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Geotechnical and Geophysical Characterization – Case Study of a Site with Steeply Dipping Rock

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Abstract. Geotechnical investigation at site for a multi-storeyed residential complex in south Delhi indicated the presence of steeply dipping and folded rock. The variation in the depth to rock within each tower highlighted the possibility of differential settlement of the raft foundation planned at basement level. To characterize the formation, seismic refraction tests were performed along four lines. The tests assisted in confirming the trend of the rock profile in the area of the towers. The geophysical evaluation was used to evaluate the dip of the rock clearly define the variation in the rock profile across the site.

Keywords: Geotechnical Investigation, Boreholes, Seismic Refraction Tests, Steeply Dipping Rock.

1 Introduction

Initial geotechnical investigation for a multi-storeyed residential complex in south Delhi the indicated substantial variation in the depth to rock across the site. To evaluate the trend of the rock profile seismic refraction tests were performed.

The paper presents the effective use of geophysical tests to characterize the stratigraphy and for effective geotechnical assessment of the site.

2 Project Description

The project site covers an area of 1.93 acres approx. The site is fairly level with ground levels varying from RL 224.0 to 222.2 from west to east. A railway track runs north of the site.

The development includes two residential towers (1 basement + stilt +12-13 floors). These towers are identified as Type V Quarters on the eastern side of the plot and Type VI Quarters on the west. In the open area between the towers, extended basement is planned for parking and utilities. The foundation was planned at about 4.5 m depth.

2.1 Scope of Geotechnical Investigation

The initial investigation at the site included eight boreholes through soil and rock. The borehole data indicated that the rock level varied from 7.5 to 12 m in the Type V Quarters. In the open area between the towers, the depth to rock is about 2.8 to 3 m. Moving further west, rock is met at 5 to 23 m depth in Type VI Quarters.

Reviewing the variation in the rock profile, it was decided to perform seismic refraction tests along four lines to evaluate the trends. The alignment of the seismic lines was selected to get maximum coverage below the tower foundations. A layout plan presenting the locations of the field investigation is illustrated on Fig. 1.

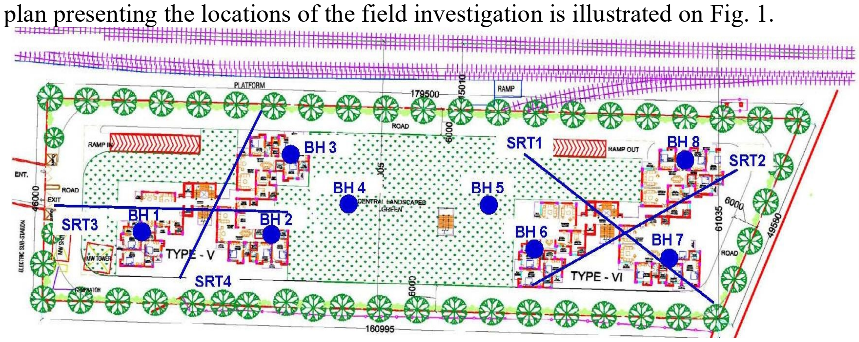

Fig. 1. Plan of Field Investigation.

3 Site Conditions

3.1 Regional Geology

The overburden soils in the area belong to the Indo-Gangetic Alluvium and are underlain by the Delhi System of rocks. The quartzites of Delhi System are massive, compact and hard. These quartzites are intruded by pegmatites. These pegmatites, on weathering, yield mica zones encountered in the area. A generalized description of geological formations encountered in Delhi [1] is given in Table 1 below.

Table 1. Geological Succession in Delhi.

Period	Formation	Description
Recent	Newer (Younger) Alluvium	Unconsolidated, inter-bedded lenses of sand, silt gravel and clay confined to flood plains of Yamuna River.
Quaternary	Older Alluvium	Consolidated inter-bedded, inter-fingering deposit of sand, clay and kankar, moderately sorted, thickness variable.
Pre-Cambrian	Pegmatite and Quartz Veins Quartzites and minor Schist Bands	Well stratified, thick-bedded brown to buff colored hard and compact quartzite, intruded locally by pegmatite and quartz veins inter-bedded with mica schists.

