IMPLEMENTING ADVANCED GEOTECHNICAL INVESTIGATION TECHNIQUES – CASE STUDY OF A MULTI-STOREYED RESIDENTIAL COMPLEX IN GURUGRAM

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ABSTRACT

This paper presents a case study of implementation of modern geotechnical investigation techniques for the design and construction of a multi-storeyed residential complex in Gurugram. The geotechnical investigation involved a comprehensive study of the site conditions and use advanced testing methods such as SPT energy measurement, Electrical Cone Penetration Test (eCPT), and footing load test. The results of the investigation provided valuable insights into the soil properties and helped to understand the foundation behavior of the site. The successful implementation of these advanced geotechnical investigation techniques resulted in an efficient and safe foundation design for the complex.

Keywords: modern geotechnical investigation techniques, SPT energy measurement, electrical cone penetration test, footing load test, foundation behavior.

INTRODUCTION

With tall buildings and heavily loaded industrial facilities doting our urban landscape, the demand for good quality geotechnical data has been growing. To obtain realistic soil parameters that represent the in-situ conditions better requires a thorough and comprehensive geotechnical investigation. The conventional geotechnical investigation methods and traditional empirical methods of foundation analysis need to be updated to generate realistic geotechnical parameters for input into the advanced analysis programs that are now being used for foundation analysis and structural design. The thrust is on reliable designs that encroach on the factor of safety while economizing the foundation system and ensuring its safety.

To this end, geotechnical investigation practice has to keep pace with the developments to stay relevant and in-tune with industry demands. In-situ testing and digital data acquisition have revolutionized the way geotechnical investigations are performed.

The paper presents a case study of a multi-storeyed residential complex where cone penetrometertests using piezo-cone and footing load tests were effectively used to optimize foundation design. SPT energy measurement helped in standardizing the SPT data.It illustrates the selection of design parameters using these tests and the benefits accrued by implementing modern in-situ tests in the foundation design.

Ravi Sundaram et al [1] discuss the state of practice of geotechnical investigations in the country and the importance of in-situ tests and digital data acquisition. The application of these technologies is discussed here.

While many of the techniques are being used in the country, the authors highlight that the use is limited and restricted to major projects only. There is limited awareness on need for correction of SPT for energy transfer or the parameters that can be interpreted from use of piezocone. Footing load tests are still not the norm for tall buildings and heavily loaded facilities. The values of modulus of subgrade reaction are usually guessed from N values which leads to a conservative design.

Further, the awareness in the industry is less about the benefits of these modern tests. There is a need to increase the field implementation and enhance the quality of geotechnical practice at grass-roots level. This paper highlights the importance of a detailed geotechnical investigation and the need to implement the modern testing methods.

PROJECT DESCRIPTION

A premium housing complex having seven towers with G + 32 floors + 2 basements is coming up in Gurugram. The towers will be about 117 m high. The basement floor shall be at a depth of 8.4 m below finished floor level. An artist's impression of what the buildings will look like is illustrated on Fig. 1.Fig. 2 presents a conceptual layout of the project.

Fig. 1. An artist's image of the project

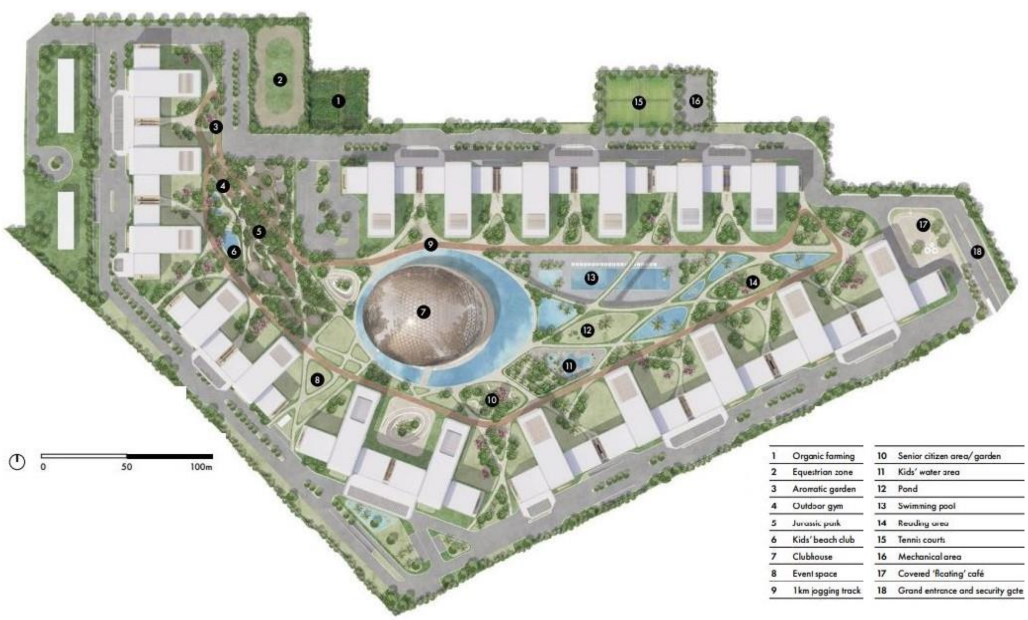


Fig. 2. Conceptual layout of the project

SCOPE OF GEOTECHNICAL INVESTIGATION

The scope of the investigation for the project included the following:

- drilling thirteen (13) exploratory boreholes to 40 m depth including routine laboratory tests on the samples as recovered;
- conducting SPT analyzer test to evaluate the hammer efficiency of the drilling rigs used;
- conducting thirty-six (36) electric cone penetration tests using piezocone (CPTu) to maximum 40 m depth or refusal, whichever is earlier;
- performing two footing load tests at the planned foundation level.

A layout plan illustrating the locations of the field investigation is illustrated on Fig. 3. Ravi Sundaram et al (2018) present a case study where use of modern testing for a tall building in Noida and developing realistic design profile was used to effectively economize the piled-raft system, resulting in a saving of nearly 23 crores [2].

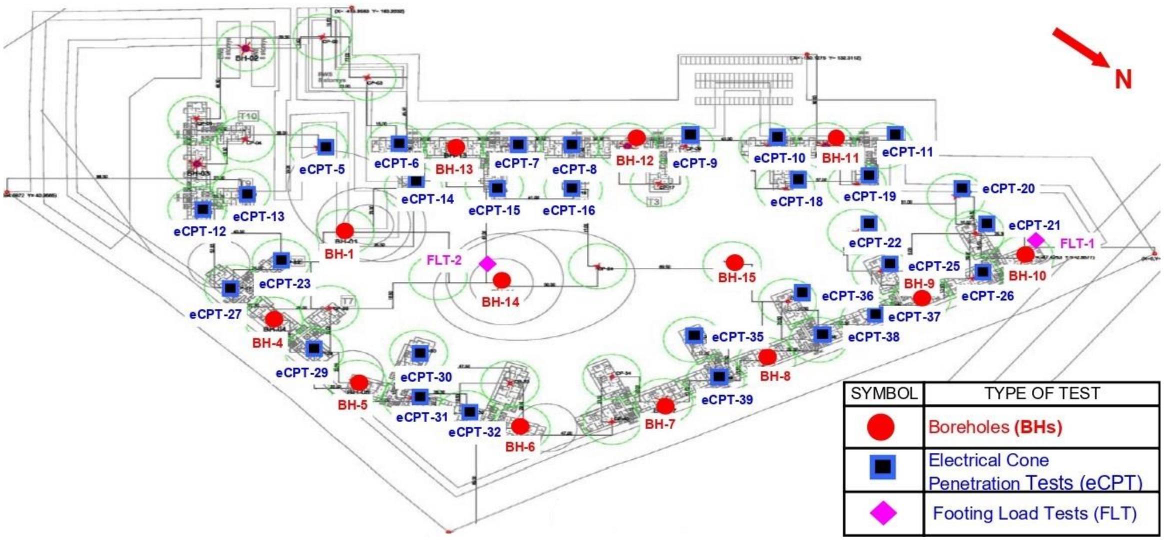


Fig. 3. Plan of Field Investigation

Fig. 4a presents borehole in progress using a mechanized shell and auger rig [3]. Fig. 4b presents eCPT test in progress [5]. Fig. 4c shows data acquisition from eCPT.

