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Logistic challenges for TBM operation during Sofia Metro Line 3 extension

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ABSTRACT: The Project Extension of the Sofia metro (Bulgaria), Line 3, phase I, aims to build almost 8 km of new line and 7 new stations. Main tunnel consists in a metro single tube configuration excavated by an EPB Machine. In order to minimize interferences with other contractors involved in the project, new intermediate site establishment to operate the TBM was planned. To maintain original TBM logistic concept, 2 temporary connection from surface to the tunnel where designed: a vertical shaft over the tunnel section, to proceed with the precast segments and other tunnel material supply; Lateral shaft with a ramp to the surface including 2 lateral connections to the main tunnel in order to manage the TBM belt conveyor and transfer out the excavated material. Planning the overall tunnel execution, logistic TBM shaft concept design and TBM performance analysis from each site establishments are presented.

1 PROJECT DESCRIPTION

"Extension of the Sofia metro, Line 3, phase I, Boulevard Valdimir Vazov-Centre-Zhitnitsa Street" aims to build almost 7.8 km of new line and seven new stations linking several residential districts with the centre of Sofia. This is the main central section of Line 3.

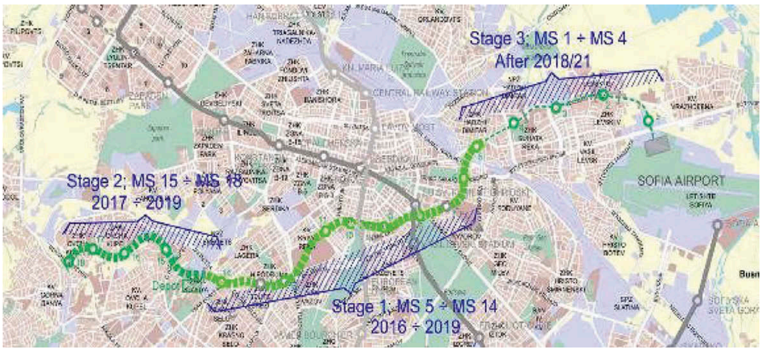

Figure 1. New Metro Line 3, stage I, route through Sofia.

Considering existing geological and hydrogeological conditions, including passing right under Perlovska River and other relevant pre-existing structure, tunnel section along the larger part of the route is being constructed by tunnel boring machine.

Main tunnel consist in a single tube configuration of 8.43 meters internal diameter excavated using an EPB Machine of 9.4 boring diameter.

A consortium of Doğuş Construction, Via Construct and Ultrastroy is the lead contractor for tunneling works. TunnelConsult Engineering has been in charge of detailed design related to the underground works (permanent and temporary structures) and technical assistance during construction.

2 TBM TUNNEL LOGISTICS AS A CHALLENGE

For Stage I of Line 3, Metropolitan (Project's owner) considered for the overall project a procurement and delivery strategy considering the splitting of major works in different contracts as follows:

- Underground stations
- Main tunnel civil works
- Rail infrastructure
- Electromechanical systems

The simultaneous presence of several contractors usually generates interferences that must be considered and analyzed during the previous phases of the project.

Regarding tunneling works, contractor (DVU JV) had to deal with every station contractors in terms of coordination for TBM arrival, crossing and launching, and on the other hand the need to release the main tunnel already constructed to the track work contractor in a very tight schedule (even with a partial delivery).

Due to this kind of project constrains, logistics for TBM operation during tunneling works was considered very challenging from early stages.

Once analyzed these factors and their influence to the overall program, Contractor decided to consider an intermediate site establishment to operate the TBM (independent of any station) in order to minimize affections to station works progress and rail infrastructure.

Initial TBM launching site located on eastern extreme of the alignment should be changed to a new location close to the central part of the alignment to release a first stretch of tunnel (including stations in between) of any activity related to TBM tunneling operations.

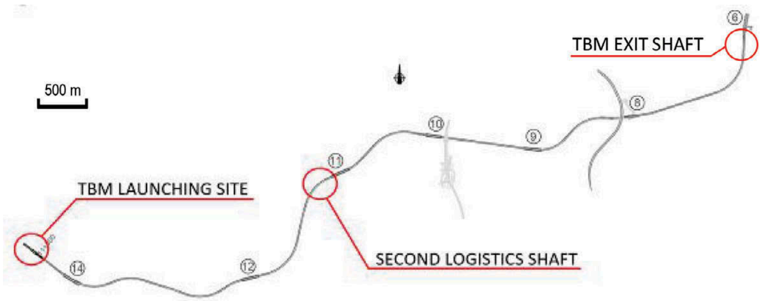

Figure 2. Project alignment showing TBM working sites location.

