Greater Metro Line 3, Cairo: Installation of underground construction pits using cut-off-wall and soft-gel-grouting

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ABSTRACT: The publication will give an overview on the preparation and execution of applied special foundation methods and a detailed description regarding installed soft-gel plugs at the Greater Cairo Metro Line 3. Detailed description will explain general assumptions during tendering and design of grout plugs, preparation of equipment, grouting procedure during execution and quality assurance activities (checking of drilling inclination, reporting of grouting) as well as reached final results.

1 GENERAL INTRODUCTION

Cairo, biggest city of the Islamic hemisphere, has approx. 25 Million inhabitants. Due to increase of local traffic, narrow streets, construction sites or broken cars, daily traffic jams (Fig. 1) and chaos on streets can be seen as usual.

The first tramway opened in 1896 and tram is still an important part of public transportation. Additionally, there are approximately 2600 busses and countless mini busses, transporting approximately 1.3 Billion customers per year. Anyhow, they are also depending on free and accessible roads.

The most important public transport system therefore is the Metro (Fig. 2), existing since 1987. Two lines with a total length of 61.5 km are already in operation and transporting approximately 950 Million customers a year (2004). Metro Line 3, connecting the airport to the city of Cairo, is already under construction and planned in several parts. The “National Authorization for Tunneling” (NAT), a Department of Ministry of Transport is the client for all construction activities.

2 CONSTRUCTION ACTIVITIES

2.1 Design and methods

BAUER Egypt, contracted as a subcontractor of Metro Line 3 JV, executed the installation of open excavation pits for the start shaft of TBM and 4 stations with several ventilation shafts. Excavation and foundation levels for stations (Fig. 3) had been planned up to 26 m below ground water level and required cut-off-retaining-walls and soft-gel-grouting-plugs down to 60 m depth. Retaining walls, as well as separating trenches in the construction area had been installed as reinforced concrete cut-off-walls (cow) using several BAUER cutters. Soil conditions at given sites had been investigated being cultural fill material (stones, concrete) and sand with silt or clay layers.

After enclosing of a complete box, grouting activities started by installation of multi-stage valves at the design depth of soft gel plug. Installation had been done by two phase method: drilling with 133 mm drilling rods and grouting with soft gel. Soft gel prepared as a mixture of sodium silicate and reactant had been prepared by a continuous mixer and grouted by using 13 pumps grouting container. Soft-gel plugs had a thickness from 4.5 to 8.5 m.

Stations are located under existing roads. Depending on traffic, the roads had to be closed completely or half-side and traffic temporary diverted. Stations had been executed as water tight construction with cut-off-walls and grouting plug. Afterwards, the JV started excavation and construction of interior parts using top down method with temporary stiffening (Fig. 4).

The tunneling machine (TBM), installed as a slurry-shield machine by Herrenknecht, has a diameter of 9.8 m and is driving from one station to the next station and manual shifted within the stations (Fig. 5). Connections to the stations, as well as to maintenance and to air circulation shafts had been made with installing a sealing block by cut-off-wall, cut by the TBM.
2.2 Staff and equipment

All together 100,000 m² cut-off-wall in different thicknesses and approx. 18,000 m² soft-gel-plug, installed with 360,000 m drilling holes had to be executed. Main equipment had been chosen to BAUER-cutters BC20, BC30, BC40 and CBC 25 (at low head room) for cut-off-wall and two B28 with 42 m one-shot-drilling boom extension for soft-gel-plug. Grouting had been done using two fully automatic 13-pumps-grouting-container. BAUER Egypt executed the project under there own responsibility, supported by technical preparation, management engineering as well as...
had been chosen to a thickness of 1.2 to 1.5 m and a depth of 30 to 60 m following the primary–secondary sequence, primary panels had a length of 8 m and secondary of 2.8 m.

Following a usual method steps, the cow will be installed by cutting an open trench, stabilized with Bentonite slurry, followed by the de-sanding and cleaning of the trench. After the installation of the reinforcement cages, concrete has to be poured into the trench without any break using several tremie pipes.

3.2 Production

Considering the previously mentioned traffic problems, all site deliveries (steel, bentonite) and removal of spoil or wasted bentonite had been done during night shift. Especially during the pouring of concrete at the primary panels (requiring in part more than 500 m³ of concrete), the main focus had been on a stable concrete supply. Therefore, the JV installed close to the sites two ready-mix-concrete-plants allowing a stable supply 24 hours a day.

Reinforcement cages had been prefabricated delivered to the site and ready assembled at a yard on site. After finishing a complete panel, cages had been lifted, using a table, and installed into the trench lengthwise by coupling of several cages.

