TBM Cutter head management sub-sea in the Arabian Gulf

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**ABSTRACT:** The Musaimeer pump station and outfall project located in Doha (Qatar) was required to construct a long outfall tunnel using an Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM) with a segmental lining. This tunnel had only one access point located at the launch shaft and was driven directly out from the shoreline, and connecting to a diffuser bed located 10.2 km offshore. The TBM cutter head was designed and equipped with both soft ground scrapers and hard ground cutter discs (Single, Twin and Double). The performance of any TBM can be influenced by many individual factors or combination of factors; perhaps the most significant of these factors is the performance of the cutting tools on the cutterhead. This paper will detail the two different specifications of hard ground cutters used and their individual performance and the impact of tribocorrosion on each type of cutter. The project had to carry out cutterhead interventions at full hydrostatic pressure (3.5 Bar) due to the extensive fractures in the seabed strata. The experience gained will be explained and the result was the changing of only 105 hard ground cutters during two years of tunnelling.

1 INTRODUCTION

The Musaimeer Pump station and outfall project is located directly south of the Hamad International Airport in Doha, Qatar. The project is owned by Ashghal (Public Works Authority) and is designed to receive both ground and storm water from 270 km² of southern Doha. The outfall tunnel extends 10.2 km offshore from the pump station, 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 Gulf. The discharging shall be performed through a vertical riser shaft and a marine outfall diffuser field. Figure 1 shows the project location.

2 GEOLOGICAL CONDITIONS

The geological formations of the Qatar Peninsula are entirely Tertiary to Quaternary in age. During this period, the Lower Eocene Rus Formation (Er) consisted of soft limestone, dolomitic limestone, chalky limestone and gypsum, anhydrite, and marl/shale, which were all deposited.

During the Lower-Middle Eocene, the Lower Dammam Sub Formation (consisting of the Dukhan Alveolina Limestone, Midra Shale and Fhaihil Velates Limestone) and the Upper Dammam Sub-formation (consisting of the Simsima and Abarug Limestone members) of the Dammam Formation were deposited. Through the passage of time these rocks have undergone weathering, fracturing, alteration, karstification and recrystallization. Overlying the above is a thin layer of sandy Quaternary Deposits.
This investigation data was combined on a long geotechnical profile and become the basis for selection of the selection of TBM and tunnel segmental lining type. Figure 2 shows the geological profile.

The tunnel alignment passed through the three different rock masses commonly encountered in Qatar’s Peninsula:

- Rus Formation (RF);
- Midra Shale (MS); and
- Simsima Limestone (SL). Highly Weathered Simsima Limestone (HWSL), Moderately Weathered Simsima Limestone (MWSL), Slightly Weathered Simsima Limestone (SWSL) and Simsima Limestone (SL).

Rus formation can be described as very weak to weak, light brown fine-grained limestone interbedded with very weak light greenish-grey siltstone with occasional veins and nodules of gypsum and some solutions vugs.

Midra Shale is a very weak to weak yellowish-brown fine-grained shale interbedded with weak to medium-strong white to light grey limestone with occasional nodules of gypsum.

Simsima Limestone is weak to medium-strong light grey to white, fine-grained dolomitic limestone with few solutions vugs and occasionally nodules of gypsum.

3 TBM AND CUTTERHEAD OVERVIEW

Based on the geological and geotechnical parameters available along the 10.2 km of subsea tunnel alignment and with previous project experience accumulated in the State of Qatar, the EPB TBM was selected with a maximum working pressure of 4.5 bar. The cutter head of 4.42 m diameter and 26 % opening ratio is equipped with 4 central twin disc cutters, 10 double
disc cutters monobloc, 5 single disc cutters being all being 17 inch, 8-gauge scrapers, 28 scrapers and 17 drag bits The general layout of the cutterhead and the location(track) of the various cutter tools are shown in Figure 3.

In addition, the cutter head had 3 ports for foam, 1 port for bentonite, 2 wear detectors, 4 mixing ports, and 1 copy cutter of 20 mm. The general layout of the cutter head is shown in Figure 3 along with the tracks of the various cutterhead tools. The TBM installed a precast concrete universal segmental ring consisting of 6 segments and a key, with and installed length of 1.35 m. The TBM installed a total of 7.813 concrete rings, in the two-year construction programme.

