A COMPREHENSIVE GEOTECHNICAL AND MARINE GEOPHYSICAL INVESTIGATION FOR AN ARABIAN GULF SUB-SEA TUNNEL PROJECT

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ABSTRACT

The Public Works Authority of Qatar intends to award a design, build, and operate contract for construction of a marine outfall and pumping station, including a 10 km long subsea tunnel in the Arabian Gulf, where tidal and weather conditions are challenging. A comprehensive geotechnical and geophysical investigation was executed, with the objective of obtaining robust ground condition data to design and price the works and effectively assess risk.

The geotechnical investigation program consisted of marine geophysical surveys (multi-single beam echosounder, side scan sonar, magnetometer and seismic reflection-refraction surveys), marine-land boring and sampling, acoustic and optic televiewer, in-situ testing (standard penetration, Lugeon, pressuremeter tests) and laboratory testing (rock strength, swell testing and abrasion indices).

The sedimentary rock formations in the project area are overlain by superficial deposits of varying and limited thickness. The geotechnical investigation program was planned and conducted taking into consideration the highly variable nature of the local soil and rock conditions. Sea water depths in this area vary from 0 to 16m. Accordingly, two jack-up barges, with different working depth ranges with crawler type drilling rigs were used to meet project requirements and a tight 6-month investigation schedule.

Investigation results are compared with each other in order to obtain reliable data to perform realistic analyses and adequately convey the highly variable nature of the ground conditions.

Keywords: marine borehole, marine geophysics, jack-up barge

1 INTRODUCTION

Construction of an outfall tunnel extending approximately 10km from the onshore pumping station to a discharge point located in the Arabian Gulf is planned as part of the project scope, in a manner that would have minimum environmental impact on the marine environment.

The project area is located approximately 8km-10km to the south-southeast of Doha City Center. The Pumping Station is located on the coast, 1.0km-1.5km to the south of the New Doha International Airport (NDIA) and approximately 2.5km-3.0km to north of Ras Abu Fontas Power and Desalination Plant.

The project comprises two primary elements; one of which is the construction of a pumping station on the coast and the second one is the construction of marine outfall tunnel extending approximately 10km from coastline, in order to discharge surface and groundwater drainage into Arabian Gulf. [1]The main purpose of this study is to determine and provide data detailing the geotechnical characteristics of the rock stratigraphic units in the project area. The scope of work consists of geophysical surveys which include multi beam and single beam echosounder (bathymetry survey), side scan sonar, magnetometer and seismic reflection-refraction surveys, in both the land and marine environments,

with in-situ tests of standard penetration (SPT), Lugeon/packer and Menard/HyperPAC pressuremeters, acoustic televiewer (ATV) for determination of structural features encountered in the exploratory boreholes; such as jointing, faulting and solution cavities, laboratory testing programme on core samples collected from the exploratory boreholes.

2 SUMMARY OF GEOTECHNICAL INVESTIGATION

2.1 Marine and Land Soil Investigations Survey Program

The marine geotechnical site investigations consisted of twenty two (22) marine boreholes having a total depth of 1,100m. Marine drilling was performed from the self-elevating platform of jack-up barges (Figure 1 & Figure 2) where the drill rig and the equipment were fixed and stabilized. For performing pressuremeter tests, additional non-cored boreholes adjacent to (The distance between two holes is 1.5m and 1.6m) selected cored boreholes were drilled. The total drill length of the non-cored boreholes is 475.5m.

Field tests for the marine borings included 22 acoustic televiewer (ATV), 58 standard penetration tests, 274 packer tests, and 99 pressuremeter tests. Packer/Lugeon and pressuremeter tests were performed at selected depth intervals in selected boreholes in accordance with project requirements and ATV logging was performed within all boreholes. A marine soil investigation layout plan is given in the below figure (Figure 3).

Figure 1. Zemin Etüd Jack-up Barge

Figure 2. Zemin Offshore Jack-up Barge

Land geotechnical subsurface investigations consisted of four (4) land boreholes having a total depth of 200.0m. Non-cored boreholes were drilled besides the main boreholes. Field tests for the land borings included 4 acoustic and optic televiewer (ATV and OTV), 12 standard Penetration Tests, 15 packer tests, and 14 pressuremeter tests.

2.2 Marine Geophysical Survey Program

The surface geophysical survey integrated various techniques to characterize soil and rock units, to determine sea floor topography and image, and also to detect anomalies; buried metal objects. For this purpose four (4) different geophysical surveys were executed; namely, bathymetry survey, side scan sonar, magnetic surveys, and seismic studies. The subject area is 416 hectares.

