Use of Pressuremeter Tests in conjunction with CPTu for Geotechnical Investigation for Tall Buildings

Utilisation d'essais pressiométriques en conjonction avec le CPTu pour l'étude géotechnique des bâtiments de grande hauteur

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ABSTRACT

Combining pressuremeter test results with those of cone penetration tests enhances the quality of the geotechnical data and helps to develop a realistic design profile for foundation analysis. A case study of geotechnical investigation for a 42-storeyed building using pressuremeter tests, CPTu and cross-hole seismic tests is presented to demonstrate the selection of parameters for foundation analysis. In addition to greater reliability in the design, it resulted in substantial savings in the foundation cost.

RESUME

La combinaison des résultats des essais pressiométriques et des essais de pénétration au cône améliore la qualité des données géotechniques et permet d'élaborer un profil de conception réaliste pour l'analyse des fondations. Une étude de cas d'investigation géotechnique d'un immeuble de 42 étages, utilisant des essais pressiométriques, des essais CPTu et des essais sismiques transversaux, est présentée afin de démontrer le choix des paramètres pour l'analyse des fondations. Outre une plus grande fiabilité de la conception, cette étude a permis de réaliser des économies substantielles sur le coût des fondations.

Keywords: pressuremeter tests; cone penetration tests; geophysical tests; geotechnical investigation; tall buildings; reliable geotechnical parameters.

1. Introduction

Geotechnical investigation for tall buildings requires more than the conventional boreholes with laboratory testing. Supplementing the borehole data with in-situ tests can enhance the quality and reliability of the data for foundation analysis.

Ching and Phoon 2012 emphasize that a variety of in-situ tests and laboratory tests and local experience reduce the uncertainties in the design parameters for reliable design of foundations. This not only fills the critical gap in current geotechnical practice but also helps to economize the foundation cost.

Of the various advanced in-situ testing methods, pressuremeter is one test that yields realistic data. The design rules for pressuremeter gives better and reliable estimates of safe bearing capacity and settlement.

Including cone penetration tests in the scope of investigation further increases the reliability of the data and soil parameters. The correlations by Robertson and Cabal 2022 give fairly reliable values of the various engineering parameters that are comparable with the estimates from pressuremeter.

Poulos and Badelow 2015 discuss the importance of effective ground investigation with relevant in-situ and laboratory tests for deriving the necessary strength and stiffness parameters.

The paper presents case study of geotechnical investigation for a multi-storeyed building which included pressuremeter tests and cone penetration tests in addition to boreholes with SPT. The benefits of using these advanced in-situ tests testing and their use to generate realistic site-specific results is discussed (Ching et al 2014). It demonstrates the significant savings in cost and time for the owner while ensuring that the foundation system is safe and reliable. In the Indian scenario, importance of in-situ tests is now recognized (Ravi Sundaram et al. 2023) and is being used on important projects.

2. Project Details

2.1. Structure Planned

A 42-storeyed building is planned in Gurugram in the state of Haryana, India. The development will consist of two high-end residential towers, each having one basement, and 39 floors. In addition, residential building for economically weaker sections (EWS), retail area, nursery school and other buildings are also planned.

2.2. Scope of Geotechnical investigation

The scope of the geotechnical investigation performed at the site included the following:

- Three boreholes to 50-60 m depth and one borehole to 20 m depth including conducting SPT and collecting undisturbed soil samples at regular depth intervals;
- Measuring Energy Transfer Ratio (ETR) to standardize the SPT values to 60% energy transfer (N_{60});
- Pressuremeter tests to 50 m depth at two borehole locations;
- Fourteen electric cone penetration tests with measurement of porewater pressure;
- Cross-hole seismic tests at two locations

A layout plan showing the locations of the field investigation is illustrated on Fig. 1.

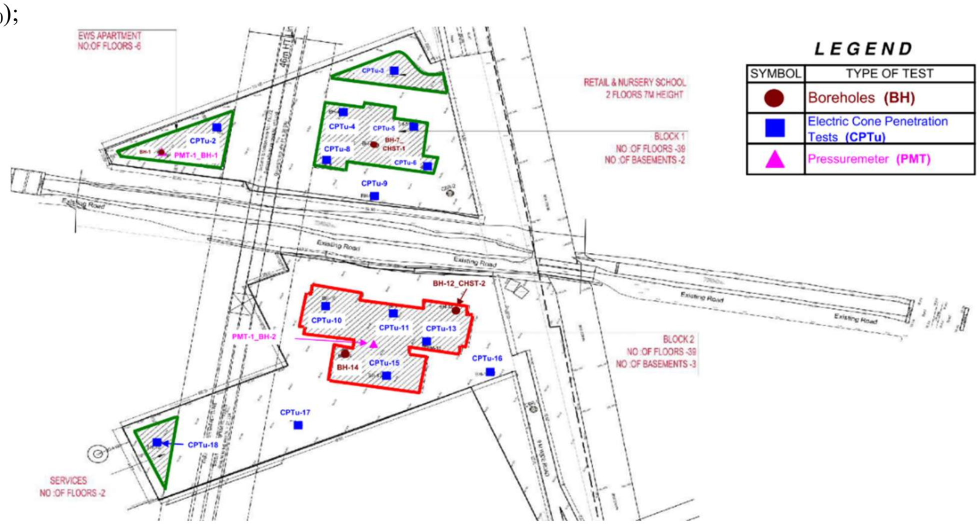


Figure 1. Plan of Field Investigation.

