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Marine Geotechnical & Geophysical Survey In Complex Geological Formations

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SUMMARY: Detailed marine geotechnical investigation was carried out offshore of Indian coast in Mumbai (Bombay) to assess the foundation design parameters for the offshore bridge project. 52 boreholes were drilled using two jack up barges along the proposed bridge alignment and field & laboratory testing program was implemented at selected locations and on selected soil and rock samples. Geophysical survey using side scan sonar, sub bottom profiler and magnetometer was also carried out to reveal continuous seabed features along the bridge alignment. The results obtained through this study were analysed and interpreted to arrive at foundation design parameters. This paper presents the details about marine geotechnical and geophysical investigation programs, thus carried out, interpreted field and lab test results and the subsurface material properties. The major challenge was carrying out the geotechnical and geophysical work within short time and in shallow water which was conducted using wireline drilling and special barge positioning technique in a planned manner. The decision to carry out geophysical survey was beneficial and provided the supplementary information on seabed stratification between the boreholes and buried objects along the proposed bridge alignment. Rock mass classification based on RQD and RMR is widely accepted to quantify rock mass discontinuities and shall be evaluated routinely during geotechnical investigations in fractured rock mass. The near shore, project with complex seabed conditions and shallow waters shall be treated with caution. The well planned investigation methodology and equipment is very crucial to successfully execute an investigation program as desired.

KEYWORDS: Marine geotechnical investigation, Geophysical survey, Jack up barge, Soil, Rock.

1 INTRODUCTION

The Western Freeway Sea Link (WFSL-Phase IIA) is an offshore bridge project connecting two major hubs from Worli to Haji Ali, running parallel to the western coastline of Mumbai, India as shown in Figure 1. This bridge (shown in white line on the south in Figure 1) is an extension of the existing offshore bridge from Bandra to Worli (shown in the red line on north in Figure 1). The main bridge will be connected to the mainland using two connector bridges at the Worli end and the Haji Ali end.

The length of the proposed bridge is 5.5 km with eight lane carriageway connecting two areas viz. Worli at north and Haji Ali at south. Geotechnical and geophysical surveys were carried out along the proposed bridge alignment as a part of the detailed investigation program to gather complete information about the sub soil stratification and the seabed features.

2 INVESTIGATION PROGRAME

2.1 Geotechnical Investigations

52 nos. boreholes were drilled using a rotary drilling method with depths varying from 13m to 34m below the seabed. 26 boreholes (M series) along the main alignment, 11 boreholes (H series) along Haji Ali connector and 15 boreholes (W series) along Worli connector as shown in Figure 1. The boring / drilling works were carried out using two Jack up barges

(JUB) with hydrostatic drilling rigs. Standard penetration tests were performed at specified intervals or at the change of soil strata. On reaching the rock strata, the rock core samples were obtained using NX-size triple tube core barrel and NQ-size double tube wire-line core barrel. The qualitative and quantitative description of natural fracture state of rock masses such as total core recovery, rock quality designation was recorded from the extracted rock cores. The pressuremeter tests were performed in weathered rock formation with a rated pressure range up to 20 MPa to evaluate in-situ rock mass parameters. The field and laboratory testing has been carried out along the proposed length of the pile shaft and below the pile tip for ease in estimation of pile shaft and tip resistances. Laboratory testing was carried on rock samples from each core run of 3m length and wherever there was a change in stratification.

2.2 Geophysical Survey

A geophysical survey was carried out in water depths varying from 3m to 12m to establish seafloor bathymetry and to map the seafloor and subsurface geological features to identify man-made structure or significant debris or pipeline within the proposed bridge corridors. The survey corridor consisted of 200m width throughout the length of 5.5 km along the proposed bridge alignment. Side scan sonar and single beam echo sounder were run within this corridor at 25m interval long lines. Sub bottom profiler, multi beam echo sounder and magnetometer were run only along the centerline of the proposed bridge alignment.

3 SUBSURFACE STRATIGRAPHY BASED ON GEOTECHNICAL INVESTIGATIONS

The geotechnical investigations revealed weathered and fractured Compact Basalt rock predominantly encountered at or just below the seabed surface along the 4.0 km length of the alignment. This layer is believed to be that of the Malabar Hill Compact Basaltic lava flow. (Birid 2006). The thickness of the weathered Compact Basalt rock varies all along the bridge alignment, but ultimately grades into fresh (unweathered) Compact Basalt at higher depths below the sea bed.

