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Suggested Reviewers:	

Advances in the State-of-Practice of Geotechnical Investigation in India

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Abstract. With greater emphasis on in-situ testing and the introduction of digital data acquisition, geotechnical investigation practice in India is advancing leaps and bounds. With a variety of tests now available, the data can be analyzed effectively to improve the quality of geotechnical parameters and enhance its reliability. Energy correction of SPT offers a scientific way of standardizing the energy transferred to the split spoon sampler and minimizes the scatter / error in the values. Electric cone penetration test is very reliable since it is independent of operator and results are repeatable. Pressuremeter tests have become quite popular in India over the last two decades. The test causes minimum disturbance to the in-situ soils. Geophysical tests such as resistivity tests, cross-hole seismic tests, SASW / MASW etc. provide a quick assessment of shear wave velocity profiles and low-strain dynamic behavior. Various correlations are available between CPT, pressuremeter and SPT as well as shear wave velocity which are not only consistent but also form the basis of selecting design parameters which are representative of the in-situ conditions. The paper highlights the various technologies available in the country together with a case study demonstrating the application of these tests.

Keywords: SPT Energy Correction, Electric Cone Penetration Test, Geophysical Tests, Correlations, State-of-Practice, Geotechnical Investigation

1 Introduction

Geotechnical investigation practice is rapidly evolving from the classical era of Terzaghi, Horslev, Skempton and other masters of the twentieth century. The developments and demands of the 21st century geotechnical practices have led to a greater emphasis on in-situ tests and introduction of various advanced tools with digital data acquisition.

The increasingly complex nature of the problems encountered has presented challenges to the new generation of geotechnical engineers where interactions with various other specialists without civil engineering background require a wider appreciation of project requirements. The effect of globalization has also introduced new challenges to geotechnical engineers where understanding of fundamental soil mechanics is important to complement local experience for works in different parts of the world.

The conventional methods of investigation are just not good enough to design complex modern structures such as tall buildings, metro and railway structures, bridges, refineries, thermal, nuclear and solar power plants, dams, hydraulic structures, etc. The thrust is on developing more realistic design parameters, encroach upon the factor of safety and enhance the factor of reliability [1].

Several infrastructure projects suffer impacts to schedule or cost due to geotechnical issues. Many of these issues relate directly or indirectly to site characterization and interpreting geotechnical design parameters from the various in-situ and laboratory tests conducted. Effective site characterization is critical for recognizing potential problems that may affect design and construction and for ensuring safe, well-performing, and cost-effective projects.

There is now a greater emphasis on in-situ tests for a more realistic estimate of design parameters. Three aspects need to be addressed as listed below:

- variety of in-situ and laboratory tests so as to predict parameters from different tests and develop correlations between various parameters,
- enhance precision of the tests, quality of data acquisition and reliability of the test data, and
- use local experience regarding the soil behavior to minimize uncertainties in the selection of design parameters

Uncertainties in geotechnical investigations include measurement error, natural variability, quantifying the variations in measured / computed values and selection of appropriate design parameters. One of the best approaches to resolve these issues is to perform in-situ tests [2]. Good quality data from in-situ tests such as standard penetration test, cone penetration test, field vane shear test, pressuremeter test, dilatometer test, plate load test and footing load test can enhance the reliability of the design.

The use of finite element method to analyze complex geotechnical problems is increasingly common. The use of powerful finite element software with user-friendly interface has generated a demand for more reliable geotechnical input data. Selection of suitable constitutive model requires that the quality of geotechnical parameters be realistic and correct.

There is a need for Indian geotechnical investigation agencies to move out of the conventional mindset and upgrade to adopt the new technologies. The paper highlights new technologies that are now available in the country and explains how these tests can enhance the quality of geotechnical data. A case study is presented that demonstrates the benefits accrued and the site-specific correlations that can be developed using the data.

2 Modern Field Tests to Obtain Quality Data

2.1 Tests Discussed in this paper

While a host of advanced tests and technologies are now available in the country to obtain good quality geotechnical data, this paper addresses the following tests:

- SPT Energy Measurement;
- Rock Drilling
- Electric Cone Penetration Test with pore water pressure measurement;
- Pressuremeter tests;
- Electrical Resistivity Tests and Electrical Resistivity Imaging;
- Geophysical (seismic) tests – Cross-hole seismic tests, seismic refraction test, SASW and MASW tests.

2.2 SPT Energy Measurement

The Standard Penetration Test (SPT) is by far the most popular and commonly used penetration test, not only in India but also worldwide. The greatest merit of the test, and the main reason for its widespread use, is that it is simple and inexpensive. Despite its many flaws, it is usual practice to correlate SPT results with soil properties relevant for geotechnical engineering design.

Except for its name, nothing is standard about the test, particularly the way it is performed in India. Some of the factors affecting SPT N value include

- Method of hammer release – manual or automatic
- Operator efficiency, local practices
- Number of turns of rope on the cathead
- Type of hammer – donut, safety, auto-trip
- Maintenance
- Rod Type
- Soil type & depth
- Verticality of rods
- Borehole cleaning

Variation in SPT N values have been observed when using different SPT test apparatus and field crew at the same location. Use of automatic trip hammer arrangement can help minimize scatter is N-values on account of inconsistent hammer fall and should be made mandatory for projects. Hammer energy efficiency should be measured and SPT N values should be normalized to energy efficiency of 60% to ensure accurate interpreted soil properties [3].

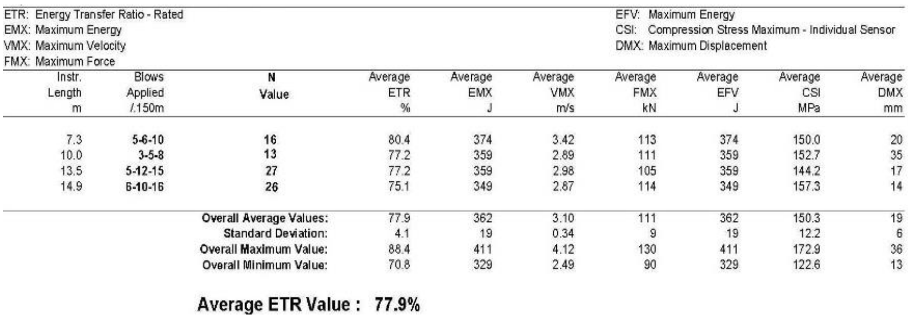
Several different types of SPT hammers are used in the industry to conduct Standard Penetration Tests. Their varying efficiencies influence the N value. “Non-standard” SPT systems may deliver highly variable energy values to drive rod. If the energy transfer is erratic, the measured N value will not be realistic. Energy measurement improves the reliability of soil strength estimates used in geotechnical applications.

Energy measurement may be done digitally using a SPT Analyzer as per the procedure in ASTM D 4663-16 [4]. It includes a rod instrumented with two calibrated strain gauges and two accelerometers. The instrumented section is inserted at the top of the drill string between the hammer and the existing sampling rod. The sensors on the rod are connected to the SPT Analyzer (computer with the relevant proprietary software). The strain gauges and accelerometers obtain force and velocity signals necessary for calculation of transferred energy to the drill string for each hammer blow. Fig. 1 presents the instrumented rod and SPT analyzer.

Fig.1. SPT Analyzer and instrumented rod.

The Pile Driving Analyzer (PDA) instrument can also be updated to include the software for the SPT analysis, thus making it an effective and economical tool.

Fig. 2 presents a typical data acquired at a project site in Noida.



ETR: Energy Transfer Ratio - Rated
EMX: Maximum Energy
VMX: Maximum Velocity
FMX: Maximum Force

EFV: Maximum Energy
CSI: Compression Stress Maximum - Individual Sensor
DMX: Maximum Displacement

Instr. Length m	Blows Applied /.150m	N Value	Average ETR %	Average EMX J	Average VMX m/s	Average FMX kN	Average EFV J	Average CSI MPa	Average DMX mm
7.3	**5-6-10**	**16**	80.4	374	3.42	113	374	150.0	20
10.0	**3-5-8**	**13**	77.2	359	2.89	111	359	152.7	35
13.5	**5-12-15**	**27**	77.2	359	2.98	105	359	144.2	17
14.9	**6-10-16**	**26**	75.1	349	2.87	114	349	157.3	14
		Overall Average Values:	77.9	362	3.10	111	362	150.3	19
		Standard Deviation:	4.1	19	0.34	9	19	12.2	6
		Overall Maximum Value:	88.4	411	4.12	130	411	172.9	36
		Overall Minimum Value:	70.8	329	2.49	90	329	122.6	13

Average ETR Value : 77.9%

Fig. 2. Typical SPT energy data acquisition on a project site in Noida.