(a) SPT being performed in borehole (b)eCPT in progress (c)eCPT data acquisition

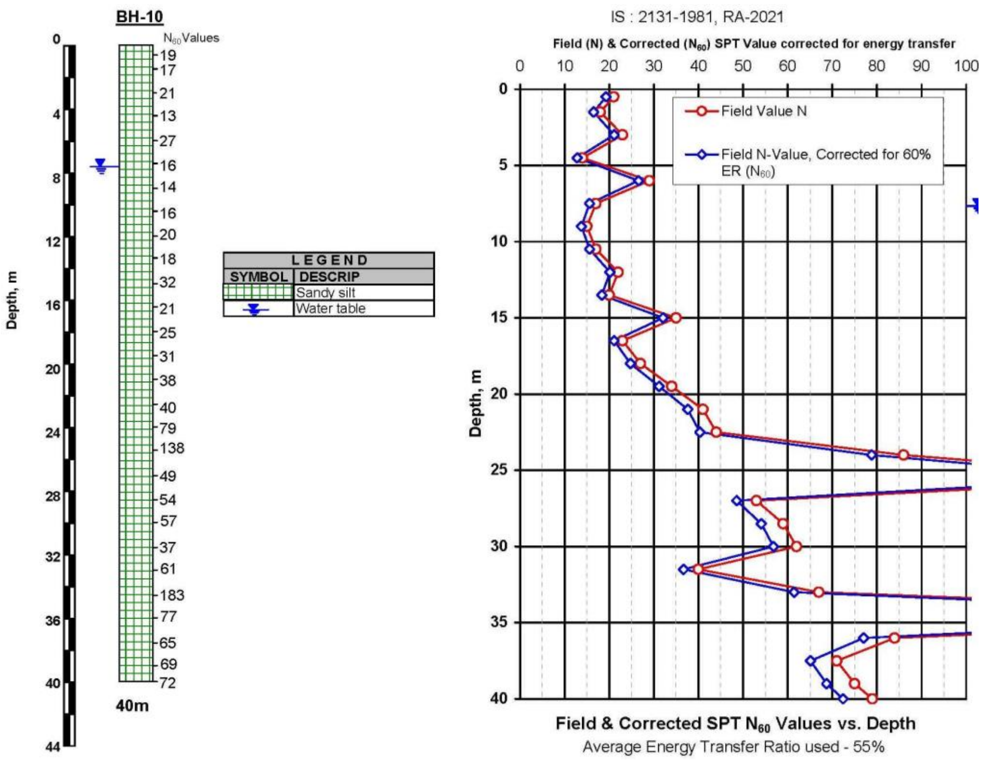
Fig.4. Field Work in Progress

In this paper, the results of the two footing load tests have been evaluated in conjunction with the nearest boreholes and eCPT results to evaluate various geotechnical parameters so as to develop the design profile for foundation analysis. Parameters analyzed include N_{60}, modulus of elasticity E, and c-ϕ values. Two sets of data have been presented and analyzed for comparison purpose and to demonstrate the trends. Each set includes one borehole, one CPT and one FLT.

The data is presented for each footing load test, comparing the geotechnical data with the test and interpreting various parameters from the various field tests to develop a realistic geotechnical design profile. The intent is to demonstrate the advanced technologies which need to be increasingly used in the Indian industry to obtain superior quality data that is comparable to international standards.

FOOTING LOAD TEST NO. 1

The data of FLT-1 has been compared with BH-10 and eCPT-26 [4]. The borelog and SPT values corrected for energy transfer [6] are presented in Fig. 5. It may be seen from Fig. 5 that the soils are primarily alluvial in nature and consist primarily of sandy silt of low plasticity with some minor discontinuous sand zones at different depths. Groundwater was met at about 7.5-8.8 m depth.



(a) Borehole profile (b)SPT values corrected for energy transfer

Fig. 5. BH10: Borehole Profile and SPT values corrected for energy transfer

Results of eCPT-26 are presented in Fig. 6.

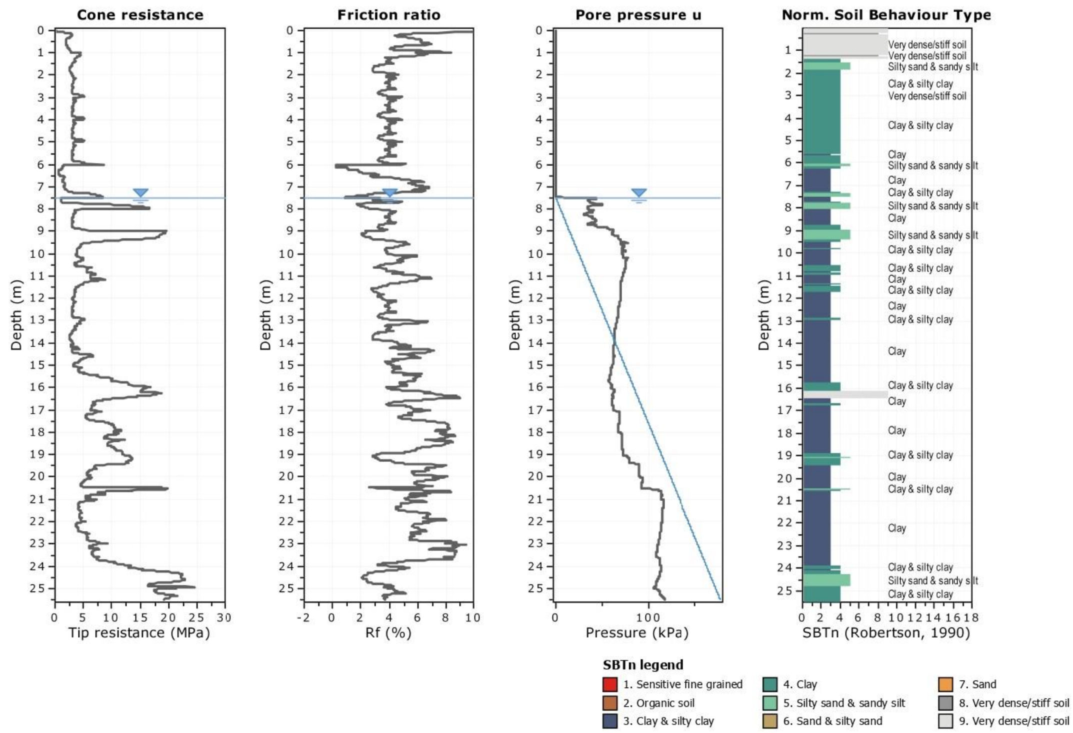
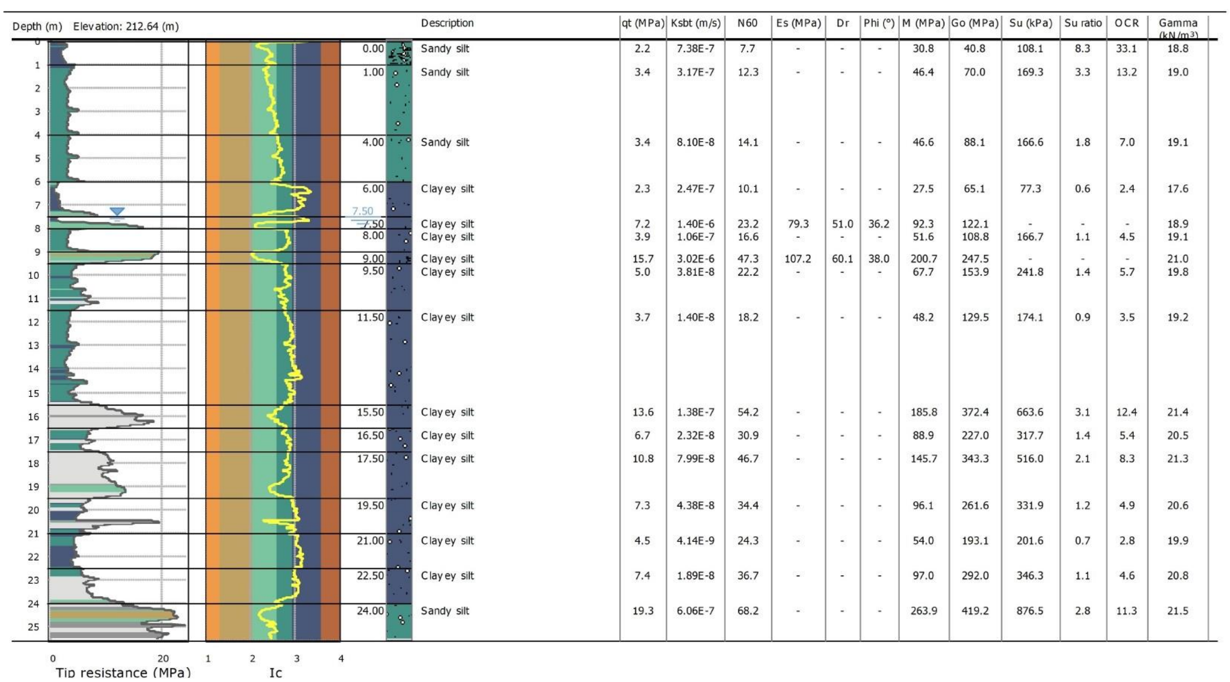


