The Line 3 of the Metro of Cairo

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ABSTRACT: A consortium of major French contractors is currently realizing the works for Line 3 of the Underground of Cairo (Cairo is the first African city to have an Underground, back in the eighties). The line is divided into 4 phases, phase 1 (4.2 km) under construction, phase 2 (6.5 km) works to start soon, phase 3 (16.6 km) under design and phase 4 (12 km) still to be designed. This 40 km new line will connect western Cairo (left bank of the river Nile) to Cairo Business District on the right bank downtown and Cairo Airport on the east of the city. Ground conditions are made by a layer of clay/silt (up to 10 m) overlying a sandy silt layer and sand from 20 m up to 90 m and more. Ground water table is a couple of meters below street level. 1 km before the end of phase 1 a major collapse occurred in the slurry TBM, whose causes are yet to be understood. TBM recovery is being carried out through a shaft that is being excavated 3 m in front of the collapse point. Its diaphragm walls have been driven DOWN to a clay layer underlying the sand level to guarantee for watertightness (over 90 m panel depth). Ground freezing is then carried out to reach the shield, that is going to be extracted from the shaft, allowing the tunnel lining to be completed. The remaining tunnel of phase 1, as well as the beginning of phase 2 and the whole of phase 3 are going to be excavated with a new slurry machine that is expected to arrive to Cairo to complete the works.

1 INTRODUCTION

1.1 Metro in Cairo

Cairo is the first African city to have an Underground metro line, Line 1, which construction dates back to the 80s. Line 2 followed shortly thereafter, and was completed in the early 2000s. Line 3 is now under construction, with a contract dated 2007.

With its huge traffic demand of 66,000 PPHPD (Passengers Per Hour Per Direction), its construction and operation are actually very challenging.

Trains are 145 m long and call for a station of similar length, and this brings all the stations to be box shaped, with a length of 150 m and a variable width, based on the traffic demand.

The Line 3 is divided into 4 design-construction stages, awarded to French Consultant Systra (Design) and to French-Egyptian Contractor ML3 (Vinci-Bouygues-Colas-Orascom). It is shown in green on the Figure 1 (Lines 1 and 2 are shown in black). In fact Systra was involved in Cairo transport Master Plan as early as the 60s, and French contractors work on Metro construction from the very beginning, showing a high reciprocal commitment between France and Egypt.

Line 3 is Y-shaped and its total length is to be approximately 40 km.

Demand is slightly unbalanced on the two branches (North and South, on the Eastern edge of the line), and this means that on 3 trains, 1 will be directed to the Southern (Mohandessin) Branch, while 2 are sent to the Northern (Imbaba) branch. The Workshop and Siding Area is located on the edge of the Northern track, with an area of 40 Hectares approximately (80 trains will be parked there).

1.2 Geology outlook

The following summarizes the general subsurface soil layering along the Metro route. The city of Cairo occupies the area of the alluvial valley of the river Nile. Before construction of the High Dam in Assouan in 1971, the river was free to flood all the area between the rocky formations of the
Mokattam hills on the East, and the area of the pyramids in Giza, on the West.

Phases 1 and 2 occupy the eastern edge of the Nile Alluvial Valley, with water table depth ranging from 2 to 10 m, and phase 4 gets in the Mokattam hill, with more rocky layers than previously.

The entire region of Phase 3 lies within the flood plain of the Nile, which at Cairo has a width of about 12 km extending from the Citadel at Gabal El-Mokattam to the Giza Pyramids Plateau, with a ground elevation generally ranging between 17 and 22 m above sea level. The geological units are mainly Nile sediments and the setting within local regions is affected by the changes in the Nile course that occurred throughout history.

Fill: A top fill layer of various depths is encountered in mostly all borings. The constituents of the fill layer vary with depth and location but it is generally characterized by the presence of bricks, pottery, concrete and limestone pieces mixed with sand, silty sands, and clays. The depth of the fill layer ranges between 1 m and 10 m from ground surface. The larger depths are mainly in the region around Attaba area. Smaller depths are encountered as we head towards Cairo Airport. Layers are as follows.

Upper sand: A sand layer generally follows the top fill layer along the metro route. The sand is of medium to fine grain size and sometimes mixed with gravel, especially around Heliopolis area till Abbasi. The sand lies in a medium to very dense condition. It thickness range between zero and 13.0 m.