Experience in different parts of Delhi have shown that the rock is highly folded due to which the depth to rock varies significantly. Variations in depth to rock have been seen over short distances. The rock has three sets of joints, one nearly horizontal, the second nearly vertical and the third set is inclined at 30 to 50 degrees. Preferential weathering has occurred along the joints due to flow of water.

3.2 Boreholes

Boreholes were drilled using a hydraulic rotary drill rig as per IS: 1892-1979 [2]. While SPT was conducted in soil at every 1.5-m depth interval, rotary core drilling using a double tube core barrel was done through the rock. The boreholes were drilled from the existing ground surface. Fig. 2 presents a photograph of a typical borehole in progress at the site.

Fig. 2. Borehole Drilling in progress.

3.3 Site Stratigraphy

Below the surficial fill that ranges from 1.5 to 6 m, the natural deposits at site consist of an alluvial overburden underlain by rock (quartzite). A pictorial summary of the borehole profiles is illustrated on Fig. 3.

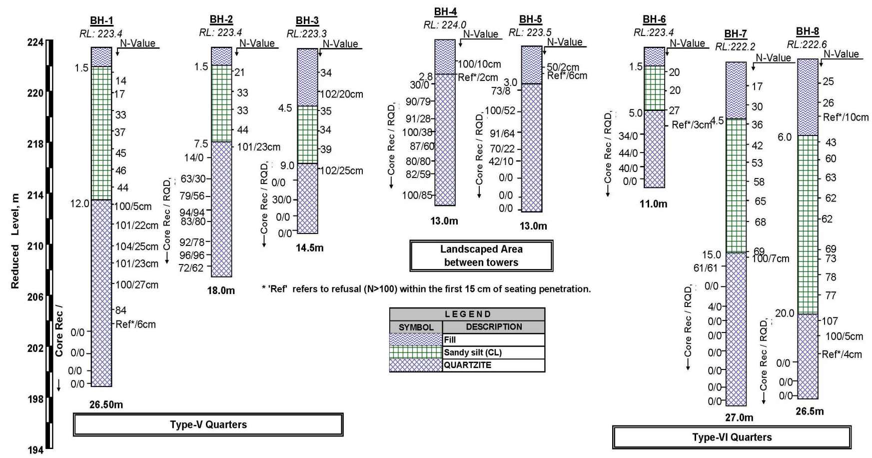

Fig. 3. Summary of borehole profiles.

The depth to rock varies substantially across the site as discussed below:

- Type V Quarters: Rock is encountered at 12 m depth (RL 211.4 m) on the western side (BH-1), rising to 7.5-9 m (RL 215.9 – 214.3 m) on the eastern side.
- Landscaped area between Towers: Rock is met at 2.8-3.0 m depth (RL 221.2 – 220.5 m) at BH-4 and 5 in the level of the rock rises rapidly from west to east with an anticline in the vicinity of BH-4 and 5.
- Type-VI Quarters: Rock is met at 5 m depth (RL 218.4 m) at BH-6 in the vicinity of the anticline. Moving further east, rock dips downwards and is encountered at 15 m depth (RL 207.2 m) at BH-7 and 23 m (RL 199.6 m) at BH-8.

Groundwater was not encountered at the borehole locations to the maximum explored depth of 27 m suggesting that it is quite deep in this locality.

3.4 Seismic Refraction Tests

Seismic refraction test (SRT) consists of recording the time taken for an artificially provoked surface vibration to propagate through the earth. By processing the data recorded at geophones placed along a line, absolute velocities, velocity contrasts and the depths of the underlying layers are determined.

These results give information about the nature and thickness of overburden soils, depth to the top of bedrock, depth of weathering zones in the rock mass, faults or weak zones, etc. (Whitley, 1994 [3]). The seismic velocities are characteristic of the thickness, nature and quality of the overburden soils and the underlying rock and may be used to identify the deposits in conjunction with the borehole data to effectively characterize the site (Anomohanran, 2013 [4]).