The paper discusses the geotechnical investigation for Tower 2. The scope of investigation for this tower included two boreholes (BH-12 & 14), measuring ETR, pressuremeter tests in BH-2 and four cone penetration tests (CPTu-10, 11, 13 and 15).

3. Site Conditions

3.1. Geology

The project site belongs to the Indo-Gangetic Alluvium and is covered by fluvial sediments of sand, silt and clay of Recent to Quaternary Age (Krishnan, 1986). Rocks of the Delhi Supergroup are exposed about 10 km east of the site. A geological map of the locality downloaded from Geological Survey of India's website Bhukosh is presented on Fig. 3.

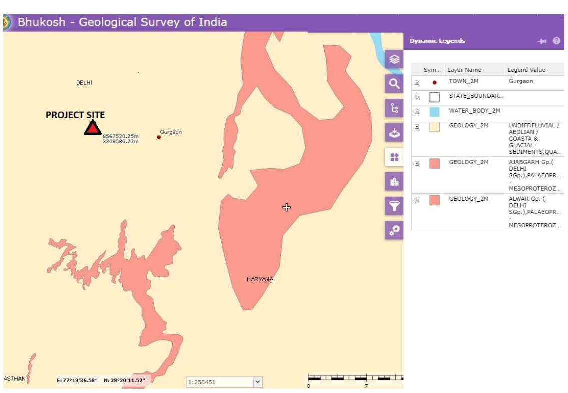


Figure 2. Local Geology of Project Area.

3.2. Stratigraphy and Soil Characteristics

The soils at the site consist primarily of sandy silt of low plasticity with some intermediate discontinuous silty sand zones. A pictorial summary of the stratigraphy at the borehole locations and strata interpreted from CPTu is illustrated on Fig. 3.

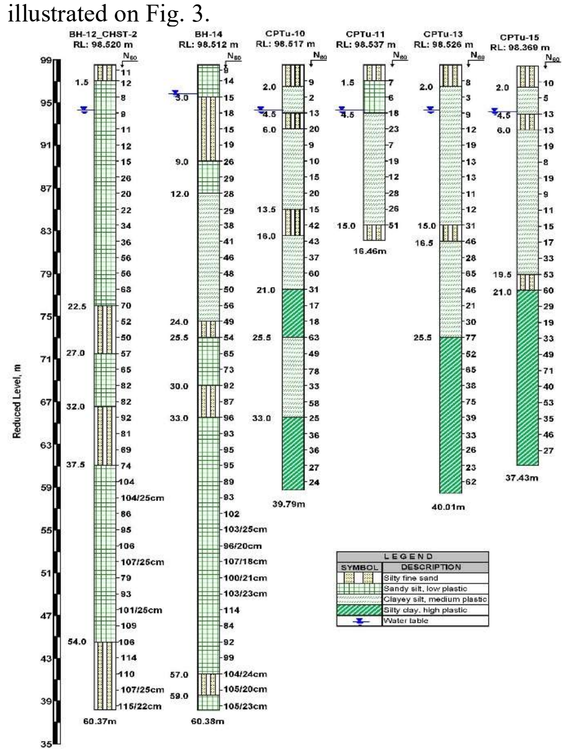
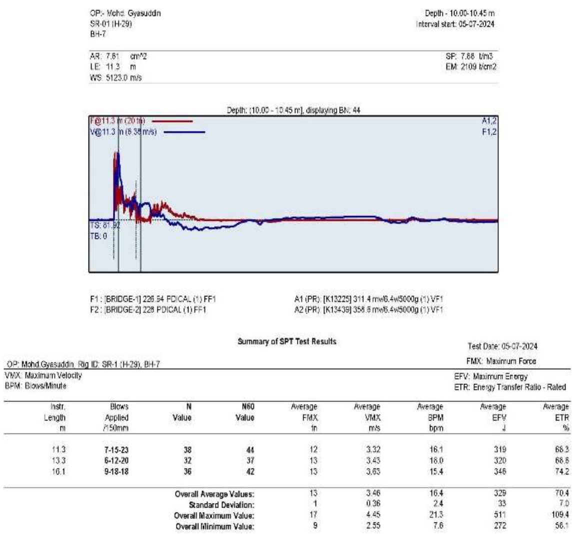


Figure 3. Summary of Borehole/CPT Profiles – Tower 2.

3.3. SPT Energy Measurement

SPT energy transferred from the driving hammer to the anvil was measured using an instrumented rod with two strain gauges and two accelerometers. The measurement was in accordance with ASTM-D-4663. Measurements were made at three different depths and the average value was used for the analysis. Typical data acquisition is presented on Fig. 4.