Recognizing the importance of energy measurement, the Bureau of Indian Standards is currently revising IS: 2131-1981 [5] to incorporate it in the national standard. IRC 78 Part VI [6] is also being updated to include energy measurement.

2.3 Rock Drilling

The practice of using light-duty “calyx” rigs for drilling through rock with single tube core barrel is used by some geotechnical investigation agencies to cut on costs. This type of drilling rig does not apply hydraulic pressure on the drill-head due to which rate of penetration is slow.Play in drilling alignmentand vibration during drilling results in low core recovery and RQD due togrinding of the core and its breakage.

Experience has shown that using a hydraulic rotary rig with double tube core barrel or preferably triple tube core barrel (particularly in fractured, friable rocks) can greatly enhance the quality of rock cores collected [7]. Use of the right kind of drilling equipment will ensure an economical design of foundations bearing on rock / piles socketed into rock, thus optimizing the foundation design.

A typical comparison of core recoveries and RQD values using calyx rig with single tube core barrel versus use of hydraulic rotary rig with triple tube core barrel for boreholes for a bridge across River Tapi is illustrated on Fig. 3.

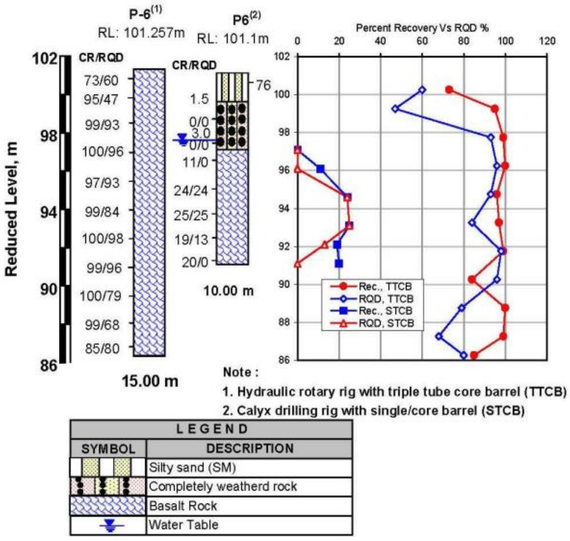


Fig. 3. Comparison of drilling data (recovery and RQD) of single tube core barrel using calyx rig and triple tube core barrel using hydraulic rotary drill rig– typical data at Bridge over River Tapi, Pier P-6.

2.4 Electric Cone Penetration Test with Pore Pressure Measurement (CPTu)

Use of electric piezo-cone (CPTu) or seismic cone (CPTs) is advantageous for better assessment of strata conditions and liquefaction assessment. The CPTu records the continuous cone penetration resistance, frictional resistance along with pore water pressure during penetration at the level of the base of the cone. All measurements are made by sensors contained in the penetrometer as per ASTM D 5778-20 [8]. Interpretation of the CPTu data may be done as described by Lunne et al [9].

The CPTu is not covered in IS: 4968 Part 3 [10] currently, but is expected to be included shortly. The piezo-cone has a limited presence in India but should become more popular in the coming years. The piezocones commonly used [11, 12] are illustrated on Fig. 4. The cones with cross-sectional areas of 10 cm^2 and 15 cm^2 and porous element at u_2 position (just above the cone) are popularly used.

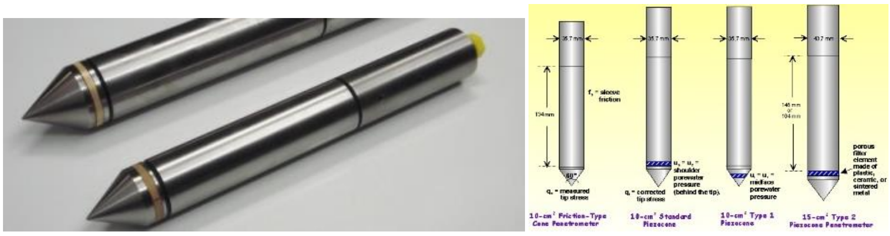


Fig. 4. Types of piezocones – porous element at u2 position is popular

2.5 Pressuremeter Test

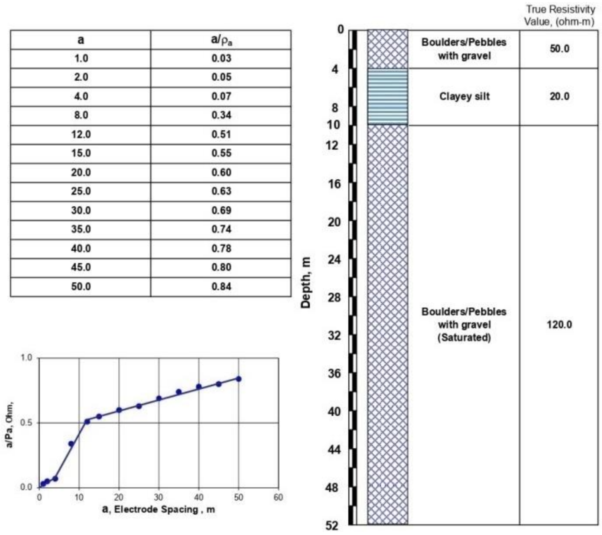
The Menard Pressuremeter and the dilatometer are finding applications in India on major power projects, bridges and metro projects, tall buildings, etc. The test is usually done in pre-bored holes; self-boring pressuremeter is not presently available in the country.

The limit pressure and deformation modulus obtained from the test may be used for bearing capacity and settlement analysis, etc [13]. The pressuremeter data is also useful in assessing in-situ horizontal stresses and can be correlated with various geotechnical parameters such as cohesion intercept, pre-consolidation pressure and over-consolidation ratio [14]. Fig. 5 presents a photograph of pressuremeter test in progress.

Fig. 5. Pressuremeter test in progress.

2.6 Electrical Resistivity Tests and Electrical Resistivity Imaging

The conventional electrical resistivity test using Wenner's configuration has been used in India for many years now. The data is analyzed using the inverse slope method to correlate with stratigraphy [15]. Fig. 6 presents a case study where stratigraphy along a bridge alignment near Jammu was effectively assessed using resistivity data [16].



a	a/ρ_a
1.0	0.03
2.0	0.05
4.0	0.07
8.0	0.34
12.0	0.51
15.0	0.55
20.0	0.60
25.0	0.63
30.0	0.69
35.0	0.74
40.0	0.78
45.0	0.80
50.0	0.84

Fig. 6. Stratigraphy interpreted from electrical resistivity test – highway project near Jammu.

Modern advancements include electrical resistivity imaging which helps electronic data acquisition and analyzing the data using advanced software to interpret the stratigraphy. Fig. 7 presents resistivity imaging performed by the authors at a station of Delhi Metro. Borehole data superimposed on the electrical resistivity image shows a good match of the lithology.

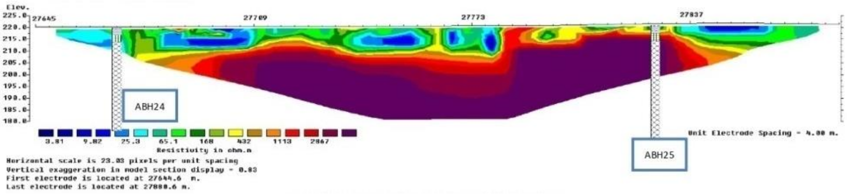


Fig. 7. Electrical Resistivity Imaging Results - Kochi.

2.7 Seismic Test

Seismic Refraction Tests. The test has been effectively used to assess the depth of bedrock and to evaluate geotechnical profile along alignments of highways, metrolines, etc. Fig. 8presents a seismic profile from the Delhi Metro project [17]. The data from two nearby boreholes shows a good match.

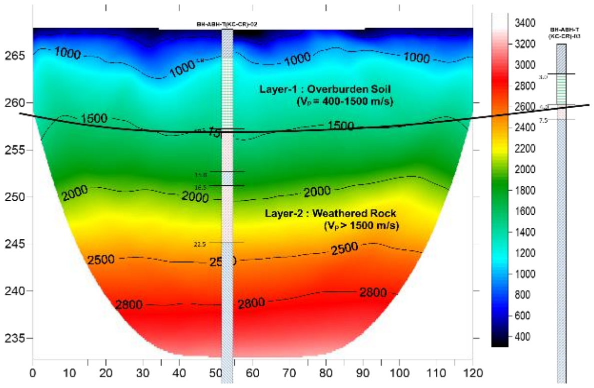
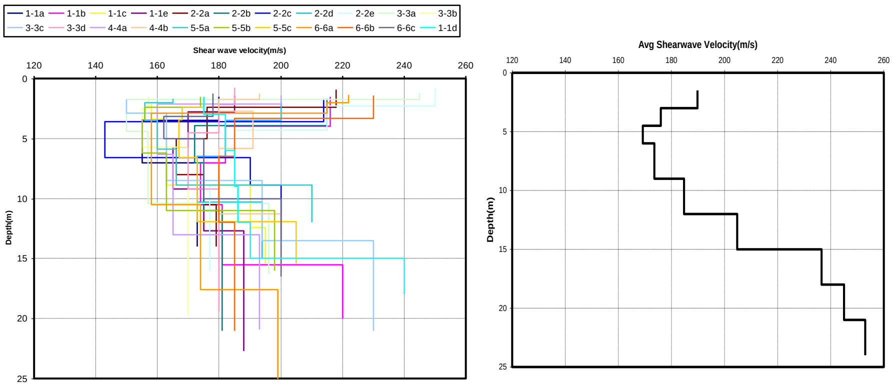


Fig. 8. Seismic refraction tests at a station along Delhi Metro alignment.