Fig. 6. eCPT-26: Plots of q_c, friction ratio, pore-water pressure and soil classification

Fig. 7 presents the interpreted eCPT profile summarizing various soil parameters interpreted from the test as per the correlations by Robertson and Cabal [8].



Depth (m)	Description	qt (MPa)	Ksbt (m/s)	N60	Es (MPa)	Dr	Phi (°)	M (MPa)	Go (MPa)	Su (kPa)	Su ratio	OCR	Gamma (kN/m³)
0.00	Sandy silt	2.2	7.38E-7	7.7	-	-	-	30.8	40.8	108.1	8.3	33.1	18.8
1.00	Sandy silt	3.4	3.17E-7	12.3	-	-	-	46.4	70.0	169.3	3.3	13.2	19.0
4.00	Sandy silt	3.4	8.10E-8	14.1	-	-	-	46.6	88.1	166.6	1.8	7.0	19.1
6.00	Clayey silt	2.3	2.47E-7	10.1	-	-	-	27.5	65.1	77.3	0.6	2.4	17.6
7.50	Clayey silt	7.2	1.40E-6	23.2	79.3	51.0	36.2	92.3	122.1	-	-	-	18.9
8.00	Clayey silt	3.9	1.06E-7	16.6	-	-	-	51.6	108.8	166.7	1.1	4.5	19.1
9.00	Clayey silt	15.7	3.02E-6	47.3	107.2	60.1	38.0	200.7	247.5	-	-	-	21.0
9.50	Clayey silt	5.0	3.81E-8	22.2	-	-	-	67.7	153.9	241.8	1.4	5.7	19.8
11.50	Clayey silt	3.7	1.40E-8	18.2	-	-	-	48.2	129.5	174.1	0.9	3.5	19.2
15.50	Clayey silt	13.6	1.38E-7	54.2	-	-	-	185.8	372.4	663.6	3.1	12.4	21.4
16.50	Clayey silt	6.7	2.32E-8	30.9	-	-	-	88.9	227.0	317.7	1.4	5.4	20.5
17.50	Clayey silt	10.8	7.99E-8	46.7	-	-	-	145.7	343.3	516.0	2.1	8.3	21.3
19.50	Clayey silt	7.3	4.38E-8	34.4	-	-	-	96.1	261.6	331.9	1.2	4.9	20.6
21.00	Clayey silt	4.5	4.14E-9	24.3	-	-	-	54.0	193.1	201.6	0.7	2.8	19.9
22.50	Clayey silt	7.4	1.89E-8	36.7	-	-	-	97.0	292.0	346.3	1.1	4.6	20.8
24.00	Sandy silt	19.3	6.06E-7	68.2	-	-	-	263.9	419.2	876.5	2.8	11.3	21.5

Fig. 7. Profile of Parameters interpreted from eCPT-26

where

q_t	:	Cone tip resistance	K_{sbt}	:	Coefficient of permeability
N_{60}	:	N value corresponding to 60% energy transfer	Es	:	Modulus of elasticity of soil
D_r	:	Relative density (for sands)	phi	:	Angle of internal friction

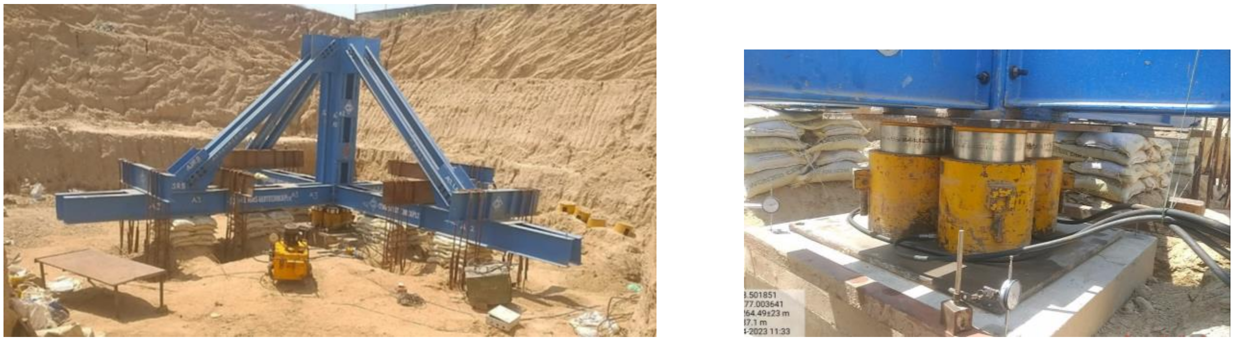
M	:	Constrained modulus	G_0	:	Shear modulus
S_u	:	Undrained shear strength (= c_u x 2)	S_u ratio	:	Undrained shear strength divided by effective overburden pressure
OCR		Over-consolidation ratio	Gamma	:	Unit weight of soil

To conduct the footing load test, excavation was carried out to 8.5 m depth. Since groundwater was encountered at 7.5 m depth, dewatering was done to lower the water table about 0.8-1 m below the footing level.

Fig. 8 shows the footing load test on a 1.5 m x 1.5 m x 0.5 m size RCC footing at 8.5 m depth in progress. A specially designed truss capable of supporting load of upto 600 T was used. Sixteen anchor piles (600 mm diameter extending to13 m depth were used. The top 4 m of the pile was filled with sand compacted approximately to the same density as the surrounding soil so that the pile does not influence the pile settlement. Each reaction pile was designed to withstand a pullout load of about 34 T.

The reinforcement of the piles was welded over the girder placed on the truss so that the reaction piles are in tension when the footing is loaded. The maximum test load was planned to be about 450 T and was applied in about 10 equal increments.

The test was performed in accordance with IS: 1888-1982 RA- 2021[7]. Each load was held till the rate of settlement was less than 0.02 mm/minute. The maximum load was maintained for 24 hours before unloading the footing in stages.