Instr. Length m	Blows Applied /150mm	N Value	N60 Value	Average FMX tn	Average VMX m/s	Average BPM bpm	Average EFV J	Average ETR %
11.3	7-15-23	38	44	12	3.32	16.1	319	68.3
13.3	6-12-20	32	37	13	3.43	18.0	320	68.6
16.1	9-18-18	36	42	13	3.63	15.4	346	74.2
			Overall Average Values:	13	3.46	16.4	329	70.4
			Standard Deviation:	1	0.36	2.4	33	7.0
			Overall Maximum Value:	17	4.45	21.3	511	109.4
			Overall Minimum Value:	9	2.55	7.6	272	56.1

Figure 4. SPT Energy Transfer Record.

Thus, reviewing the results, an average Energy Transfer Ratio (ETR) of 70.4% was used. The N_{60} values for BH-2 and 14 given on Fig. 3

3.4. Pressuremeter Test Results

Pressuremeter tests were performed in NX-size hole in BH-2 at every 5-m depth interval. Thus, in a 60-m deep borehole, 12 tests were conducted using a GA Menard Pressuremeter equipment (capacity 80 bars) as illustrated on Fig. 5.

Figure 5. Pressuremeter Test in progress.

The measured pressure and volume were corrected for stiffness of the membrane and expansion of the hoses. A typical curve of pressure versus volume is illustrated on Fig. 6.

Fig. 7 presents a typical plot of pressure versus creep volume (V_{60}-V_{30}). The pressure corresponding to which the creep volume is minimum corresponds to the horizontal stress at the test depth (Clarke 1995).

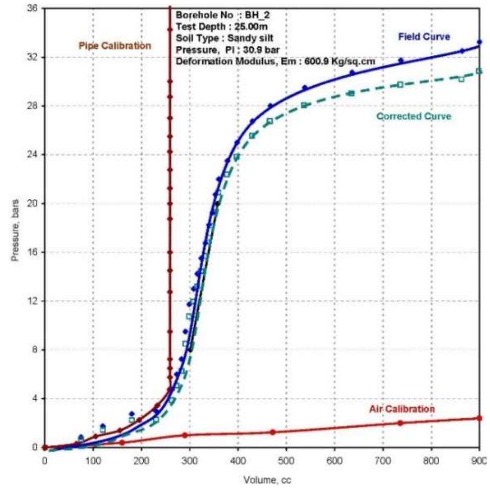


Figure 6. Typical Pressure vs Volume curve – Tower 2.

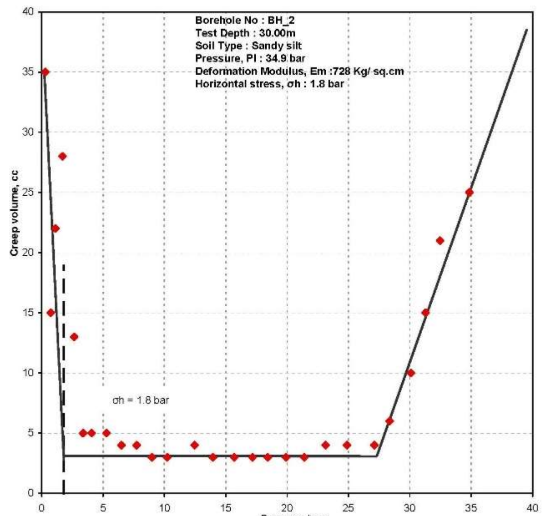


Figure 7. Typical plot of Pressure vs Creep Volume.

The profile of limit pressure and deformation modulus with depth at BH-2 is presented on Fig. 7. It also presents the horizontal stress interpreted from plot of creep volume versus pressure along with a comparison of the estimated horizontal stress corresponding to k_0 = 0.55.

3.5. Cross-hole Seismic Test Results

To conduct the cross-hole seismic test, three boreholes were drilled at spacing of 3 m centre-to-centre. One of the boreholes was used to generate an impact using a piezo-electric source. In the other two boreholes, geophones were placed at the same depth at which the impact was generated. The velocity of the primary and shears were determined from the time of arrival. The dynamic shear modulus and dynamic Young's modulus were determined using the data (Ravi Sundaram et al 2018). The results are presented graphically on Fig. 9.