SASW and MASW. The tests rely on the dispersive characteristics of Raliegh wave to determine the shear wave velocity. Typical results of SASW tests performed at the Commonwealth Games village complex in Delhi is presented on Fig. 9[18].



(a) Measured Shear wave velocity along 6 lines at site (b) Average shear wave velocity used for design

Fig. 9. Shear wave velocity tests using SASW tests at Commonwealth Games Village at Delhi.

3 Case Study

3.1 Project Details and Scope of Work

The project site is within a refinery complex in the Indo-Gangetic alluvium and includes mounded bullets, large diameter tanks for storage of petroleum products, heavy equipment for Propylene Recovery Unit (PRU), and associated facilities. The scope of the geotechnical investigation included the following:

- 19 boreholes to 30 m depth;
- SPT analyzer tests in two boreholes;

- nine electric cone penetration tests (eCPTu) with porewater pressure measurement;
- pressuremeter tests in 4 boreholes;
- cross-hole seismic test at one location; and
- five thermal resistivity tests.

The scope also included trial pits, electrical resistivity and thermal conductivity tests, field CBR tests, etc. In the paper, data from one borehole (BH-9), one cone penetration test (eCPT-5), pressuremeter tests (PMT-3) and cross-hole seismic tests (SCH-1) performed in the vicinity have been evaluated in detail to bring out the correlations and the benefits accrued by performing a variety of tests to assess various geotechnical parameters. Fig.10 presents a layout plan identifying the location of the tests conducted for the PRU unit.

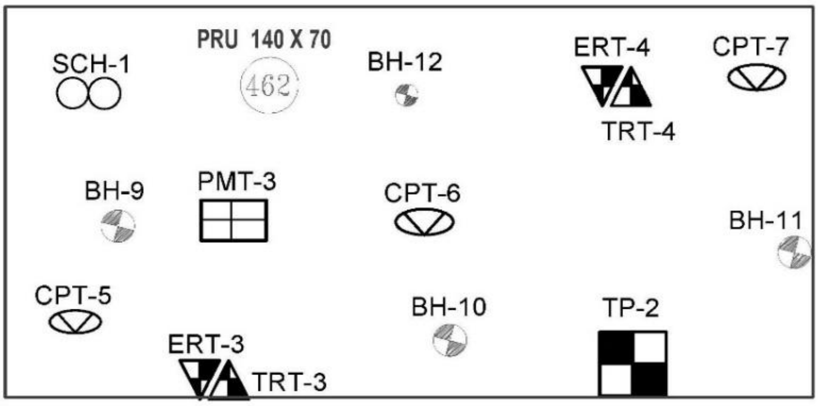


Fig. 10. Layout Plan – PRU Unit.

3.2 SiteStratigraphy

At the PRU, a fill was met at site to 1.0-1.5 m depth. Below this sandy silt/clayey silt was met at site to 6.0-7.5 m depth underlain by silty sand/ fine sand to the final explored depth of 30.0 m. Groundwater was encountered at 4.4-4.9 m depth during the period of the investigation. Typical profiles for four selected boreholes are presented on Fig. 11.

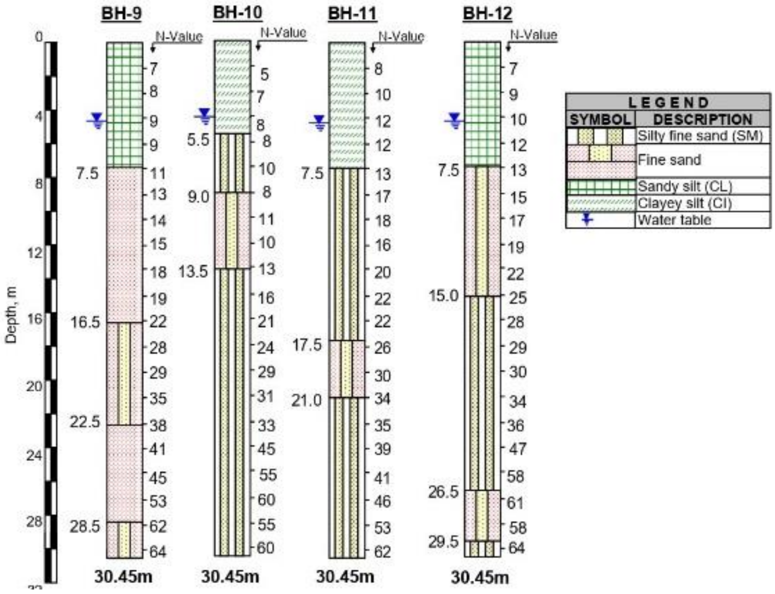


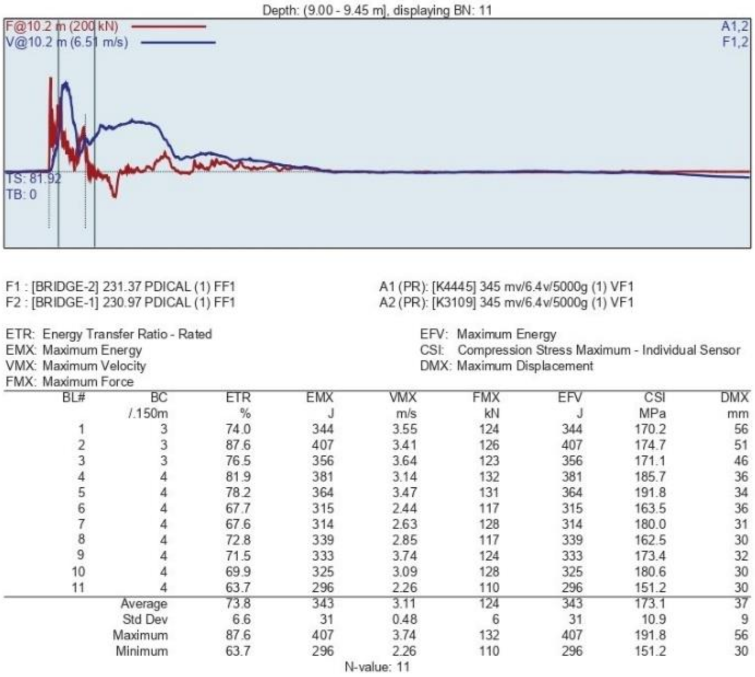
Fig. 11. Typical Borehole Data – PRU Unit.

3.3 SPT Energy Measurement

Since two rigs were used at site, SPT energy measurements were done in two boreholes, one for each rig at two depths. Typical energy measurement records are presented on Fig. 12. The test results are summarized on Table 1.

Table 1.SPT Energy Measurement – Case Study

RigNo.	Depth, m	Average Energy Transferred, %	Design Value
RR-4	7.5	72.8	73%
	9.0	73.8	
RR-6	3.0	80.2	84%
	4.5	88.7	



F1 : [BRIDGE-2] 231.37 PDICAL (1) FF1
F2 : [BRIDGE-1] 230.97 PDICAL (1) FF1

A1 (PR): [K4445] 345 mv/6.4v/5000g (1) VF1
A2 (PR): [K3109] 345 mv/6.4v/5000g (1) VF1

ETR: Energy Transfer Ratio - Rated
EMX: Maximum Energy
VMX: Maximum Velocity
FMX: Maximum Force

EFV: Maximum Energy
CSI: Compression Stress Maximum - Individual Sensor
DMX: Maximum Displacement

BL#	BC /.150m	ETR %	EMX J	VMX m/s	FMX kN	EFV J	CSI MPa	DMX mm
1	3	74.0	344	3.55	124	344	170.2	56
2	3	87.6	407	3.41	126	407	174.7	51
3	3	76.5	356	3.64	123	356	171.1	46
4	4	81.9	381	3.14	132	381	185.7	36
5	4	78.2	364	3.47	131	364	191.8	34
6	4	67.7	315	2.44	117	315	163.5	36
7	4	67.6	314	2.63	128	314	180.0	31
8	4	72.8	339	2.85	117	339	162.5	30
9	4	71.5	333	3.74	124	333	173.4	32
10	4	69.9	325	3.09	128	325	180.6	30
11	4	63.7	296	2.26	110	296	151.2	30
	Average	73.8	343	3.11	124	343	173.1	37
	Std Dev	6.6	31	0.48	6	31	10.9	9
	Maximum	87.6	407	3.74	132	407	191.8	56
	Minimum	63.7	296	2.26	110	296	151.2	30

N-value: 11

Fig. 12. SPT Energy Measurement Tests.