Bathymetry survey was executed with multi-beam and single beam echo-sounder to determine seafloor depth. Side scan sonar and magnetic surveys were performed for detecting UXO (unexploded ordnance), pipeline, shipwrecks and metallic object in the project area. Seismic reflection and refraction studies were carried out to determine discontinuities, velocities, thicknesses of layers, and depth of rock formation.

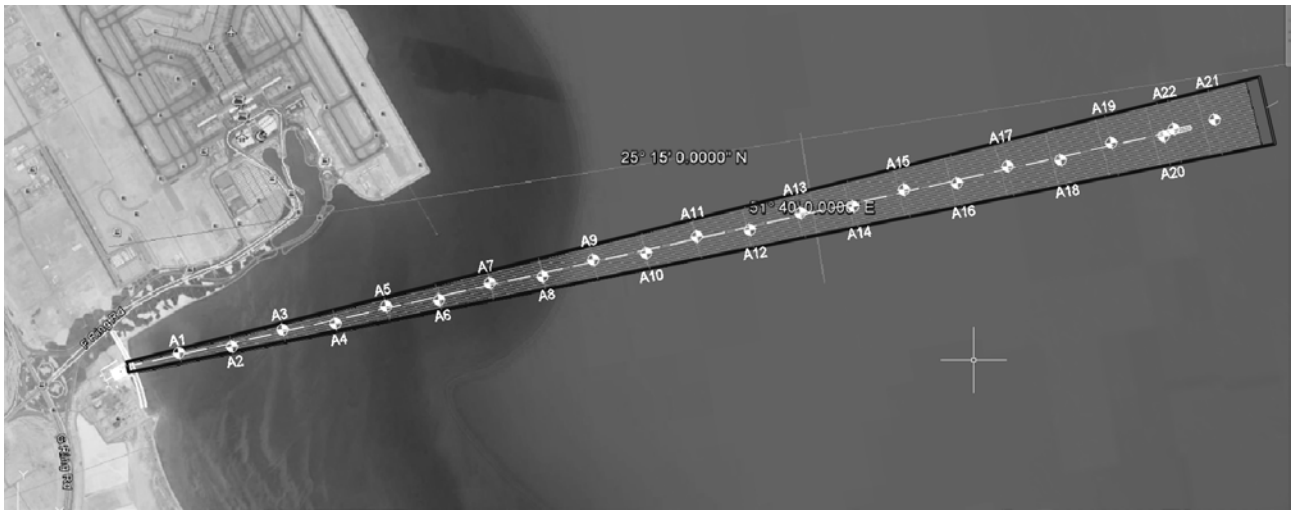

Figure 3. Marine soil and geophysical investigation lay-out plan

2.3 Soil and Rock Mechanics Laboratory Tests

Besides soil investigations, soil and rock mechanics laboratory tests were performed on the retrieved core and the representative soil samples. Samples were selected for the laboratory programme representing encountered lithological units. Considering the size, importance of the project, and utilization of tunnel boring machine (TBM), advanced rock mechanics tests were applied including rock swelling tests, rock tests for drill-ability (DRI-BWI-CLI)) at different university laboratories in Turkey, Qatar, and Canada. In order to obtain geotechnical parameters, laboratory tests were performed on soil, rock, and groundwater samples retrieved from boreholes.

3 LOCAL GEOLOGY AND SEISMICITY OF THE SUBJECT SITE

3.1 Local Geology

The soil overburden and the rock stratigraphic units encountered in the exploratory boreholes observed in the project area can be identified and generalized below in order.

1) Made ground and unconsolidated soil
2) Simsima Limestone
3) Midra Shale
4) Rus Formation

The typical geological characteristics of rock stratigraphic units encountered in the exploratory boreholes are the occurrence of poor bedding structure developed horizontal to sub-horizontal. In addition, there is no significant evidence indicating any displacement of encountered rock units and also no observation recorded (no brecciation in core with the presence of significant infill and fault gouge) from the cores for determining major or minor fault zones.

Jointing system exists throughout the rock mass; a number of joint sets were evident from inspection of cores and acoustic televiewer records. The encountered joints from the exploratory boreholes indicated predominant development of horizontal to sub-horizontal structures/sets in the project area. A number of core samples were analysed for mineralogical and petrographic description of each stratigraphic unit and generally they were determined as dolomitic limestone.