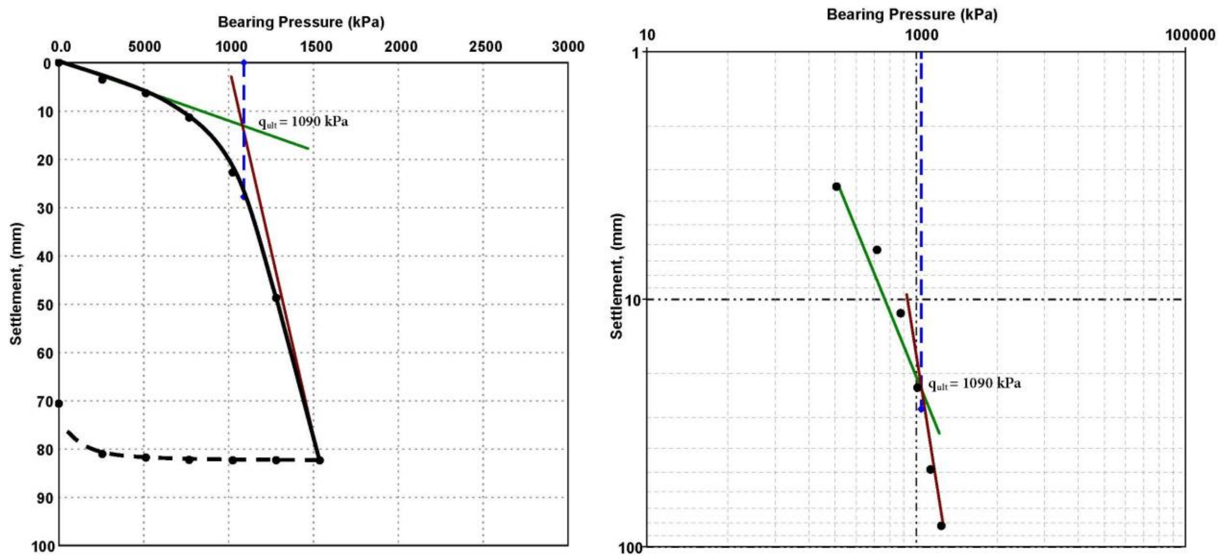


(a) Truss with 16 anchor piles installed over the footing (b)Close-up view showing hydraulic jacks and dial gauges

Fig. 8. Footing Load Test in Progress

Fig. 8 presents load-settlement curve for FLT-1 on natural as well as log-log scales. The interpreted ultimate bearing capacity of the 1.5 x 1.5 m size footing works out as 1090 kPa.The measured settlement at the ultimate bearing pressure is 13 mm.

The modulus of subgrade reaction, k_s has been interpreted from the load-settlement curve computed as per IS: 9214-1979 RA 2021[11]. After applying corrections for the shape of the curve, upward bending of the footing and effects of saturation, the interpreted value of k_s = 33.5 MN/m^3.



(a) Load settlement curve – natural scale (b)Load settlement curve – log-log plot

Fig. 9. Applied bearing pressure versus footing settlement: FLT-1

The modulus of elasticity of the soils below the footing has been computed using the following equation [9]:

$$k_s = \frac{E_s}{B\,(1-\mu^2)} \quad \ldots (1)$$

where

k_s = Modulus of subgrade reaction, kN/m^3
E_s= Modulus of elasticity, kPa
B = width of footing, m
μ = Poisson's ratio

Since k_s has been determined from the footing load test, Es may be determined using Equation (1). The computed E_s value from the test is 44.8MPa.

FOOTING LOAD TEST NO. 2

The data of FLT-2 has been compared with BH-14 and eCPT-30. The borelog and SPT values corrected for energy transfer are presented in Fig. 10. It may be seen from Fig. 5 that the soils are primarily alluvial in nature and consist primarily of sandy silt of low plasticity with some minor discontinuous sand zones at different depths. Groundwater was met at about 7.5-8.8 m depth.

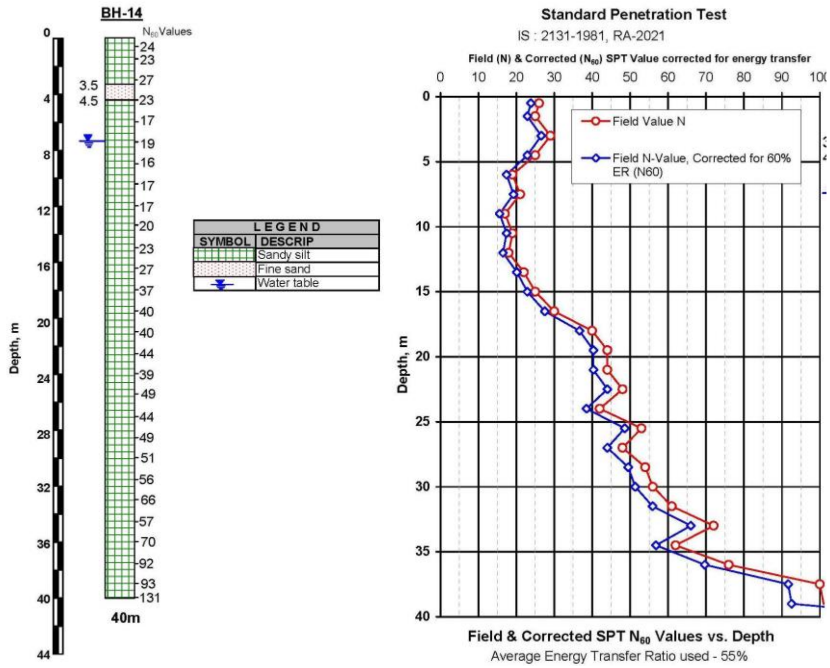


Fig. 10. BH 14: Borehole Profile and SPT values corrected for energy transfer

Results of eCPT-30 are presented in Fig. 11.

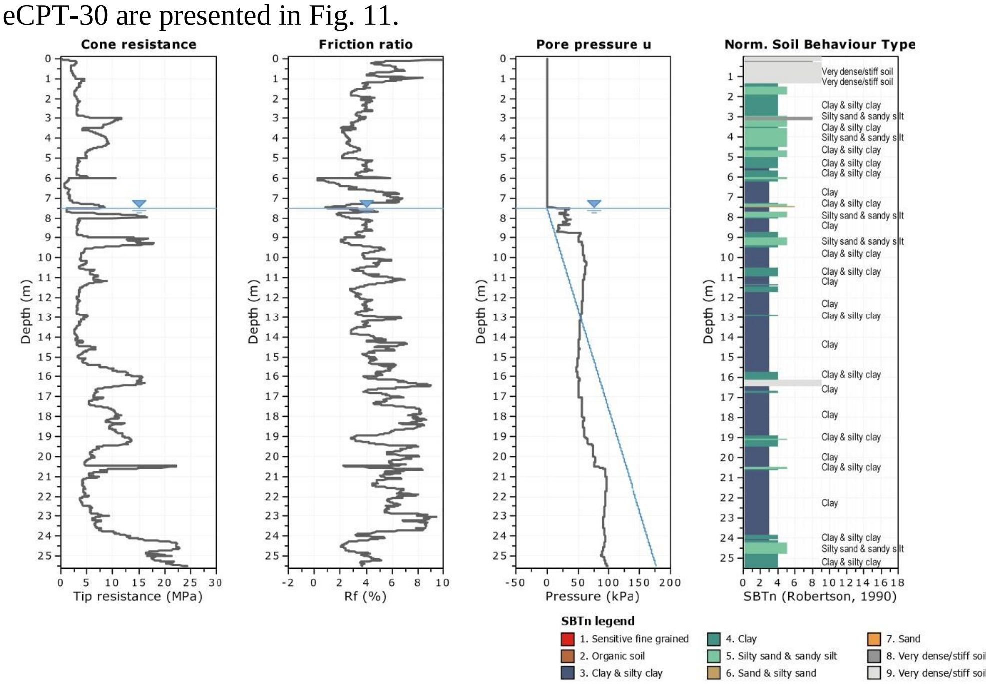
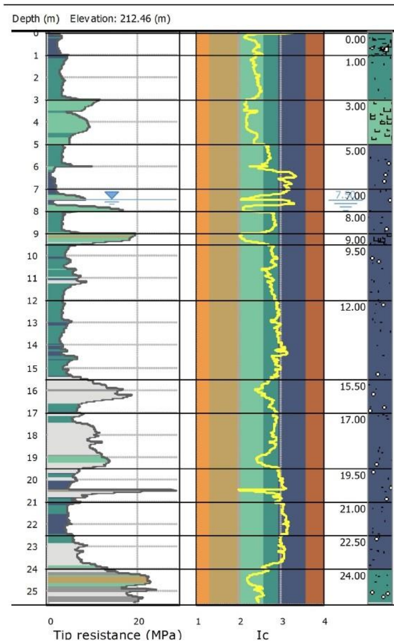


Fig.11. eCPT-30: Plots of q_c, friction ratio, pore-water pressure and soil classification

Fig. 12 presents the interpreted eCPT profile summarizing various soil parameters interpreted from the test as per the correlations by Robertson and Cabal [8].

