Comparison of Geotechnical Investigation Results with Encountered Ground Conditions During Subsea Tunnelling in Qatar

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Abstract

Starting in 2018, Musaimeer Pumping Station and Outfall Project (MPSO) was constructed to manage ground and storm water received from 270 km^2 area of southern Doha, Qatar. The project consists of a pumping station, subsea tunnel, (constructed through Rus formation, Midra shale and Simsima limestone), riser shaft and diffuser bed structure. An Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM) was used for subsea tunnelling where ground water inflows, mixed ground condition with the presence of vertical and lateral fractures connected to the seabed were encountered during tunnelling activity. This paper analyses the reliability of geotechnical investigation results and interpretations by comparison with encountered conditions. This will be beneficial to design a reliable geotechnical investigation programme for future projects of similar scope in the state of Qatar. Results and interpretations from drilled bore holes and geophysical survey provided an overall picture of underground conditions along the tunnel alignment, which identified the critical tunnelling areas for cutter head intervention and maintenance. These results were then compared with the built geotechnical conditions accessed by collecting data through the onboard TBM monitoring equipment, collecting rock mass samples, and performing geological face mappings during tunnelling activity.Comparison of pre-tendered investigation results with the built geotechnical conditions concluded that investigation results and encountered rock mass conditions were in line with each other. Geotechnical investigation programme followed for this project and interpretation as a result, made the tunnelling under sea to be carried out in more careful and low risk manner.

Keywords: MPSO, TBM, Geotechnical

1 Introduction

Musaimeer pumping station and outfall project was constructed south of Hammad International Airport, Doha. The project is designed to manage surface and rainwater received from the drainage networks from 270 km^2 of urban areas in southern Doha. It consists of pumping station with pumping capacity of $19.7 m^3$ per second and 10.2 km long subsea outfall tunnel. The project outline is shown in Figure 1.

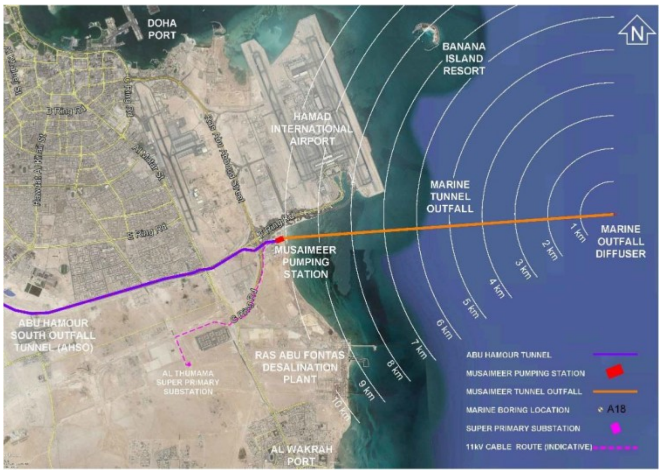


Fig. 1: Project Location

The objective of this paper is to compare the results of geotechnical investigations conducted for the project with encountered geotechnical conditions during the construction of outfall tunnel. Geotechnical information was collected by drilling bore holes and geophysical surveys. Foreseen ground information was used to predict ground condition along the alignment of tunnel. Observations during tunnel excavation operations were made by collecting rock mass samples, measuring fluctuations in water pressure, performing rock mass classification.

2 Geotechnical Investigation Results

As part of pre-tendered geotechnical investigations, borehole drilling (A1 to A22) and geophysical surveys, including Seismic reflection, Seismic refraction, were performed to access the in-situ ground conditions. Figure 2 shows the tunnel alignment, bore holes and geological formations.

