Tunnel Surveying Works: A Technical Challenge of 10 km-long tunnel under the Arabian Gulf-Qatar

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Abstract

The Musaimeer Pump Station & Outfall Tunnel project (MPSO) was constructed as one of the longest Outfall tunnels in the World with a total length of 10.189m and at the same time being the longest undersea tunnel in the Middle East. MPSO will manage ground- and storm-water from the Southern Doha District and dispose of this water via a diffuser bed connected to the outfall tunnel. Difficulties faced during the project execution were firstly, the tunnel network itself. It was necessary to maintain precision and reliability of the 10km network, in a tunnel of smaller than 5m in diameter, starting from a 26m diameter drop shaft. Secondly, the breakthrough was into a 3m diameter vertically positioned riser shaft encased in a 5m x 5m concrete block which was positioned and constructed offshore by utilizing different network of 10km Global Positioning System Real-Time Kinematic (GPS RTK) readings. The key problem was confirming that both survey networks used were homogenous as the marine tolerances in comparison to the tunnel tolerances were very different. Thirdly, the actual Tunnel Boring Machine (TBM) connection was under the sea. The TBM excavated through a concrete filled shaft 0.6m beneath the riser shaft invert, then excavated 35m to create working space for civil works. The tunnel's crown was then cut using a 3m diameter opening to connect into the bottom of the riser shaft. This study serves to describe the Survey technical issues faced in the construction and coordination of underground tunneling and interfacing with offshore works.

Keywords: Tunnel; Surveying works; Network; Onshore; Offshore; Tolerance; Gyroscope

1 Introduction

1.1 General Information

Construction of outfall tunnels is often an effective and sustainable solution to improve the quality of life in the coastal areas. Also, the cities are interested in building longer tunnels as they allow to spread the wastewater further away from the coast. At the same time the longer the tunnel – the bigger is the potential survey error. So, the importance of the topic lies in the solution of the survey problem for a long underwater tunnel.

The basis for this research was some previous publications done by our surveyor colleagues. Robert Benecke and Uwe Kalz from DMT (Benecke & Kanz, 2006), leading company in producing of gyroscopic survey equipment, published their work 'Ensuring tunnel navigation by cost-effective gyroscope control measurements'. Their paper clarifies by practical examples, how the problem of positioning errors in tunnel surveying can be solved cost-effectively with high-accuracy gyroscopic measurements.

Another valuable research was done by Andrew Hung Shing Lee. It is also a case study research which among others describes the 'double zigzag' traversing method used at 3.2 km TBM Tunnel of Lok Ma Chau Spur Line, Hong Kong and 7.5 km railway project constructed for Kowloon Canton Railway Corporation, Hong Kong (Lee, 2007).

The article by 'Implementation of gyroscope measurements in underground mines' (Szafarczyk & Skaba, 2019) is a case study research describing the implementation of gyroscopic measurements with gyrotheodolite Sokkia GYRO X1 II into the survey procedures in the coal-mining industry. The work deals with the parameters of the network and describes improvements achieved with the use of gyroscopic measurements.

1.2 Methodology

The research is also a case study based on the survey works done by Noack Engineering GmbH for the Musaimeer Pumping Station and Outfall Tunnel. This is qualitative research describing methods used to achieve required construction tolerance of the breakthrough. Stage-by-stage descriptions of different levels of our network are provided. The chosen approach for the tunnel network was developed internally and includes multiple network observations to a high accuracy prism installed every 50m and combined with the tunnel brackets installed every 200m, allowing to create one of the most stable network structures. In addition, an important part of the network was the gyroscopic survey.

All described activities were based on the Method Statement prepared prior to the start of the mining and approved by the client.

The data was processed and analysed using specialized survey software Microsurvey Star*net.

1.3 Technical Information

The Musaimeer Pumping Station and Outfall tunnel is a 10km long undersea tunnel. By the time of its construction, it was reported to be the 7th longest underwater tunnel in the World and the longest outfall tunnel in the Middle East. Being one of the major infrastructural projects of Qatar to be completed before the FIFA 2022 World Cup, it will have huge impact on the city's development in the future decades. The project aims to discharge the surface and stormwater, thus decreasing the surface water level and reducing pumping costs in construction projects around the country. It will also preserve the foundations of buildings and reduce land subsidence due to rain.

