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ORIGINAL PAPER

Dilatometer—an in Situ Soil Exploration Tool for Problematic Ground Conditions vis-à-vis for Economizing Construction Activities

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Abstract Proper identification and characterization of subsoil profile depends on thorough geotechnical investigation. Standard Penetration Test and collection of undisturbed soil samples are age-old common techniques. But from the last decades, it has been observed that there is a major shift in this field. Confidence has been generated more into obtaining results directly from in situ testing. In situ tests (e.g. Cone Penetration Test (CPT), Standard Penetration Test (SPT), and Flat Dilatometer Test (DMT) etc.) are fast, economical and highly informative. Important engineering properties such as undrained cohesion (c_u), angle of internal friction (φ) and vertical drained constrained modulus (M) can be estimated by the Flat Dilatometer test with high degree of accuracy. In this paper, the undrained cohesion (c_u) and constrained modulus (M) are obtained from Dilatometer Tests and the values have been compared with other field and laboratory test results from three different test sites in Kolkata. Apart from this, two numbers of software, namely DMT Settlement and PLAXIS 2D, were used to draw a comparison on the settlement of the foundation between the estimated value, based on constrained modulus (M) obtained from DMT, CPT tests data and conventional shear strength parameters obtained from conventional boring practices. Finally, it is concluded that geotechnical properties obtained from DMT tests are conservative in nature and settlement obtained from DMT test is well comparable with regard to estimated and observed settlement from other test results. Besides, use of DMT tests reduces overall construction cost and can be performed with confidence in difficult ground condition.

Keywords Flat Dilatometer test (DMT) · Undrained cohesion (c_u) · Vertical drained constrained modulus (M) · DMT Settlement software · PLAXIS 2D

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Introduction

Standard Penetration Test (SPT) and collection of undisturbed soil samples are one of the most common practices used in geotechnical engineering field. Recent practice shows inclination is more towards in situ testing instead of collecting samples from conventional borehole or drill hole to predict sub-soil profile. In situ tests (e.g. Cone Penetration Test (CPT), Standard Penetration Test, Flat Dilatometer test (DMT) etc.) are fast, economical, and highly informative. The Cone Penetration Test (CPT) equipment was developed at the Dutch Laboratory in the 1950s to investigate soft soils. The Standard Penetration Test (SPT) was initially introduced during the beginning of 1920s.

On the other hand, Marchetti Flat Dilatometer (DMT) has been introduced in this family in very recent period. This instrument was developed by Prof. (Dr.) Silvano Marchetti in 1974 at the L'Aquila University in Italy.

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Important soil parameters such as undrained cohesion (c_u), angle of internal friction (φ), and vertical drained constrained modulus (M) can be estimated by the Flat Dilatometer test. Generally from DMT tests, stiffness and some of the elastic parameters may also be obtained in addition to the shear strength parameters and constrained modulus as explained above. When only DMT tests are conducted, elastic modulus E (Young's modulus) may be obtained from constrained modulus by correlations using theory of elasticity equations. When the seismic probe is used along with the Dilatometer blade (known as SDMT), shear modulus, G may be obtained directly from field shear wave velocity (V_s) values measured from shear wave velocity tests. Besides, shear wave velocity (V_s) can also be measured by adding an add-on seismic module to the DMT control box.

In this paper, three case studies are presented. The first one is from Science City site where initial soil exploration revealed high depth of filling and consequently, deep foundations for all the proposed buildings were recommended. Subsequently, DMT tests were conducted at this site with a view to finding the possibility of using shallow foundations as this test determines geotechnical properties at intervals over very short thickness. Findings from this investigation showed that shallow foundations could be used satisfactorily for low to medium-rise buildings negating the use of piles.

The second case study discusses the application of DMT tests within Hon'ble High Court building. The northwest corner of the building had shown tell-tale sign of excessive settlement. As a consequence, many structural components including the floor and walls developed huge cracks rendering the building almost unusable. Subsequently, ground improvement techniques to arrest the settlement were recommended by the experts. Since this part of the building had very little space to accommodate the boring rig for carrying out soil exploration by wash-boring method, DMT and CPT tests up to the depth of approximately 8 to 9 m were suggested to be conducted to investigate the effectiveness of the proposed ground improvement technique. Total eight nos. of points were selected. Out of these at four of these locations, DMT tests were conducted and at other four adjacent locations CPT tests were performed to compare results with findings from DMT tests. This case study delineated a classic example on the comparison of DMT-predicted settlement vs. observed settlement at site.