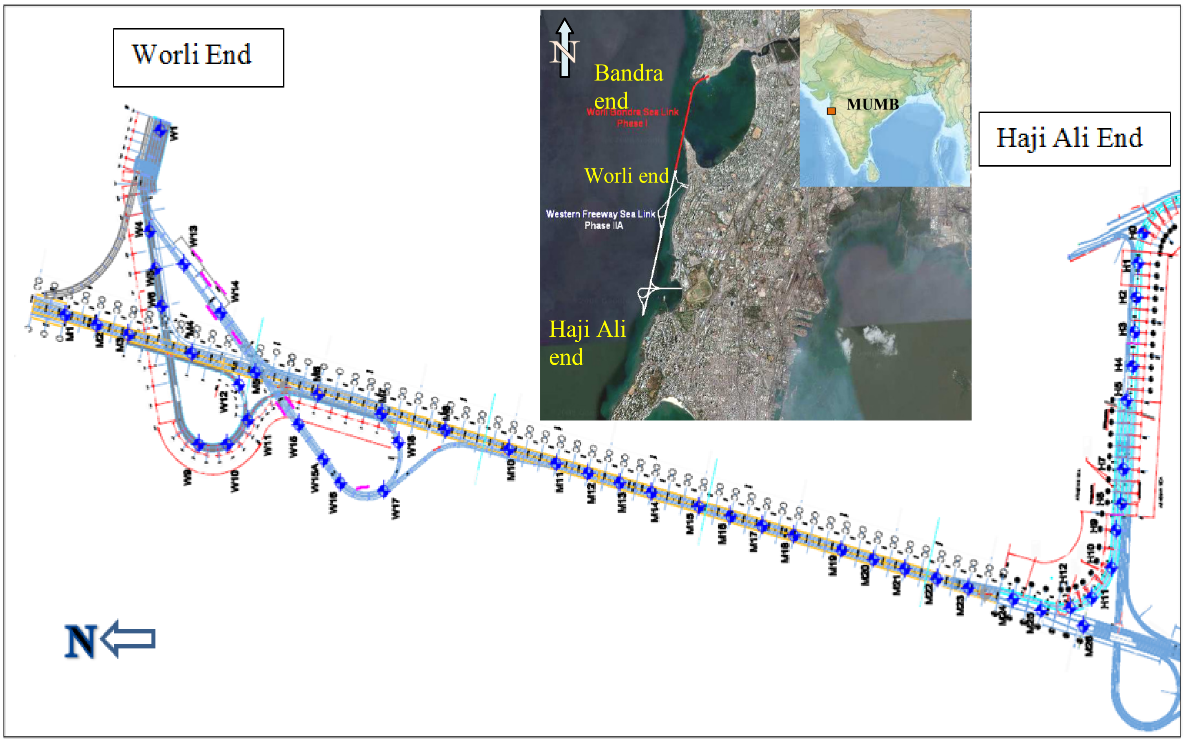


Figure 1. Proposed bridge alignment and borehole locations.

The intertrappean layer underlying the Malabar Hill Compact Basaltic flow was encountered along the east direction of the main alignment along the eastern half of the Haji Ali connector. Based on the stratification, the survey corridor is broadly divided into two distinct regions such as I) Main alignment with Worli end and II) Haji Ali end.

The variation in stratification along the main alignment and Worli connector are as shown in Figure 2 (a) & (b) respectively.