This new location needed to be able to supply the TBM with all materials and utilities for the boring process, and allow the muck out of the excavated material, managing the tunnel belt conveyor to the surface.

Location options for requested intermediate shafts were very limited due to the population density close to Sofia city center, with all the typical constrains related to land availability, tight working space, narrow right of way and interference with existing structures and utilities implications of dealing with them.

Finally a suitable area for the planned second stage was located just before the MC11 station, with an available area of 350 square meters close to the Medical University Complex of Sofia.

To be able to keep all the functionalities requested for tunnel boring machine operation, 2 temporary connection from surface to the tunnel where designed at the second logistic site.

A vertical round shaft over the tunnel section (6.75 meters diameter and 12 m depth) in order to proceed with the segments, backfill mortar and other material supply to the tunnel MSVs and the rest of TBM linear utilities.

Vertical shaft beside the main tunnel with a ramp up to the surface with a lateral connection to the TBM tunnel in order to facilitate the exit of the belt conveyor to the surface.

Detailed engineering for conveyor belt configuration to muck out through the opening and achieve the belt conveyor storage unit on surface, was defined by H+E logistics according to DVU JV indications.

3 TUNNEL CONNECTIONS CONCEPT DESIGN

DVU JV (Tunnel contractor) main requirement was to design a final solution for each connection minimizing the works inside the main tunnel, to not interfere with the TBM operations and be able to advance most of the works regardless the TBM position.

Another major requirement was to avoid the use of any temporary heavy steel frame inside the tunnel to hold the segments during ring opening and connection works, very common in usual openings associated to cross passage construction or ventilation connections.

One of the main challenges was the unforeseen use of any special heavy segment or any use of shear-cones between ring to ring, to redistribute loads from the opened rings to the adjacent ones prior to the construction of the permanent structure.

All these limiting factors were key-points in order to find out a proper technical solution.

Proposed design considered all the construction stages from surface with special focus on reinforcement connecting new structures to the main tunnel prior the saw cut of the segmental lining from inside.

Two concept connections were developed:

- One upper connection for TBM logistic porpoises, basically to feed MSVs with segments by a tower crane.
- One lateral connection, to manage tunnel belt conveyor to muck out the excavated TBM material.

Required dimensions for segments logistic shaft were already fixed, showing a minimum area for lift operations about 35 square meters in the upper part of the main tunnel.

For belt conveyor connection, the early requests were to allow a minimum lateral opening about 40 square meters, for and easy fit of the overall conveyor diversion concept.

This preliminary request implies an opening of a minimum of 4 contiguous rings.

This situation was impossible to handle without the installation of complementary temporary steel frames inside the tunnel or the use of heavy segments in combination with shear cones between rings, as was discarded from the beginning.

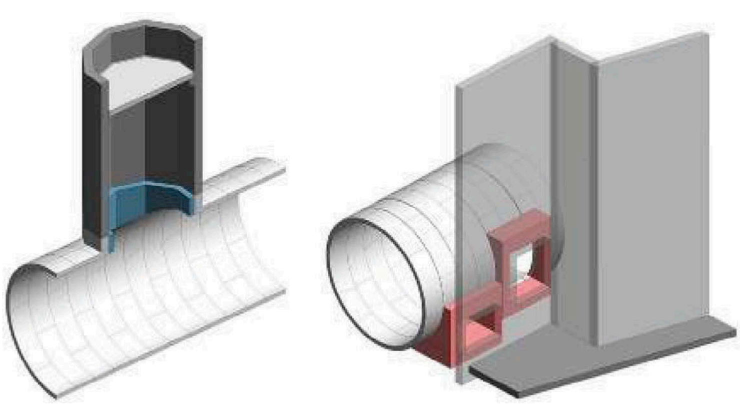

Figure 3. Connection concept designs for each option.

Due to these mandatory constrains, a more adjusted option was developed including 2 small openings (10.5 and 6.7 m^2 each one) adapted to the minimum space required for H+E for each conveyor belt included in the design (main tunnel conveyor and transverse conveyor).

