



TBM Challenges on Musaimeer outfall tunnel

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Abstract

Musaimeer outfall tunnel is the longest outfall tunnel in the Middle East. The tunnel was excavated by Earth Pressure Balance (EPB), Tunnel Boring Machine (TBM) and encountered three distinct rock masses namely Rus Formation, Midra-Shale, and Simsim Limestone along with water inflows at high pressure, complex mixed ground, and weaker ground strata prone to cavities with the presence of vertical and lateral fractures connected to the seabed.

These conditions resulted in the TBM operating in very dry conditions where the addition of soil conditioners and water sprayed in the excavations chamber and cutter head were required to avoid clogging situations and create a pasty excavation material, which impacted TBM operation. The opposite scenario occurred when the TBM encountered very wet conditions while passing through weathered Simsim Limestone fully connected hydrostatically with the seabed. Such situations directly impacted the productions rates, quantities of consumables, extra cost on the tunnel enabling activities and finally, the need of both atmospheric and hyperbaric interventions into the cutter head up to 3.5 bar to replace cutting tools. Long tunnels with only one access shaft pose many programme problems for logistics, combine these with the requirement to drive directly out under the seabed for 10.2 km, and the programme issues become even more challenging. To meet and eventually improve on the planned completion date required a complex and extensive management of all tunnel logistics activities required to support consistent tunnelling for a two-year period. This technical paper will discuss the management issues and solutions implemented to meet the challenges of the outfall tunnel construction.

Keywords: TBM; Sub- Sea tunnel; Hydrostatic pressure, Non-intrusive radar system (BEAM), TBM parameters

1 Introduction

The outfall tunnel extends from the pump station, 10.2 km offshore and connects via a riser shaft to a diffuser field. This allows the safe and environmentally compliant discharging of storm and ground water flows into the Arabian Gulf. The discharge from the structure to the sea is via 84 duckbill valves located at the equal spacing along the 6-arm structure (Public Works Authority, 2017). The project location is shown in Figure 1.



Fig. 1: Project Location

2 Geological and Geotechnical Conditions

Referring to boreholes information and additional geophysical investigation the TBM excavated through three general geological formations: Rus Formation (RF), Midra Shale (MS), and Simsima Limestone (SL). As the TBM passes from one to another the excavation face will include both strata. Water pressure both Low (LP) and high (HP) was expected and encountered, hence, the TBM excavated through 7 mining zones, as follows. The three geological formations are shown in Figure 2.

- Rus Formation (RF) – full face.
- Rus Formation with Midra Shale (MS).
- Midra Shale – full face.
- Midra Shale with Simsima Limestone (SL)
- Simsima Limestone – full face (Low Pressure (LP) and High Pressure (HP)).
- Simsima Limestone with Midra Shale.
- Simsima Limestone – full face (Low Pressure (LP) and High Pressure (HP)).

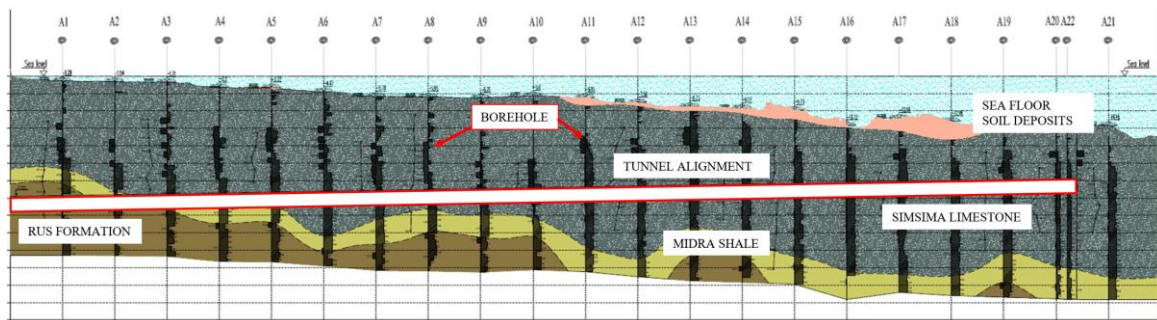


Fig. 2: Outfall Tunnel Geotechnical Section

From a hydrological point of view, the most crucial aspect is the aquifers at the Simsimal Limestone-Midra Shale interface and the interface between Midra Shale-Rus Formation, where the transmissivity was very high in both locations.

