

Real-time prediction during TBM advance.

Risk management through the BEAM in Doha Metro Project

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ABSTRACT: The Bore Tunnelling Electrical Ahead Monitoring (BEAM) system has been installed in all the 6 TBMs utilized in the excavation of the Gold Line metro of Doha (Qatar). The intent was to get a continuous real-time geological forecast ahead of TBMs, useful to predict the quality of the groundmass and the presence of large quantities of water. The article describes how the system was set up, including a back-analysis of the correlation between the data registered and shown by the BEAM, the actual hydrogeological conditions encountered by the TBM and the TBM operational parameters. Finally, the article assesses about the reliability of the BEAM system in providing an accurate forecast of the different hydrogeological parameters of the formations in front of the TBM and of the expected TBM performances and criticalities.

1 THE PROJECT: A GENERAL OVERVIEW

The Doha Metro Project includes four lines (Red, Gold, Green and Blue) for a total length of 358 km, out of which 119 km underground and 100 stations. The TBMs' excavation phase has been completed for three lines out of four.

The present paper analyzes the real-time monitoring carried out during the TBM boring of the tunnels included in the Gold Line, that connects the East side with the West side of the city.

This line is developed totally underground for a length of 14 km with 11 stations. The underground section is made up of two twin tunnels running parallel at an average distance of approximately 10 m, connected by cross passages every 250 m.

The tunnel excavation has been performed by 4 EPB (Earth Pressure Balance) machines having a boring diameter of 7150 mm, that advanced installing a precast segmental lining made of high strength concrete reinforced by steel fibers.

The precast lining ring was a 6+1 Universal design type having 1,5 m length, an inner

diameter of 6170 mm and a thickness of 330 mm, thus leaving an annulus gap of 160 mm.

2 GEOLOGICAL INFORMATION

Doha lies on a plateau (Qatari peninsula) that belongs to Arabic Gulf. No big seismic activities occurred in the area over the years, thus no major faults are recorded in the area. Basically the main structure of Qatari strata can be summarized as a rhythmic sequence of different limestone, shale (schist), dolomite, marl and gypsums (see Figure 1). Right now the exposed formations in Qatar belong to Tertiary or Quaternary.

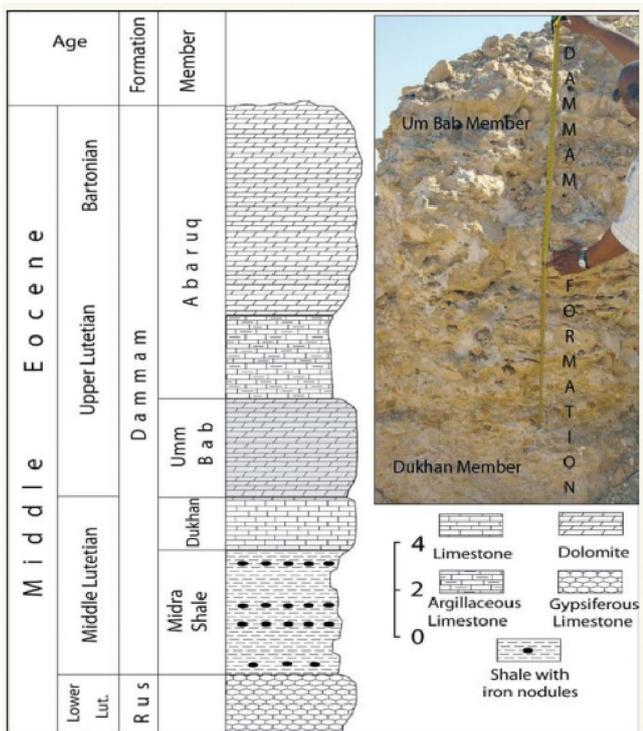


Figure 1. A typical “cut” of Doha’s subsurface.

The TBMs advanced under variable cover at depth below the surface ranging from 15 to 30

m.

The main formations encountered along the TBM drives can be summarized as follows:

- RUS formation: it includes basically soft limestone, dolomitic limestone and gypsum and has a thickness of about 100 m, with evident phenomena of gypsum’s dissolution, thus generating cavities and subsidence (Embabi & Ali, 1990).
- Dammam: this formation lies above the RUS and covers the majority of Qatari area. It includes Upper Limestone, Midra Shale, Lower Limestone and it can reach up to 30 m of thickness.
- Simsima: it is made by dark white to slightly brown limestone, medium grained, with presence of gypsum and dolomite, irregular joints filled by siltstone and clay.