Following the preparation of on-site borehole logging, discontinuity logging for each borehole was also prepared. Discontinuity logs include:

- Identification of all discontinuities and foliation by center line depth,
- Dip, dip direction, angle with core axis, discontinuity type, and infilling description, amount of infilling, joint shape and roughness, Q and RMR descriptions,
- Full description of discontinuity types and descriptions of infillings.

3.2 Seismicity

Qatar is situated on a relatively stable platform, subjected to little tectonic uplift, faulting or folding. No major faulting is indicated in the Doha area. The highest magnitude of recorded seismic activity between 1900 and 2013 is M<5[2-3].

4 GEOTECHNICAL IN-SITU TESTING

4.1 Drilling Operation and Standard Penetration Testing

The wireline rotary drilling was carried out by using PQ3 type core barrel equipment with 82mm of core diameter in order to generate high core recovery with good core quality on land and marine boreholes. Standard Penetration Tests (SPT) were carried out in accordance with BSEN ISO 22476-3 by using a split spoon sampler with automatically falling hammer in the zone where soil overburden and soft rock were encountered and within the zone having low total core recovery, TCR. The compaction of this horizon is relatively described as loose to very dense, with 'N' values of SPT ranging from N=4 to N=71 recorded from borehole A5 and borehole A18.

4.2 Pressuremeter and Packer Testing

Menard - HyperPAC Pressuremeter was used to determine the strength parameters of soil/rock. Pressuremeter test was performed at the requested depths within the non-cored boreholes as per ASTM 4719 Standard. The deformation modulus E_M and the net limit pressure p*lm values were calculated for each test elevation and E_M values are given versus depth in Figure 4. In addition to these parameters, Young's Modulus, horizontal stress, undrained shear strength, and at rest coefficient of lateral earth pressure were obtained from the pressuremeter tests results.

Based on pressuremeter test results, relatively lower E_m and p*lm values were recorded in the zone where soil overburden and soft rock were encountered compared to the higher values recorded for the strong rock units.

In the scope of geotechnical subsurface investigation two hundred and eighty nine (289) packer tests were executed in selected boreholes at the requested depths. Lugeon values obtained from packer tests are plotted against depth and given below in Figure 5. Lugeon values varied between 0.1 and 170 and permeability coefficients varyied between 5.52E-09 and 2.30E-05. As seen in the below figures Lugeon values concentrated in the order of 100 within the strong rock formation. For soil overburden and soft rock formation, Lugeon values are accumulated between 0.1 and 10.

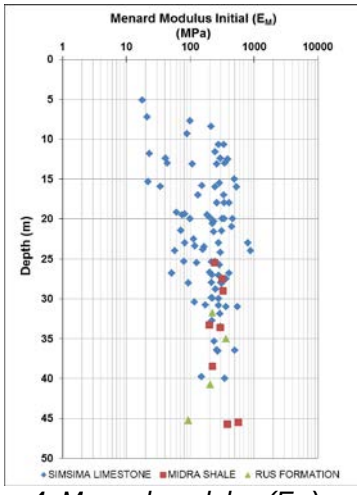

Figure 4. Menard modulus (E_m) against depth classified based on each formation

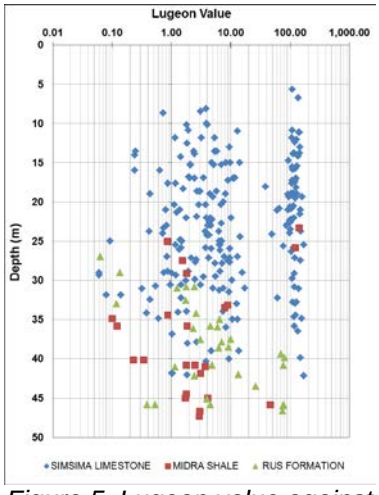

Figure 5. Lugeon value against classified based on each formation

4.3 Acoustic and Optic Televiewer

Acoustic televiewer was performed as per ASTM D 5753-05 in all boreholes. The main purpose of this logging is to acquire true depths, dip angles and dip directions of discontinuity planes. Amplitude,

tadpole, dip angle and dip direction angle were determined with acoustic televiewer versus true depth. Based on acoustic televiewer image the encountered joints from the exploratory boreholes are horizontal to sub-horizontal structures/sets in the project area (Figure 6).