The client of the project was Ashghal, construction was awarded to the joint venture (JV) of Hamad Bin Khalid Contracting Company and PORR Qatar Construction Company (HBK-PORR). The tunnelling survey works were completed by Noack Engineering, Germany. The offshore works by installation of Polyvinyl Chloride (PVC) pipe were performed by MIC Construct (MIC). The mining started on February 3, 2019 and was completed on February 3, 2021, exactly 2 years later. The maximum daily mining speed was achieved on November 28, 2019 – 33.8m (26 rings).

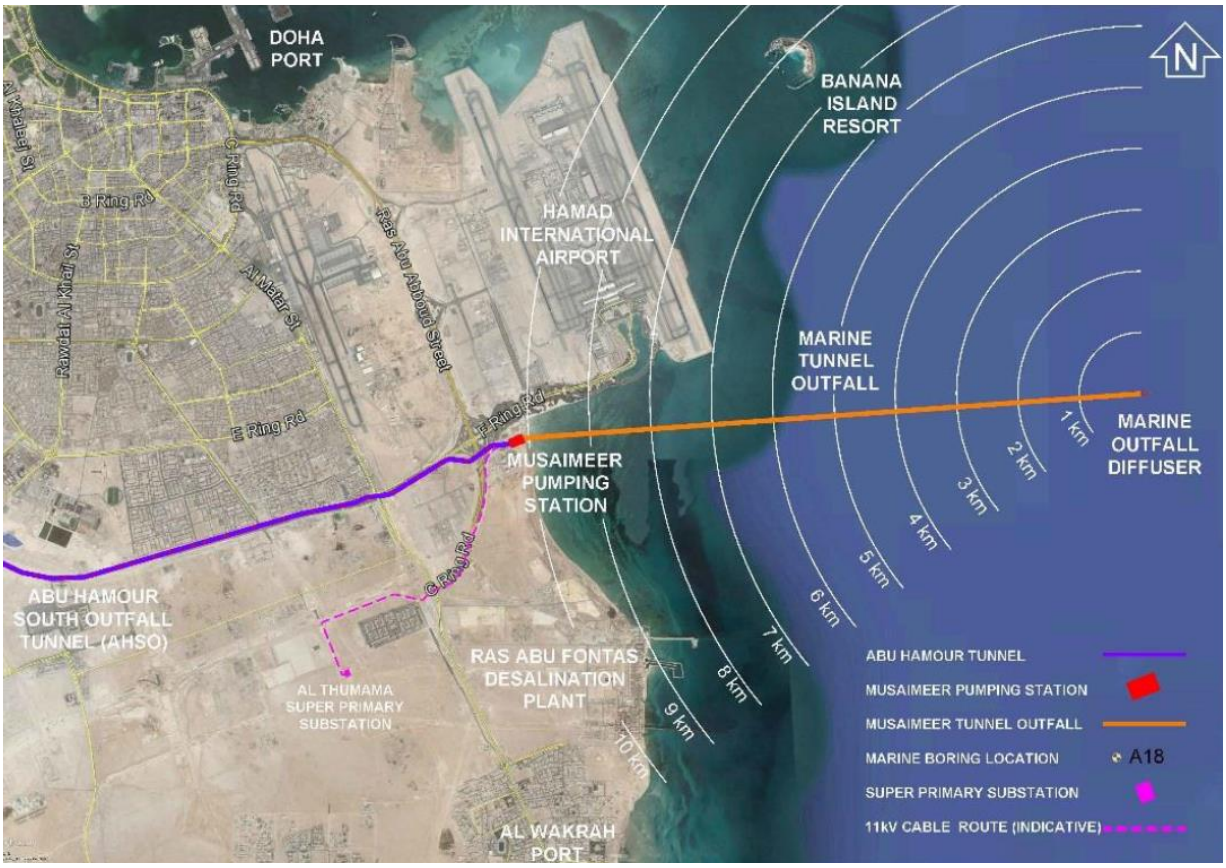

Fig. 1: Tunnel Alignment

Figure 1 shows the project alignment. The tunnel starts from a 37m deep shaft on the shore and follows a 10km alignment under the seabed. The horizontal alignment of the tunnel was a straight line connecting the launching shaft and the receiving riser shaft. The vertical alignment was also a straight line with a permanent inclination of +0.05% (50 mm/m). The vertical alignment increased from -36m to -31m below sea level. Which was approximately 15m below the seabed level. Mining was completed by a TBM. The tunnel has a diameter of 3.7m, with each ring at a length of 1.3m. The launching shaft had a 26m diameter and was 40m Deep with the receiving PVC pipe with a 3m diameter and encased in a 5m block of concrete.