The two main problems affecting the TBMs advance in the geology of the project have been the local presence of large water inflows originated by Karst phenomena and an excessive consumption of cutting tools (cutters)

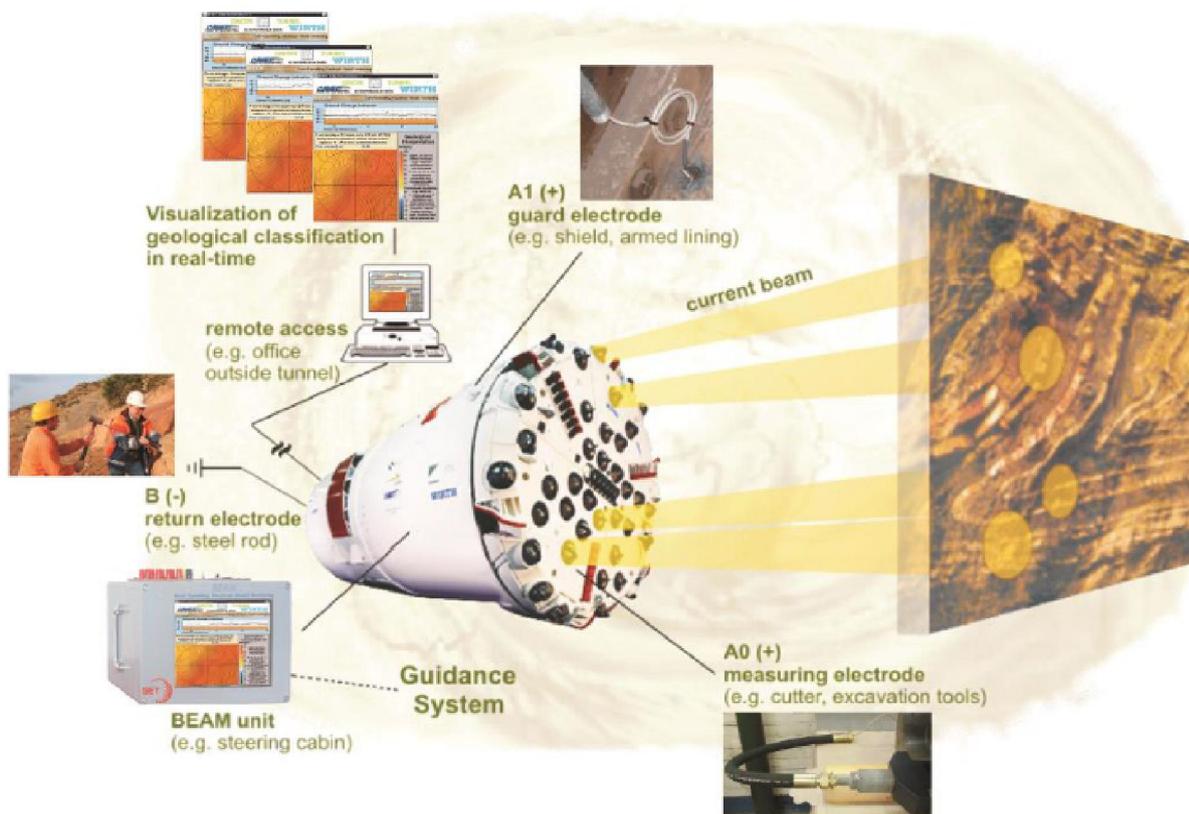


Figure 2. BEAM’s schematic layout and communication system.

due to a non-ideal selection of the tool types and cutter-head arrangement.

3 THE BEAM TECHNOLOGY

The Bore Tunneling Electrical Ahead Monitoring - BEAM -, developed by the GET Company (Kaus & Boening, 2008), is a geophysical ground prediction technique especially designed for TBM operations.

BEAM is a non-intrusive focused-electrical induced polarization ground prediction technique, permanently operating while the TBM advances.

The main components forming the system are: the measuring unit placed in the TBM operator cabin and the specially equipped excavation tools, which are used as electrodes. The unit is connected to the guidance system, and shows in real time to the TBM operator the foreseen geology ahead of the TBM on an integrated monitor. Communication facilities transfer the same forecast shown to the TBM operator to every accredited computer simultaneously (see Figure 2).