The SPT value was first corrected for energy; then the overburden and dilatancy corrections were applied. The corrected N value (N_{60}) for one typical borehole is presented on Fig. 13.

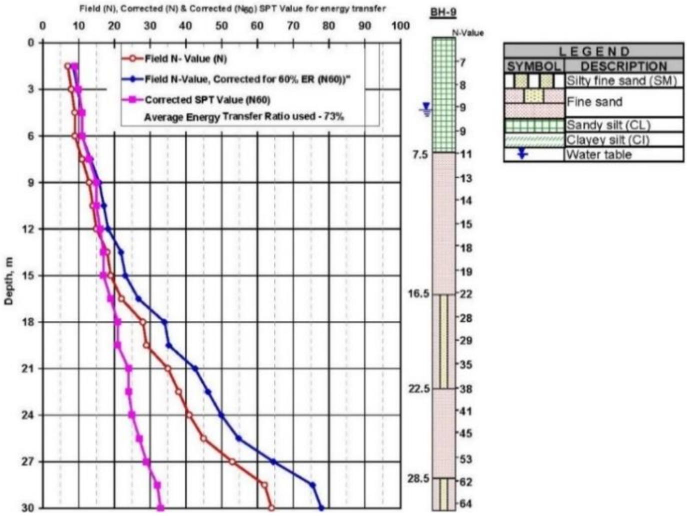


Fig. 13. SPT values plot for one typical borehole (BH-9) showing N values corrected for energy, overburden & dilatancy (PRU).

3.4 eCPT

Nine eCPT tests were conducted at the site (3 Nos. in PRU). Results of one typical test (CPT-5) is illustrated on Fig. 14.

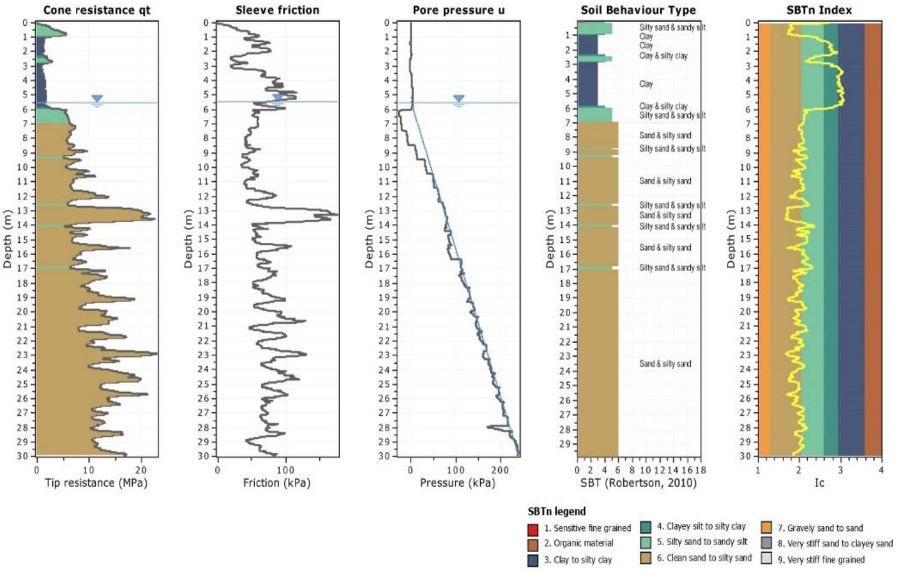


Fig. 14. Typical eCPT plot (CPT-5) showing cone tip resistance, friction ratio and pore water pressure together with soil behavior type classification (PRU).

The soil behavior type index, SBTn index proposed and updated by Robertson, 2010 [19] provides an effective method to classify the soils based on the cone tip resistance and friction ratio. Robertson developed a chart to assess the soil behavior index.Fig. 15 presents plot of normalized cone resistance versus normalized friction ratio to identify the soil classification based on SBTn.

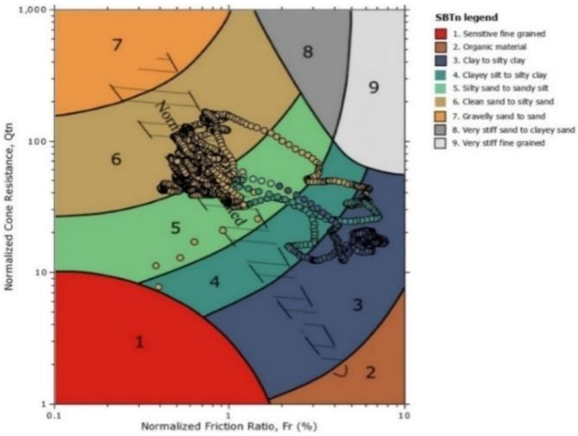
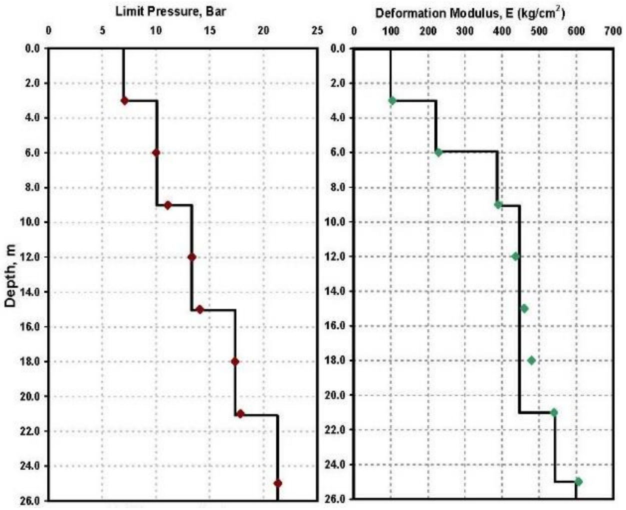


Fig. 15. Normalized SBTn plot – eCPT-5 (PRU).

3.5 Pressuremeter Tests

Pressuremeter data from one typical borehole (PMT-3) is presented on Fig. 16 showing theprofile of limit pressure and deformation modulus with depth.



Profile of limit pressure and deformation modulus versus depth

Fig. 16. Pressuremeter test results – PMT-3(PRU).

3.6 Cross-Hole Seismic Tests

One cross-hole test was performed at the PRU unit. Three boreholes were drilled at a spacing of 3-m centre-to-centre. One borehole was used as source borehole and geophones were placed in the other two boreholes (receiver). The primary and shear wave velocities were determined from the test. Results were evaluated to assess the dynamic shear modulus and dynamic Young’s modulus. The results are presented graphically on Fig. 17.

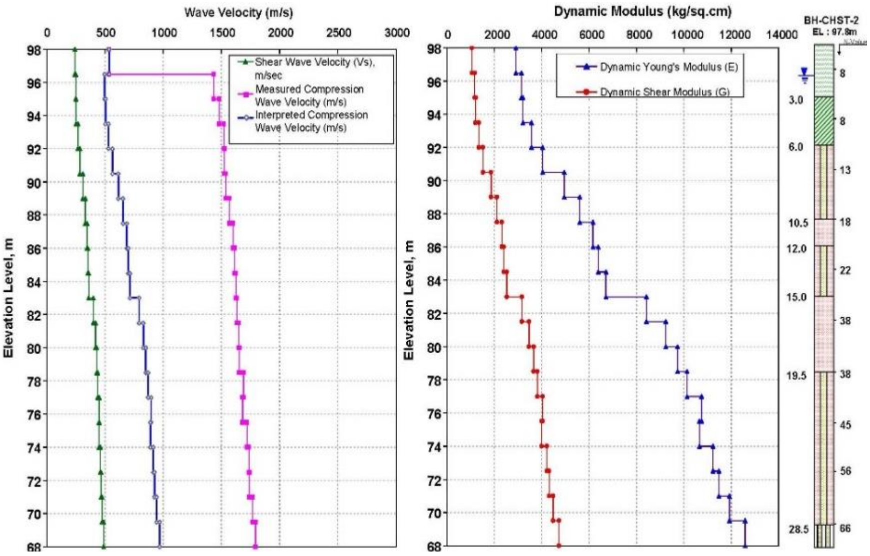


Fig. 17. Results of cross-hole seismic test SCH-1 (PRU).