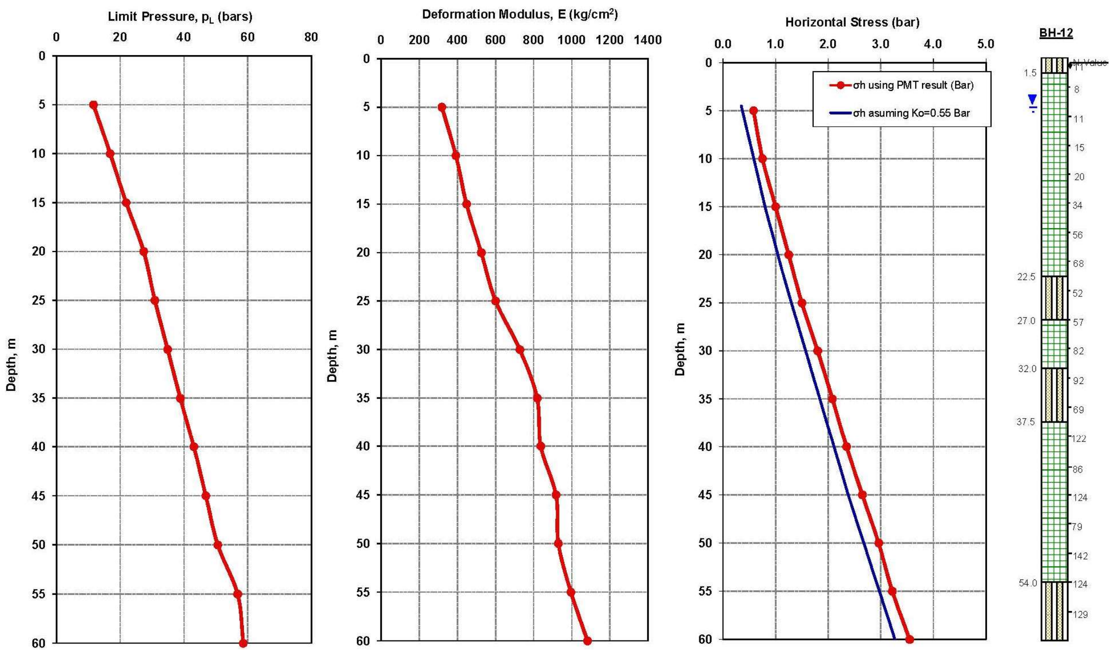


Figure 8. Profile of parameters interpreted from pressuremeter test versus depth

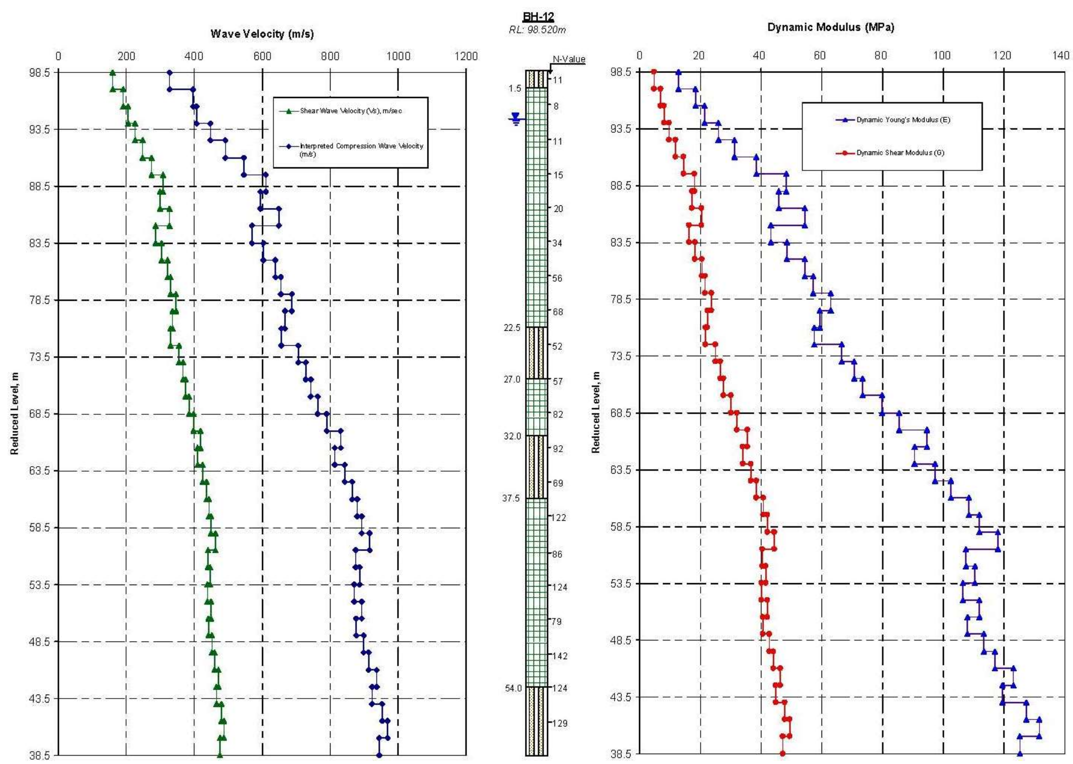


Figure 9. Cross-hole seismic test – Wave velocities and dynamic moduli

3.6. Cone Penetration Test Results

A photograph of the cone penetration test on progress is illustrated on Fig. 10. The average CPT profile (mean of CPTu-10, 11, 13 & 15) for Tower 2 is presented on Fig. 11. It presents the cone tip resistance, sleeve friction, friction ratio and pore pressure together with the soil type.

Figure 10. Cone Penetration Test in progress.

Fig. 12 presents N_{60}, undrained shear strength (s_u), angle of internal friction, (ϕ) and bulk unit weight (γ) interpreted from the CPT data using correlations developed by Robertson & Cabal (2022).

N_{60}, the SPT values corrected for energy transfer have been plotted on the average CPT profile for comparison purpose. The values of s_u (UU triaxial test), and γ determined from the laboratory tests on undisturbed samples have also been plotted on graph for comparison.