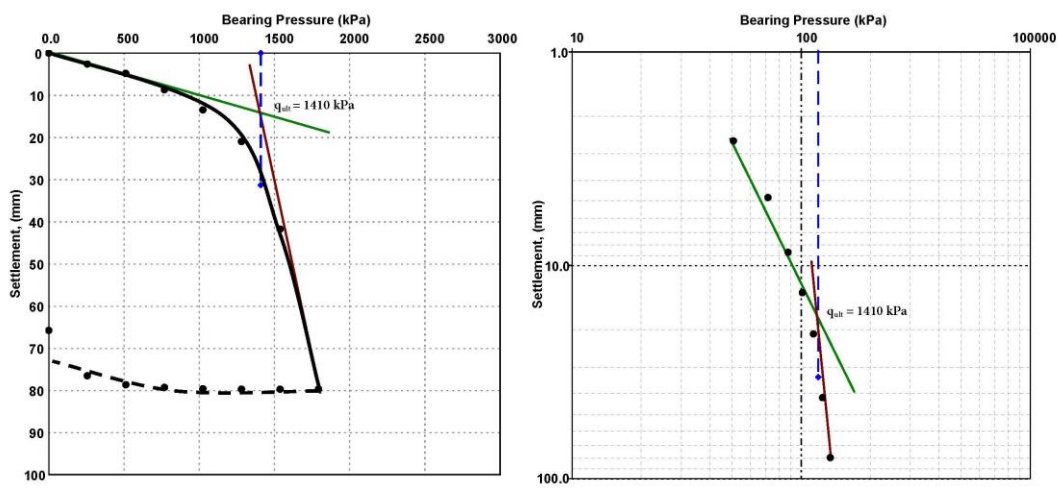


Depth (m)	Description	qt (MPa)	Ksbt (m/s)	N60	Es (MPa)	Dr	Phi (°)	M (MPa)	Go (MPa)	Su (kPa)	Su ratio	OCR	Gamma (kN/m³)
0.00	Sandy silt	2.2	7.39E-7	7.7	-	-	-	30.8	40.8	108.1	8.3	33.1	18.8
1.00	Sandy silt	3.4	4.21E-7	12.0	-	-	-	47.2	66.6	170.2	3.9	15.5	19.0
3.00	Silty sand	7.4	1.43E-6	23.4	53.9	51.6	36.0	103.2	120.8	-	-	-	19.8
5.00	Clayey silt	2.4	6.26E-8	10.7	-	-	-	30.2	69.1	113.3	1.0	4.1	18.0
7.00	Clayey silt	5.8	1.04E-6	19.9	-	-	-	74.6	112.0	98.0	0.7	2.9	19.0
8.00	Clayey silt	3.9	1.25E-7	16.5	-	-	-	51.6	107.9	163.7	1.1	4.4	19.1
9.00	Clayey silt	15.7	2.98E-6	47.4	107.4	59.9	37.0	201.0	248.0	-	-	-	21.0
9.50	Clayey silt	4.7	3.45E-8	21.0	-	-	-	63.1	144.5	225.5	1.3	5.2	19.6
12.00	Clayey silt	3.8	1.23E-8	18.5	-	-	-	48.5	133.3	175.6	0.9	3.5	19.3
15.50	Clayey silt	11.4	1.00E-7	46.8	-	-	-	155.2	326.1	554.3	2.5	10.1	21.1
17.00	Clayey silt	9.9	6.65E-8	43.3	-	-	-	133.1	319.4	470.6	1.9	7.6	21.2
19.50	Clayey silt	7.5	1.59E-7	34.9	-	-	-	98.9	262.7	317.5	1.2	4.7	20.6
21.00	Clayey silt	4.5	4.07E-9	24.3	-	-	-	53.7	193.4	201.3	0.7	2.8	19.9
22.50	Clayey silt	7.4	1.87E-8	36.8	-	-	-	96.9	292.4	345.9	1.1	4.5	20.8
24.00	Sandy silt	19.3	6.00E-7	68.3	-	-	-	263.7	420.0	876.0	2.8	11.3	21.5

Fig. 12. Profile of Parameters interpreted from eCPT-30

FLT-2 was conducted on a 1.5 x 1.5 m size footing at the location illustrated on Fig. 3. The truss and the test details are similar to that for FLT-1. Fig. 13 presents the test results.

The ultimate bearing pressure as interpreted from the test is about 1410kPa. The measured settlement at the ultimate bearing pressure is14 mm.



(a) Load settlement curve – natural scale (b)Load settlement curve – log-log plot

Fig. 13. Applied bearing pressure versus footing settlement: FLT-2

The modulus of subgrade reaction, $k_s$is interpreted from the load-settlement curve computed as per IS: 9214-1979 RA 2021[11]. After applying corrections for the shape of the curve, upward bending of the footing and saturation, k_s =42.5 MN/m^3.

The modulus of elasticity of the soils below the footing has been computed using Equation (1). The computed E_s value from the test is 56.8MPa.

CORRELATIONS

An attempt has been made to correlate the various geotechnical parameters from N_{60}, q_c and FLT results. The purpose is to assess the various tests so as to develop a realistic and reliable design profile for foundation design. Parameters assessed in addition to N_{60} include the cohesion intercept (undrained "c_u" value), bulk density of soil, modulus of elasticity (E_s) and the coefficient of volume compressibility (m_v).

Cohesion Intercept

The c value has been evaluated from the following:

- From N_{60} using the correlation for N versus q_c given by Bowles[9]
- From CPT $q_c$values using the equationproposed by Robertson & Cabal [8]

$$s_u = \frac{(q_t - \sigma_{v0})}{N_{kt}} \quad \ldots(2)$$

where

s_u = Undrained shear strength, kN/m^2

σ_{v0}= Overburden pressure, kN/m^2

N_{kt}= 10.5 log (F_r) … (3)

F_r = Normalized friction ratio, %

$$F_r = \left(\frac{f_s}{q_t - \sigma_{v0}}\right) \quad \ldots (4)$$

f_s = Cone sleeve resistance, kN/m^2

- Determined from UU triaxial test in the laboratory tests on undisturbed soil samples

Bulk Density

The bulk density, "γ" has been evaluated from the following:

- From N_{60} using the correlations for N versus γ given by Bowles[9]
- From CPT q_c values using the equation proposed by Robertson & Cabal [8]

$$\gamma = \gamma_w \cdot \left[0.27\, log\left[R_f\right] + 0.36\, log\left[\frac{q_t}{P_a}\right] + 1.236\right] \quad \ldots (5)$$

where

γ = Bulk density, kN/m^2

γ_w = Unit weight of water, kN/m^2

R_f = Friction ration. %

P_a= Atmospheric pressure, kN/m^2

- Determined from laboratory measurements on undisturbed soil samples

Fig. 14 and 15 present plots of N_{60} "c_u" and "γ" versus depth as interpreted from the various tests conducted for the two sets of data presented in this paper.