To evaluate the trend of the rock profile, seismic refraction tests were performed along four selected lines. Two lines in the area of the Type V Quarters and two lines in the area of the Type VI Quarters as identified on Fig. 1were investigated.

The tests were performed after excavation was done in the area of Type V Quarters to the planned basement level of 4.5 m. At the Type VI Quarters, excavation had not started and the tests were done from ground level. Each line was 60 m long. Fig. 4 shows data acquisition for the seismic test in progress using an array of geophones spaced 5 m apart.

Typical seismic refraction lines are illustrated on Fig. 5 (Type V Quarters) and Fig. 6 (Type VI Quarters). The borehole data is superimposed on the seismic profile to compare the stratigraphy.

Fig. 4. Seismic Refraction Test – Data Acquisition in progress.

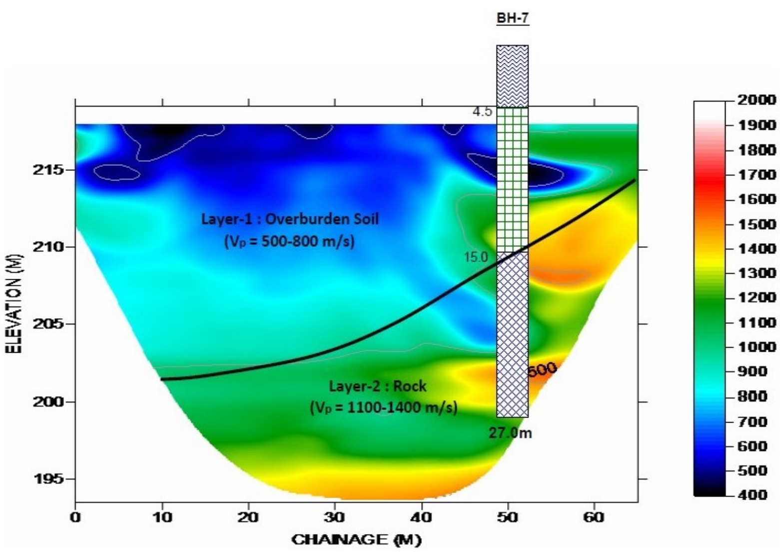

Fig. 5. Seismic Profile along SRT-1 (Type V Quarters).

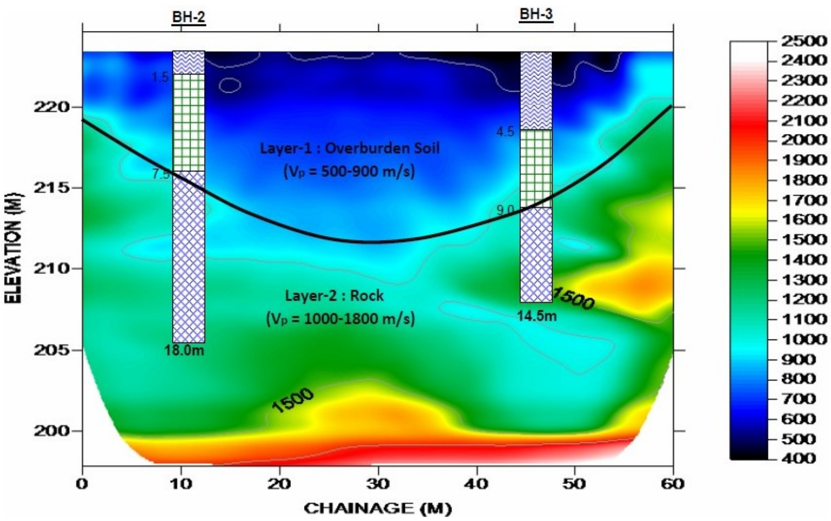

Fig. 6. Seismic Profile along SRT-4 (Type VI Quarters).

4 Site Characterization

The boreholes and seismic refraction tests effectively confirm that the rock levels vary significantly across the site. The rock levels interpreted from the seismic refraction tests along the four selected lines are plotted on Fig. 7.