The s_u value for the cohesive soils, interpreted from the pressuremeter tests (Ravi Sundaram et al 2019) are also plotted on the graph for comparison.

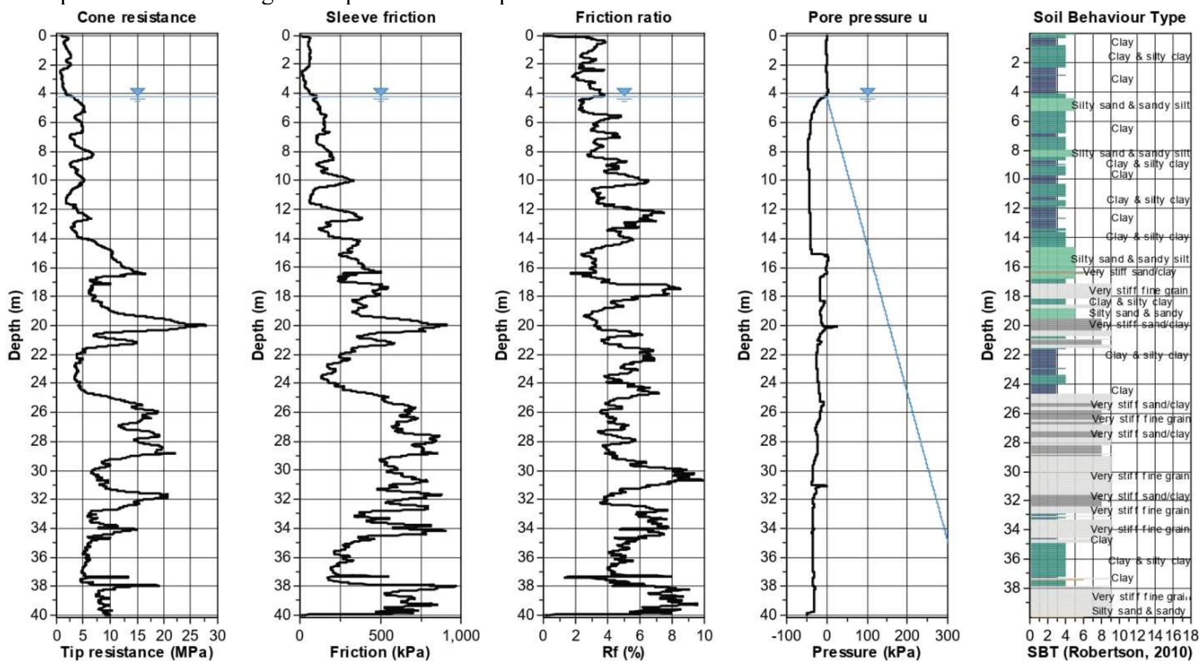


Figure 11. Average CPT plot (CPTu 10, 11, 13, 15) for Tower 2 - q_c, sleeve friction, friction ratio, pore pressure and soil type versus depth.

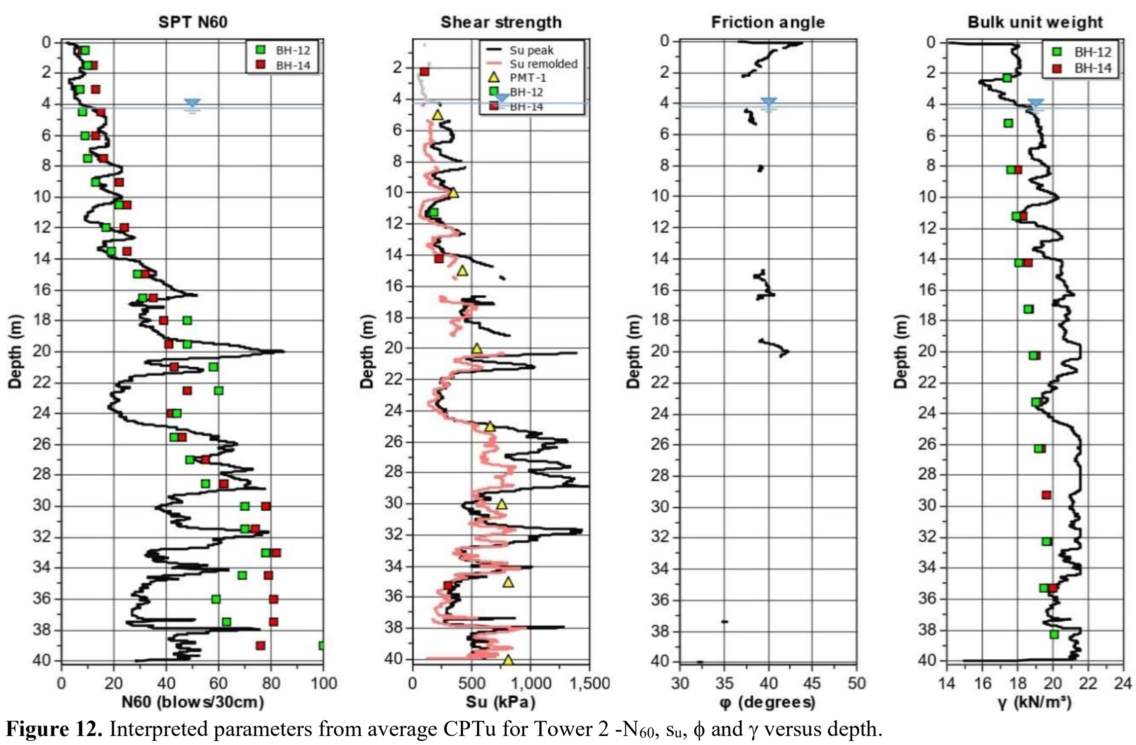


Figure 12. Interpreted parameters from average CPTu for Tower 2 -N_{60}, s_u, ϕ and γ versus depth.