3 Tunnel Boring Machined (Tbm) Selection

The TBM was designed, Specification for tunnelling (2010), and manufactured by CREG/Wirth. The TBM selected to excavate the outfall tunnel was an EPB (Earth Pressure Balance) designed as per Qatar Construction Standards (2014) to support a maximum face working pressure of 4.5 bar (full

hydrostatic). EPB configuration has a cutter head, excavation chamber, main bearing or drive, screw conveyor, front, middle and tail shields, personnel locks, thrust system, articulation, erector, and special brushes as part of the tail shield seal system. In addition, there are 18 gantries, 160 m long accommodating all electromechanical parts, additive tanks, and rescue chambers. The TBM was designed to erect a concrete tunnel ring of six segments with a linear length of 1.35 m, the internal diameter being 3.7 m (Maidl, 2014).

The TBM Technical description (2018), was designed and equipped with:

- Optimized cutting tools combination for hard rock and soft rock.
- Operate in open mode or closed mode.
- Materials and equipment to support a maximum face working pressure of 4.5 bar.
- Eliminate the risk of uncontrolled water inflow into the tunnel during construction.
- The screw conveyor had two sets of gates for emergency purpose in high pressure.
- Long screw conveyor to dissipate the maximum pressure of 4.5 bar.
- Extra wire brush seals to withstand high pressure.
- Removable probe drilling machine.
- Real time probing system using BEAM (The Bore-tunnelling Electrical Ahead Monitoring).

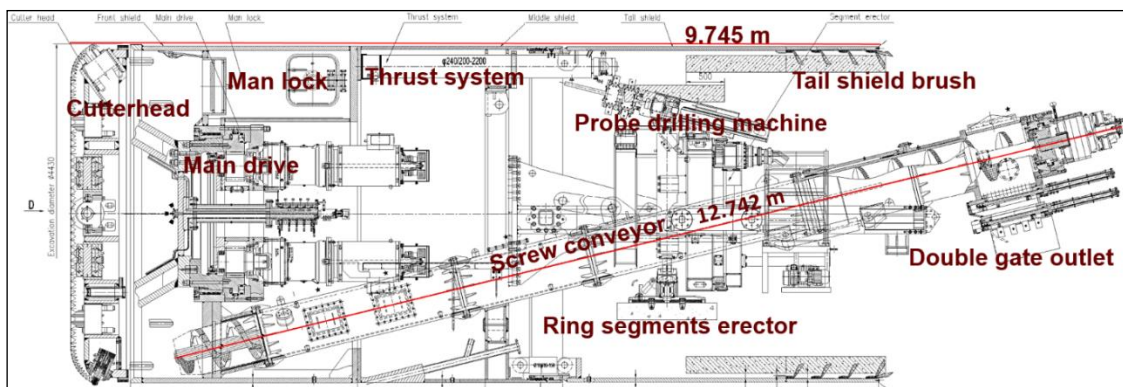


Fig. 3: TBM main components

4 Access Shaft Arrangements

4.1 Introduction

The project configuration included a drop shaft from the pump station, which connected to the outfall tunnel. This allows the treated surface and stormwater to transfer from the pump station to the outfall tunnel.

4.2 Drop Shaft

The Drop shaft was considered as a possible access shaft for the TBM works but at only 12 m in diameter is too restricted and this shaft would not be able to be completed until after TBM works had finished. This would put severe pressure on the overall completion date of the project. It was decided to not use the drop shaft for TBM access.

4.3 Logistic shaft

It was decided that a temporary logistics shaft has the most effective structure to construct the outfall tunnel. It was located directly behind the drop shaft (48 m deep) and along the same alignment is the

outfall tunnel. This structure consisted of a 26 m diameter shotcrete lined shaft and an extension tunnel of 26 m, capable of installing three separate rail tracks side by side. The logistic shaft and extension tunnel arrangement is shown in Figure 4 along with the two types of rail transport systems].