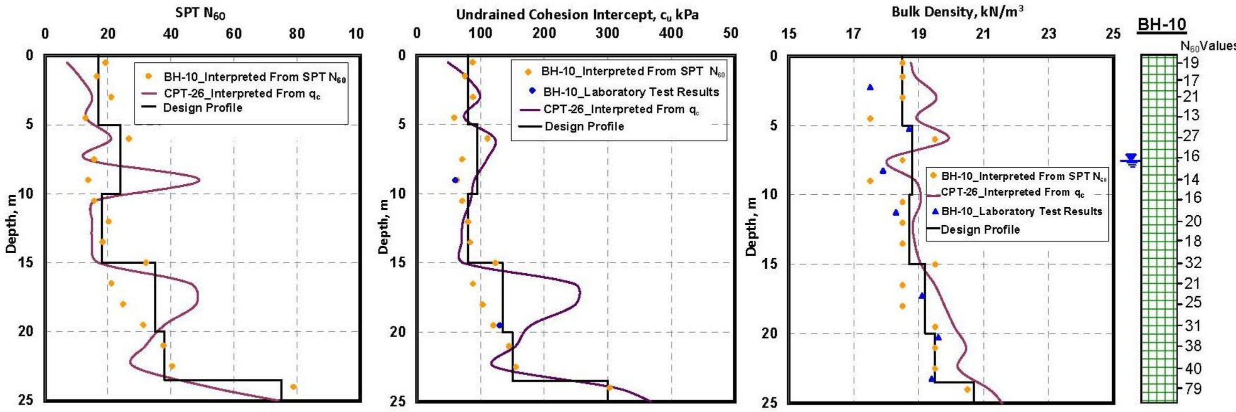


Fig. 14. Correlations of N_{60} and cohesion intercept: BH-10, eCPT-26 and FLT-1

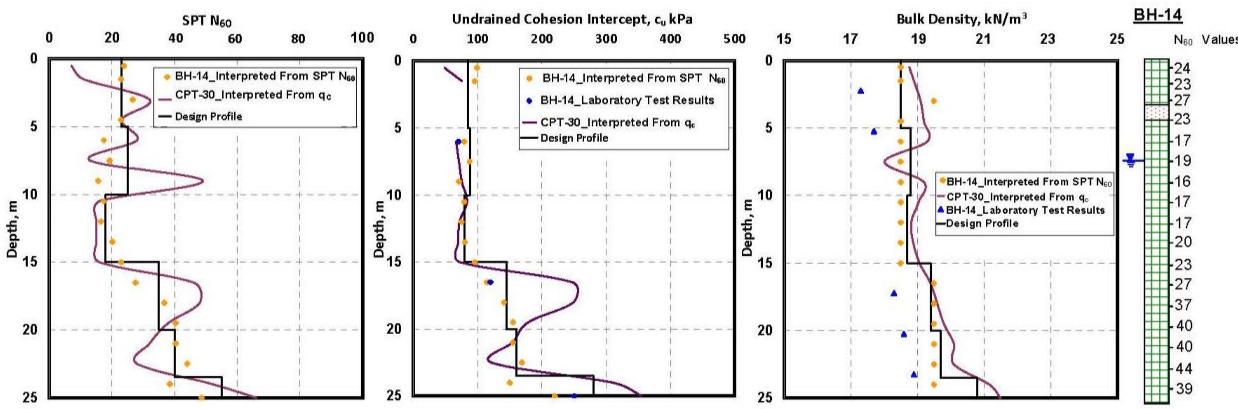


Fig. 15. Correlations of N_{60} and cohesion intercept: BH-14, eCPT-30 and FLT-2

Modulus of Elasticity

The modulus of elasticity has been assessed from the following:

- From N_{60} using the correlation [9] $E_s = 300(N_{60}+6)$ … (6)
- From CPT q_c values using the equation [9] $E_s = (3.5 \text{ to } 5)q_c$ … (7)
- Interpreted from footing load test by calculating E_s from k_s using Equation (1)

Coefficient of Volume Compressibility (m_v)

The coefficient of volume compressibility (m_v) is an important parameter used to assess the consolidation settlement of the foundation. It has been computed as follows:

- From one-dimensional consolidation tests performed in the laboratory as per IS: 2720 Part 15-1986 RA 2021[10].
- The constrained modulus of the soil, M, is calculated from CPT data using the equationproposed by Robertson and Cabal [8]

  $$M_{CPT} = \alpha[q_t - \sigma_{v0}] \quad \text{… (8)}$$

  If $I_c > 2.2$ $\alpha = 14$ for $Q_{tn} > 14$, $\alpha = Q_{tn}$ for $Q_{tn} \leq 14$
  If $I_c < 2.2$ $\alpha = 0.01855(10^{0.55\,Ic+1.68})$ … (9)
  I_c = Soil behavior type index Q_{tn} = Normalized cone resistance

The value of m_v is calculated as $$m_v = {}^{1}/_{M_{CPT}} \qquad \dots (10)$$

where

m_v = Coefficient of volume compressibility, m^2/kN

M_{CPT}= Constrained modulus, kN/m^2

Fig. 16 and 17 present plots of E_s and m_v versus depth as interpreted from the various tests conducted for the two sets of data presented in this paper.