1.4 Challenges

The survey works were faced with a few challenges:

1. Breakthrough to a riser shaft constructed offshore by another subcontractor –MIC. Therefore, it was extremely important to provide uniformity of survey networks between the two parties.
2. Accurate transference of the survey network from the surface to the base of the launching shaft and subsequently the TBM guidance system.
3. The length of the tunnel. The tunnel is 10km long without exit to the surface (no shafts, wells, openings etc.). This is combined with a small diameter of 3.7m. In addition, the tunnel started from a 40m deep shaft with a 26m diameter, which drastically reduced the accuracy of the launching bearing.

4. Differences in atmospheric conditions inside the tunnel, especially for the first 1,300m were very humid. Obviously, sudden changes of temperature and humidity caused air refraction and additional distortion to the measurement's accuracy.
5. Tough conditions of the mining required full time presence of survey team on the TBM. The inner space of the TBM was very congested. The survey window in which the navigation system was located was unfortunately located on the walkway; this meant the instrument had to be always manned to protect it from outside interference.

2 Main Surface Network

The network originated from 4 survey control pillars installed on the site by utilising Global Navigation Satellite System (GNSS) measurements. The points were located by utilising GNSS Static measurements which were processed against Qatar Network for Continuously Operating Reference Stations (QCORS) reference points.

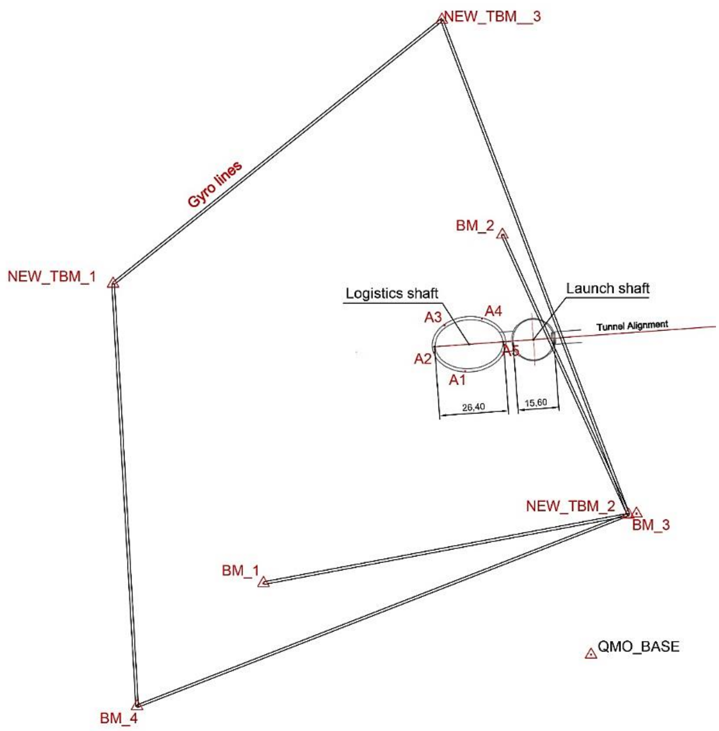

Fig. 2: Control points of the First and Second levels

These benchmarks where then also precisely levelled and coordinated from a minimum of Order 1 Qatar National Datum (QND) issued points to ensure they tied in with the QND network. In total these 4 points were located strategically on the edges of the site to maximise sighting distance and angle geometry. Figure 2 shows the location of site controls.

At the same time, MIC was responsible for the offshore works namely, PVC pipe installation (Riser shaft). MIC installed their first-order network base – point QMO_Base on the roof of HBK-PORR workshop at MPSO Site office. Government control point GD17 was used as main control point to calibrate the base station QMO_Base. A GNSS antenna receiver was set up on a tripod and tribrach plumbed above the control points; and GPS RTK measurements were recorded for at least 20 minutes (1200 epochs). After being established, QMO_Base broadcast the signal, ±10 kilometre offshore, to the barge area. Noack Engineers Survey team did some verification of this point in Horizontal and Vertical positions to make sure that both parties work with a matching and consistent network.

3 Second Level Network

3.1 Site Network

The network derivative from the Main Surface Network was developed on site. As some of the primary pillars were obstructed on later stages – the survey team had to create derivative points NEW_TBM1, NEW_TBM2, NEW_TBM3. In addition to the pillars, in the Second level network 5 control points were created on the edge of the Launching shaft (A1 – A5) which has the largest diameter. The points on the edge of the shaft were 3D mini prism which could be observed both from the surface and the shaft. These points became the basis for the shaft network.