With this option, even a ground improvement was required for the lateral connections, the openings were feasible in structural terms without any complementary temporary structure inside the tunnel.

In order to evaluate the influence of the connections construction foreseen in each location and to analyze the forces acting on the opened rings, different 3D FEM model of the tunnel aperture were performed using Sap2000 and MIDAS GTS software.

In each developed model, the ground is modeled through three-dimensional elements, which behavior for this particular case has been defined according the geotechnical parameters obtained from boreholes on site and laboratory tests results.

3D model was used to simulate the whole process of connection construction:

- Main tunnel excavation using the deconfinement method.
- Ground treatments execution by modifying soil properties.
- Excavation to the main tunnel.
- Opening the segmental lining.

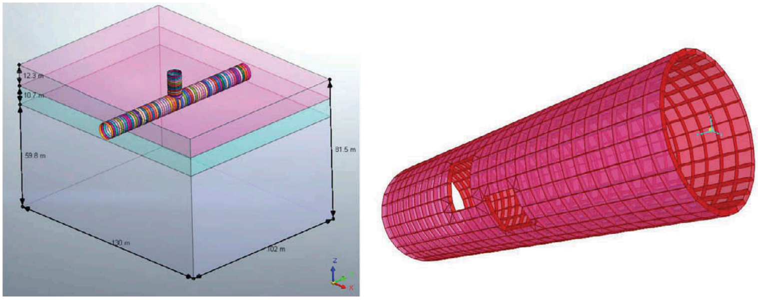

Figure 4. 3D models used showing geology scheme considered for vertical shaft and lateral openings geometry for conveyor connection.

New forces redistribution (axial forces N, moments M and shear forces T), on the segmental lining after ground excavation phase and after the rings opening was pointed out. In particular, shear forces that are transferred to adjacent rings, after the opening.

Using these results, connections between structures by collar beams were defined in order to achieve a successful design.

4 PLANNED TBM LOGISTICS

4.1 *Initial portal logistic concept*

Located at Zithnitsa depot area, 510 square meters were used to launch and perform the initial TBM works.

Ancillary equipment included were:

- Conveyor belt for the muck
- Muck pit
- Batching plant
- Pumps and piping for air and water supply
- MSV vehicles for the segments and grout transport
- Warehouse
- Ring segments storage area…

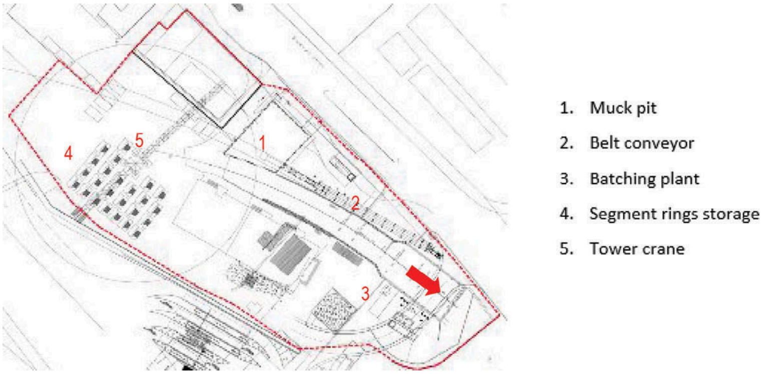

Figure 5. TBM launching site layout.

All the logistics to transport materials in and out of the tunnel were originally designed to enable the EPBM to work in a full capacity of 40 m/day (26 rings/day).

Mucking pit volume capacity was about 3.000 cubic meters of spoil, corresponding to 1,5 times maximum daily production rate considered.

With a main conveyor belt along the tunnel transporting the muck directly to the surface, only one tower crane was required for loading the segments on MSVs, in addition, the segment transport gained independence from the muck transport, permitting the use of only 3 MSVs per tunnel (2 for segments and 1 for grout and personnel).

Figure 6. Main tunnel conveyor on launching site, and MSVs used in the Project.

For MSV circulation along the tunnel, concrete backfill was planned after each Station arrival, in order to allow the MSV crossing inside the tunnel during TBM advance and minimize possible stops due to lack of materials provided by MSVs.

4.2 *Intermediate TBM logistics shaft*

New location at Sveti Georgi Sofiyski Street with an area of 350 square meters was performed, just beside the Medical University complex of Sofia.