Figure 3. General Cutterhead layout.

3.1 Cutter head interventions

A total of 38 cutterhead interventions were performed during the excavation of the outfall tunnel, from February 2019 to February 2021. 36 were under atmospheric conditions and 2 were under hyperbaric conditions, replacing 105 cutters, 19 scrappers, and 14-gauge scrapers. Figure 4 details the numbers of cutters replaced per intervention with the geological formations and water pressure conditions. The type and number of cutters changed at each intervention are shown above the tunnel ring number on the bottom horizontal axis. The different shading starts for central twin cutters, then double cutters and finally single cutters. The axis on the left hand side of Figure 4 represents the number of cutters changed per intervention whilst the axis on the right hand side is the cumulative cutters changed over the full length of the tunnel.

Figure 4. Cutter change details per interventions.

Out of 36 cutter head interventions carried out in atmospheric conditions, 25 interventions required the replacement of cutting tools whilst in the remaining 11 interventions did not require cutting tool replacements, but was related to clogging issues in the cutter head, inspection of the main bearing bolts, maintenance of soil conditioning lines, replacement of
electronic sensors and evaluation of water inflow while the TBM was approaching the riser shaft, and while passing through under the riser shaft.

3.2 Hyperbaric intervention

Following the recommendations as per Guide to the Work in Compressed Air Regulations 1996, and in order to be ready in the event of cutterhead intervention in hyperbaric conditions, a specialist compressed air contractor was appointed with specialist operatives and equipment being available on site 24/7. These services included: an appointed doctor, hyperbaric intervention supervisor, divers, personnel lock operators, medical lock and operators, nurses, and a portable fully equipped clinic. The Public Health system in the State of Qatar was notified of the hyperbaric intervention 24 hours in advance.

Starting in January 2020, the metal detector alarm was triggered by debris from a cutter after 283 rings. The analysis of the debris encountered indicated that to continue excavation, the screw conveyer should be placed on risk. The decision to perform cutterhead intervention in hyperbaric conditions was taken and the preparation works started. However, during the preparation work the pressure encountered was not stable, and it was concluded that there was air loss through the rock mass. The issues and the associated risk evaluated and the decision to perform grouting works as rock mass improvement were taken.

During probe drilling activities through the shield of the TBM there were several difficulties encountered; namely, the time needed, but most critical, the risk of a break to the rod between the shield and rock mass, which could lead to blocking and hindering the movement of the TBM. In addition, the permeability and porosity were high in the rock mass which could allow the planned grout to travel around the shield and block the TBM. The grouting works were discarded in favour of the cutterhead intervention in more suitable ground conditions.

The TBM continued excavation under detailed monitoring condition to avoid damages on other cutting tools and screw conveyor with the intention of finding better rock mass conditions that allow work in compressed air conditions.

To reduce and control the air losses, bentonite was used. However, difficulties were observed due to the interface between bentonite, limestone, and water under high pressure resulting in difficulty establishing the stability of a bentonite cake on the face. After several trials with different bentonite compositions, a good bentonite cake was achieved after 12 hours in the excavation chambers.

Diving crews of 2 divers each were established to each work in a cycle of 2 hours working under 3.5 bar compressed air conditions and 3 hours in decompression as dictated in the COMEX diving tables.

A total of 35 individual hyperbaric interventions were performed at this location of which 26 were successful whilst 9 were unsuccessful due to high air losses. Figure 5 contains a sample of the problems observed during the intervention, including clogging and disintegrated cutters.

Figure 5. Cutter change details.

The next cutterhead intervention decision came after excavating 818 rings from the last cutterhead intervention in full hydrostatic conditions of 3.5 bar, with the aim of avoiding another 3.5 hyperbaric intervention. This intervention was carried out in May 2020 in atmospheric
conditions where 19 cutters, 7 scrappers and 7-gauge scrapers were replaced. During this intervention, the screw conveyor gates were replaced due excessive wearing problems.