It may be seen from Fig. 12 that a reasonably good match is observed in case of N_{60} and s_u. The laboratory γ values are somewhat lower, probably due to sample disturbance.

Experience in the Indo-Gangetic alluvium has shown CPT results match well with N_{60} and pressuremeter (Ravi Sundaram et al. 2024).

The constrained modulus (M), Young's modulus (E_s), over-consolidation ratio (OCR) and shear wave velocity

(V_s) interpreted from CPT using correlations by Robertson and Cabal, 2022 are presented on Fig. 13. The laboratory values of OCR and the OCR values interpreted from pressuremeter are overlain on this plot to compare the values. The shear wave velocity determined from cross-hole seismic test is also plotted on the graph for comparison purpose.

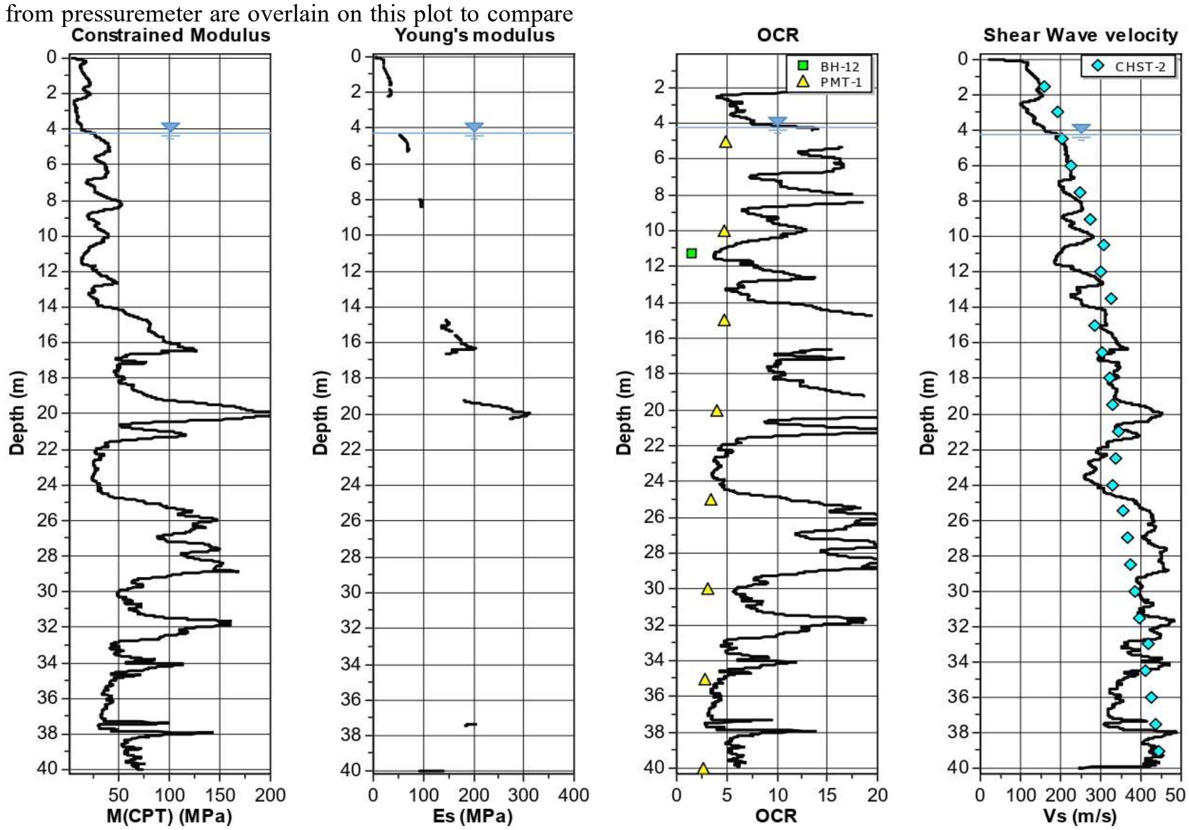


Figure 13. Interpreted parameters from average CPTu for Tower 2 -constrained modulus (M), modulus of elasticity (E_s), over-consolidation ratio (OCR) and shear wave velocity (V_s) versus depth.

The OCR values from the laboratory are lower than that interpreted from CPT, probably due to sample disturbance. The OCR values from pressuremeter are marginally lower than the CPT-interpreted values. Shear wave velocities from CPT show a good match with the measured V_s values.