Clay: Layers of stiff to very stiff silty clay, mixed sometimes with gravel or sand, appear generally after the previously described layers. The sequence of these layers is generally consistent throughout the metro route. The thickness of the clay layer varies between zero and 15.0 m in average. The layer generally appears under water table, except in the areas near Cairo airport such as Omar Ibn El-Khabab region.

Lower sand: Layers of generally very dense fine to medium grained sand always appear following all the above layers and extend to the end of the boreholes. The layer also appeared alternatively with clay layers around the area of the river Nile near 26th of July Street and Zamalek.

Gravel: Occasionally, a layer of gravel, mostly mixed with sand, of a thickness ranges between 4.0 m and 13.0 m appears from depths ranges between 5.0 m and 10.0 m. The presence of this layer is verified in the area from Heliopolis to El Geish.

Ground water: Ground water depth ranges between 2.0 m and 20.0 m below existing ground surface along most of the line. However, no ground water table is encountered in the areas of Cairo Airport.

2 CONSTRUCTION OF LINE 3—PHASE 1

A preliminary design for the whole line was carried out in 2000–2002 by Consultant SYSTRA. After a few years' stop of construction activities in Cairo, works started in 2007 with the development of the Basic Design and the actual start of construction activities for Phase 1. Phase 1 is actually the central part of the line, and it was decided to start with the construction of the northern edge station, named “Abbasia” that is also the TBM launching site.

2.1 Construction method

The construction is based on a simple scheme, in which all the stations are built with diaphragm wall support and heavy civil works completed before the station's crossing by the TBM. The tunnel is one double track tunnel Ø8.35 internal/9.15 m external, as was the case for Line 2.

2.1.1 Stations

The construction sequence is generally “top down”, with all the intermediate slabs cast while driving down the excavation, the slabs also serving as props to the diaphragm walls.

However, once the perimetral D-walls are executed, an injected plug will need to be realized to enable excavation below the water table.

According to the available data, the hydraulic conductivity of the geotechnical units is $3.0 \times 10^{-4}$ m/s for the Lower Sand and $3.0 \times 10^{-5}$ m/s for the Upper Sand. The high value of the hydraulic conductivity combined with the position of the water table lead to a preliminarily estimate of the average water inflow of 2,000 l/s for each station (7,200 m³/h).

Pumping a flow of water of the order of 2,000 l/s during the excavation of the stations has been disregarded because of possible detrimental effects on the surrounding buildings, as well as logistic problems. Before starting the excavation, a bottom plug is created at the bottom of the D-walls to enable excavation under the water table with the use of dewatering wells inside the station box, that are deeper than the final excavation level.

In practice, permeability is the key parameter for the choice of permeation grout. The soil voids determine whether the grout flows freely or is obstructed by filtration. As a general guide, it is difficult to permeate soils with a permeability of
The plug is created with low pressure permeation grouting (bentonite-cement + silicates gel). Then, the efficiency of the plug can be checked with a pumping test, with actual inflows to be compared to theoretical values.

Excavation can start, with conventional top-down techniques, up to the bottom of the base raft, with all the intermediate slabs being cast while proceeding with the excavation. Before reaching the final excavation level and casting the raft, one or two levels of struts are installed, in order to continue the excavation up to the final level.

Once the bottom raft is cast, then the TBM can pass through the station. In some cases, a complete top down technique could be used, and the slabs were all cast while driving down the excavation.

2.1.2 Tunnels

In proximity of the Nile alluvial valley, for phases 1 and 3, the tunnels are excavated with a Slurry TBM, while the rest, phases 2 and 4 will be excavated with an EPB machine. Up to the 3rd September 2009, all the slurry Tunnels were due to be excavated by the same “Cleopatra” machine which was also used for the construction of Line 2 in the nineties contemporary to Rome’s “prolungamento Linea A” and the road tunnel “Al Azhar”, in central Cairo.

With Slurry TBMs, the face pressure is kept by a circuit of bentonite, with “clean” bentonite being brought to the face and “heavy” bentonite, (bentonite + muck) extracted from the face and sent to a recycling plant to the surface. The face pressure of the bentonite is adjusted through an air bubble, whose pressure is controlled by the pilot.

One special mention is given by the so-called “bell” method, that is used in Cairo for the machine to break-in and break-out from the stations. This is an alternate solution to the case in which a curtain of soil treatment (generally Jet Grouting) is created adjacent to the station box.

The “bell” method consists in putting in place a steel cylinder as shown on the following sketch, that would enable the annular gap between the bell and the tailskin, with convenient (gasket + seal), to hold the pressure.

A simplified sketch explaining the principles governing the Bell system shown on Figure 4.