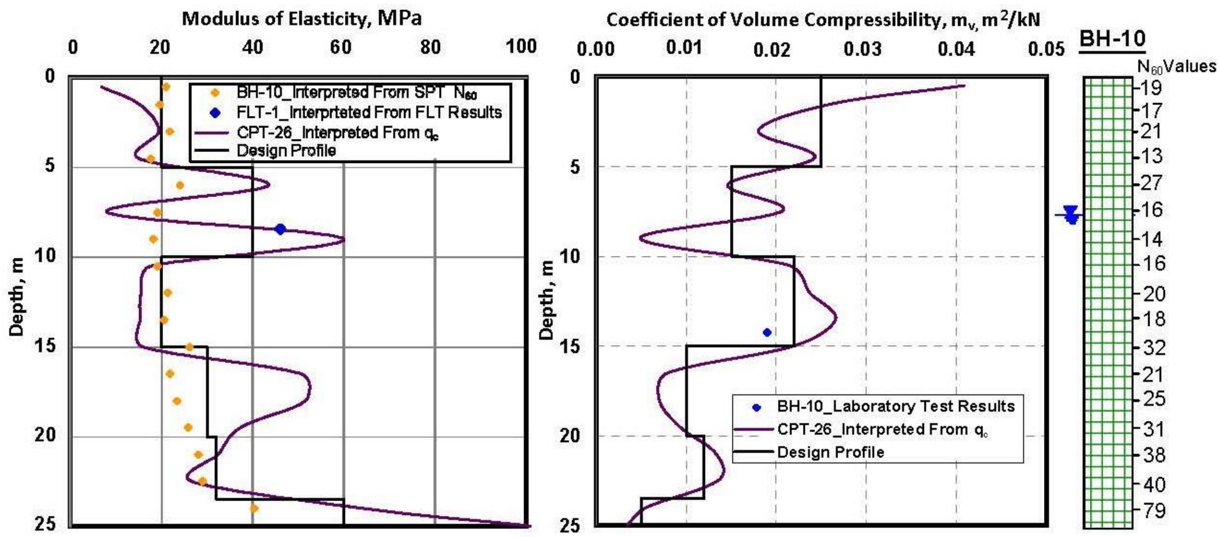


Fig. 16. Correlations of E and m_v: BH-10, eCPT-26 and FLT-1

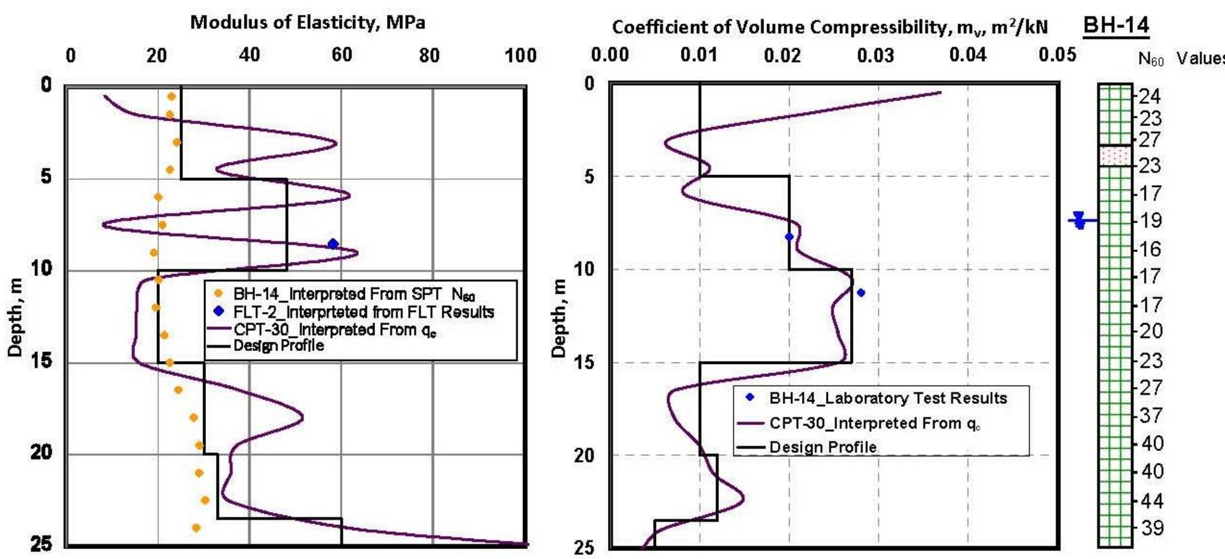


Fig. 17. Correlations of E and m_v: BH-14, eCPT-30 and FLT-2

It may be seen from the above plots that there is a very good correlation of parameters interpreted from N_{60}, q_c and FLT results. This not just confirms the quality of data generated but also ensures a greater level of reliability in the design. However, E_s value computed from N_{60} is somewhat lower.

Pre-consolidation Pressure and Over-consolidation Ratio

The pre-consolidation pressure and over-consolidation ratio has been determined from laboratory tests and also interpreted from CPT results [12, 13]. The footing load test does not simulate the consolidation settlement. The consolidation settlement may be computed using the parameters interpreted from laboratory tests and CPT interpretations. The immediate settlement, computed using the $E_s$values as given above, may be added to the estimated consolidation settlement to evaluate the total settlement. Fig. 18 and 19 present plots of p_c and OCR versus depth.

The preconsolidation pressure (p_c) and Overconsolidation ratio (OCR) is an important parameter used to assess the consolidation settlement of the foundation. It has been computed as follows:

- From one-dimensional consolidation tests performed in the laboratory as per IS: 2720 Part 15-1986 RA 2021[10].
- The preconsolidation pressure and Overconsolidation ratio of the soil is calculated from CPT data using the equationproposed by Robertson and Cabal [8]

$$OCR = k_{OCR} Q_{tn} \quad \ldots(11)$$

$$k_{OCR} = \left(\frac{Q_{tn}^{0.2}}{0.25(10.5+\log(F_r))}\right) \quad \ldots(12)$$

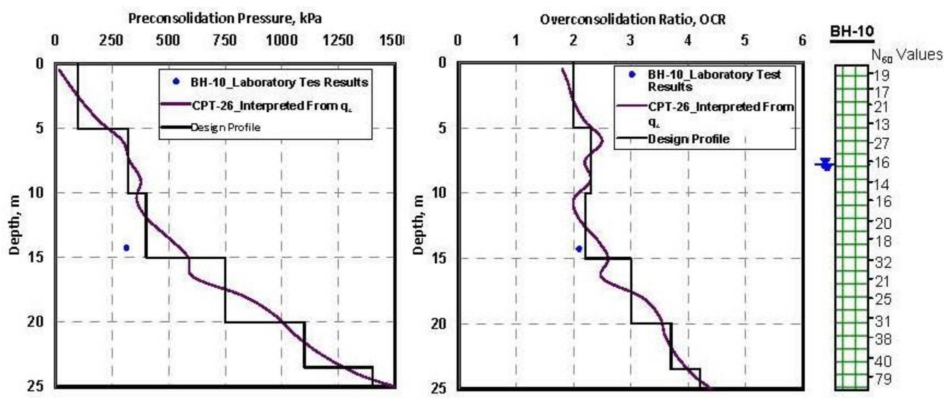


Fig. 18. Correlations of p_c and OCR: BH-10 and eCPT-26

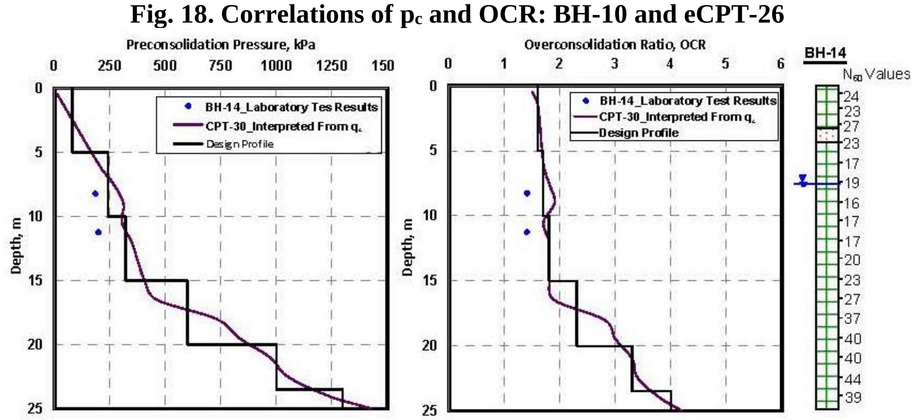


Fig. 19. Correlations of p_c and OCR: BH-14 and eCPT-30

DESIGN PROFILE

Using the various parameters interpreted and correlated from the various tests performed, the design profile for foundation analysis has been developed. For each soil layer, the soil parameters assessed include N_{60}, bulk density, γ, undrained cohesion intercept, "c_u", modulus of elasticity E_s, pre-consolidation pressure, p_c, OCR and m_v have been assessed based on the different tests performed for a realistic evaluation of these parameters. The modulus of subgrade reaction k interpreted from the footing load test was used for soil-structure interaction analysis for better assessment of the raft behavior.

Fig. 20 and 21 present the design profiles at the two locations presented in this paper. These profiles present the scatter in the data from the various tests and the final values selected for the design.