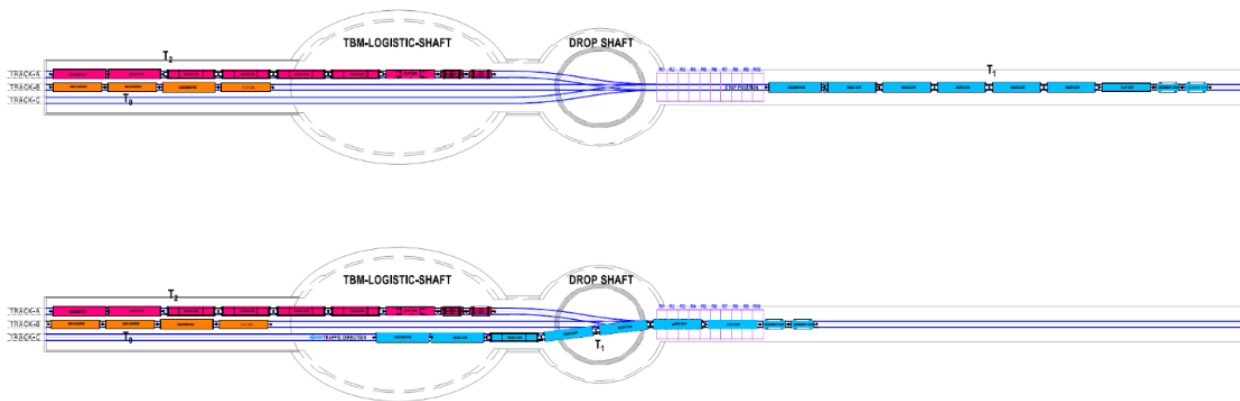


Fig. 4: Logistic & Drop shafts and Outfall tunnel arrangements.

5 Tunnel Logistics Options

5.1 Introduction

As the tunnel construction progresses the locomotive journey times increase until, at some point, they result in the TBM having to stop and wait for the locomotive bringing the next tunnel segmental ring, empty material skips and additional supplies back to it before it can start excavating again. To avoid this, one or more California (rail) crossings can be introduced in long tunnels to keep the tunnelling continuous. This allows more than one locomotive to operate on the railway line at once, and allows locomotives to wait closer to the TBM, ready to supply it from a shorter distance. Figure 5 illustrates the simple arrangement with one California crossing.

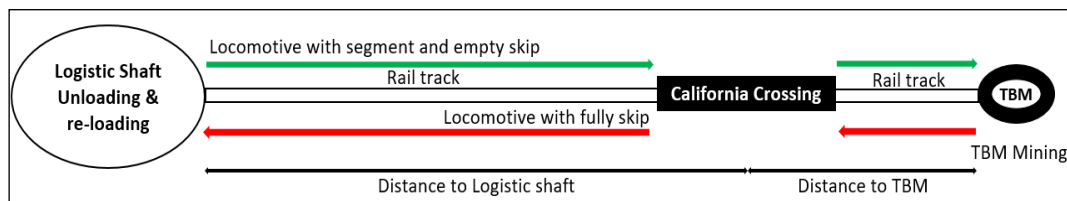


Fig. 5: Train traffic plan with California crossing

5.2 Single and Multiple Crossings considerations

During the planning stages analysis must be made as to the expected delay time which would be incurred supplying the TBM as the tunnel length increases daily. A California crossing is a complex structure which must take into consideration many variables and as such will take many months to fabricate. The variables to be considered in the design of a California crossing for the outfall tunnel are:

- Safety of TBM personnel.
- Working shifts number and duration per day.
- Number of working days per week.
- Length of combined material/segment and personnel trains (normal conditions).

- Additional excavated material skips for adverse conditions.
- Ease of installation.
- Ease of relocating within the tunnel 2 days per relocation.
- Impact of TBM services within the tunnel.
- Minimal impact on ventilation system.
- Efficient access and exit of the structure for the various rolling stock.