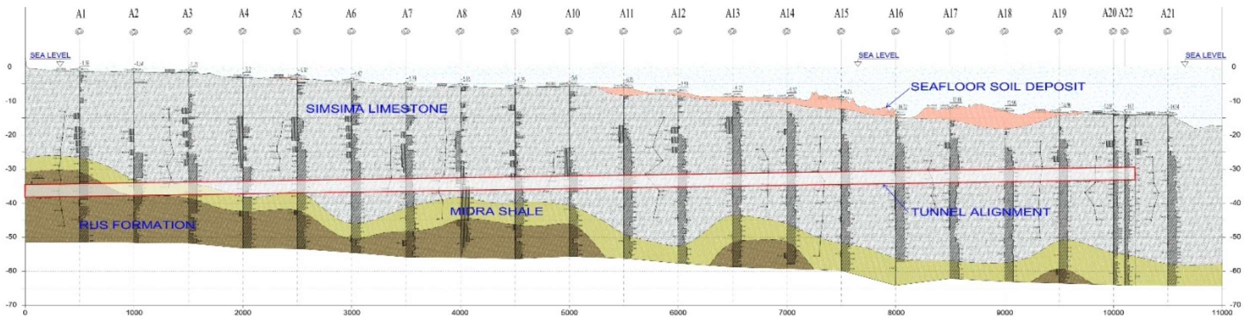


Fig. 2: Lithological Cross Correlation from drilled boreholes

2.1 Core Drilling Results

Core drilling was carried out along the tunnel alignment by 22 marine boreholes, 50 m in depth and 500 m apart from each other along the tunnel alignment. The rock stratigraphic units encountered were identified as made ground, unconsolidated soil, Simsima limestone, Midra Shale and Rus formation.

The characteristics of these geological units were poor bedding structures oriented in horizontal to sub-horizontal as cross-correlated from all the boreholes findings. There was no evidence of active faulting across the lithological units. Jointing systems indicated the predominant development of horizontal to sub-horizontal joint sets in the project area. The characteristics of stratigraphic units of the project are described as follows.

2.1.1 Made Ground

Made ground was encountered as unconsolidated sediment with shells from the marine borings, at a thickness varying from 0.45 to 5.20 m.

2.1.2 Simsima Limestone

The Simsima limestone was encountered as an underlying stratigraphic unit of made ground or unconsolidated superficial deposits. Typical geological characteristics observed from the Simsima limestone was the occurrence of poorly developed bedding structure with horizontal to sub horizontal dipping angle and generally increased in thickness towards the east. The thickness of this rock unit varies from 20.7 m to 44.0 m. Simsima limestone is predominantly dolomitic in composition and illustrates considerable variations in rock quality as indicated by Rock Quality Designation (RQD) values in association with weathering degree also illustrated by frequency of solution features with increasing depth. The uppermost section of the rock is distinctly weathered and fractured and is poor to very poor in quality compared to the deeper parts which are less weathered and more competent. Karagkounis, N. et al. (November 2016).

2.1.3 Midra Shale

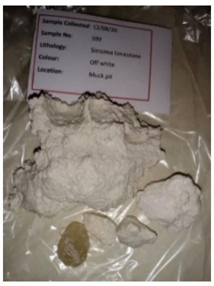
Midra shale was encountered in all boreholes at variable thicknesses ranging from 4.0 m to 8.6 m, yellowish brown to greenish in colour. Weak to medium strong mudstone, interbedded with layers of pinkish grey coloured, moderately strong, slightly to moderately weathered limestone. This rock stratigraphic unit is moderately to highly weathered with intense yellowish-brown iron oxide staining in parts. Midra shale is overlain by Simsima limestone and underlain by Rus formation. Karagkounis, N. et al. (November 2016).

2.1.4 Rus Formation

This is the oldest rock stratigraphic unit encountered boreholes, underlying the Midra shale in the project area. Rus formation is composed of beige, tan, grey, yellowish-brown coloured, medium strong to strong, slightly to moderately weathered, moderately fractured dolomitic limestone interbedded with less prominent, pale grey to brown/greenish brown coloured, weak to medium strong, moderately weathered, moderately fractured calcitic layers. This rock unit contains gypsum inclusions and veins, with the presence of solution cavities and vugs having occasional silty sand infills. The unit shows horizontal to sub-horizontal fractures with spacing close to wide. The joint surfaces are generally undulating and rough. Karagkounis, N. et al. (November 2016).

2.2 Encountered Rock Mass Sampling and Results

During tunnel excavation, rock mass samples were collected, at the chainages where investigation boreholes were drilled. Rock mass properties, RQD, weathering, hardness, from samples were observed and compared with the results of investigation. Reports were produced for sample collected from borehole locations whenever TBM crossed that location. Figure 3 shows the type of samples taken at these locations



(a): Simsima limestone **(b):** Midra Shale **(c):** Rus Formation

Fig. 3: Samples collected during TBM Tunnelling (Representative)

From the findings of the sampling reports, rock mass condition, its physical properties were found to be same as observed during investigation stage except at two locations where mixed rock mass was found. This validates the reliability of methods, procedures used during borehole drilling. As built geological plan and section was prepared in the form of geological sheet. Each geological sheet was composed of 260 m of tunnel alignment. Table 1 contains the pretender geological data along with details of the encountered ground conditions. The table shows in the remark's column that the "Lithological conditions confirmed" is the predominate finding.