4 CUTTERS GEOMETRY AND MATERIAL CHARACTERISTICS

At the commencement of excavation HRC 56 type cutters were installed on the TBM cutterhead. These cutting tools, especially the cutters, were having a medium carbon alloy composition based on C, Cr, Mo for the body of the cutter while for the disc was based on C, Cr, Mo, V. The forging, rolling and heat treatment is not available from the cutter manufacturer. HRC 56 type cutters were solely used up to ring 2,100. At this point analysis of the failures, in particular to the center cutters, prompted a review of the type (geometry and material). Up to this point no cutters had been changed due to normal wear, all cutters had been changed due to a failure of one kind or another. The review resulted in the trial of a second type of cutter assembly, namely HRC 52. The main reason for this was to try and improve the ductility behaviour and attempt to reduce the cutter failures in general and the center cutters in particular.

From tunnel ring 2,100 both types of cutter disc configuration were used on the cutterhead. This was intentional with the aim to try and assess the performance and ascertain if one type performed better than the other. Although detailed record keeping was obtained on the type and reason for all cutter assembly changes, there was not clear evidence that either HRC 56 or HRC 52 out-performed one other. Therefore, further analysis discussed in this paper treats the cutter changes and failures has though they are a single type.

5 ANALYSIS OF CUTTER FAILURES

A total of 105 cutters have been replaced during the excavation of the outfall tunnel and the distribution according to the type and location of cutter. Although this was below what was expected and planned for, the mode of failures was unusual and was investigated thoroughly from the start of tunnelling.

Examples of the types of failures observed throughout the tunnelling operation are illustrated in Figure 6. It can be seen that there was one failure mode not observed and that was normal wear of the cutters, even in the gauge cutter location.

Figure 6. Type of failures of the cutters.
The statistical analysis carried out over the 105 damaged cutters is summarized in Table 1. It shows the prevalence of cracking as the main mode of failure. Most of crack failures occurred on the center cutters with 78% and 74% in the case of single cutters. In the case of face cutters, the issues related to cracks were much lower in number with only 9%. The cause of these type of damages is directly connected to fatigue scenarios from different sources like cycling loading of the cutters, wear and corrosion among others.

Table 1. Cutter failure by category.

<table>
<thead>
<tr>
<th>Type of cutter</th>
<th>Damaged cutters</th>
<th>Damage cutter by type of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quantity</td>
<td>Quantity (%)</td>
</tr>
<tr>
<td>Center cutter</td>
<td>32</td>
<td>30.5</td>
</tr>
<tr>
<td>Face cutter</td>
<td>54</td>
<td>51.4</td>
</tr>
<tr>
<td>Single cutter</td>
<td>19</td>
<td>18.1</td>
</tr>
</tbody>
</table>

Global Damages statistics

| General (%) | 42 | 17 | 10 | 12 | 18 |

All failures were collected and subjected to further analysis. Moreover, as per Figure 7, two examples show the extent of fatigue failure which can be related to a local change of load over the cutter probably due to impact associated with the mixed face conditions that were encountered.

The failure mode of chippings which represented 26% in the case of face cutters and 21% in the case of single cutters are due to the debris from adjacent cutters, impacting the cutters before exiting the cutterhead via the screw conveyor. To minimize these issues the TBM was equipped with 2 metal detectors along the conveyor belt. The TBM crews were trained to respond to the alarms of the metal detectors and discovery of debris by performing a cutterhead intervention as soon as possible after the metal detector was triggered.

Regarding the remaining failure modes of bearing damaged, cutter destroyed and cutter broke perpendicular to the axis, the visual inspections pointed to the cause of the damage has a combination of fatigue, presence of manufacture defects, combination of corrosion and steel wear known has tribocorrosion.

5.1 Tribocorrosion

Visual inspection of the cutter discs failures changed during the second intervention in hyperbaric conditions resulted in the pitting phenomenon being observed on the surface of the entire cutter assembly. The same phenomenon was observed on subsequent cutter replacement during the cutter head intervention done in May 2020. Figure 7 contains the photos of several cutter assembles changed clearly showing the pitting damages on the body of the cuter and the cutter disc surface.

Figure 7. Cutter failures showing Tribocorrosion and fatigue failures.

Considering the geotechnical conditions, the ground water (saline direct from the sea), EPB pressure and soil conditioning, indicates that cavities on the surface steel of the cutter are a direct consequence of corrosion. All these constituents are contusive to the type of corrosion being directly connected with tribocorrosion which is the deterioration process of materials, in this case alloy steel, due simultaneous effects of wear and corrosion.
In these tunneling conditions, especially the combined actions of abrasion on the cutters while rolling against the rock and the mineralogy and chemical composition of the rock, generated the phenomenon of tribocorrosion developing on the cutter assemblies, in some cases after exposure to the tunnelling conditions for only 8 weeks.