The actual steel bell is shown on Figure 5.

Such grouts are generally used in a pre-injection phase to fill large voids. Chemical grouts can be used to permeate fine-grained soils as they can penetrate finer voids than even the finest particulate cement grouts.

In fact, the plug is not designed to be a watertight plug, but rather a treatment in which the permeability of the ground is reduced to a value that would reduce the gradient of water pressures within its thickness.

The simple rule that has been used up to now is given by the need to reduce to 1/3 such gradient. For example, if the water pressure to be counterbalanced is 30 m (3 bars), then a thickness of 10 m is required for the plug. Verification of the uplift of the plug also has to be carried out. In usual conditions, the soil left in place between the bottom of the excavation and the base of the plug would need to have a thickness roughly half that of the water pressure to be balanced (eg 30 m thickness for 3 bars of water).

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ing pipes to be fed with brine to be drilled all around the shield. It is interesting to observe the increased performances of freezing plants in the last 10 years, with brine temperature being today as low as \(-30^\circ C\), while only \(-23^\circ C\) were reached back in 1999. Figure 7 shows a section of the shaft, and of the freezing pipes.

To avoid having to realize the bottom plug, it was decided to drive the D-walls where driven down to a clay layer some 95 m deep from the street level (compared to the level of the TBM to be rescued of \(-30\) m). Figure 8 shows the freezing pipes once they were drilled from the Rescue Shaft.

Brine circulation was started in the beginning of April, and temperature measurement pipes allowed to check the drop of the surrounding temperatures. Such pipes were both parallel to the freezing pipes and perpendicular pipes, drilled from the surface. These permit to follow the thickness of the ice wall.

To gain information about the actual configuration of the collapsed area from the inside, a team

and Bab El Shaaria, a sinkhole took place during excavation of the tunnel, and the crew was obliged to abandon the machine in place. Fortunately, no injured were recorded, but the project took a serious stop in its construction, as the tunnel was flooded with mud.

A 3 m thick wall was constructed 200 m behind the cutterhead, water was pumped in the empty tunnel and brought in equilibrium with the ground water table (roughly 2 bars) to stabilize water and soil movements, while a rescue shaft was constructed from the street with the D walls, located 2 m in plan in front of the stuck machine, and ground treatment with injections was initiated from the street level to compact the soil layers around the collapse area.

Ground freezing was selected as the option to recover the TBM, with 2 rows of 30 m long freez-
of divers was sent to the plugged TBM, from a Man Lock on the 3 m wall. They could observe the lining up to the collapsed area, whose integrity is essential to ensure the effectiveness of the Ground Freezing, and put in place a few additional temperature monitoring points.

Closure of the ice-wall was observed 4 weeks after start, with a sharp increase of the water pressure inside the tunnel due to ice expansion. The tunnel was dewatered in 3 steps with 24 hours stops between the steps, to ensure no leakage.

Tunnel was then made accessible with demolition of the 3 m wall, and it was possible to get to the TBM backup trailers, as seen in Figure 10.

At the same time, on the other side of the machine, demolition of the wall of the Rescue Shaft was executed ads access to the cutter head was made possible.

Recovery has been completed in January 2011.

During the recovery, a new Slurry TBM was brought to Cairo to finish up the works for phase 1 and continue on phase 2 and phase 3. It started at the opposite edge of Phase 1, in the Station of Attaba, heading eastward towards the rescue Shaft where the old TBM was being recovered.

The rescue shaft was reached by the new slurry machine in December 2010, thus phase 1 tunnels were completed, then the TBM was brought to Abbasia station to start phase 2 tunneling.

3 DESIGN OF LINE 3—PHASE 3

Phase 3 is the Western Edge of Line 3. It starts in the same station of Attaba, downtown, and drives westwards. The tunnel is obviously the same that was described for phase 1 and it will be excavated with the same Slurry Machine that was described for phase 1.

For the stations, the same design principles of Phases 1 and 2 have been kept here, trying to keep all the stations with the typical “box” shape, with no “mining” techniques.

The typical stations used in the design of Cairo Metro are the usual rectangular box shape, whose length is going to be of 150 m and whose minimum
width is 21 m and is generally adjusted to traffic demand of each station.
The main critical points of the line are be described hereafter.