With the above design complete, the next stage was to simulate how the California crossing(s) would affect the tunneling production and to decide on how many would be required for the 10.2 km tunnel length. During this simulation the following would be estimated, and various ranges considered:

- Accelerate from logistic shaft.
- Top speed expected of the rail.
- Deaccelerated on approach to California crossing.
- Access onto California crossing.
- Traversing the Californian crossing.
- Exit California crossing.
- Accelerate from California crossing.
- Top speed expected of rail.
- Deaccelerated on approach to TBM/additional California crossing.
- Time to travel within the TBM Gantries.

During the tunnel construction, decision was taken to implement one California crossing.

6 Soil Conditioning

The primary necessity of soil conditioning is to obtain a suitable mixture of excavated material to build up and maintain the necessary pressure in the bulkhead to support the pressure of the soil and the water at the tunnel face, improvement of advance rates, reduction in the wear of cutting tools and cutter head torque.

The ground conditioning is carried out during the excavation at the tunnel face, in front of the cutter head, to avoid the clogging of the cutter head (cutting tools) with openings in the screw conveyor and excavation chamber. The TBM was provided with 4 injection lines for conditioning direct into the front of the cutter head, 3 lines to the chamber and screw conveyor, and the water spray injection lines to the excavation chambers. These lines were designed for different soil conditioners requiring foam, polymers, and bentonite in exceptional cases. During the design stages, the estimation of soil conditioners consumption assumed for the excavation of 1 ring (20 m³) was 12 to 15 liters of concentrated liquid of foam, depending on the manufacturer, and 1,000 to 2,000 liters of water per tunnel ring.

7 TBM in Very Dry Conditions

During the initial stage and the learning curve of the TBM operation, the TBM was passing through the Rus Formation, the regular operation, the consumption of soil conditioners, the consistency of the paste, the quantity of excavated material per ring was as per expectations. However, after passing ring Number 450, the TBM entered mixed face conditions of Rus Formation and Midra Shale with higher clay content, which resulted in a reduced advance rate.

Once the TBM entered fully in Midra Shale occurring between tunnel ring 550 and 1150 the ground conditions were extremely dry, requiring extra addition of soils conditioning materials such as foam and water spray in the cutter head and excavation chamber to control the TBM parameters such as torque, thrust and reach and maximize possible advance rates in the difficult ground conditions.

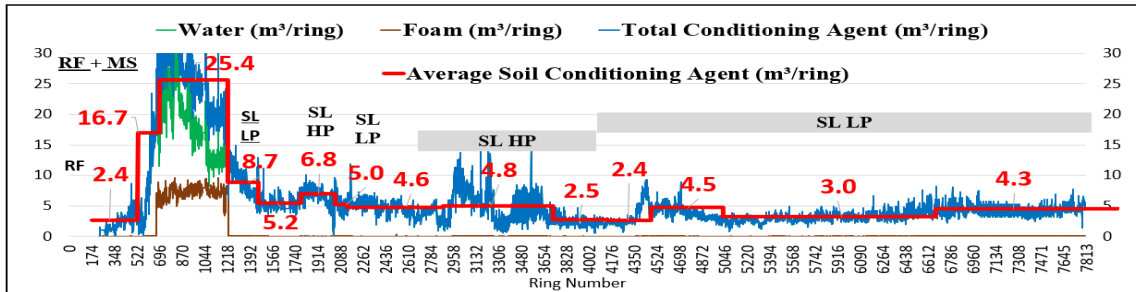


Fig. 6: Average Consumption of Soil Conditioning Agent at Each Geological Formation and Conditions

Figure 6 above shows the volume of soil conditioners (foam and water) added increased from 2.4 m³/ring up to 25.5 m³ per tunnel ring. Therefore, the addition of soil conditioners, the swelling factor greatly increased the quantity of excavated material per tunnel ring from 4 to 8 skips per tunnel ring and occasionally 9 skips per tunnel ring as shown in Figure 7. This resulted in an increase of supply trains by 2 and sometimes 3 trains to excavate a ring instead of 1 as planned. To help mitigate the impact of increasing the number of trains, the installation of the California crossing was brought forward to tunnel ring 550. Figure 7 illustrates the number of skips required to remove the excavated material for one tunnel ring against ground condition types over the length of the tunnel. Figure 7 also indicated the net boring time take to excavate one tunnel ring, which increased with increasing quantity of excavated material.