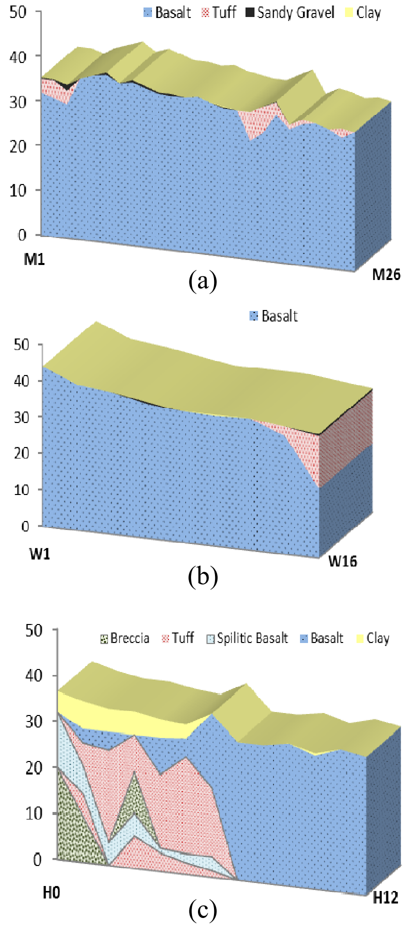


Figure 2. Subsurface stratification along the main alignment (M1-M26), Worli connector (W1-W16) and Haji Ali connector (H0-H12).

The generalized stratification consists of following layers;

- Layer I: Soil overburden of sandy clay/clayey sand up to 1m depth,
- Layer II: Weathered Compact Basalt rock up to 8m depth with occasionally Tuff formations,
- Layer III: Fresh Compact Basalt rock.

The variation of stratification along Haji Ali connector is as shown in Figure 2 (c). The generalized stratification at the Haji Ali end consisted of following layers;

- Layer I: Soil overburden of sandy clay up to 6m depth below seabed,
- Layer IIa: Intertrappean consisting of Tuff, Shale and Breccia,
- Layer IIb: Spilitic Basalt at few locations.

The soil strata overlying the rock head is predominantly soft sandy clay. The depth of the soil overburden ranges from 0m to 1.1m along the main alignment and 6m within a bay location at Haji Ali.

The weathered and fractured Compact Basalt was generally encountered either immediately at sea bed level or underlying the soil overburden. The degree of weathering of the Compact Basalt varied from completely to moderately weathered. Fresh Compact Basalt rock was observed underlying the layer of weathered Compact Basalt rock. Low RQD values within the fresh Compact Basalt at various depths are attributed to zones of intense fracturing.

The different areas along the bridge alignment with predominant rock types are shown in Figure 3.

Figure 3. Areas with different rock types along proposed bridge alignment

The intertrappean layers comprised of a combination of Tuffs, Breccias and Shales. These layers were encountered predominantly within a bay along the eastern half of the Haji Ali connector to a significant depth below the sea bed level.

Spilitic Basalt rock is formed because of chemical alteration of Compact Basalt and was encountered only at the connector near south Haji Ali end interspersed with Tuff and Breccia.

4 ENGINEERING PROPERTIES OF SOIL AND ROCK

The physical properties of soil such as grain size distribution and Liquid limit (LL) and Plastic Limits (PL) are evaluated as per ASTM D422 and D4318 respectively and presented in table 1. Based on the test results it has been observed that the majority of soil overburden consists of sandy clay strata.

Table 1. Range of soil properties

Loca-tion	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	LL (%)	PL (%)	PI (%)
MA*	0-32	30-96	8-44	5-26	52-53	23-27	25-30
HAC**	0-4	25-48	35-64	9-17	39-44	17-27	15-24
WC***	0-60	2-97	9-75	3-23	49	24	25

* MA - Main Alignment, ** HAC - Haji Ali Connector at the south end, *** WC – Worli Connector at the north end, PI- Plasticity Index

The index properties of rock are evaluated as per ASTM C127, D3967, D5731, D7012 and the range of results is presented in table 2.

The lower limit of UCS for Compact Basalt is attributed to weathering and micro fracturing. The fresh Compact Basalt is the strongest and Tuff is the weakest rock encountered along the bridge alignment.

5 ROCK MASS CHARACTERISTICS

Each core run was classified and quantified using geomechanical classification or rock mass rating (RMR) system as per Bieniawski 1989. Table 3 indicates the range of RMR values for different rock types with varying degree of weathering for entire rock mass along the proposed bridge alignment. The rock mass elastic moduli from 22 nos. pressuremeter tests, rock quality designation (RQD) at the test depth and the corresponding RMR values have been presented in table 3.