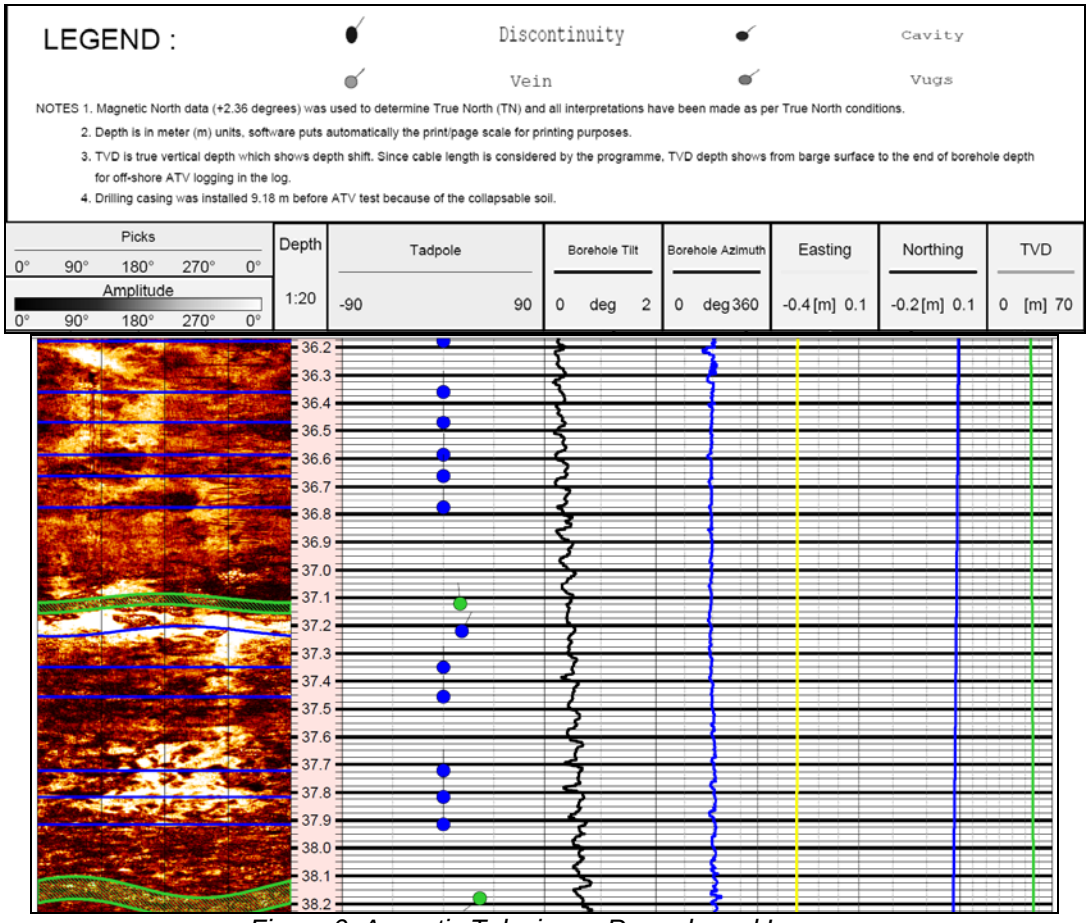

Figure 6. Acoustic Televiewer Records and Image

5 GEOPHYSICAL SURVEY

Seafloor and ground surface elevations were found out to be between -18.37m and 2.89m above datum at the investigation site in the bathymetry survey (Figure 7). Also, during the bathymetry survey tide measurements were recorded. Low tide was measured as -0.47m at 11:37 time and high tide was recorded as +0.40m at 17:13 on April 04, 2015. Also, an excavated channel with a width of 120m and depth of approximately 2m was identified close to borehole A16.

According to magnetometer survey, magnetic anomalies were present at A1, A2, A3, A4, A6, A7 and A8 boreholes locations. Another anomaly was seen 20m north of the A10 borehole and continues towards the North (Figure 8). A total of 99 magnetic anomalies were identified at the investigation site with the magnetometer survey. Ten detected anomalies are given in Table 1 with respect to distances from tunnel alignment and with their coordinates as a sample.