Stations had been planned using the complete space under existing roads. So, space at site had been limited by the width of the road and the planned length of a station. Using the complete area for production, only at the front faces of each station site installation for offices, batching, storage and recycling of slurry was possible. Using the complete width of the already existing roads, at several stations no public traffic, except pedestrian traffic was possible along the site. Increasing the challenges, a road had been closed only half

3 CONSTRUCTION OF CUT-OFF-WALL

3.1 Design and method

During the installation of cut-off-walls, the excavation of trenches down to the final depth usually will be done using cutters. Cutter wheels are cutting the soil and spoil will be removed mixed with Bentonite slurry. Bentonite slurry is used as supporting as well as transportation fluid for spoil. De-sanding units, installed at site separate excavated spoil from the Bentonite slurry, see Figure 6.

At the Metro Cairo, perimeter cut-off-walls had been designed using steel reinforcement. Considering a cutting of cow along the axis by the TBM, these sections had been fitted by installing fibered glass reinforcement. Generally, cow dimensions

Figure 7. BAUER-cutter in front of occupied houses.
side at Bab El Sharia (Fig. 8) leading to only half a space at site and finally double organization expense.

The complete utilization of the street width implied the installation of cow direct in front of partly more than 100 years old houses with unknown foundation design and in a state of disrepair.

Considering a lot of houses in state of disrepair, in preparation of the project all houses surrounding the stations had been investigated and documented according their conditions. Having doubts of sufficient stability, houses had been bought or evacuated before starting activities (Fig. 9).

Another challenge had been handled by execution of cow under several existing bridges with maximum limited working high of 5 m. In this area activities had been executed using a BAUER CBC 25 low head room (Fig. 10).

All together 10 construction sites, distributed over a wide area of Cairo, had completely different soil conditions, but had to be handled with the given equipments and methods. So, in some areas clay layers had to be penetrated with the cutter, leading to well known problems with sticky cutter wheels and thickening of bentonite slurry.

3.3 QA/QC

Walls had to be installed as permanent walls under very sensitive conditions (refilled substrata, houses in a state of disrepair). To ensure no collapse or insufficient durability, monitoring instrumentation had been installed for the installation of cow and the behaviour of the structure and the surrounding buildings.

The installation of cow had been done under very close monitoring and supervision. A fully automatic documentation for deviation and twist etc. installed into the cutter gave a complete picture for predicting overlapping of joints and location of wall for excavation phase. Additional monitoring for rheological properties of slurry (viscosity, yield point, sand content, filtrate loss and filter-cake) and workability as well as hardened properties of concrete had been done assuring integrity and durability of wall.

Considering adjoining buildings as well as different static retaining systems during excavation and strutting, a surveying system (fixed points, inclination, movements of walls) had been installed and operated during the complete construction.
All together, the monitoring showed a very safe installation of cow, without any collapses and no water and soil delivering gabs during excavation.

4 GROUTING PLUGS

4.1 Design and tendering
Considering the soft ground with high water levels, open construction pits have to be sealed by a grout plug in a depth, safe against uplift forces. The installation procedure for grout-plugs is shown in Figure 11. To have proper sealing against water access, the cow had to be installed up to the depth of plug and the plug grouted afterwards. Depending on water level, excavation depth and specific soil gravity, the cow had been designed at depth between 37 m (Abassia station) and 60 m (El Geish station).

Considering a required excavation level of 20 to 27 m and an existing water pressure of 14 to 25 m the thickness of plug can be calculated. For all plugs a gradient of $i = 3$ for the existing water pressure had been requested by the client. Grouting plugs had been chosen to a thickness of 4.5 m (Abassia station) to 8.5 m (Bab El Sharia station). All together, more than 120,000 m$^3$ of soil had to be treated and sealed.

Considering a deviation of 1 to 2% for drilling, grid had been fixed, assuring both: no exceeded space between grouting points with insufficient treatment of soil and less overlapping of drilling points with the risk of damage grouting points.

Finally, triangular grid usually had been considered with a space of 1.5 to 2.5 m.

4.2 Adoption of the BAUER grouting system
Following grouting activities at the Metro Line 1 and 2, the client requested Grouting by TaM-pipes and the application of cement-grout/chemical-grout with Sodium-bi-carbonate. During the tender stage and approval by the client, BAUER negotiated recommended grouting system and own experiences as following:

4.2.1 TaM-pipes vs. multi-stage-valve-system
Knowing advantages and disadvantages of the system like less vertical space between grouting stages or grouting, stage wise with intensive flushing of pipes, BAUER decided to install a multi-stage-valve-system (Fig. 12) as a bundle of several valves, fitted to a multiple-grouting-pipe. At every drilling point one bundle with valves distributed over the thickness of plug had been installed. This was the first time, the valve system had been applied at Metro Cairo, anyhow the system had been approved at many projects before.