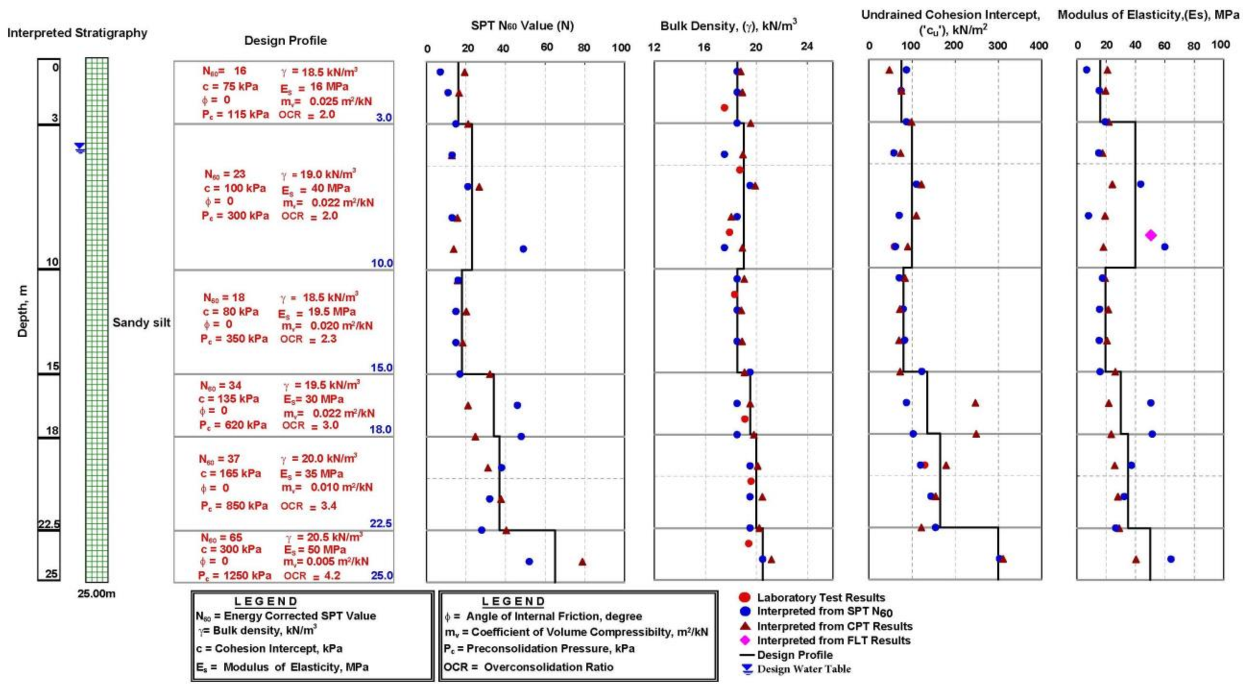


Fig. 20. Design Profile: BH-10, eCPT-26 and FLT-1

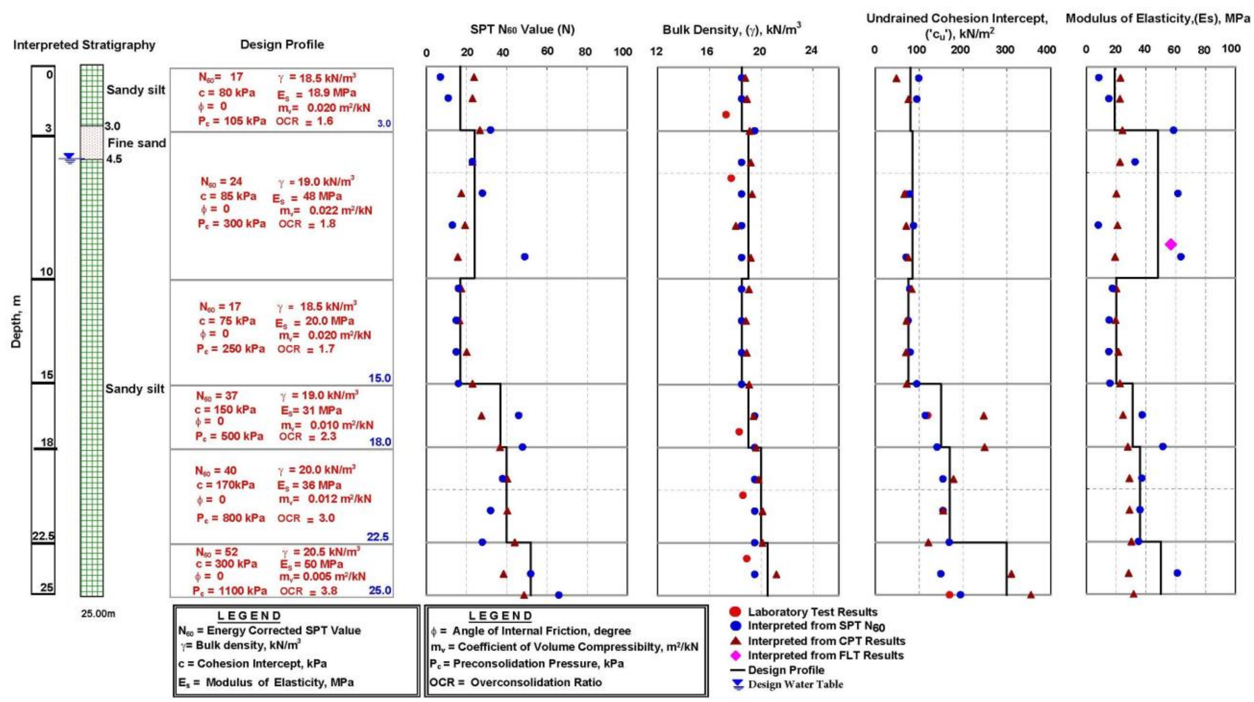


Fig. 21. Design Profile: BH-14, eCPT-30 and FLT-2

It may be seen from the above that the values interpreted from the different tests are generally within a narrow band of ±10~15% with only a few values being off the general trends.

FOUNDATION ANALYSIS

Raft foundation bearing at 8.5 m depth below ground level were used to support the 32-storeyed building. The need for piles was eliminated since higher SBC values could be justified. Bearing capacity analysis for the raft was performed using the c-ϕ values determined from laboratory tests as well as that interpreted from CPT and N-values. The total settlement of the raft foundation was computed as the sum of the immediate settlement and the consolidation settlement.

The E-value profile as given in Figs. 20 and 21 were used for computing the immediate settlement as per IS: 8009 Part 1-1976 [14]. The consolidation settlement (long-term settlement) has been computed using the mv values interpreted from CPTu (computed as inverse of the constrained modulus) as well as the laboratory consolidation test results. These were further refined using other borehole and CPTu data at the tower location. For other towers, appropriate data based on the corresponding boreholes/CPT were used. As per IS: 16700-2017 [15], the permissible total settlement was taken as 125 mm.

The design profile based on SPT data only was somewhat conservative. The CPT tests helped in developing a greater level of confidence in the data and somewhat higher values the parameters such as c, ϕ, γ, E, consolidation parameters (mv), etc. could be used (in comparison to the values that would have been selected based on a conventional investigation with SPT only). As a result, the safe bearing pressure used for the design was more than 25% higher than that estimated from conventional analysis using borehole data only.

The raft was analyzed using PLAXIS 3D to evaluate the settlement profile and to confirm that the differential settlement across the raft is within permissible limits. Structural analysis software was also used for the detailed design. The authors were involved only in the geotechnical investigation part of the work. The content of this paper is limited to presenting the results of the investigation and highlighting the benefits accrued by incorporating some of the advanced tests in the scope.

The detailed analysis of foundation settlement is not included in this paper since the thrust here is on emphasizing the importance of the advanced geotechnical investigation methods. However, the authors highlight that the immediate and consolidation settlements computed using the parameters interpreted from CPTu are much less than that computed using the parameters interpreted from borehole data only. Thus, higher SBC values could be used leading to economy in foundation design while enhancing the reliability of the design parameters.

CONCLUDING REMARKS

The paper highlights the importance of using modern geotechnical investigation techniques in designing safe and efficient foundations for multi-storeyed buildings. The case study presented demonstrates the successful implementation of advanced testing methods such as SPT energy measurement, eCPT, and footing load test for a residential complex in Gurugram. The investigation provided valuable insights into the soil properties and helped to understand the foundation behavior of the site, which ultimately resulted in an efficient and safe foundation design for the complex. Some of the benefits accrued from the implementation of these advanced testing methods are:

- A more reliable design profile could be developed with parameters cross-checked from the various tests. The conventional analysis using borehole data only results in a conservative design profile resulting in an uneconomical foundation design.

- SBC values justified were substantially higher than those that would otherwise have been used by analyzing borehole data only. Savings of more than 20-30% may be achieved in the foundation costs.
- The modulus of subgrade reaction justified from the plate load tests are much higher than the values that would have been estimated from N values. This resulted in a greater economy in the raft design.
- The need for piles was eliminated resulting in substantial savings.

The authors emphasize that the use of advanced geotechnical investigation techniques can significantly improve the accuracy of the foundation design and reduce the risk of failure during construction and operation. Therefore, it is essential to invest in modern geotechnical investigation methods to ensure economy in foundation design with enhanced reliability.

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