The points BM1, BM2, BM3, BM4 as well as NEW_TBM1, NEW_TBM2, NEW_TBM3 were built as pillars with the forced centering plate. They were designed this way to be used for the gyroscopic campaigns. In this case pillars were the best solution. They were located in protected areas on site (e.g. corners of the site) so that they could survive the duration of the project. It proved much easier and more precise to execute gyroscopic measurements on pillars rather than ground points.

3.2 Barge Network

MIC completed the works on installation of the PVC pipe, 10 km away from the seashore. The construction works were carried out from an anchored self-elevating platform (barge).

On specific locations of the barge, the survey team bolted tribrachs where a GNSS antennas were installed, and measurements conducted. Once coordinated with GPS coordinates on the QND grid system circular prisms were placed on the tribrachs. These points were measured with GPS in reference to the site office base point QMO Base. A total of 3 control points were installed on the barge. Each of them was observed in fast-static mode with a minimum period of 5 min. This exercise was conducted 4 times to verify the concordance of the observations. The barge points BM0, BM2, BM3 were used to install the PVC pipe according project coordinate system. Figure 3 shows the location of these points.

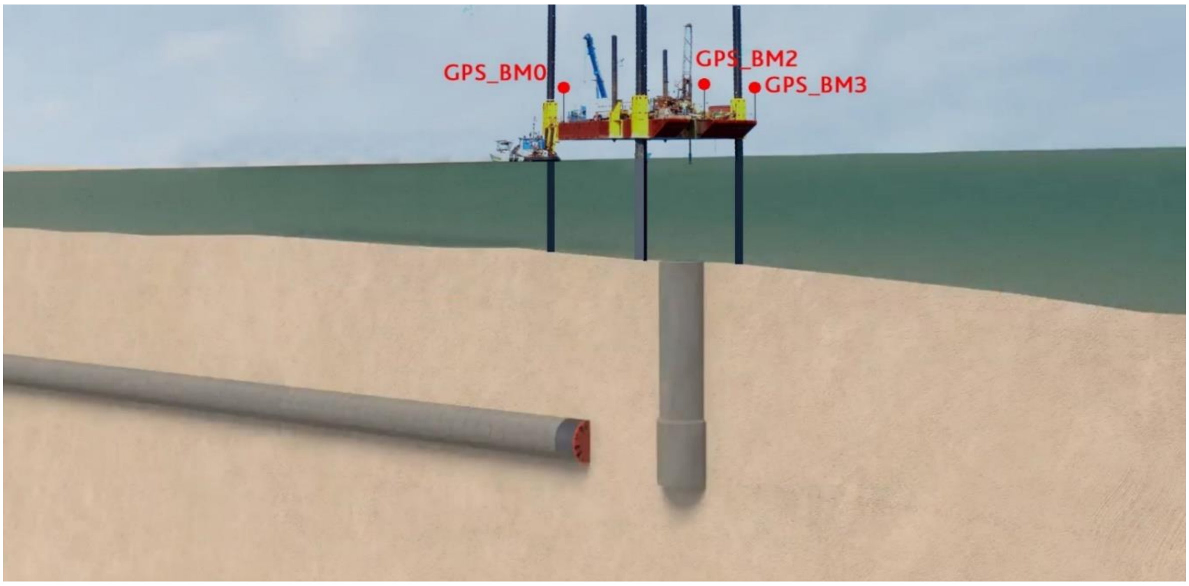

Fig. 3: PVC pipe installation from the Barge

Due to the different approaches of network creation, there were challenges to be overcome to ensure an accurate breakthrough. The surface points at the shaft area were measured by Noack Engineering for 4 hours on static GPS measurements. However, MIC used GPS RTK measurement which inherently had a 20 mm 3DCQ (3D Quality) and this would have increased over the 10km. This gave 70 mm displacement of the PVC pipe. Hence, course correction was applied to the TBM at breakthrough to align to this. Also, the MIC team were working on a scale factor of 1 whereas the project scale was 0.99999 meaning at 10km there was already a 100 mm error in distance. This factor was also taken into consideration by the Noack team.