4 Correlations

An attempt has been made to compare the CPT correlations proposed by Robertson & Cabal [20] with measured field data so as to develop a confidence in the quality and reliability of data and to assess the scatter in the various parameters interpreted from different tests.

The authors have compared the CPT correlations with correlations based on borehole data, pressuremeter tests and cross-hole seismic tests. For the purpose of comparison, results from BH-9, CPT-5, PMT-3 and SCH-1 have been used.

Published CPT based correlations by Robertson and Cabal [20] are summarized in Appendix-A. Correlations for pressuremeter(PMT) parametersgivenby Clarke [13] are given in Appendix-B.

4.1 SPT value – N_{60} and Fines Content

Robertson [21] correlated the $(q_c/p_a)/N_{60}$(p_a = atmospheric pressure) to soil gradation and found a reliable trend. Grain characteristics have been estimated from CPT results using SBTn charts. The SBTn charts show a clear trend of increasing friction ratio with increasing fines content and decreasing grain size.

The $(q_c/p_a)/N_{60}$ ratio ranges from 2 for sensitive fine-grained soils and silt mixtures to 3 for sand mixtures and 5 for clean sands. A similar correlation is also given by

Bowles [22]. Fig. 18 presents the SPT plot correlation at eCPT-5 compared with N_{60} recorded at BH-9.

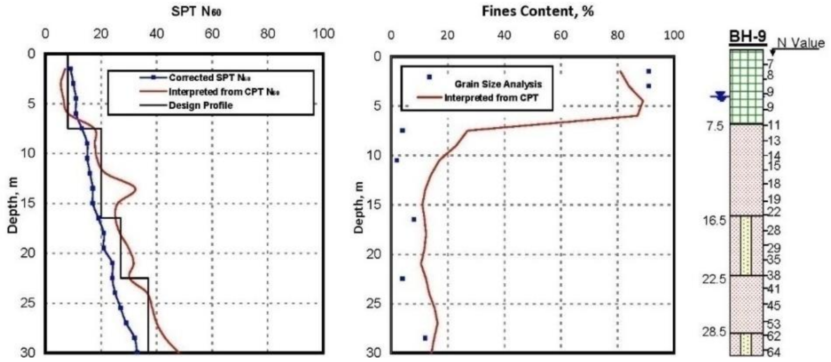


Fig. 18. Comparison of N_{60} from boreholes with N_{60} interpreted from eCPTand % fines as interpreted from CPT (friction ratio) - PRU.

4.2 Total Unit Weight / Bulk Density

Soil total unit weight or bulk density (γ_t) is best obtained from relatively undisturbed samples. When this is not feasible, the total unit weight can be estimated from CPT results using the correlation proposed by Robertson and Cabal [20] or SPT correlations given by Bowles [22]. Fig. 19 presents the γ_t values from undisturbed samples compared with the values interpreted from CPT.

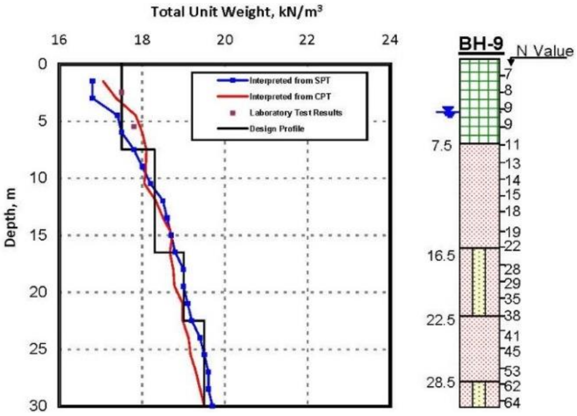


Fig. 19. Comparison of γ_t from UDS with γ_t interpreted from CPT (PRU).

4.3 Cohesion Intercept

Cohesive soil was met from the ground surface to 7.5 m depth. The laboratory c values from UU triaxial tests have been compared with the c value interpreted from CPT as well as pressuremeter test (Baguelin et al [23]) on Fig. 20. The undrained c value interpreted from CPT and pressuremeter test are somewhat higher from that obtained from laboratory test (probably due to sample disturbance) suggesting superior quality of in-situ test data.

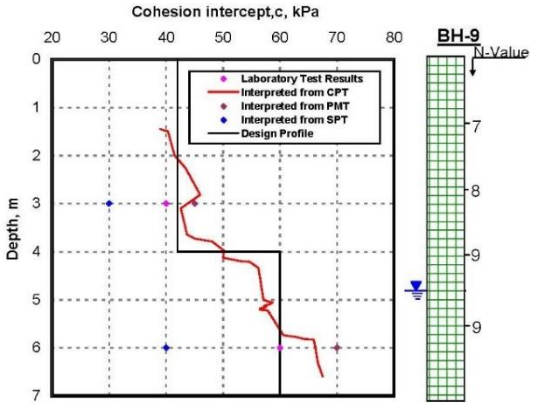


Fig. 20. Comparison of laboratory c values with c interpreted from CPT, SPT and pressure-metertest (PRU).

4.4 Angle of Internal Friction ϕ

Sand / silty sand was met below 7.5 m depth. The laboratory c values from CDdirect shear tests performed on the sand stratum have been compared with the ϕvalue interpreted from CPT [21] andSPT values(IS: 6403-1981 [24])on Fig. 21.

It may be seen that ϕ interpreted from CPT is generally higher than the laboratory values suggesting that the in-situ ϕ is higher than the values determined in the laboratory. The ϕ interpreted from SPT is lower than the CPT interpretation to 20-25 m depth below which SPT based ϕ is higher and may not be reliable.

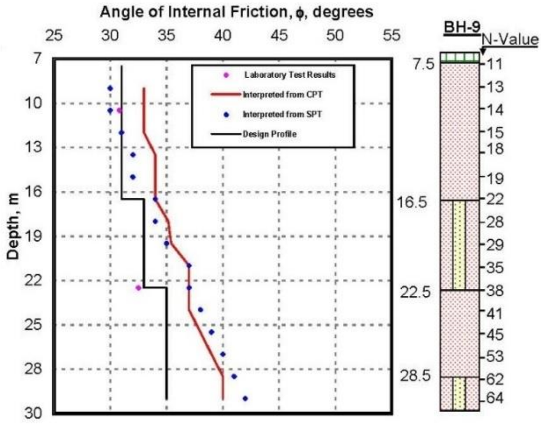


Fig. 21. Comparison of laboratory ϕ values with ϕ interpreted from CPT and SPT (PRU).

The design ϕ value used for the project as illustrated in Fig. 21 was somewhat conservative. The authors believe that for well-constructed piles, the value of f can probably be increased by 2-3°.

4.5 Modulus of Elasticity

The modulus of elasticity E is correlated from N values as per the correlation given by Bowles[22]. Robertson & Cabal [20] state that correlation between q_c and Young'smodulus (E) is sensitive to stress-strain history, mineralogy, aging and drainage conditions.

Pressuremeter tests give deformation modulus based on volumetric strains. Being an in-situ test in the borehole, pressuremeter test causes least disturbance to in-situ conditions and is therefore very reliable. Haberfield [25] proposed that E values obtained from geophysical tests may be multiplied by 0.2 to obtain the E value for static loading.

Fig. 22 presents the E values correlated from various tests. It is evident that CPT and CHST and pressuremeter give higher values of E in comparison to that interpreted from SPT. The design E value may be considered closer to CPT and CHST.

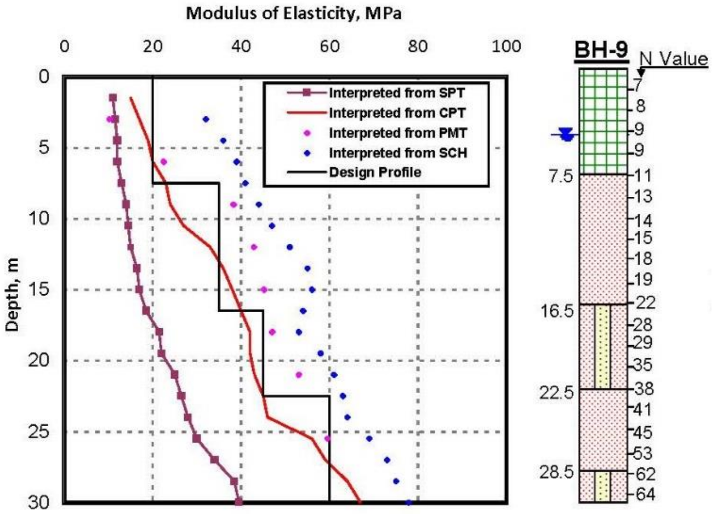


Fig. 22. E-values interpreted from CPT, SPT, pressuremeter and cross-hole seismic test (PRU).