4. Foundation Analysis

4.1. Foundation Type and Depth

Since one basement is planned, the founding level is expected to be at 4.5-5.5 m depth. The multi-storeyed tower shall bear on raft foundation / piled raft. The extended basement shall have isolated foundations. Accordingly, foundation analysis was performed for the following cases:

1. Isolated foundations for extended basement at 4.5-5.5 m depth.
2. Raft foundation at 4.5-5.5 m depth.
3. RCC bored cast-in-situ pile of 1000 mm diameter with cut-off level at 4.5 m depth.

4.2. Design Profile

Reviewing the results of the various field and laboratory tests conducted, Table 1 presents the design profile selected for the foundation analysis.

Table 1. Design Profile

Depth, m From	Depth, m To	Soil Classification	N_{60}	c, kN/m²	ϕ, degrees	q_c MPa	E, (T/m²)	γ, kN/m³	p_L (bar)	E_{PMT}, MPa
0.0	4.5	Sandy silt	5	30	4	200	1000	17.5	11.3	-
4.5	9.0	Sandy silt	10	60	4	380	2000	18.0	16.8	30.92
9.0	15.0	Sandy silt	14	70	5	380	2400	18.5	20.9	38.25
15.0	19.0	Sandy silt	25	100	5	1130	3700	19.0	26.7	42.76
19.0	22.0	Sandy silt	41	125	5	1130	5600	19.5	31.2	62.55
22.0	25.0	Sandy silt	24	110	5	480	3700	19.5	35.2	71.23
25.0	33.0	Sandy silt	50	170	5	1540	6600	20.0	38.4	78.04
33.0	45.0	Sandy silt	53	180	5	800	6900	20.0	43.0	80.15
45.0	60.0	Sandy silt	70	240	5	800	8400	21.0	47.7	80.50

where:

γ	= bulk unit weight	c	= cohesion intercept	ϕ	= angle of internal friction
E	= Modulus of Elasticity	q_c	= Cone tip resistance		
p_L	= Limit pressure	E_{PMT}	= Deformation modulus (pressuremeter)		

4.3. Isolated Foundations & Raft Foundations

The safe net bearing pressure of isolated foundations and raft foundations is evaluated as the lower of the two values obtained from

- the bearing capacity shear criterion and
- the permissible settlement criterion.

4.3.1. Bearing Capacity

Bearing capacity analysis for isolated foundations and raft foundations were performed by the following methods:

- Conventional approach using c-ϕ values as given in Indian Standard Code IS: 6403-1981.
- Design rules for pressuremeter as given by Clarke 1995.
- Using qc profile as proposed by Eslaamizaad & Robertson 1996.

Analysis was done for 3 m size square isolated foundation as well as raft foundation (≥ 20 m width) at 4.5 and 5.5 m depths). Results are presented graphically on Figs. 14 and 15.

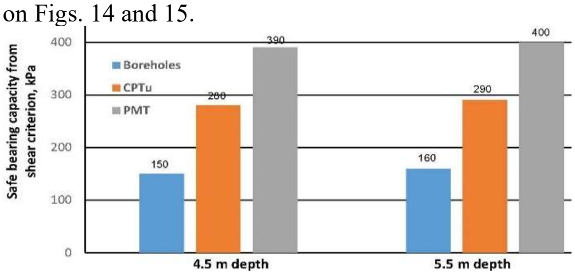


Figure 14. Bearing capacity analysis - 3x3 m size footing.

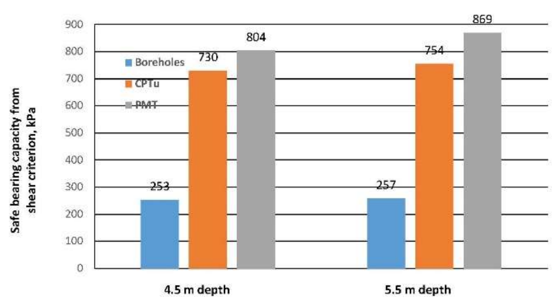


Figure 15. Bearing capacity analysis - raft foundation (20x20 m)

4.3.2. Settlement analysis

Settlement analysis for isolated foundations and raft foundations were performed by the following methods:

- Conventional analysis: Total settlement is the sum of immediate settlement and primary consolidation settlement (Clause 9.2 of IS: 8009 Part 1-1976).
- Design rules for pressuremeter as given by Clarke 1995.
- CPT based settlement analysis proposed by Robertson and Cabal 2022.

Results of analysis for 3 m size square foundation as well as raft foundation (≥ 20 m width) at 4.5 and 5.5 m depths are presented on Figs. 16 and 17.

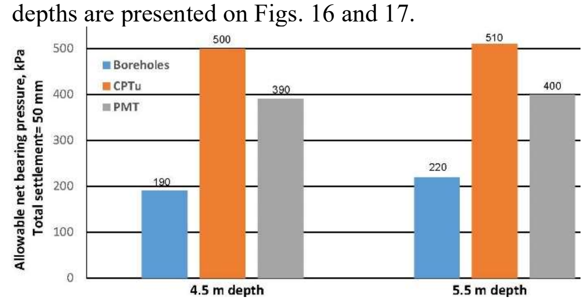


Figure 16. Settlement analysis - 3 x 3 m size footing.