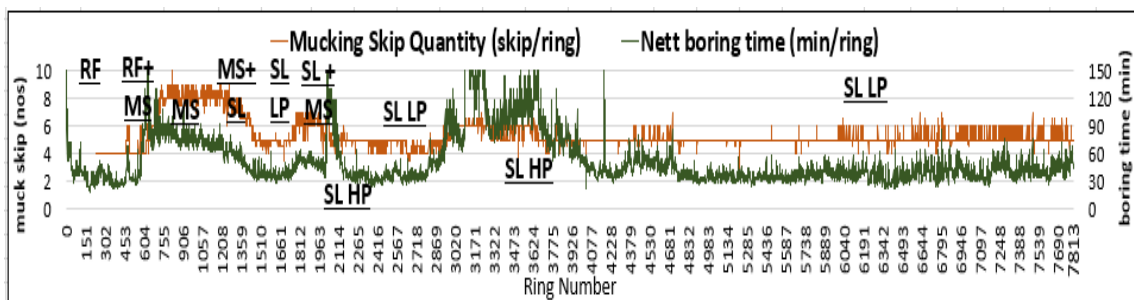


Fig. 7: Quantity of Muck Materials against the Boring Time

8 TBM in Very High Water Pressures

Opposite to the previous scenario occurred when the TBM encountered 2 areas of high-water pressure conditions while excavating through the weathered Simsimia Limestone Formation fully connected hydrostatically to the seabed.

The first area was from tunnel ring 2,000 to 2,130 and the second area was from tunnel ring 2,830 to 4,100 where the TBM passed through a fault area (Figure 2), the EPB pressure instantly reached 3.5 bar.

After the necessary assessment of the geological conditions, adjustment on the main drive seal of the TBM to work in close mode, safety toolbox talk with the operatives, specifics drive instruction

parameter sheet was issued to the TBM operator on how to excavate through these areas.

From a soil-conditioning point of view, polymers were added in the excavation chamber and screw conveyor to control the effect of high-water inflow. Unfortunately, the results were not satisfactory enough in this situation considering the size of the excavation chamber.

To evaluate the differences of excavation with or without addition of polymer, two options were observed. The first was adding polymers and pushing the TBM slow enough to have time to condition the soil in the chamber and get it pasty enough, but the TBM's speed was slow, around 4 to 6 mm per minute. The second was without adding polymer, getting the muck without pasty consistency, to reach the advanced speed of 12 to 15 mm/min.

After analyzing the data and evaluating the advantages, disadvantages, and risk of the second option mentioned above, it was decided to continue advance without polymers and conditioning only with foam for lubrication purposes only to reach the maximum safe advance rate speed in relation to the conditions.

The logistics, as expected, was affected due to the excavated material quantity being higher than the theoretical. In this case, five skips per tunnel ring becomes the usual. For that, all the trains (3 units) were modified to be able to accommodate five skips. Regarding the California crossing, only one unit was installed and relocated based on not more than 20 hours idle time per week.

9 Cutter Head Interventions

A total of 7 cutter head interventions in atmospheric conditions were performed while excavating Midra shale, replacing 17 cutter discs. Two interventions in hyperbaric conditions, BS 6164 (2011) The life of cutter discs was expected to be around 70 tunnel rings per cutter, the actual cutter disc life per geological formation type is shown in Figure 8. The average being 77 tunnel rings per cutter.