Since the E value influences the foundation settlement analysis, the selection of a realistic value of E has a great bearing on the foundation design.

4.6 Pre-consolidation Pressure and Over-consolidation Ratio

The pre-consolidation pressure (p_c) is usually determined from consolidation tests performed in the laboratory. CPT correlations by Robertson are based on correlations by Kulhawy and Mayne [26] and Mayne [27].

Clarke [13] also gives a correlation be-tween pre-consolidation pressure and limit pressure from pressuremeter tests.Fig.23 presents a plot of $p_c$and over-consolidation ratio (OCR) versus depth as interpreted from the various tests.

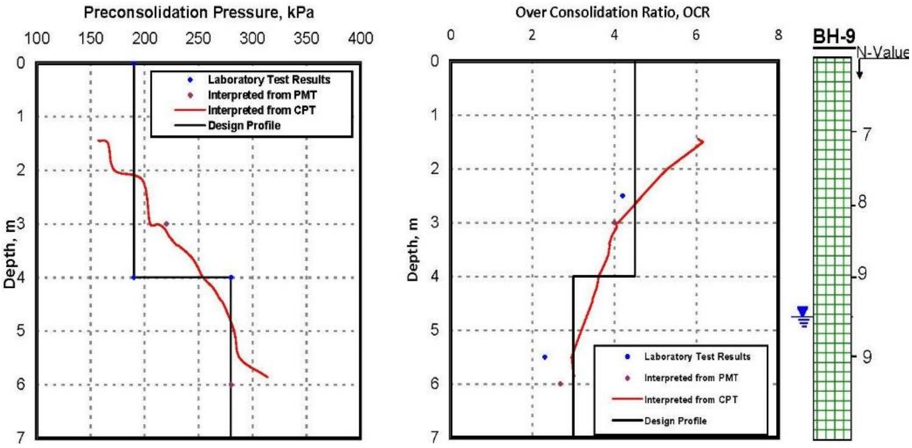


Fig. 23. Pre-consolidation pressure (p_c) and OCR from laboratory tests compared with values interpreted from CPT and pressuremeter test (PRU).

The OCR and p_c will influence the consolidation settlement of the foundation. Selection of realistic values from field tests can be a great advantage. Where critical, conducting dissipation tests using eCPTu to assess the time for dissipation of pore water pressure can assist in estimating settlement as well as time for consolidation.

4.7 In-Situ Horizontal Stress

The in-situ horizontal stress may be determined from pressuremeter test by plotting creep volume versus pressure (Ravi Sundaram et al [14]). This has been compared with the in-situ horizontal stress from CPT on Fig. 24. A reference line of in-situ horizontal stress computed assuming coefficient of earth pressure at rest (k_0) is also plotted on the graph for comparison purpose. A good match is seen between k_0 calculated from CPT and PMT.

The horizontal earth pressure as well as k_0 are used to design pressures on deep excavation supports, tunnel linings, etc. CPT and pressuremeter tests can be used to make a realistic evaluation.

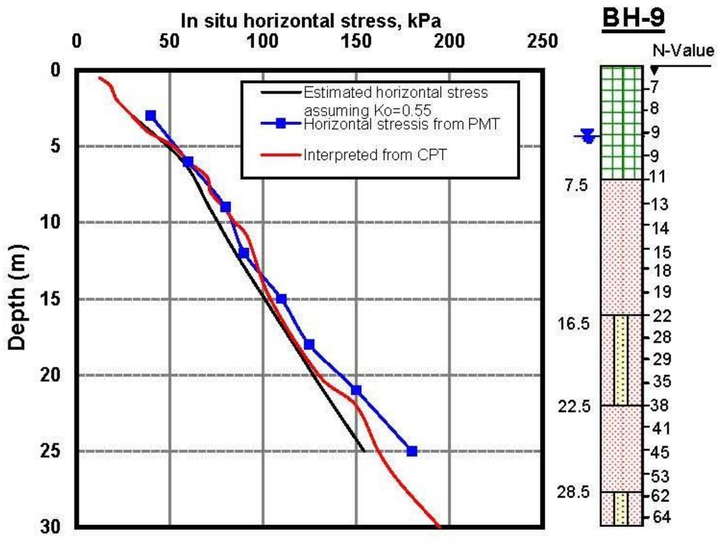


Fig. 24. In-situ horizontal stress from pressuremeter compared with stresses interpreted from CPT (PRU).

4.8 Shear Wave Velocity and Dynamic Shear Modulus

Correlation proposed by Robertson & Cabal [20] and Mayne & Rix [28] for CPT has been compared with the measured shear wave velocity and computed dynamic shear modulus from cross-hole seismic test (CHST) on Fig. 25. Results show a good match to about 18-20 m depth below which measured Vs values are somewhat higher.

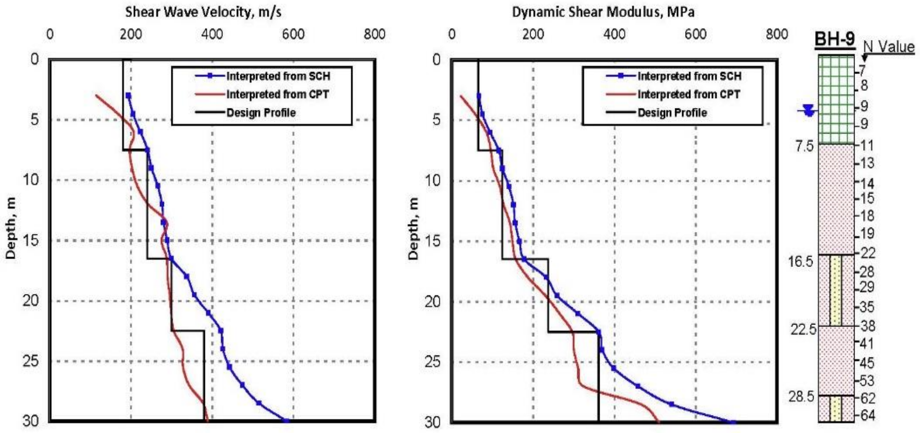


Fig. 25. Shear Wave Velocity from cross-hole seismic test compared with values interpreted from CPT (PRU).

The shear wave velocity is usually used for earthquake analysis and design of dynamically loaded foundations. Where geophysical test for measuring V_s is not done, the CPT correlations can be useful and reliable.

5 Liquefaction Analysis

Liquefaction analysis has been performed using the SPT values, CPT profile and Vs profile (from CHST) in accordance with Annex F of IS: 1893 Part 1 [29]. The highest groundwater level was taken at 2 m depth for the worst condition. The CSR, CRR and factor of safety are presented on Fig. 26.

The liquefaction analysis was done for the following conditions:

Design Earthquake Magnitude	: 6.5 on Richter scale
Peak Ground Acceleration	: 0.24g

Liquefaction is likely in the sand stratum below 7.5 m depth. Results indicate that the depth of liquefaction may range from 7.5 m depth to10-20 m for a factor of safety of 1.0. The analysis using V_s indicates liquefaction to deeper depth.However, SPT and CPT based analysis suggests liquefaction to 9-14.5 m depth. For design purpose, the authors suggest that the liquefaction may be considered occur between 7.5 and 14.5 m depth (FOS = 1).

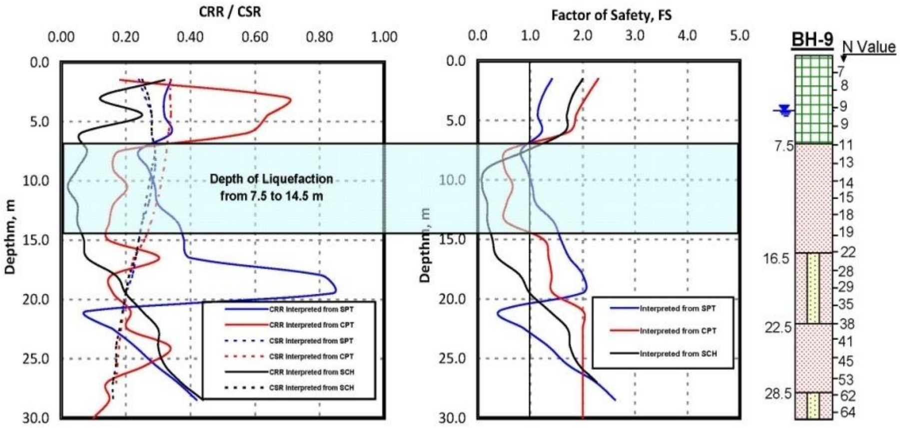


Fig. 26. Results of liquefaction analysis using SPT, CPT and Shear wave velocity (PRU).

6 Design Profile

Reviewing all the correlations from the various tests, the design profile for the PRU facility as interpreted from the geotechnical investigation is given in Fig. 27.