The system measures two basic parameters:

- **Resistivity:** low and high frequency alternating current is applied to measure corresponding resistivities of the rock mass, whereby the resistivity at the lower frequency is visualized on the display for further interpretation. Expressed in ohm meter, this parameter is sensitive to the hydrogeological conditions of the rock mass and therefore is useful for predicting the presence of groundwater. Lower values of resistivity provide indication of the presence of water in the rock mass.
- **PFE (Percent Frequency Effect):** this parameter is sensitive to the grade of fracturing/porosity of the rock/soil. The induced polarization PFE index is calculated by a relationship between the low frequency and high frequency resistivity. It characterizes the mobility of ions in the water and moisture containing fracture and karst space of the rock mass. Thus, it is reciprocally correlated to the effective porosity and can be used for a relative estimation. The PFE index is useful to predict the degree of frac-

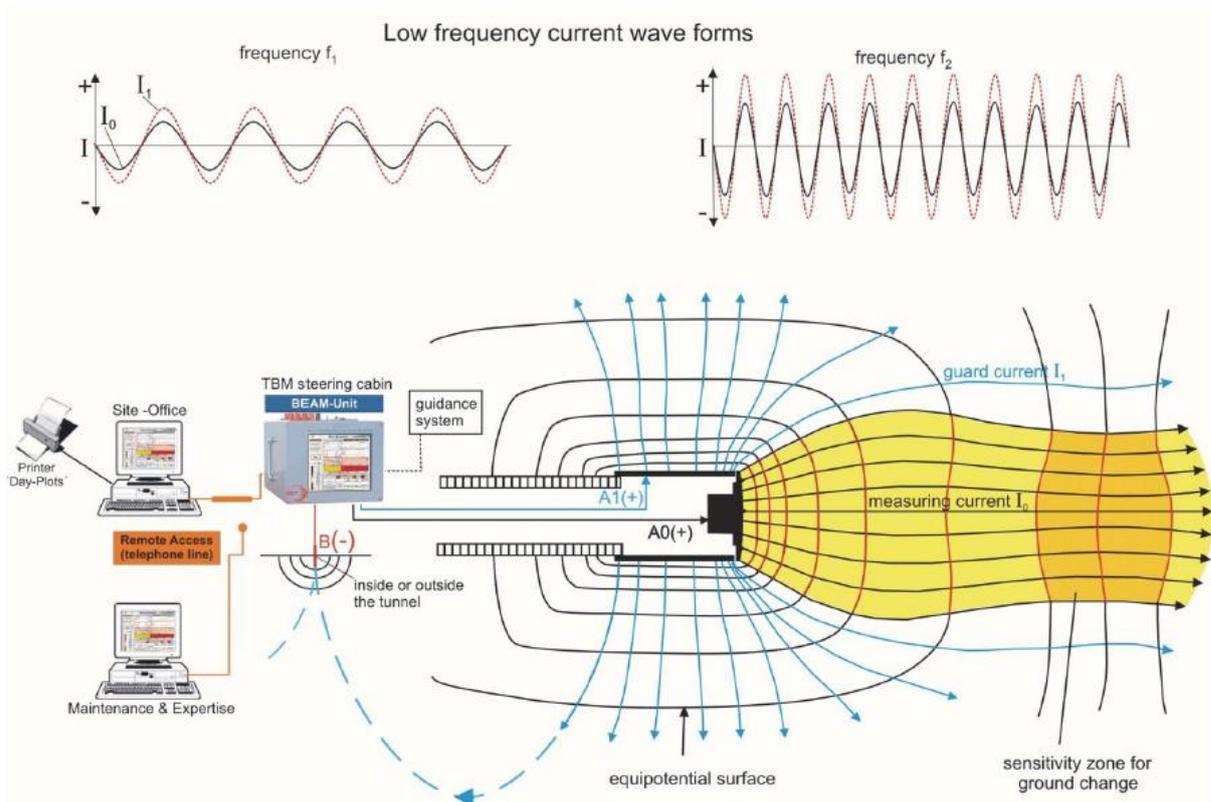


Figure 3. Schematic representation of the BEAM operating principles.

turing of the rock mass ahead of the TBM.

Based on the measurements made at short time intervals of the two above parameters the BEAM system, utilizing advanced evaluation software, is able to provide in real time a geo-electrical-geological/hydrogeological classification and interpretation of the rock/ground mass in front of the TBM (see Figure 3). Data acquisition is performed automatically and continuously whereby measured data is attributed to a small sensitivity zone located about 3-times the tunnel diameter ahead of the face.