Note than the area available was roughly a 40% less than the initial launching site, were no space limitation was considered.

This site configuration includes two different shafts, one located on the left side of the tunnel for belt conveyor system and one located over the tunnel for TBM logistics.

At the lateral shaft, a transverse conveyor belt transported the muck through the tunnel connection to another conveyor belt to transport the muck from the pit bottom to the surface in an inclination of 17°.

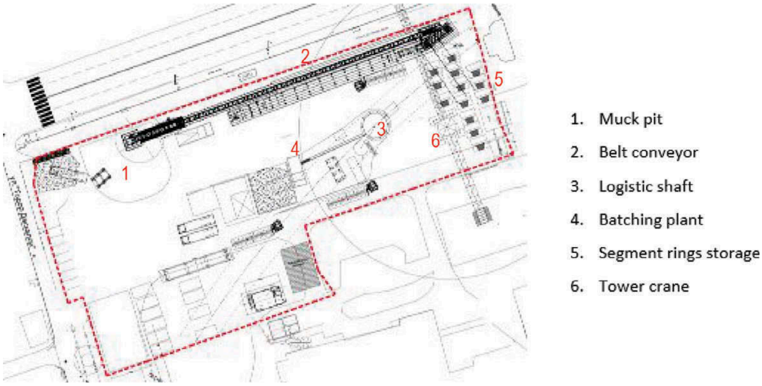

Figure 7. Intermediate TBM logistic shaft layout.

Figure 8. Belt conveyor exiting from the main tunnel and ancillary inclined belt conveyor mucking out.

Mucking pit capacity on the site was adjusted up to 2.135 cubic meters, corresponding to 18,5 excavated rings, lower than original site establishment.

In that case, the absence of a reasonable buffer in accordance with the maximum planned TBM rate, made the handling of the muck specially challenging due to the new location close to the city center.

Time constraints for trucks circulation to the landfill in order to minimize discomfort in the neighborhood, as well as the greater intensity of traffic around the work site during peak hours, were limiting factors during the advance of the tunnel boring machine.

In order to facilitate the main conveyor extension operations, horizontal storage unit was placed on surface. Two 90 degrees turnings on the belt conveyor (including vertical disposal) were used to achieve the surface on the new logistic site.

Figure 9. Vertical disposal of the main tunnel conveyor belt to reach the horizontal storage unit on the surface.

Through the shaft over the main tunnel, segmental lining and other complementary materials were loaded to the MSVs, and the rest of linear items as well.

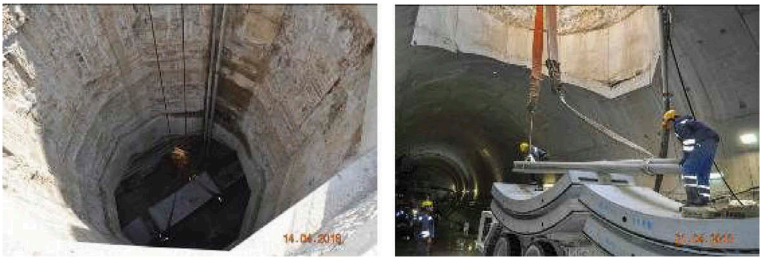

Figure 10. Loading materials on an MSV through the logistic shaft.

Related to the new site relocation, defined deadlines were met, including the belt conveyor set-up process and the rest of ancillary equipment, allowing to restart TBM operations in 2 months' time.

Moving of logistics from initial construction site to new intermediate TBM logistic site was carried out following the break through into MC11 station, the third one after launching the TBM.

About 80 per cent of structures and equipment from initial site were relocated at intermediate shaft.

During the course of the logistics moving operation, TBM was being pulled through MC11 station and a maintenance program for the TBM was performed, not interfering any of scheduled activities for connections.

Table 1. Main activities durations related to the new site set-up.

	Start date	Finishing date	Duration
D-Walls and shafts excavation	02.06.2017	25.11.2017	176 days
Ground improvement works	14.12.2017	27.01.2018	41 days
Conveyor belt/vertical shaft set-up	28.01.2018	31.03.2018	62 days
Site mobilization	03.02.2018	12.04.2018	69 days

5 TBM PERFORMANCE FROM EACH LOGISTIC SITE

TBM launching was performed on March 2.017, and after a first stretch to the Station MC14 considered as a learning curve process, following sections achieved expected advance rates.