Table 1: Lithology found in investigation vs encountered lithology

Borehole No	Borehole depth (m)	Sea Floor Elevation (m)	Lithology encountered at Tunnel elevation	Start Date of excavation through borehole location	End date excavation across borehole location	Ground conditions encountered during TBM Tunnelling	Remarks
A1	50	-1.39	Rus	03.4.2019	4.4.2019	Rus	Lithological conditions confirmed
A2	50	-1.54	Rus	22.5.2019	23.5.2019	Mixed Ground	Rus formation and Midra shale mixed
A3	50	-1.71	Midra Shale	13.7.2019	14.7.2019	Clay-Midrashale	Lithological conditions confirmed
A4	50	-3.20	Midra Shale	25.8.2019	26.8.2019	Clay- Midra shale	Lithological conditions confirmed
A5	50	-3.32	Simsima	27.9.2019	29.9.2019	Mixed ground	Midra Shale and Simsima limestone mixed
A6	50	-4.47	Simsima	7.11.2019	9.11.2019	Simsima	Lithological conditions confirmed
A7	50	-5.79	Simsima	2.12.2019	3.12.2019	Simsima	Lithological conditions confirmed
A8	50	-5.95	Simsima	3.1.2020	3.1.2020	Simsima	Lithological conditions confirmed
A9	50	-6.25	Simsima	26.3.2020	26.3.2020	Simsima	Lithological conditions confirmed
A10	50	-5.60	Simsima	4.4.2020	4.4.2020	Simsima	Lithological conditions confirmed
A11	50	-6.15	Simsima	9.6.2020	9.6.2020	Simsima	Lithological conditions confirmed
A12	50	-7.58	Simsima	7.7.2020	7.7.2020	Simsima	Lithological conditions confirmed
A13	50	-8.73	Simsima	2.8.2020	2.8.2020	Simsima	Lithological conditions confirmed

Borehole No	Borehole depth (m)	Sea Floor Elevation (m)	Lithology encountered at Tunnel elevation	Start Date of excavation through borehole location	End date excavation across borehole location	Ground conditions encountered during TBM Tunnelling	Remarks
A14	50	-9.17	Simsima	26.8.2020	27.8.2020	Simsima	Lithological conditions confirmed
A15	50	-9.73	Simsima	17.9.2020	18.9.2020	Simsima	Lithological conditions confirmed
A16	50	-14.12	Simsima	11.10.2020	11.10.2020	Simsima	Lithological conditions confirmed
A17	50	-12.60	Simsima	03.11.2020	03.11.2020	Simsima	Lithological conditions confirmed
A18	50	-12.98	Simsima	30.11.2020	30.11.2020	Simsima	Lithological conditions confirmed
A19	50	-13.46	Simsima	27.12.2020	27.12.2020	Simsima	Lithological conditions confirmed
A20	50	-13.91	Simsima	24.01.2021	24.01.2021	Simsima	Lithological conditions confirmed
A21	50	-14.14	TBM did not pass through this location as this borehole was located away from end of TBM tunnel				
A22	50	-14.10	This borehole was located near BH-A20 and investigated lithological conditions were confirmed as TBM passed through this location				

2.3 Geophysical surveys

Seismic refraction and reflection surveys were performed as part of pre-tendered investigations. Electric resistivity tomography (ERT) survey was performed as post-tendered investigation.

2.3.1 Seismic Refraction Survey (Pre-Tender)

Generally, four to five different seismic mediums (SM) were determined. SM-1 (Weak Limestone) started first 5m-10m from the sea floor and velocity range Vp=1600-2250m/s, SM-2 (Weak to medium strong Limestone) between 10m-20m, Vp= 2250-3400 m/s, SM-3 (Medium Strong to Strong Lime Stone) between 20m to 30 m and Vp= 4100-4900 m/s, SM-4 (Strong to very strong Limestone) between 30m-50m, Vp=4100-4900 m/s. Values of Vp=4900-5400 m/s were also recorded which were considered as compact material. Figure 4 shows a typical Seismic velocity section.