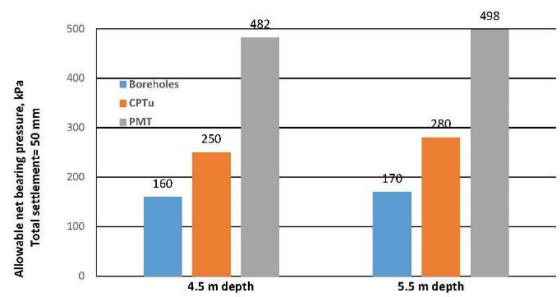


Figure 17. Settlement analysis - raft foundation (20 x 20 m).

Table 2 presents a comparison of the values from the different analysis methods. Comparing with the conventional approach, the analysis shows that analysis based on pressuremeter as well as CPTu yield significantly higher values of net bearing pressure. Even taking average of safe net bearing pressure from pressuremeter and CPTu, the increase in the design values of net bearing pressure is in the range of 44 to 51%.

Table 2. Comparison of Bearing Capacity and Analyses – Conventional Approach vs Advanced Testing Technologies

Foundation Size, m	Depth, m	Bearing Capacity Shear Criterion, kPa				Settlement Criterion, kPa (Total Settlement = 50 mm)				Selected Value †	% Increase*
		c-ϕ	Advanced Methods			Elastic + Consol	Advanced Methods				
			PMT	CPT	Average		PMT	CPT	Average		
3 x 3	4.5	*150*	390	280	**335**	190	390	500	445	335	123%
	5.5	*160*	400	290	**345**	220	400	510	455	345	115%
20 x 20	4.5	*253*	804	730	767	160	482	250	**366**	366	44%
	5.5	*257*	869	754	797	170	498	280	**389**	389	51%

PMT: Analysis based on pressuremeter data CPT: Analysis based on cone penetration test data

† Lower of the two values from shear and settlement criteria * Percentage increase as compared to conventional analysis

The numbers in italics are the governing criterion for conventional approach (lower of the two values from shear and settlement criteria).

The numbers in bold are based the governing criterion for the advanced methods of analysis (lower of the two values from shear and settlement criteria)

4.4. Pile Foundations

Since the tower is planned to have 42 floors, the client was considering use of piled-raft foundation. Analysis was performed for 1000 mm diameter RCC bored cast-in-situ piles with cut-off level at 4.5 m depth for lengths of 28 and 30 m. The methods used for analysis are:

- Conventional static analysis using c-ϕ value in accordance with IS: 2911 Part 1 Section 2 – 2010.
- Design rules for pressuremeter as given by Clarke.
- CPT based analysis using Robertson et al (1988) approach proposed by Bustamante and Gianeselli.

For the conventional analysis, factor of safety of 2.5 was applied as per IS: 1904-2021. For pressuremeter and CPT based analysis, factor of safety of 3 was used. Results of the analysis are summarized in Fig. 18.

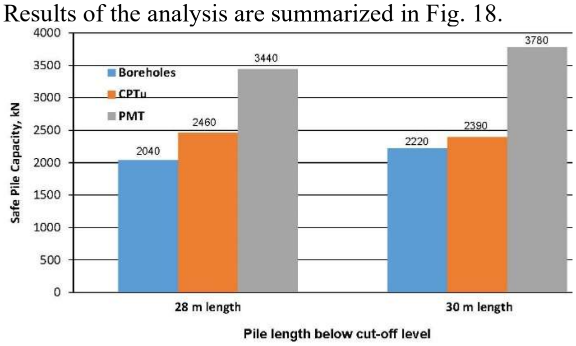


Figure 18. Computed safe pile capacities – 1000 mm dia pile.

It may be seen that the pressuremeter and CPT based analysis yield significantly higher pile capacities. Considering the average of the pile capacities from the CPT and PMT, the increase is on the order of 37-45% in comparison to the conventional approach.

4.5. Implication for Design

The higher safe bearing pressures and pile capacities meant that the foundation design could be optimized and designed for significantly higher loads. The foundation cost was reduced by over 50% resulting in a saving of over INR 100 million (€1.09 million) per tower.

The cost of the additional investigation (pressuremeter tests and CPTu) was less than 2% of the savings realized. The savings is huge and fully justified.

The authors are of the opinion that advanced testing methods can significantly enhance the reliability of the design. In this case, it has also yielded a substantial increase in the net bearing pressure and pile capacities.

5. Concluding Remarks

The paper presents a case study illustrating use of pressuremeter in conjunction with cone penetration tests and geophysical tests to develop reliable geotechnical parameters and economize the design of foundation for a 42-storeyed building in the Indo-Gangetic Alluvium.

Soil parameters as interpreted from SPT N_{60}, pressuremeter and CPTu have been compared so as to develop a realistic and reliable design profile for foundation analysis. The enhancement in design parameters achieved and increase in design net bearing pressures and pile capacities that can be justified by use of advanced testing technologies is explained.

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