Early warning information of significant ground changes allows to minimize the geological risks while tunneling and, thus, provides the possibility to promptly react and apply any needed countermeasure.

On the other hand, when the BEAM system indicates non-critical ground conditions ahead of the face, the TBM operating crew can concentrate its efforts on achieving the best

possible productivity.

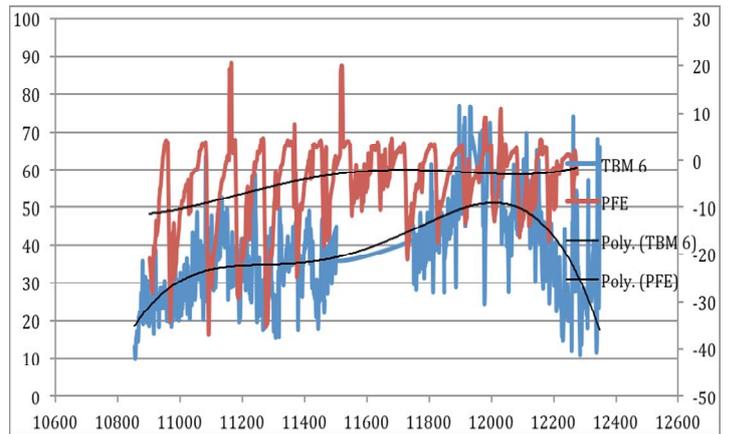


Figure 4. TBM's penetration rate and PFE values.

4 PFE AND TBM PERFORMANCES

A certain correlation has been observed between the TBM penetration rates and the PFE values.

The better penetration rates are experienced in those areas where the PFE increases.

In Figure 4 are reported the data recorded in one TBM drive section of about 1,5 km length.