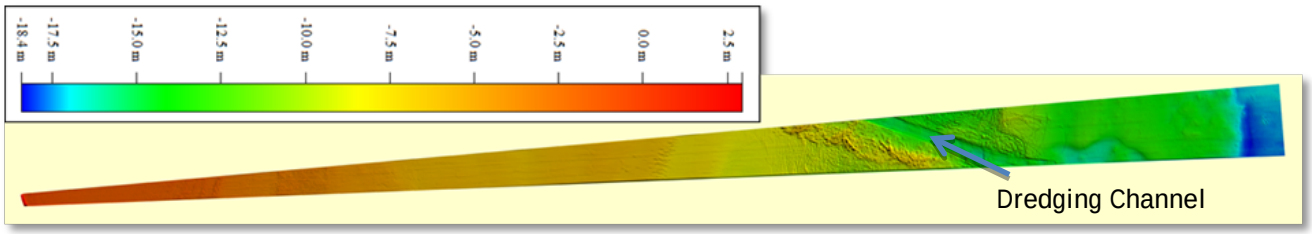

Figure 7. Bathymetry map of survey area

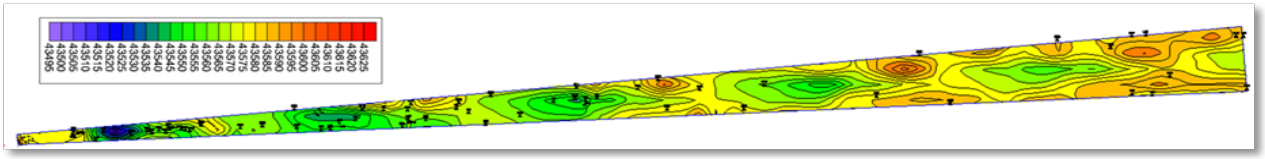

Figure 8. 2-D magnetic anomaly map for survey area

Table 1. Magnetic Anomalies List

Mark ID	Date	Survey Time	Northing	Easting	Distance From Tunnel Alignment (m)
M1	07-Apr-15	09:49:07	243774.613	387839.315	25.32
M2	07-Apr-15	09:55:44	242735.622	387761.635	26.56
M3	07-Apr-15	10:02:11	241725.127	387689.978	24.7
M4	08-Apr-15	07:43:38	243883.955	387902.098	29.73
M5	08-Apr-15	07:44:16	243783.843	387882.269	18.82
M6	08-Apr-15	07:45:59	243497.245	387870.411	25.96
M7	08-Apr-15	07:51:10	242630.614	387805.302	23.42
M8	08-Apr-15	08:10:30	241381.692	387741.557	52.42
M9	08-Apr-15	08:14:29	241976.144	387784.484	81.87
M10	08-Apr-15	08:32:27	244803.091	387988.934	50.23

Seismic refraction data was obtained by hi-res single channel streamer on the very shallow areas. Boat speed was selected as 2.0kn-4.5kn. Ship position was achieved with a Differential Global Positioning System (DGPS) and/or Global Positioning System (GPS). All seismic raw data was recorded in standard SEG Y format. Refraction and reflection waves were recorded using AQ 2000 hydrophones due to their frequency range (10Hz-10.000Hz). Land seismic equipment (Geometrix device) was used intertidal zone. Seismic refraction and seismic reflection data were collected by continuous recording along the proposed tunnel axis every 25m and perpendicular to it at 500m centers, passing through every borehole. Single channel was used for seismic reflection and 48 channel streamers were used for seismic refraction. All seismic cross-sections were checked for their compatibility with each other and also with other geophysical measurements, borehole logs, and televiewer log data. The velocity values were derived from seismic refraction of each layer. The top layer having approximately 8-15m thickness has a P wave velocity between Vp = 1600-2250 m/s. Approximately 20m thick second layer has a P wave velocity between 2250-3400 m/s. Similarly, another 20m thick third layer having a P wave velocity between Vp = 3400 - 4100 m/s exists. The last layer observed is interpreted as Rus Formation, having seismic P wave velocity about 4900-5400 m/s. Reflection, refraction and layer thicknesses of the borehole log were consistent with each other. As a result of data processing generally two units were determined at the investigation site. These are Simsima Limestone and Rus Formation. In addition, thin layers of shale and mudstone were observed at different depths at the cross sections.

6 CONCLUSION

Extensive geophysical and geotechnical investigations comprizing advanced survey and laboratory methods are utilized within the scope of the investigations for the pumping station and outfall tunnel project. The main objective of this investigation was to obtain data diversity from a wide spectrum of survey and laboratory methods, which is required for the utmost economical and safe design of the pumping station and especially for the proposed marine tunnel, within the time constraints. This study is an example of extensive surveys, which provided broad data for geotechnical design. This study presents several clear consistencies between in-situ tests, borings and geophysical measurements. Discontinuities determined from acoustic televiewer and retrieved cores from boreholes were coherent. Lugeon test permeability results and pressuremeter test results noticeably match results from with lithological data obtained from borehole logs. Recorded P-wave velocities from seismic refraction were found to be concordant with borehole log data and the discontinuities determined from seismic reflection were accordant with borehole log and acoustic televiewers.

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