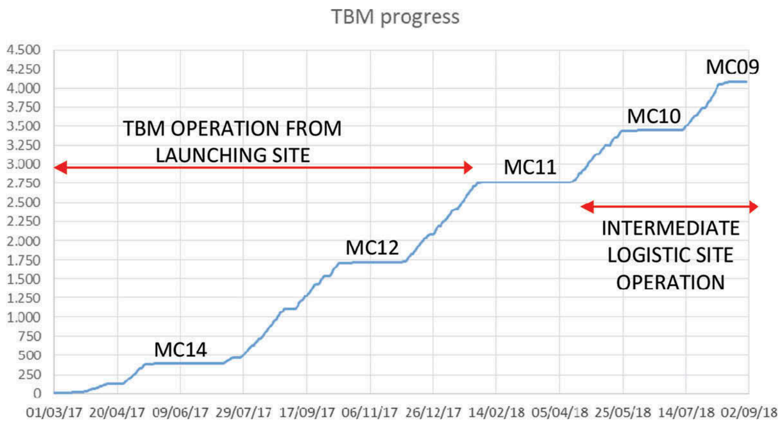

Figure 11. Frequency analysis regarding rings per day production.

A good daily maintenance plan, combined with a highly skilled staff in charge of TBM operations, had allowed to achieve really high and maintained performance in time.

As can be seen in the following table, once the learning curve was overcome after TBM launching, performance achieved was very regular all along the alignment around 10–11 rings per day as an average.

Table 2. Main TBM performance data during tunnel excavation.

	Length	m/day	ring/day	Best day (rings)
LS to MC14 (*)	375	5.21	3.47	15
MC14 to MC12 (*)	1323	14.07	9.38	21
MC12 to MC11 (*)	1032	16.65	11.10	21
MC11 to MC10 (**)	678	16.14	10.76	21
MC10 to MC09 (**)	634.5	17.15	11.43	25

* Logistics from initial launching site
** Logistics from intermediate shaft

If the frequency of rings per working day is analyzed, it can be noted that there is no difference in terms of TBM performance capacity, despite from which logistic site was operating.

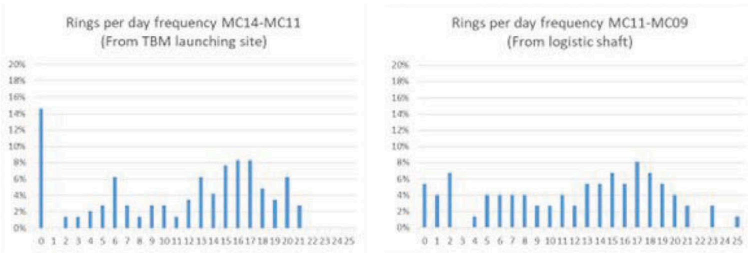

Figure 12. Frequency analysis regarding rings per day production.

These statistics shows that even original launching shaft configuration was planned for a full capacity of 26 ring/day, intermediate site with greater restrictions in terms of space and general availability, tunneling performance was not been affected thanks to the previous work of sizing and planning on this option.

Rest of stretches from MC09 to the exit shaft are still ongoing (September 2018), and expected TBM rates for the rest of the sections seem that can be maintained without major problems until the end of the project.

End of tunneling works included in Phase I of Line 3, are planned to be finished for first quarter of 2019.

6 CONCLUSIONS

Most of challenges in urban tunneling are related to tight working space, narrow right of way and interference with existing structures and utilities implications of dealing with them.

In the top of this, if the overall project involves due to the planned delivery strategy, different contractors in charge of different parts of the same project, inevitable interferences are expected and some challenges can achieve higher levels of difficulty (as the example of Sofia metro project).

Dealing with these challenges starts in the conceptual design and continue through the preliminary and detailed design when constrains and solutions are detected and defined during the early stages of the project.

During planning and construction stage, Contractor may find some answers to face design challenges and cost savings through innovative solutions and methods.

Sofia Metro Line III can be considered a good example about this kind of planning in early stages performed by Doğuş Construction, Via Construct and Ultrastroy JV.

Presented temporary logistic shaft for TBM operation has been successfully constructed during the project execution, fulfilling all the considered requirements during planning stage, allowing a high TBM performance until the end of the Project.

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