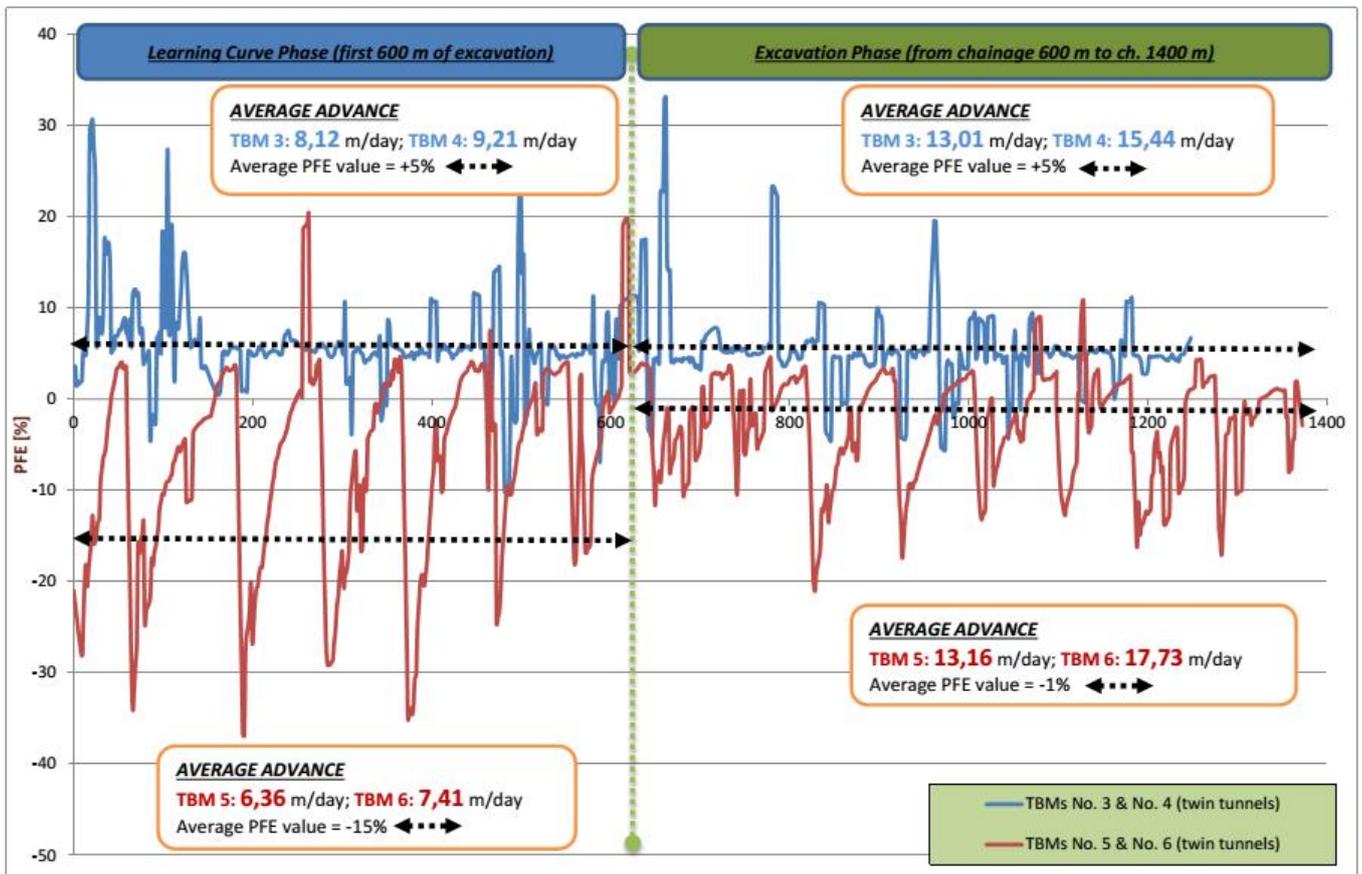


Figure 5. Average TBMs' advance rates and PFE values.

In Figure 5 a general overview of the four TBMs' average advance rate is presented, overlapped with the PFE values recorded. It is quite evident that better PFE values are correlated to better performances. In details, the following issues are worth to be pointed out:

- TBMs no. 3 and no. 4 in the first 600 m of excavation bored in a formation with higher PFE. Thus, they recorded a better advance in comparison with TBMs no. 5 and no. 6, that excavated in a formation with lower PFE. In summary, the average advance rate in the first 600 m is 6,8 m/day for TBMs no. 5 and no. 6 and 8,7 m/day for TBMs no. 3 and no. 4 (+28% of increment on average advance rate, due to better rock mass conditions).
- Focusing only on TBMs no. 3 and no. 4, that have experienced an almost constant good geology (i.e. PFE almost constant), it is worth to point out that the difference between the reduced performance in the first 600 m and the better result achieved in the following stretches of tunnel, basically is due to the “learning curve” phase, typical of such mechanized works.
- In the second section of the project all TBMs advanced in formation with similar PFE values and the productions were also closer and comparable, ranging between an average of 14,2 m/day for TBMs no. 3 and no. 4 and 15,4 m/day for TBMs no. 5 and no. 6 (+8% of difference).

5 CORRELATIONS WITH THE RQD

Further analyses have been carried out in order to find a correlation between the average RQD recorded at tunnel level by the observation of the cores of the boreholes performed before the start of the project and the PFE values measured by the BEAM in the same area during the TBMs' advance.

A correlation between RQD and resistivity of both rock mass and joints had been already proposed, as summarized in the following formula (Hong, 2015):

$$r = 100 / \{[(100 - RQD)/r_1] + (RQD/r_2)\} \quad (1)$$

being r the electrical resistivity of the rock mass, r_1 the electrical resistivity of the joints and r_2 the one of the intact rock. Even if not expressed in the formula, it is likely that different families of joint and/or various orientations can make the interpretation more difficult.

By analyzing the data of the Doha project, a very loose to inconsistent correlation of the RQD value with the PFE index can be observed (see Figure 6).

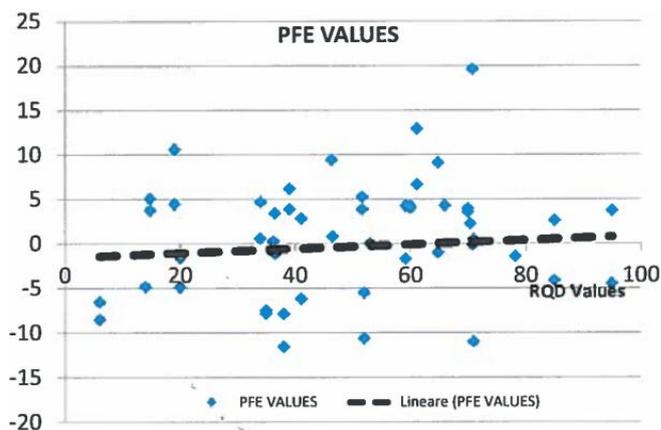


Figure 6. PFE values correlated to RQD.