4 Third Level Network – Shaft Network

The aim of the 3rd Level network was to bring the coordinates from the Site network down to the tunnel portal. Inside the shaft there are installed four arrays of 3D prism. From top to bottom there were there 3 levels of targets. Each level consists of 5 targets. As mentioned before, the prisms on the top edge were the part of the 2nd Level network – they were linked with observations to the pillars. Also, they were observed from the bottom of the shaft. As many measurements as possible are recorded to tighten the network. Figure 4 shows the location of shaft controls.

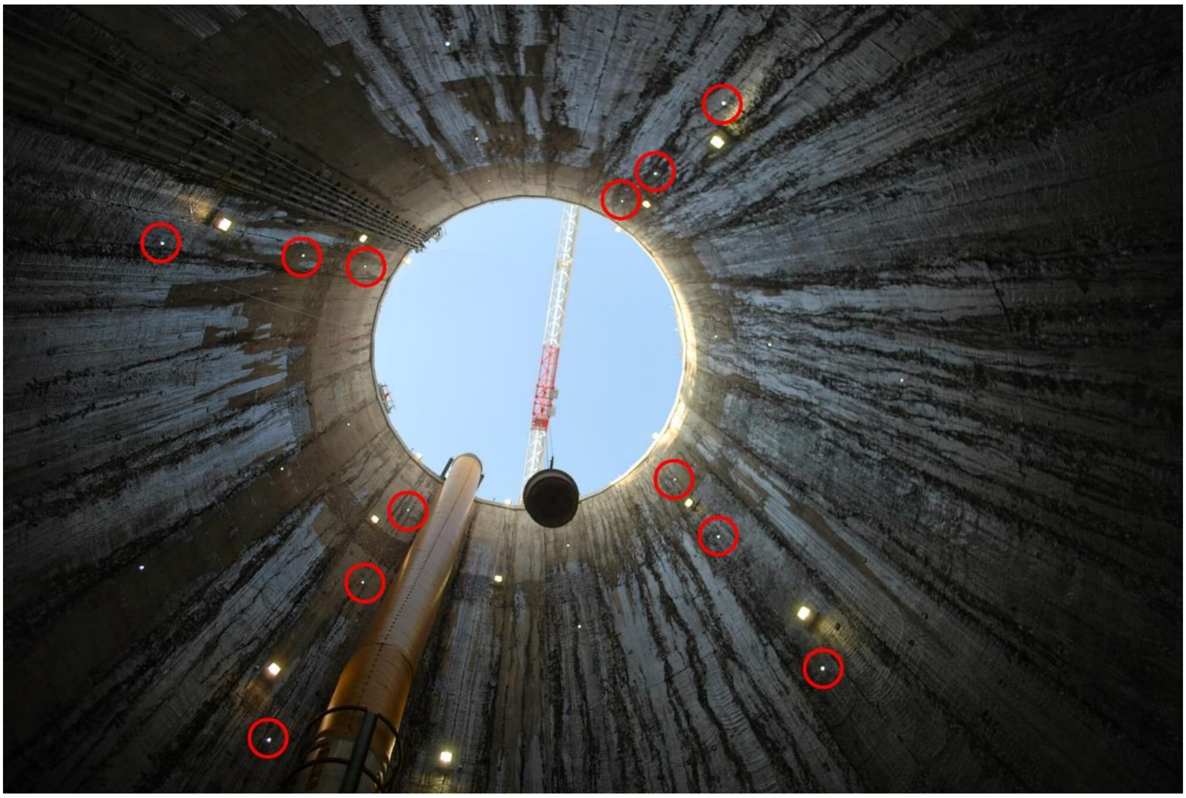

Fig. 4: Location of Shaft network controls (masked with red circles)

5 Fourth Level – Tunnel Network

Tunnel network was derivative from the shaft network. It was used for the TBM navigation and on-going wriggle as built in the rings. This network consisted of 3D prisms installed and anchored to the constructed segment via a brass spigot. These spigots were installed in pairs every 30 rings (about 48 meters) (e.g. on ring 840 left side, ring 845 right side, ring 870 left side, ring 875 right side). All tunnel control points were installed and observed with 11R5-W Leica Prism Adaptors with circular prism. The length offset from base of adaptor to prism centre is 100 mm. Figure 5 illustrates the sample of the tunnel control point.