The tribocorrosion effects occurred over the tunnel alignment from tunnel ring 1,835 to the end of the tunnel and particularly when the TBM was working under hyperbaric conditions and in direct contact with saline water from the sea. In total, 4 twin cutters, 16 face cutters and 9 single cutters were damaged by tribocorrosion and replaced accordingly. The presence of tribocorrosion itself was not the main reason for the cutter failure and or the decision to change but was a major accelerant to the other forms of failures observed, to such an event that all cutters changed were not due to normal wear.

6 CUTTER FAILURES IN RELATION TO GEOLOGICAL CONDITIONS

Further analysis was carried out from geological formation point of view, the TBM excavated through 7 distinct geological zones with different geotechnical behavior. The zones were:

- Rus Formation (RF);
- Rus Formation and Midra Shale (RF+MS);
- Midra Shale (MS);
- Midra Shale and Simsima Limestone (MS+SL); and
- Simsima Limestone (SL) with EPB pressures low and high (LP, HP) respectively.

Table 1 presents the data for the cutter life data compared to the geological zones excavated, showing that by far the most challenging geological conditions being the mixed ground conditions i.e. a combination of Rus Formation and Midra Shale.

The TBM was excavating under full hydrostatics conditions up to 3.5 bar for 1.6 km with cutter life of 1,691 m$^3$ per cutter. This was considered a good average in comparison with previous records in similar conditions within Qatar, which was around 600 m$^3$ per cutter. This value was opposite to the general mechanized tunnelling rule, this being that the higher the pressure is, the lower the life of cutter, provided all renaming parameters are the same.

To maintain the higher-than-expected cutter life rates above, the TBM team decided to operate the TBM more conservatively to preserve the life of cutter and avoid wherever possible interventions in hyperbaric conditions. Figure 8 illustrates the key parameters of penetration measured in millimeters advanced per revolution of the cutterhead. The TBM was operated at low penetration rates to extend the life of cutters as much as possible. Figure 8 illustrates that the optimum performance was achieved at an average penetration rate of 10 mm/revolution, from ring 4000 (Last major hyperbaric intervention) onwards. The graph shows the consistency and this section equates to 60% of the tunnel excavation being achieved with a cutter life of approximately 1400 m$^3$/cutter.

Figure 9 illustrates the exact data for cutter disc life with the 7 different geological zones. The data shows that the Simsima Limestone with low groundwater pressure exhibits the best
results on a long terms basis for cutter life (rate of tunnel rings per cutter), on average 93.9 tunnel rings per cutter changed. However, in high pressure Simsima Limestone, cutter life reduces to 41.6 tunnel rings per cutter changed. Overall, the averages of cutter disc life are 77 tunnel rings per cutter.

Figure 9. Cutter disc life in different ground conditions.

7 CONCLUSIONS

All of the cutterhead interventions (38 No) carried out under the Arabian Gulf were performed safely, and two interventions in hyperbaric conditions up to 3.5 bar. This is the highest pressure for any cutterhead intervention carried out in Qatar.

The two different types of cutters (geometry and material of the cutter used) did not show important improvement in terms of cutter life, and during the project execution it was not possible to notice the difference either in the type of cutter failures or of life of cutters. No cutter was changed due to normal wear.

Tribocorrosion has been recognized as the cause of probable acceleration of the various types of cutter failure and connected with the presence of saline water from the Arabian Gulf though the Simsima limestone formation.

Mixed face conditions of Midra shale formation in combination with Rus Formation and Simsima Limestone are the primary cause of the shorter life of the cutter and several events of cutter head clogging issues.

The decision to operate the TBM conservatively to extend the life of cutter to avoid cutterhead interventions even if it were to penalize production was correct.

In general, the life of cutter used was higher around 75 to 100% than expected based on the experience from similar projects in Qatar.

Aside of the rock mass conditions, cutters, cutterhead design, soil conditioning among other, in MPSO the key role was played by controlling and adjusting the penetration rates.

REFERENCES


Decompression tables. Blackpool and COMEX tables.