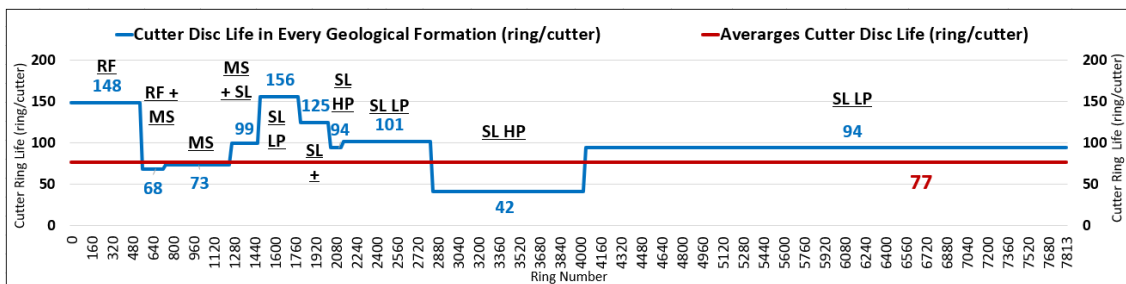


Fig. 8: Cutter Disc Life in Every Geological Formation and Condition



Clogging



Clogging



Disintegrated cutter

Fig. 9: Status of the Opening during Cutter head Intervention (clogging issues)

Some of the cutter head interventions were required to clean the clogged openings, as shown in Figure 9, which affects the speed of the TBM advance.

In terms of cutting tools consumption, the wearing was higher than expected due to hyperbaric conditions, in these cases, the lifetime decreased to 42 tunnel rings per cutter.

10 TBM Average Progress

Figure 10 shows the average progress along the different geological formations being 7.6 tunnel rings per day and 8.7 tunnel rings per day while the TBM was working in high water pressure conditions.

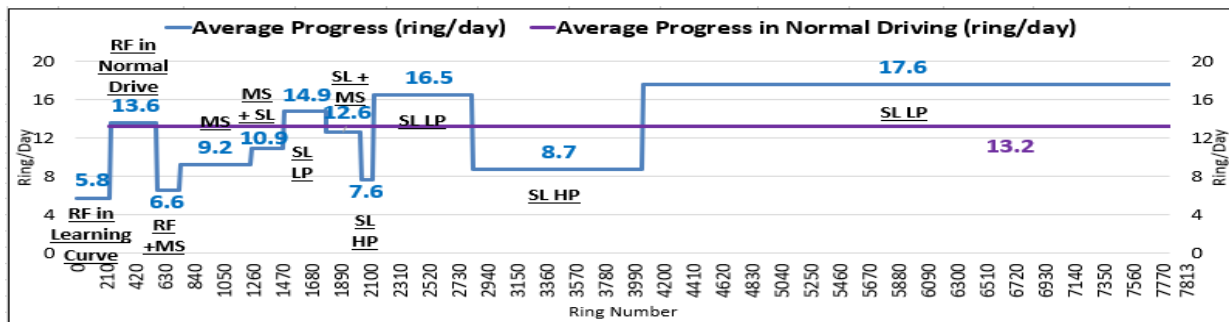


Fig. 10: TBM Average Progress

While the TBM was excavating in hyperbaric conditions, unusual wearing was observed in the screw conveyor gates as consequence of poor soil conditioning and high pressures in the excavation chamber, along the screw conveyor and rubber conveyor belt requiring early replacement.

11 Conclusions

The TBM completed the drive 58 days ahead of programme despite the difficulties, passing through geological formations in extreme ground water conditions. The lowest performance of the TBM occurred in these two extreme conditions. This is because the consumption of the consumables like soil conditions and greases were up to 4 times higher than average values along the tunnel.

The constant monitoring of the TBM parameters helps the crew to adjust them and obtain the best possible performance, minimizing lost time. The logistics' flexibility helped during the adverse scenarios during TBM drive, allowing modifying the train and using only one California crossing, which greatly reduced lost time.

The wearing of cutting tools was high but somehow expected when the TBM is mining in hyperbaric conditions. The lack of high-water pressure nozzles in the bulkhead might help in case of clogging issues, a lesson learned for following similar projects. Poor soil conditioning during high water pressure conditions resulted in some mechanical issues in terms of excessive wearing of the screw conveyor gates and the rubber conveyor belt.

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