Table 3. Rock Mass Rating (RMR)

Rock type	RMR	RQD (%)	Rock Mass Elastic Modulus from pressuremeter test (GPa)
Strong Compact Basalt	40-85	0-100	0.008-4.761
HW* to MW** Compact Basalt	29-50		
Tuff / Tuffaceous Breccia	40-63	9-53	0.164-6.835
HW to MW Tuff / Tuff with Shale	21-40		
Breccia	31-51	0-50	0.017-1.942

* HW - Highly Weathered, ** MW - Moderately Weathered.

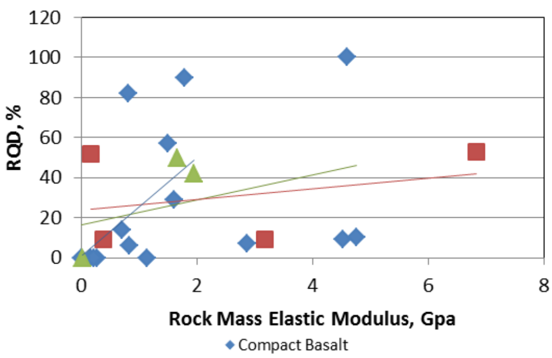
It has been observed from the pressuremeter test results that the rock mass elastic modulus increases with the increase in RQD as shown in

Table 2. Properties of rock

Tests \ Rock type	Compact Basalt	Spilitic Basalt	Tuff	Tuff with Shale	Breccia/ Tuffaceous Breccia
Dry Density (kN/m^3)	24.0 -29.3	23.2-29.2	19.3-27.3	20.3-26.4	22.6-25.1
Specific Gravity	2.55-2.90	2.43-2.70	2.60-2.78	2.19-2.64	2.57
Porosity (%)	0.13-8.10	0.53-9.11	1.25-29.13	2.56-18.41	2.44-7.72
UCS (Mpa)	10-260	13-96	2-40	7-37	12-35
PL (Mpa)	0-11	0.5-3	0-5	0-1	*
Tensile Strength (Mpa)	2.40-29.00	2.65-23.23	0.17-2.11	1.93-4.77	*
Lab Elastic Modulus (Mpa)	1141-128571	1427-82500	1479-13600		1066-2199

* Testing not carried out.

Figure 4. However, when compared rock mass elastic moduli with RMR values, similar trend could not be obtained probably because of less number of test results as shown in Figure 4.



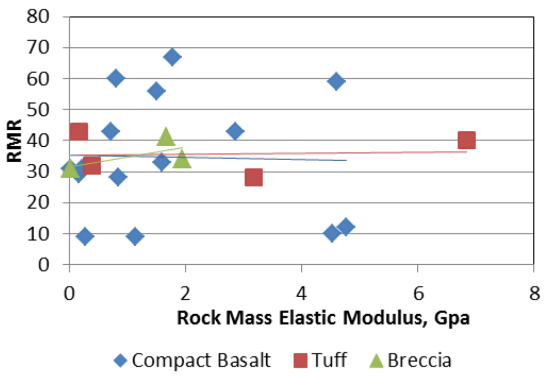


Figure 4. Rock mass elastic modulus from pressuremeter Vs RQD and RMR

6 SEABED CHARACTERISATION BASED ON GEOPHYSICAL SURVEY

The geophysical survey was carried out along the corridor of proposed bridge using side scan sonar, sub bottom profiler, echo sounder and magnetometer. The survey revealed a generally flat seabed profile.

The side scan sonar record revealed following reflectivity patterns in the present survey area;

Type 1: Low Reflectivity (Silty Sands/ Sandy Silt) over most survey areas,

Type 2: High Dappled Reflectivity (Weathered Rock with jagged surfaces and rock pinnacles)

The dappled reflectivity occurs possibly due to jagged surfaces of the weathered rock and the isolated rock pinnacles. No significant features such as pipelines, cables and the other submarine facilities were observed in the side scan sonar records within the survey corridor.

The correlation of the sub-bottom profiler records along with adjacent cross-lines also contributed to arriving at the distribution of the below mentioned stratigraphy units.

Strata A: Consisting of fine to medium grained silty sands /sandy silts underlain by;

Strata B: Weathered bedrock.