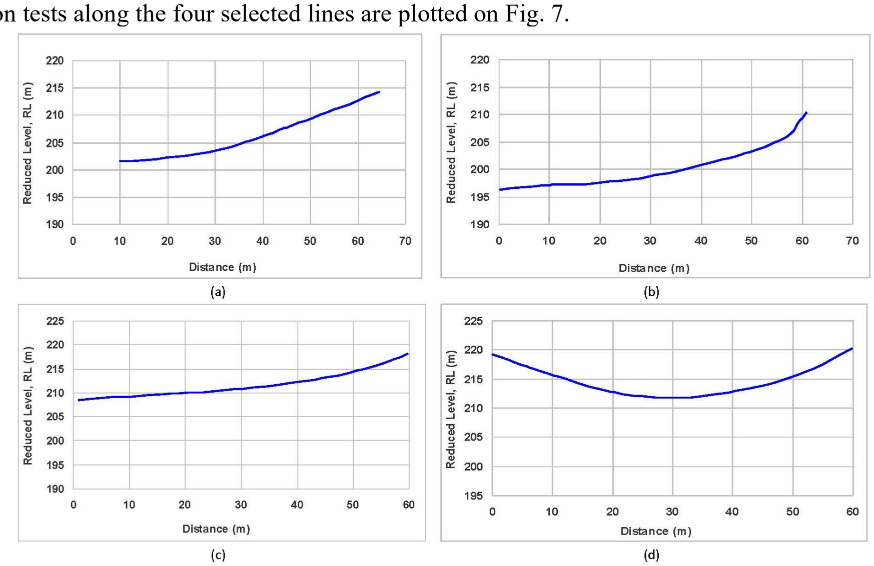

Fig. 7. Interpreted rock profile along seismic lines: Type V Quarters – (a) SRT-1 (b) SRT-2 Type VI Quarters – (c) SRT-3 (d) SRT-4.

Seismic Line 1: On the northwest end of the line, rock is met at 15 m depth (RL 203 m). Towards the middle of the line, the rock level rises gently to about RL. 203.5 m. It then rises steeply and is met at RL 214 m at the southeast end of the line. Rock level at BH-7 at 10 m depth below excavated level (RL 208 m) matches well with the seismic profile.

Seismic Line 2: Rock is met at 23 m depth (RL 196 m) on the northeast end of the line. Towards the middle of the line, the rock is met at about RL 200 m. It then rises steeply and is met at RL 210 m at the southwest end of the line. The rock level at BH-8 is at 19 m depth below excavated level which matches well with the seismic profile. At BH-6, rock is encountered at 1 m depth below excavated level (218.4 m). This also matches well extrapolated seismic profile.

Seismic Line 3: Rock is at 14 m depth (RL 209 m) on the west end of the line. Towards the middle of the line, rock is at about RL 211 m, matching with BH-1. The rock then rises steeply and is met at RL 218 m at the east end of the line. The rock level at BH-2 at 7.5 m depth (RL 215.9 m) matches well with the seismic profile.

Seismic Line 4: Rock is at 3 m depth (RL 219 m) on the southeast end of the line. Towards the middle of the line, the rock dips steeply downward to about RL 211 m. The rock then rises steadily and is met at RL 220 m at the northeast end of the line, suggesting a synclinal fold. The rock level at BH-2 at 7.5 m depth (RL 215.9 m) and BH-3 at 9.0 m depth (RL 214.3 m) match well with the seismic profile.

Reviewing the trend of rock as obtained from the boreholes and SRT lines, contours of rock level are illustrated on Fig. 8.

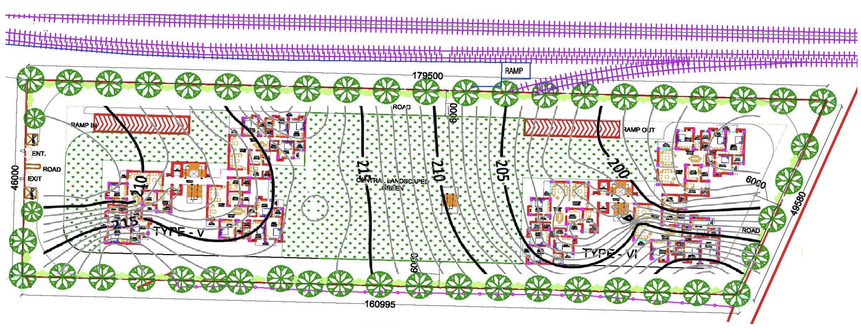

Fig. 8. Contours of rock level.