3.1 Underpass of line 2

Attaba square is already the location of one Line 2 station, whose layout is perpendicular to Line 3. Line 3 underpasses Line 2 right after Attaba station, with one very critical design challenge. It is required for the plan alignment of Line 3 to turn a tight curve to the left to be able to reach the following (Nasser) station, and at the same time it is essential for the profile to dip down, maximizing the cover between Line 2 existing tunnel and the new Line 3 tunnel. The vertical and plan transition curves, cannot be superimposed and because of this is it was not possible to guarantee a sufficient distance between the two tunnels. Specific compensation grouting and/or Jet Grouting interventions are planned to reduce the risk of movements in the Line 2 tunnel that will be closed to traffic during a few days for the crossing to happen with no risk to the metro users.

Compensation grouting, as shown on Figure 12 has been selected among the mitigation measures.

3.2 Station nasser

The first station, called Nasser is probably the most difficult of the whole line because of the huge traffic demand (it is a correspondence station with Line 1) together with a very small space available. The Traffic demand is estimated to be of 25,000 exiting passengers in the peak hour and this brings the platforms to be at least 5 m wide.

It is important to note that because of the depth of the Line 2 Tunnel crossing, and the maximum slope of 4% for the ramps, the station will need to be a deep station, with 4 levels (1 Ticket Level, 2 Intermediate Levels and 1 Platform Level, plus the Underplatform). This brings the rail level to be 30 m from street level.

The designers studied all possibilities, to avoid demolition of existing buildings and found that the only possible solution would be to bring the D walls very close to the existing building, leaving a very tiny space for utilities and residents during the works. An alternative would have been the excavation of the accesses to the platform using traditional “mining” techniques with ground strengthening by jet grouting or ground freezing. However, because of the lack of experience in these grounds in Cairo, with cohesionless material and very high water table, it was decided to avoid the construction of tunnels beneath the existing buildings, which are old, with poor foundations and with very little information available. Diaphragm walls layout is shown on Figure 13 (total length of the station is 200 m).

One particular aspect of Nasser station is a tunnel to connect the two paid areas (thus with a deep tunnel to be constructed with traditional techniques). The following picture shows the final configuration of the pedestrian tunnel and the metro tunnel (deeper).

A section is shown on Figure 14.

One fundamental design parameter is the order of construction of these two tunnels. The TBM tunnel will probably be constructed first because it lies on the critical path in the overall construction programme and any delay on it will be reflected by a delay on the final construction schedule.

3.3 Underpass of the 25th July flyover

The 25th July flyover was built in the eighties to give a breath to the continuously increasing traffic.
Due to the lack of reliable data on pile length, stability of the viaduct will need to be closely monitored during construction of the tunnel, possibly with traffic closure.

3.4 Nile crossing

The TBM tunnel will pass twice beneath the Nile River, before and after Zamalek area.

The position of the tunnel with respect to the river bed has been evaluated on the basis of preliminary bathymetric survey of the river bed.

A sufficient tunnel overburden (at least 1 diameter) is guaranteed when tunnelling beneath the Nile River. No major problems are foreseen if tunnelling in controlled conditions, with pressurized tunnel face within the prescribed operational values.

3.5 Zamalek station

The Third Station along the Line in Phase 3 is on the island of Zamalek, in between the two Nile crossings above.

Again, because of the depth of the Nile crossing, and the maximum slope of 4% for the ramps, the station will need to have 4 levels (1 Ticket Level, 2 Intermediate Levels and 1 Platform Level, plus the Underplatform. This brings the rail level to be just below 30 m from street level.

Again, the lack of space is the major design constraint, but the small passengers number of 5,000 exiting passengers in the peak hour made it possible to design a station between D Walls with minimal expropriations.

3.6 Buildings underpass

In order to roughly estimate the risk of damage for each building, and consequently the need of soil treatment the following Rankin's damage criteria (Rankin W.J., 1988, Ground movements resulting from urban tunnelling: Predictions and Effects) are used. This table is commonly used for preliminary damage characterisation. The threshold values indicated in the table do not consider the conservation...
conditions and the existing state of cracking of the building, i.e., it is assumed that the building is in a perfect state of conservation. A factor of safety of 2 can be considered on these values to take into consideration the lack of knowledge (at this stage of the design) in Cairo of the real conditions of the buildings along the alignment.

Soil treatments were then decided based on the expected settlements.

4 CONCLUSIONS

The construction of a new Metro line in an old city as Cairo, where modern activities overly several millenaries of history, requires careful design and construction. These included the use of a pressurized TBM for tunnel excavation. Elaborate ground treatment technologies were also implemented by the Contractor after the occurrence of a collapse that caused the machine to be blocked underground.