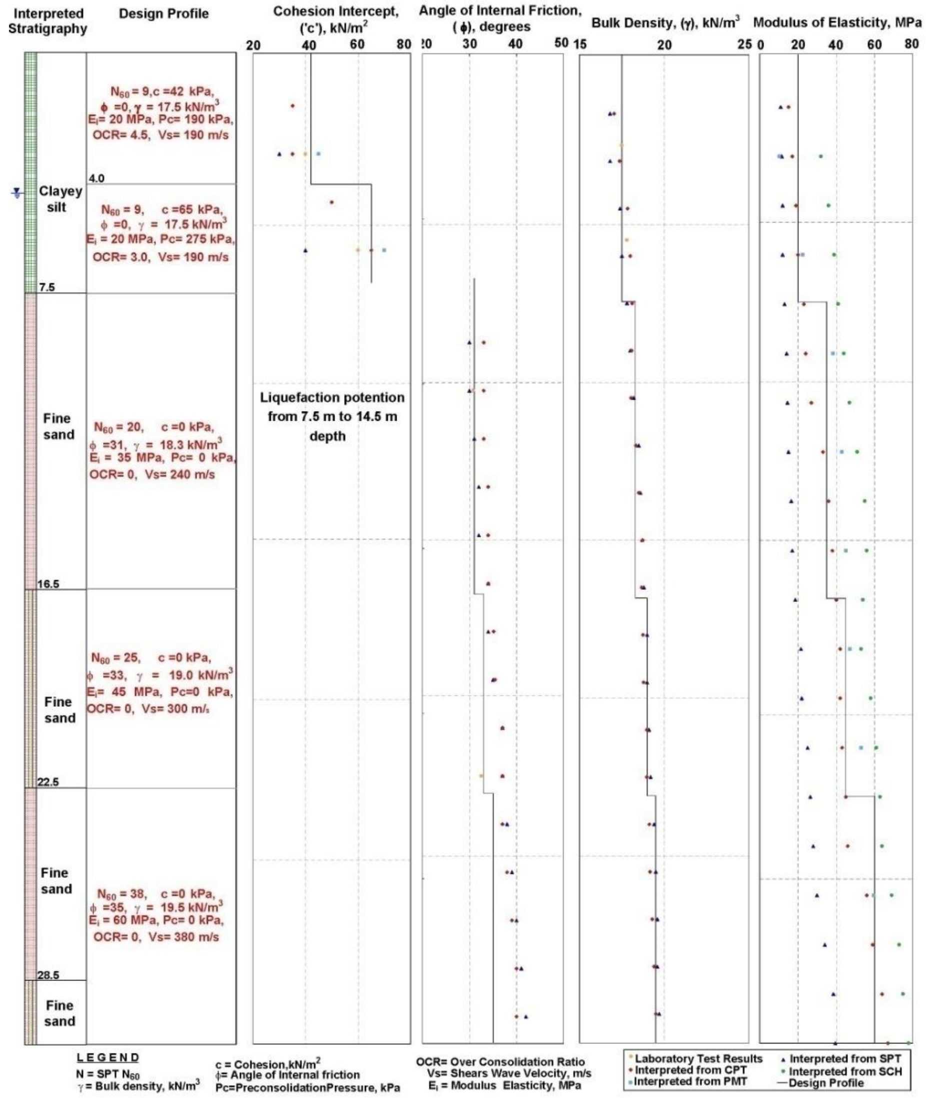


Fig. 27. Design Profile as interpreted from the various tests conducted (PRU).

The updated design profile prepared after review of parameters from a variety of tests ensured a more reliable and economical design of the foundation system for the PRU unit.

7 Concluding Remarks

With a variety of in-situ tests available, modern geotechnical investigations need to effectively collate data from various tests to select a realistic design profile for foundation analysis. Improved ability to and characterize the subsurface is important to evaluate geotechnical issues on projects. Improved data acquisition and digital data processing can assist in analysis of large quantum of data. This improves the geotechnical engineer's ability to characterize soil variability and the uncertainty in soil properties to reliably predict soil behavior.

The modern testing techniques highlighted in the paper are now available in the country and are being used effectively to enhance the quality of geotechnical investigations on major projects. There is a need to make these technologies mandatory and common practice in the Indian industry so as to match international practices and norms.

Published correlations are available for a host of geotechnical parameters using CPT and pressuremeter data.Some of these are summarized in Appendices A and B. There is a need for evaluating and updating these correlations based on data from sites in India. This requires building up of a large data base from Indian sites to develop correlations that are reliable and universally applicable.

References

1. Sanjay Gupta, Ravi Sundaram: In-situ Testing - Current Trends in Geotechnical Investigations. Proceedings, Indian Geotechnical Conference (IGC-2003), Roorkee, Volume-II, pp 635-645(2003).
2. Jianye Ching, Kok-Kwang Phoon: Value of Geotechnical Site Investigation in Reliability-Based Design. Advances in Structural Engineering, Vol. 15(11), pp.1935-1945 (2012).
3. Anbazhagan, P., Kumar Ayush, Yadhunandan, M. E., Kumar Siriwanth, Suryanarayana, Sahodar, K. G.: Effective Use of SPT: Hammer Energy Measurement and Integrated Subsurface Investigation.Indian Geotechnical Journal, Vol. 52(5), pp. 1079–1096(2022).
4. ASTM D 4663: Standard Test Method for Energy Measurement for Dynamic Penetrometers. ASTM International, West Conshohocken, PA-2020 (2016).
5. IS: 2131: Method for Standard Penetration Test for Soils. Indian Standard Code of Practice, Bureau of Indian Standards, New Delhi (1981).
6. IRC:78: Standard Specifications and Code of Practice for Road Bridges, Section VII: Foundation and Substructure. Indian Roads Congress, New Delhi (2014)
7. Ravi Sundaram, Sanjay Gupta, Sorabh Gupta, Rajesh Gupta: Optimizing Foundation Design through Quality Geotechnical Investigation: Case Study of Bridge across River Tapi. Journal of the Indian Roads, ISSN 0258-0500 Volume 81-3, pp. 46-53 (2022).
8. ASTM D5778: Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils. ASTM International, West Conshohocken, PA-2020 (2020)
9. Lunne, T., Robertson, P.K., Powell, J.J.M.: Cone Penetration Testing in Geotechnical Practice. Blackie Academic & Professional, an Imprint of Chapman & Hall, London(1997).

10. IS: 4968: Method for Subsurface Sounding of Soils, Part 3: Static Cone Penetration Test, Indian Standard Code of Practice, Bureau of Indian Standards, New Delhi (1976).
11. http://www.lankelma.co.uk/cone-penetration-testing/cone-penetrometers/piezocone/
12. http://commonfinchjuly.cocolog-nifty.com/blog/2012/12/cone-penetratio.html
13. Clarke, B. G.: Pressuremeters in Geotechnical Design. Blackie Academic &Professional (1995).
14. Ravi Sundaram, Sanjay Gupta, Sorabh Gupta, Bhajan Lal: Geotechnical Design Parameters for a Metro Tunnel from Pressuremeter Tests. Geotechnics for Transportation Infrastructure. Ravi Sundaram, J.T. Shahu & Vasant Havanagi (eds), Springer Nature, Singapore, Vol 2 pp. 57-69 (2019).
15. Ravi Sundaram, Sanjay Gupta: Use of Electrical Resistivity Tests for Geotechnical Investigation for Bridges. Journal of the Indian Roads Congress, Paper No.473, Volume 62-1, pp 115-131(2001).
16. Ravi Sundaram: Geotechnical Investigation under Difficult Soil Conditions – Indian Experiences. Sixth Madhav Lecture, Hyderabad (2017).
17. Ravi Sundaram, Sanjay Gupta, Sorabh Gupta: Geophysical Characterization of Metro Station Sites. International Conference on Geotechnics for High-Speed Corridors, Thiruvananthapuram, India (2019).
18. Sanjay Gupta, Ravi Sundaram, Sorabh Gupta, G.V. Ramana, Masthan, G., Sen, R., Surya Narayana, K.: Liquefaction Susceptibility Study at Commonwealth Games Village Delhi. Proceedings, Indian Geotechnical Conference (IGC-2008), Bangalore, Volume-II, pp 436-440(2008).
19. Robertson, P. K.: Soil behavior type from the CPT: an update. Proceedings, 2nd International Symposium on Cone Penetration Testing, Huntington Beach, CA, USA (2010).
20. Robertson, P. K., Cabal, K. L: Guide to Cone Penetration Testing for Geotechnical Engineering.Gregg Drilling & Testing, Inc., 6th edition (2014).
21. Robertson, P. K.: Estimating in-situ state parameter and friction angle in sandy soils from CPT. Proceedings, 2nd International Symposium on Cone Penetration Testing, Huntington Beach, CA, USA (2014).
22. Bowles, J. E: Foundation Analysis and Design. Fifth edition, The McGraw-Hill Companies Inc. (1996).
23. Baguelin, F., Jezequel, J.F., Shields, D.H.:ThePressuremeter and Foundation Engineering. Trans Tech Publications, Clausthal(1978).
24. IS 6403: Code of Practice for Determining Bearing Capacity of Shallow Foundations. Indian Standard Code of Practice, Bureau of Indian Standards, New Delhi (1981 Reaffirmed 2002).
25. Haberfield, C. M.: Practical experience in piled-raft design for tall buildings. Proceedings, 18th ICSMGE, Paris (2013).
26. Kulhawy, F.H., and Mayne: Manual on estimating soil properties for foundation design. Report EL-6800 Electric Power Research Institute, EPRI [1990].
27. Mayne, P.W.: NCHRP Synthesis ‘Cone Penetration Testing State-of-Practice’. Transportation Research Board Report Project 20-05. 118 pages. www.trb.org (2007).
28. Mayne, P. W., Rix, G. J.: Correlations between shear Wave Velocity and Cone tip Resistance in Natural Clays. Soils and Foundations Vol. 35, No. 2, pp.107-110, Japanese Society of Soil Mechanics and Foundation Engineering (1995).
29. IS 1893: Criteria for Earthquake Resistant Design of Structures Part 1 - General Provisions and Buildings. Indian Standard Code of Practice, Bureau of Indian Standards, New Delhi (2016).