Anyhow, the following issues need to be highlighted:

- The pool of data available is limited;
- The boreholes utilized to measure the RQD value at tunnel level are positioned within a distance of 5-15 m from the point where PFE has been recorded.

A clearer correlation could probably be achieved by solving the above two issues, in particular refining the analysis through available boreholes lying on the tunnel axis.

Nevertheless, since RQD values are measured in a linear basis and they are constrained to the direction of the boreholes (as well as of the joints), a “tight” correlation between RQD and PFE index might be difficult to achieve.

6 WATER AND CAVITIES' FORECAST

The BEAM has been a useful tool in the decision-making process to carry out cutter-head's checks and cutter changes.

The many interventions into the cutter-head chamber carried out along the TBM drives have shown that the Beam predictions are sufficiently reliable, with an accuracy around 80%. In other words, on average 4 times out of 5 the amount of water inflows encountered when accessing the excavation chamber confirmed the forecasts of the BEAM system.

Due to the above the decision to stop the TBMs for cutter-head interventions were normally based on the assessment of the BEAM's report (see Figure 7), selecting a chainage where small-medium risk of water inflow and karst cavities were foreseen.

Normally, as anticipated above the actual situation encountered into the cutter-head (see Figure 8) confirmed the absence of water and the good quality of the rock.



Figure 8. The cutter-head's dry conditions during one intervention.

Creation Date: 01.10.2015 Creation Time: 23:26:07
 Face Position: 11623.50m Data Position: 11644.80m

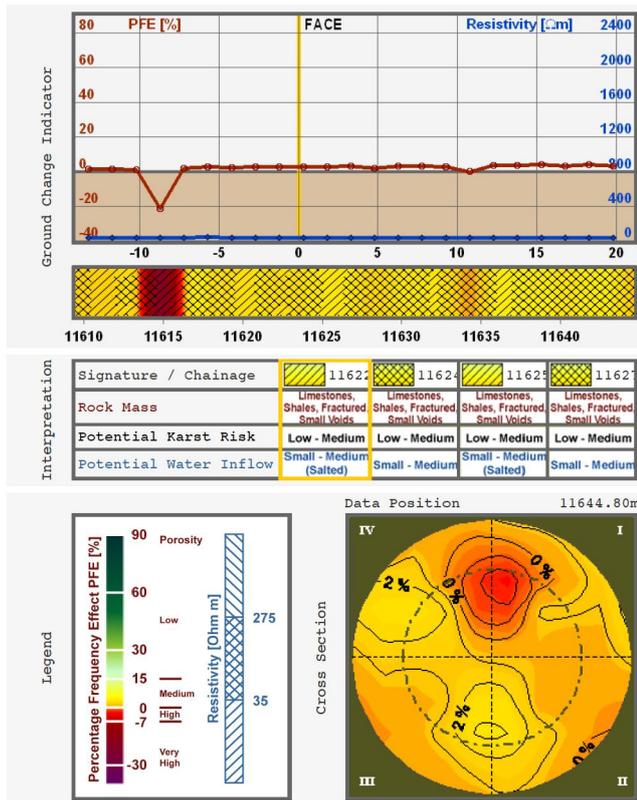


Figure 7. A typical example of real-time BEAM's output, recorded during a cutter-head intervention.

CONCLUSION

In the geology of the Doha Metro, and in particular in the Gold Line Tunnel drives, a quite good correlation have been experienced between the BEAM's real time forecasts and the actual geology encountered.

This correlation has been useful to plan the cutter-head interventions in the right sections, were low water inflows and good rock quality were foreseen.

Furthermore a good correlation has been found between PFE values and TBM penetration/advance and between the resistivity and presence of water in the rock mass.

The BEAM system's predictions of ground water inflow have been reliable in the project in almost 80% of the cases: they allowed to be prepared to the geology ahead of the TBM and to better plan the TBMs operation and maintenance.

On the other side the study of the correlation between the PFE index and RQD values shall be improved with further applications of the BEAM system in different geologies and with an enlarged pool of data.

Lastly, the reliability of the system in rock/ground formations different from the ones encountered in the Gold Line of the Doha Metro shall be analyzed and tested.

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