4.2.2 Grouting of cement/chemical grout with Sodium-bi-carbonate
BAUER executed several grouting-plugs with cement-grout as well a chemical-grout using Sodium-bi-carbonate or Sodium-aluminate as reactant. Knowing risks of insufficient penetration and permeation of soil by cement grout, caused by soil fracturing, or insufficient stability of carbonated hardener, BAUER decided to use Chemical Grout with Sodium-aluminate hardener only.
4.2.3 Grouting depth vs. uplift force
Installation of up to 8.5 m thick grout plugs has to assure getting the lowest permeability at a depth, save against buoyancy. Especially at sites with irregular soil composition, minimum two grouting stages and main grouting quantities had been positioned two meters below depth of buoyancy.

4.2.4 Design volume
Considering the soil investigation reliable, the volume of grout had been calculated according grain size distribution and given void ratio of 30 to 40%. Anyhow, the volume had been overestimated by an additional grout volume considering a worst case event to compensate a given average drilling deviations in opposite directions as well as a partly escape of grout upwards. Final grout volumes for main points at plug had been fixed to partially more than 2400 l/point.

4.2.5 Grouting procedure
Depending on plug thickness and number of grouting stages, an individual grouting procedure had been fixed for every site. Usually, the procedure involves several phases of grouting vertical, to assure a covering from top and an increased treatment at bottom. Grouting in horizontal direction usually had been considered as fresh grouting in fresh grouting following the wave-theory.

4.2.6 Grouting pressure
Grouting pressure has not chosen to a fixed value, but tried to avoid pressures above 25 bar. During the grouting, the residual grouting pressure had been monitored and recorded automatically by measuring the total grouting pressure, reduced by the measured skin friction for every line.

4.2.7 Estimation of flow rate
Flow rate had been prefixed to a certain value, considering experienced monitoring at previous sites, theoretical assumptions based on soil permeability and finally reviewed regarding the pressure development and pressure drops monitored during the grouting.

4.3 Production
Following the tendered requirements, as well as explained and negotiated procedure, BAUER installed grouting valves, using two BG 28 with a 50 m boom extension, fitted to a one-stage-drilling-depth of 42 m (Fig. 14). Grouting holes had been refilled with Bentonite-Cement-Grout as a sleeve mix to seal installed valves. Grouting had been done using two 13 pumps grouting containers. Material had been delivered by trucks and stored in silos. Considering a scheduled time space between drilling and grouting, the grout–plug had been installed very fast and efficiently.

In order to reduce the risk of failure, as well as having an early handing over of already finished areas, station pits had been separated into several (max. 5) segments using concrete participants walls. Before handing over, every segment had been checked for water access by a pumping test.

4.4 QA/QC and pumping tests
In order to achieve a prediction for ground treatment, drilling and grouting had been monitored automatically as well as manually and fitted by additional features as visible below:

4.4.1 Drilling
Fully automatic documentation with records for every drilling point showing different graphs vs. depth for speed, thrust, torque, flow rate, flow pressure, used mixture, execution time. Multi-stage

Figure 13. Chemical grouting body at a test field excavation.

Figure 14. Installation of 60 m deep grouting hole for soft-gel-plug using BG28.
Grouting valves had been assembled at site and checked for length of tubes and positioning of valves. Confirming and reviewing the grout quantities, valve position had been checked at 20% of holes by inclinometer measurement.

4.4.2 Grouting
Grouting also had been documented using the full automatic documentation unit of the grouting container with following parameters: grouting time, Grout mixture, graphics for flow rate, quantity and pressure. Additional manual record sheets for the grouting procedure with executed numbers of grout valves, sequence and additional information for fresh grout gravity, shear strength of the sleeve mix, setting time of grout or unexpected occurrences, being prepared by the grouting operator.

4.4.3 Pumping test
Checking all documentation records, main point had been considered for perfect numbering and documentation of drilling points, as well as drilling deviation. For the grouting phase, main attention was laying on grouted points as well as pressure development. After reviewing all documents, site management decided executing of pumping tests. For every pit segment a pumping test had been done. After leveling down the water to the target level, remaining water access had been evaluated. Results showing values for dewatering of 0.03 to 0.85 l/sec*1000 m², which corresponds to a permeability of 7*10⁻⁷ to 2*10⁻₈ m/sec

5 RESULT AND PERSPECTIVES
Reviewing on results of the project, BAUER had to handle a lot of technical challenges, all production deadlines had been followed, without any disturbance or collapses or increased water accesses. Using the well known cow method, BAUER also introduced a lot of changes for grouting with procedures, which are widely different from the previous applied grouting techniques at Metro Line 1 and Metro Line 2. The method itself had been applied at many projects with more than 300,000 m² plug installation, but anyhow hasn’t offered to the NAT before. After an initial review and skepticism regarding success and risk management by the JV and the client (NAT), the grouting method could be shown as an effective and safe method for soil treatment. A high leveled quality work handed over to the full convenience of the JV and the client. All unexpected problems had been solved in cooperation of the BAUER-Network in a current interest, leading to new contracts for BAUER at Phase 2 of Metro Line 3. Furthermore, BAUER executed the installation of a 97 m deep cut-off-wall-shaft and soil stabilisation with freezing method for rescuing of lost slurry-shield-machine.