These contours have been developed from the depth to rock observed at the borehole locations as well as the interpreted level of rock along the SRT lines. The building layout superimposed on the contours indicates rock level variation of over 20 m over a 170 m distance. A synclinal basin is also observed at Type VI Quarters.

5 Foundation Design

Since one basement was planned, the raft foundation for the towers were planned at RL 219 m. The minimum and maximum depth of rock below the founding level was estimated from the trend of contours given on Fig. 8.

Since groundwater was not encountered to the maximum explored depth, the raft settlement is expected to be essentially immediate. The rock surface was treated as a rigid layer for the purpose of analysis. The immediate settlement was computed in accordance with Clause 9.2.3.2 of IS: 8009-1976 [5].

The raft foundation covering the whole area of the tower is expected to experience a net bearing pressure of 15 T/m^2 at the planned founding level (corresponding gross bearing pressure = 23 T/m^2). Table 2 below presents the minimum and maximum depth to rock below foundation for the two towers together with settlement analysis for the following two cases:

- the best case (minimum thickness of soil overburden above rock): This will estimate the minimum settlement that may occur, and
- the worst case (maximum thickness of soil overburden above rock): This will estimate the maximum settlement that may occur

The difference between the best-case settlement and the worst-case settlement is an indicator of the differential settlement that could potentially occur.

Table 2. Depth of rock and estimated foundation settlement

Building	Analysis Case	RL of Rock m	Depth of Rock below Founding level (RL 219 m)	Estimated Settlement, mm
Type V Quarters	Best Worst	RL 215.9 RL 211.4	3.1 m 7.6 m	Best Case: 14 mm Worst Case 31 mm
Type VI Quarters	Best Worst	RL 218.4 RL 199.6	0.6 m 19.4 m	Best Case: 5 mm Worst Case 40 mm

For both towers, the computed angular distortion was substantially less than 1/500 as permitted in IS: 1904-1986 [6]. Hence, the towers were judged to be safe under the planned applied bearing pressure.

6 Geotechnical Investigation on Sites with Varying Rock Profile

Where the depth to rock / hard strata varies across the site, the authors suggest that the geotechnical investigation program should be coupled with a geophysical study to evaluate the trend of the depth to rock. Boreholes should extend at least 5 m into rock to confirm the continuity of the rock and to assess the rock characteristics. Rock drilling should be done using a hydraulic rotary drill rig and a double tube core barrel. In areas of weathered rock, triple tube core barrel may help in maximizing core recovery.

Static cone penetration tests as per IS: 4968 (Part 3)-1976 RA-2002 [7] may also be used to map the depth to refusal strata and to obtain additional data for foundation analysis.

The authors are of the opinion that boreholes and cone penetration tests should be supplemented by a geophysical investigation on sites with varying depth to rock in order to obtain the rock profile along selected lines. This may include:

- Seismic refraction tests
- MASW / SASW tests
- Electrical resistivity tests or electrical resistivity imaging.

Using a combination of these tests, the depth to rock all over the site should be properly mapped out. Contours of rock level should be prepared to assess the trends and in areas where the variations are unusual, additional tests may be performed to identify the depth to rock and also identify anomalies, if any.

The foundation design should then be done structure-wise keeping the variations in view and ensuring that the total and differential settlements are within permissible limits.

7 Concluding Remarks

Geophysical tests in conjunction with borehole data are an effective way to characterize sites with varying rock profile. The case study illustrates an effective characterization of a site with folded and steeply dipping rock using seismic refraction tests.

The foundations were designed considering the variation in the rock level and it has been ensured that the differential settlement due to the variation in the depth to rock across the site is within the permissible limits.

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