Appendix-A: Correlations of q_c with geotechnical parameters

Corrected Cone Resistance, q_t

$$q_t = q_c + u_2\,(1 - a)$$

Where a = net area Ratio determined from laboratory calibration (typical value is between 0.70 and 0.85). In sands, $q_t = q_c$

Normalized Cone Resistance, Q_t

$$Q_t = \left[\frac{q_t - \sigma_{v0}}{\sigma'_{v0}}\right]$$

Friction Ratio, R_f (%)

$$R_{f}= \left[\frac{f_s}{\sigma_{v0}}\right] x100\%$$

Normalized Friction Ratio, F_r (%)

$$F_r = \left[\frac{f_s}{q_t - \sigma_{v0}}\right]\ x\ 100$$

Soil Behavior Type Index, I_c

$$I_c = (3.47 - \log Q_t)^2 + (\log F_r + 1.22)^2)^{0.5}$$

I_{c_cutoff}= I_c limit for cohesive and granular soil

If I_c>2.6, soil is classified as cohesive

If I_c<2.6, soil is classified as granular

Normalized Cone Resistance, Q_{tn}(Atmosphere)

$$Q_{tn} = \left[\frac{q_t - \sigma_{v0}}{P_a}\right]\left(\frac{P_a}{\sigma'_{v0}}\right)^n$$

$$n = 0.381I_c + 0.05\left[\frac{\sigma'_{v0}}{P_a}\right] - 0.15$$

Unit Weight, γ(kN/m³)

$$\gamma = \gamma_w\left[0.27\log[R_f]0.36\log\left[\frac{q_t}{P_a}\right] + 1.236\right]$$

SPT N_{60}

$$N_{60} = \left[\frac{q_c}{P_a}\right]\frac{1}{10^{1.1268-0.2817\,I_c}}$$

Young's Modulus, Es (MPa)

$$E_s = [q_t - \sigma_{v0}]0.015.\,10^{0.55.I_c+1.68}$$

Note: Applicable only to I_c<2.6

Relative Density, Dr (%)

$$D_r = 100\sqrt{\frac{Q_{tn}}{K_{DR}}}$$

Note: Applicable only to SBTn: 5, 6, 7 and or I_c<I_{c_cutoff}

Undrained Peak Shear Strength, S_u(kPa)

$$S_u = \frac{[q_t - \sigma_{vo}]}{N_{kt}} N_{kt} = 10.5\log[F_r]$$

Note: Applicable only to SBTn: 1, 2, 3, 4 and 9 or I_c>I_{c_cutoff}

Friction Angle, ϕ°(Degree)

$$\phi^\circ = 29.5^\circ\,B_q^{0.121}(0.256 + 0.336B_q + \log Q_t)$$

Note: Applicable for 0.10 <B_q<1.00

$$B_q = \frac{\Delta_u}{q_n}\Delta_u = u_2 - u_o q_n = q_t - \sigma_{v0}$$

Over-consolidation Ratio, OCR

$$K_{OCR} = \left[\frac{{Q_{tn}}^{0.20}}{0.25(10.50 + 7\log(F_r))}\right]$$

$$OCR = K_{OCR}Q_{tn}$$

Note: Applicable only to SBTn: 1, 2, 3, 4 and / or I_c> I_{c_cutoff}

In situ Stress Ratio, k_0 (coefficient of earth pressure at rest)

$$k_0 = [1 - \sin\,\phi^\circ]OCR^{\sin\phi^\circ}$$

Note: Applicable only to SBT n: 1,2,3,4 and 9 or I_c or I_c> I_{c_cutoff}

Shear Wave Velocity, Vs (m/s)

$$V_s = \left[\frac{G_o}{\rho}\right]^{0.5}$$

Small Strain Shear Modulus, G_o (MPa)

$$G_o = [q_t - \sigma_{v0}]0.0188.\,10^{0.55\,I_c+1.68}$$

Permeability, k (m/s)

$k = 10^{0.952-3.04\,I_c}$ for 1.0<I_c<3.27

$k = 10^{-4.52-1.37.I_C}$ for 3.27<$I_c \leq 4.0$

1-D constrained modulus, M (MPa)

$$M_{CPT} = \alpha\,[q_t - \sigma_v]$$

If I_c> 2.20

α = 14 for Q_{tn}> 14   α = Q_{tn} for $Q_{tn} \leq 14$

If I_c< 2.2, $\alpha = 0.0188[10^{0.55I_c+1.68}]$

where

γ	:	Unit weight, kN/m^3	I_c	:	Soil behavior type index
γ_w	:	Unit weight ofwater, kN/m^3	I_{c_cutoff}	:	I_c limit for cohesive soil i.e., >2.6
q_c	:	Cone tip resistance, kPa	Q_{tn}	:	Normalized cone resistance, (Atmospheric)
f_s	:	Sleeve friction, kPa	q_t	:	Corrected cone resistance, kPa
S_u	:	Undrained shear strength, kPa	$\phi°$	:	Friction angle (Degree)
P_a	:	Atmospheric pressure = 100 kPa	N_{Kt}	:	Cone factor value
σ_{v0}	:	Total overburden pressure, kPa	F_r	:	Normalized friction ratio. %
σ'_{vo}	:	Effective overburden pressure, kPa	n	:	Stress exponent
R_f	:	friction ratio. %	SBTn	:	Soil behavior type index number
B_q	:	Pore pressure ratio	Δ_u	:	Excess pore-water pressure, kPa
Q_t	:	Normalized cone resistance	u_2	:	Pore-water pressure, kPa
K_{OCR}	:	OCR number	u_0	:	Initial pore-water pressure, kPa
OCR	:	Over-consolidation ratio	G_0	:	Small-strain shear modulus, MPa
M_{CPT}	:	1-D Constrained modulus, MPa	N_{60}	:	SPT value corresponding to 60% energy transfer
k_0	:	In situ stress ratio	p	:	Mass density of soil,
k	:	Permeability, m/s	V_s	:	Shear wave velocity, m/s
ɑ	:	Soil factor	a	:	Net area ratio

Appendix-B: Correlations of PMTbased geotechnical parameters

$E = k\dfrac{\Delta p}{\Delta V}$ PMT probe dimensional coefficient $k = (1+\mu)\,2(V_0 + V_m)$

$s_u = \dfrac{(p_L - p_0)}{N_p}$ Correlation factor $N_p = 1 + \ln(E_m / 3s_u)$ where ln=(log)$_e$

$p_c = \dfrac{4s_u}{M}$ Critical state parameter M = 6 sin ϕ/(3-sin ϕ)

where:

E =pressuremeter modulus or deformation modulus

μ =Poisson's ratio

Δp = change in pressure corresponding to change in radius of cavity Δr

V = volume of the cavity at the instant when (measured in the pseudo-elastic phase of test)

ΔV= change in volume corresponding to change in pressure Δp

V_0 = initial or at rest volume of the measuring cell

V_m = mean additional volume injected (read directly on the sight tube of Menard Pressuremeter)

s_u = undrained shear strength (= 2c)

p_L = limit pressure determined from pressuremeter test

p_0 = in-situ horizontal stress

p_c = pre-consolidation pressure

s_u = undrained shear strength

ϕ = effective angle of shearing resistance, determined from CU triaxial tests