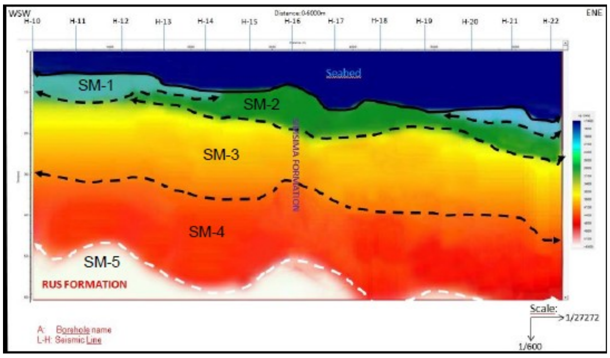


Fig. 4: Seismic velocity section

2.3.2 Seismic Reflection Survey (Pre-Tender)

Seismic reflection data was well matched with seismic refraction and core drilling results. Three seismic mediums M1, M2, M3 were observed. Figure 5 sows a typical seismic reflection survey result.

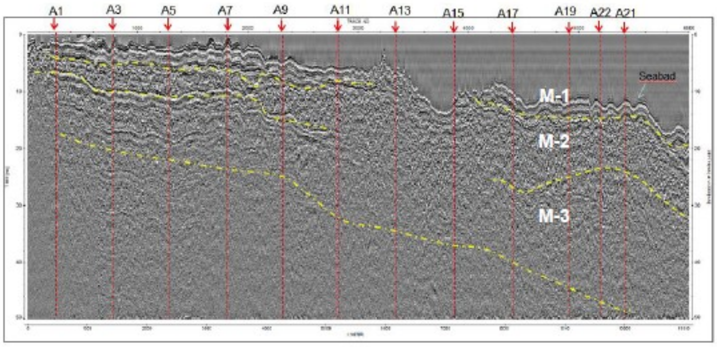


Fig. 5: Cross section of seismic reflection

Seismic refraction and reflection sections are in harmony with each other. Depth and thickness of layer for seismic reflection cross section were calculated based on thickness of layer obtained from seismic refraction for time to depth conversion. Seismic interpretations were made by the developed cross sections. The thickness of the layers was correlated with drilling logs. The yellow lines in Figures 5 & 6 represent the layers from reflection anomalies.

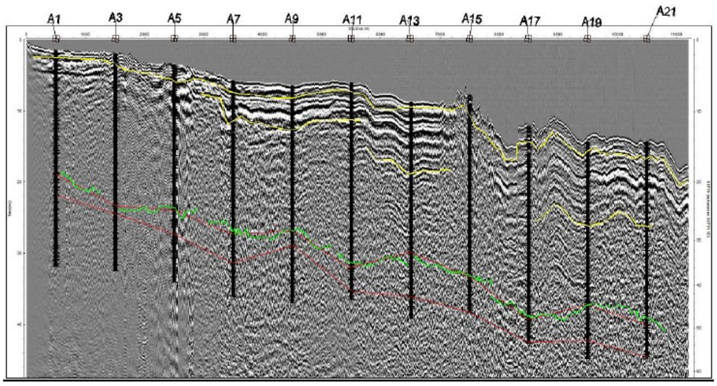


Fig. 6: Seismic reflection cross section and boreholes

Generally, two units were determined, Sismsima limestone and Rus formation. In addition, from time to time at different depths, thin Midra shale, mudstone layers were detected in bands. Interpretation of pre and post tender investigations result in the identification of 20 anomalies of note classified as F1 to F20.

2.3.3 Electric Resistivity Tomography

Electric resistivity tomography (ERT) was performed at post tendered stage along the entire tunnel alignment. Several conductive anomalies and resistive anomalies were detected during the first 2km of the survey. The final phase of study confirmed that those anomalies were probably connected to fractures or fracturing systems. Distances along the tunnel alignment start at zero at the pump station and increase to 10.2km at the end of the outfall tunnel

The resistive anomalies are associated to possible different nature and geological risks, however only the one between chainage 6.7 and 6.9 km at depth greater than 50.0 m, could be associated to a possible karstic risk (cavity). However, the tunnel alignment was above that anomaly. The area between 5.2 to 7.4 km was affected by a significant increasing degree of fracturing and was considered as potential high permeability zone.

The area between 7.6 to 8 km was also considered an anomalous area. The evidence of a drop of resistivity values of more than 10 ohm-m along the tunnel alignment, was a warning of increasing permeability, and possible hydrostatic connection to the seabed. Figure 8 shows ERT for the entire tunnel alignment.

