u (KPa)	$\emptyset_u$ $(°)$	E_u (MPa)
Recent Man-Made Fill	Unit (1)	0.0 – 3.0	12	38	0.50	1.80	0.0	30	12
Upper Sand Formation	Unit (2-a)	3.0 – 6.0	34	69	0.43	1.95	0.0	35	45
Upper Clay Formation	Unit (3-a)	6.0 – 10.0	18	--	0.53	1.85	120	0.0	25
Middle Sand Formation	Unit (2-b)	10.0 – 11.3	74	92	0.37	2.00	0.0	39	95
Middle Gravelly Sand Formation	Unit (2-b. G)	11.3 – 22.7	85	96	0.36	2.10	0.0	40	145
Lower Laminated Clay Formation	Unit (3-b)	15.6 – 26.0	26	--	0.52	1.88	160	0.0	40
Lower Cemented Sand Formation	Unit (2-c)	22.7 – 35.0	90	100	0.36	2.10	0.0	40	150
Weathered Rock Formation	Unit (4)	24.6 – 28.7	---	---	---	---	---	---	---

SPT N= N-value of Standard Penetration Test, Dr = Relative density of soils, γ_b= Bulk density, C_u= Undrained cohesion, $\emptyset_u$= Undrained angle of internal friction, E_u=Young's modulus (undrained).

https://dx.doi.org/10.22161/ijaems.4.1.8 ISSN: 2454-1311

Table.8: Daily field records of TBM 2 under existing buildings at the location of Lot 11-c.

Building	Average TBM Advance Speed, *AS* (mm/min)	Average TBM Cutterhead Speed (rev/min)	Average TBM Penetration Rate (mm/rev)	Machine Utilization, *U* (%)	*AR* (m/day)
11-c-31	42.55	1.91	22.27	45%	29
Oxygen Station	48.80	2.05	23.83	32%	26
11-c-25	50.29	2.06	24.36	28%	20
11-c-26	47.76	2.04	23.44	35%	26
11-c-27	49.51	2.06	24.02	35%	26
Ain Shams Hospital	50.55	2.06	24.50	37%	27
Faculty of Arts	48.42	2.04	23.78	33%	25
Ain Shams Information Center-11-c-06	49.55	2.03	24.38	28%	20
Average	48.43	2.03	23.82	34%	24.88

Table.9: Daily field records of TBM 2 under existing bridge footings at the location of Lot 11-c.

Pile Foundation	Average TBM Advance Speed, *AS* (mm/min)	Average TBM Cutterhead Speed (rev/min)	Average TBM Penetration Rate (mm/rev)	Machine Utilization, *U* (%)	*AR* (m/day)
Foundation of 6th October Bridge Western Ramp	29.44	1.72	17.19	42%	21.00
Foundation of 6th October Bridge Eastern Ramp	48.09	1.89	25.39	33%	22.00
Average	38.76	1.81	21.29	38%	21.50

Table.10: Daily field records of TBM 2 under existing utility tunnels at the location of Lot 11-c.

Sewer Tunnels (Utility Tunnels)	Average TBM Advance Speed, *AS* (mm/min)	Average TBM Cutterhead Speed (rev/min)	Average TBM Penetration Rate (mm/rev)	Machine Utilization, *U* (%)	*AR* (m/day)
Sewer Tunnel, Diameter = 1.00 m	32.97	1.69	19.47	43%	23.00
Sewer Tunnel, Diameter = 2.25 m	33.62	1.69	19.93	43%	23.00
Sewer Tunnel, Diameter = 1.80 m	40.32	1.93	20.86	43%	23.00
Sewer Tunnel, Diameter = 1.50 m	30.26	1.78	16.96	42%	21.00
Average	34.29	1.77	19.31	43%	22.50

Table.11: Daily field records of TBM 2 under existing annexed structures at the location of Lot 11-c.

Annexed structure	Average TBM Advance Speed, *AS* (mm/min)	Average TBM Cutterhead Speed (rev/min)	Average TBM Penetration Rate (mm/rev)	Machine Utilization, *U* (%)	*AR* (m/day)
Annexed structure 11-A	12.70	2.31	6.00	28%	5.00
Annexed structure 11-B	9.80	2.03	5.00	46%	6.00
Average	11.25	2.17	5.50	37%	5.50