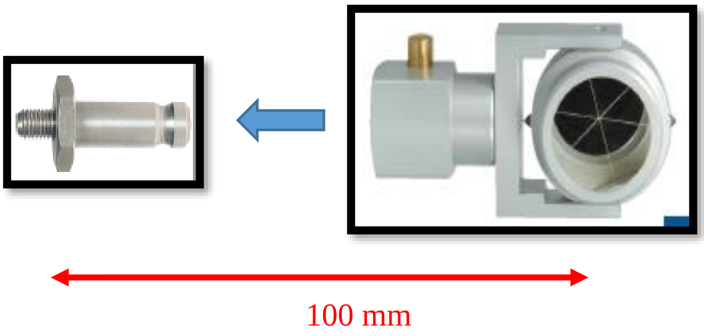

Fig. 5: Tunnel Control Point

The gyroscope brackets were installed every 126 rings (about 200 m) from each other. All network measurements were completed using a robotic 1-inch total station. From each station the surveyor observed as many targets as possible. As the result a dense, multi-shot network was formed. All the traverse works were repeated 3 times. Height values were controlled by precise levelling carried out by a digital level. The scheme of tunnel network is shown on Figure 7.

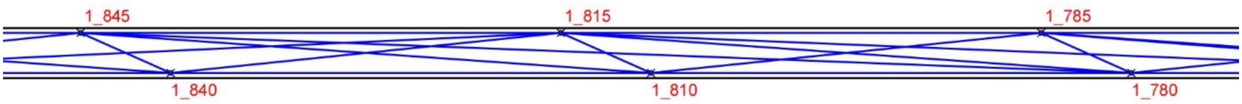

Fig. 6: Scheme of tunnel network

Concerning the fact that this network was created from transferring coordinates from the surface via a deep narrow shaft, it was expected that there would be a gyroscopic shift applied after the first gyroscope measurement as the initial launch bearing would be affected by the depth and narrow network transferred from the surface. Gyroscope measurements in the humidity and climate of Qatar meant all measurements had to be done in cooled shelters and also at night to mitigate the effects of the heat and humidity. The baselines had to be shorter to eliminate distortion due to the high humidity and temperature.

The gyroscopic measurements were done with the GYROMAT 3000 instrument by DMT, Germany. Initially the measurements were planned to be executed once the TBM would reach 500 m, and then subsequently every 1000-1500m. However, COVID-19 pandemic changed this schedule dramatically. The first campaign was taken at 779m, the second at 2210m, as planned. But the third campaign had to be postponed as no engineers from Germany could travel to Qatar during the lockdown. Due to such restrictions the third campaign (at 8138m) and the fourth campaign (at 9295m) were carried out by the Noack survey team, controlled via online internet connection by engineers from DMT offices in Germany.

In gyroscopic calculation the surface network baselines between pillars NEW_TBM_1, NEW_TBM_2, NEW_TBM_3 and BM_1, BM_2, and BM_4 were used.

6 Discussion and Conclusion

This is the case study, and it has limitations inherently peculiar to the MPSO project based on its specification, location and design. This being said, the issues, achievements and methodology used are not 100% representative of all industry practices and methods.

To sum up:

The accuracies utilized for the offshore work were determined by the 10km baseline achieved the Real-Time kinematic GNSS measurements, this in addition to the marine construction tolerances provided a large discrepancy in comparison to the strict tunnel drive tolerances. The depth and acute diameter of the launch shaft proved difficult to transfer accurate levels & Coordinates to the base. The 3.7m diameter of the tunnel and the 26m diameter of the shaft increased the initial error prior to launch as the horizontal angles measured in the launch adit were very acute with this alongside the short sighting distance meant the error factor was increased.

Temperature and humidity affected greatly our instrumentation from corrosion and reduction in accuracy on our network measurements and on the guidance system. Surveyors had to overcome harsh atmospheric conditions at the TBM, and these conditions were difficult for the navigation equipment. The total stations often required repairing – this is why there were 2 total stations on site – operational and spare.

All these major challenges were solved: A consistent surface network was built on the shore and offshore using the GNSS method, in order to make sure that the tunnel is constructed. This case study shows importance of coordination between two interface companies, Transfer the surface network to the shaft, then build an accurate tunnel network for the whole length of 10 km, Proper organization of the works helped to avoid delays in construction and minimize delays. A crucial part of the solution was introduction of 4 gyroscopic campaigns which were carried out during the Covid-19 travel restrictions, which was yet another challenge to the project.

Finally on February 3, 2021 the TBM has reached its final destination, passing through the concrete block of the shaft. Later the tunnel crown was opened and the final breakthrough result, considering all tolerances was 0.200m. Efforts and deep cooperation of the tunnel construction team and survey team made this landmark project true.

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