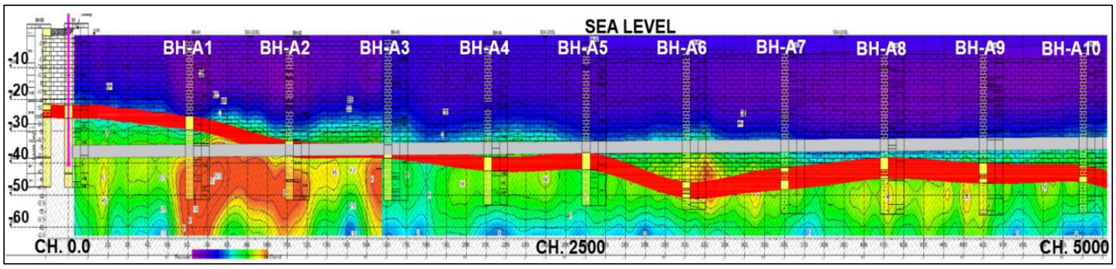


Fig. 8: ERT line from 0 to 10.2 km

3 Foreseen Geotechnical Conditions along the Tunnel

Pre-tender and post tender geotechnical information were combined according to the tunnel chainage to classify potential ground condition and were classified as favourable, moderately favourable, unfavourable and a reference chart was developed by combining geotechnical investigation data and ground classification. That chart was used to plan for TBM cutter head maintenance operations, the principal aim was to avoid unfavourable ground conditions for cutter head intervention, since that scenario would greatly increase the complexity and safety of the operations.

3.1 Bored Tunnelling Electric Ahead Meter Results

The TBM was equipped with Bored Tunnelling Electric Ahead Meter (BEAM) system, which is a non-intrusive electrically induced polarization system able to predict ground conditions up to 12 m ahead. Information is displayed in a matrix which combines resistivity and percentage frequency effect (PFE).

The interpretation of the matrix, which is shown in Figure 9, is based on the columns and rows; factors on the columns refer to the karst interpretation (P1:P4) while factors on the rows (R3:R1) refer to the possibility of water inflow.

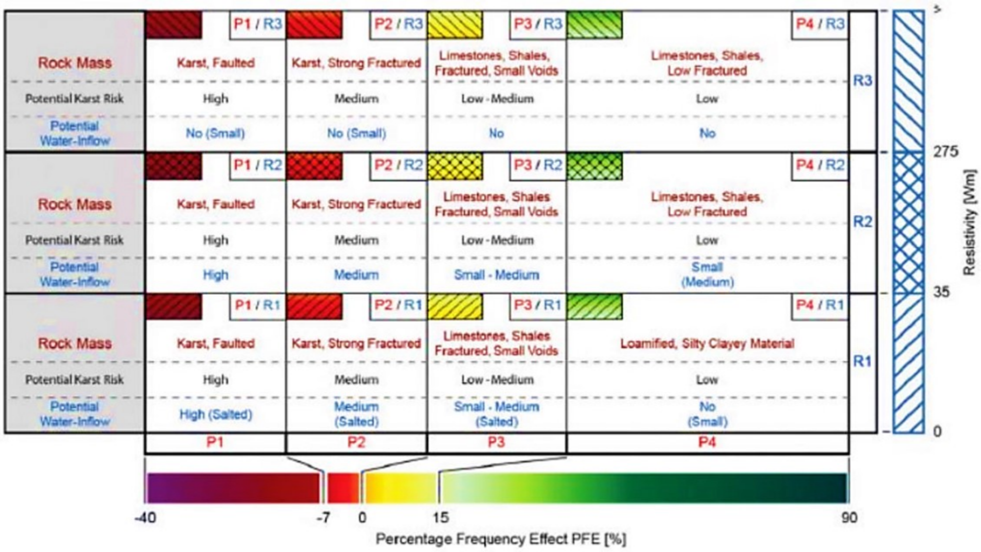
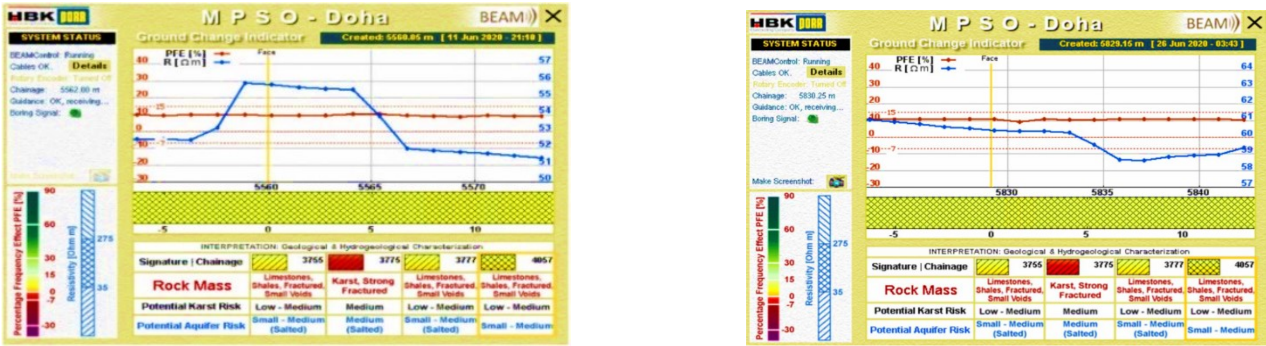