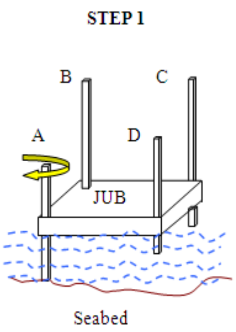
The sub-bottom profiler revealed no evidence of occurrences of buried pipelines, buried objects, shallow gas, faulting and slumps within the survey corridor.

The rapid anomaly variations in the magnetometer data were attributed to the weathered bedrock which is Compact Basaltic in nature.

7 CHALLENGES FACED DURING SURVEY IN SHALLOW WATER

The connectors connecting the main bridge to the land are located within the intertidal zones with the water depths varying from 0m during low tides to maximum 4m during the high tides, making it practically impossible to carry out any kind of survey in this area. The ground conditions at intertidal zone were highly undulating with exposed Compact Basalt at Worli end and soil overburden at the Haji Ali end.

The two JUBs were engaged to carry out the entire geotechnical investigations with minimum required water draft of 0.8m and 1.5m. Considering the undulating ground and the risk of JUB being ground, it was necessary to maintain the position of JUB so that at least 2.5m to 3.0m of water depth is available for safe operation and for safe movement of tugboats and service boat. As it was not possible to pull the JUB close to shore using a tug boat which had a higher draft requirement than JUB, shifting technique was adopted during a spring tide in the steps shown in Figure 5.



Worli End

Haji Ali End

Figure 5. Positioning of JUB in shallow water.

Step 1: Touching one leg A of JUB to the seabed (as shown in Figure 5) with other three legs in an upright position.
Step 2: Laterally pulling the leg C and rotating the JUB around leg A using a tug boat.
Step 3: Once the tug boat approaches shallow water near shore while rotating the JUB, it was detached from leg C and attached to leg B with leg D touching the seabed for further pulling of JUB near to shore and at the same time keeping the tub boat away from the shore. However, even with this technique, JUB positioning could not be done beyond the certain water depths. The other option was the construction of staging (various levels of steel platform) resting on the seabed for two boreholes within intertidal zone. However, this location consisted of very strong Compact Basalt outcrops with large seabed undulations making it impossible to anchor the staging platform with a risk of being tilted or collapsed due to wind and tidal actions. Hence it was decided to skip the two inertial boreholes and use engineering interpretations and judgment to establish the subsurface stratigraphy. The shallow sea bed depth where the borehole was drilled using JUB was having seabed level of only 0.17m below the chart datum at Worli end and 0.70m above the chart datum at the Haji Ali end (see Figure 5).

The available time period for field operations was limited as the offshore activities are restricted during 5 months of the monsoon season. Thus a proper balance was required to be maintained to perform a quality job within the assigned budget and the stipulated time frame by overcoming unforeseen difficulties faced during drilling, sampling, barge positioning etc. In order to shorten the drilling time, the wireline drilling system was adopted. With this system, a core barrel can be removed from borehole bottom without removing the drill rod assembly. Thus a lot of time was saved which otherwise would have required in hoisting and lowering the drill road assembly after every 3m core run. Often the onsite decisions and deviations with respect to the planned activities were taken to decide field test locations, test depths, selection of laboratory test samples and test quantities.

8 CONCLUSIONS

The decision to carry out geophysical survey was beneficial and provided the supplementary information on seabed stratification between the boreholes and buried objects along the proposed bridge alignment. Due to its importance and the low cost, such survey is recommended for the marine infrastructure project. However, in order to acquire accurate survey output, minimum 2m of water depth is recommended.

In varying geological conditions, the laboratory and in-situ testing shall be planned properly to reveal crucial engineering properties of different formations accurately as the data interpretations and evaluation of foundation design parameters largely depends on outcome of laboratory and in-situ testing. Design of deep foundations in rock, often requires details on rock mass discontinuities. Hence it becomes imperative to carry out detailed borehole logging in case of fractured rock mass. Rock mass classification based on RQD and RMR is widely accepted to quantify rock mass discontinuities and shall be evaluated routinely during geotechnical investigations in fractured rock mass.

The near shore, project with complex seabed conditions and shallow waters shall be treated with caution. The well planned investigation methodology and equipment is very crucial to successfully execute an investigation program as desired.

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