Fig. 9: BEAM Interpretation Matrix

3.2 Examples of Bored Tunnelling Electric Ahead Meter Results

In Figure 10 the bored tunnelling electric ahead meter (BEAM) display indicates the results of crossing two anomaly zones identified by the post tender geotechnical surveys.



(a): Fault zone F10

(b): Fault zone F13

Fig. 10: BEAM Display at Fault zone F10 – F13

It is important to note that there are limitations on the precision accuracy of the system. The system is not able to identify whether the TBM is passing through Rus formation, Midra Shale or Simsima limestone; it can only identify intrinsic properties of rock mass. It is not possible to measure the exact amount of water inflow and location. The system can provide an estimation of the possibility that water inflow or aquifers might be encountered. Sadiq, A.M. & Nasir, S.J. (Septmber 2002)

3.3 Comparison of Foreseen Rock Mass Condition with Bored Tunnelling Electric Ahead Meter Data

With reference to foreseen ground conditions, it was predicted that the TBM will pass through 20 zones classified as F1 to F20. During tunnelling, the BEAM system also predicted those anomalies 10 to 15 m before encountering them. Table 2 shows the anomalies predicted during investigation stage and those picked by BEAM system during tunnel excavation.

Table 2: Foreseen geotechnical condition Vs actual and BEAM

No.	Fault Zone	Predicted Location	Actual Chainage	Picked up by BEAM	Remark

		Chainage	From	To	Yes	No	
1	F1	500	528	608	✓		Increase the pressure (2.6 bar)
2	F2	900	-	-		✓	In the Midra Shale, the fractured condition did not affect the EPB and TBM operation, the fracture looked like not connected to the seabed.
3	F3	1150	-	-		✓	
4	F4	1300	-	-		✓	
5	F5	1750	-	-		✓	
6	F6	1900	-	-		✓	
7	F7	2600	2638	2756	✓		High groundwater pressure (3.5 bar)
8	F8	3700	3678	-	✓		High groundwater pressure (3.5 bar) for 1569 m
9	F9	5200	-	5247	✓		
10	F10	5500	5437	5600	✓		Increase the pressure (2.4-3.4 bar)
11	F11	5800	5808	5884	✓		Fluctuated pressure (2.4-3.2 bar)
12	F12	6100	6079	6170	✓		Fluctuated pressure (2.4-2.8 bar)
13	F13	6350	-	-		✓	Not increase the pressure
14	F14	7000	6620	6820	✓		Fluctuated pressure (2.2-2.7 bar)
15	F15	7100	-	-		✓	Not increase the pressure
16	F16	7300	-	-		✓	Not increase the pressure
17	F17	8250	7820	8260	✓		Fluctuated pressure (2.2-2.7 bar)
18	F18	8450	-	-		✓	Not increase the pressure
19	F19	9550	9550	9650	✓		Low pressure, muck material increase
20	F20	9750	9650	9760	✓		Low pressure, muck material increase

4 Conclusion and Lesson Learned

- Geotechnical investigations, performed at pre-tender stage provided enough necessary information about rock mass along tunnel alignment.
- Plan for advance of tunnel proved to be a good tool for deciding intervention location.
- Although BEAM is giving good results about the presence of water ahead of tunnel, however it cannot predict the quantity of water and rock mass type through which TBM passes
- Around 60% of the rock mass condition is accurately encountered, as marked before start of mining operation through a different investigation.
- Observation and record of excavated material provides a good check on rock mass condition.
- Face mapping during cutter head intervention provides a good overview of rock mass condition, which was encountered during mining.
- Monthly updates of geotechnical properties of rock mass provides an opportunity to actively keep on observing the built geotechnical condition in comparison with pre-tendered observations.

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