The third case study at Rajarhat, Kolkata, is presented to delineate and compare DMT test results with conventional CPT and ordinary wash-boring method. The sole purpose of this test is to show that DMT tests give results which are well comparable to other conventional tests.

Undrained cohesion (c_u) and vertical drained constrained modulus (M) are obtained from Dilatometer tests, and these values have been compared with other field and laboratory test results from other conventional tests for three different test sites (e.g. Science City, High Court and Rajarhat) in Kolkata.

Apart from this, a comparison has been drawn on the settlement of the foundation between the estimated value, based on vertical drained constrained modulus (M) obtained from DMT, CPT test data and shear strength parameters obtained from conventional boring approach. Two numbers of software namely DMT Settlement and PLAXIS 2D were used to estimate settlement numerically.

Methodology

Conventional Boring Approach

In this study, boreholes were dug within the proposed site up to an average depth of 20 m. The undisturbed samples were collected from every 3.0 m depth interval, and the Standard Penetration tests were done at every 1.5 m depth interval inside the borehole. The SPT tests were carried out as per [1]. The number of blows required for the last 30 cm penetration of the split spoon sampler was recorded as 'N'-value. Also the laboratory triaxial tests (UU) were conducted on collected undisturbed samples [2] to estimate the undrained cohesion (c_u).

Cone Penetration Test

Cone penetration Test (CPT) is widely accepted test in geotechnical investigation purpose. The CPT test is done by pushing the cone (Begemann Bit) vertically into the ground surface at a constant strain rate ($\approx$2 cm/s). Three numbers of readings, namely $\underline{R_p}$, $R_p + R_L$ and R_T, are recorded during the penetration of the cone for a particular depth. These readings are recorded at depth intervals of nearly 20 cm. Two numbers of basic parameters i.e. cone resistance (q_c) and frictional resistance (f_s) are calculated from the recorded readings [3–8].

The undrained cohesion (c_u) and vertical drained constrain modulus (M) are calculated based on the correlations on corrected cone resistance (q_c) [3, 4, 6–9] as per Eqs. (1) and (2) below.

$$c_u = (q_t - \sigma_v)/N_{kt} \tag{1}$$

$$M = 8.25 \times \left(q_c - \sigma'_{v0}\right) \tag{2}$$

where,

q_t = corrected cone resistance (q_c) for CPT tests without piezocone,

σ_v = total overburden pressure (i.e. $\Sigma Z_i * \gamma_i$),

Z_i = depth of the ith layer from the ground surface,

γ_i = soil unit weight of the ith layer,

N_{kt} = Cone factor (here it is 14). The cone factor (N_{kt}) varies from 10 to 20. Detailed literature review suggests that the value of N_{kt} may be considered as 14 as general value for different types of soils [10].

σ'_{v0} = effective overburden pressure,

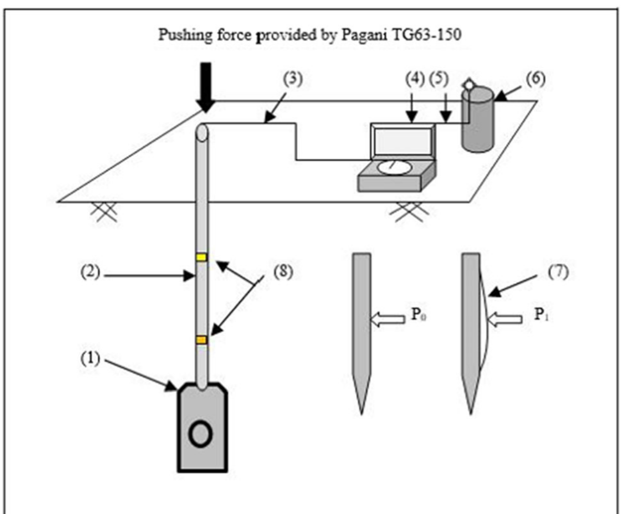
q_c = corrected cone resistance,

Flat Dilatometer Test

The Flat Dilatometer Test (DMT) is used to evaluate the compressibility characteristics along with shear strength parameters of the soils in very short time with accuracy. The flat dilatometer consists of a steel blade with size of 95 mm × 200 mm × 15 mm, having one side consisting of an expandable steel membrane. The gas (nitrogen gas) pressure is required to expand the membrane. When the membrane is expanded by allowing gas pressure, the soil is compressed. Two numbers of pressure readings (A and B) are then taken from pressure gauges fitted to the control unit, for a particular test depth. After completion of B reading, further the blade is pushed to the next depth. This control unit is connected to the DMT blade and the gas tank through pneumatic-electrical cable (p-e cable).

The main purpose of the DMT test was to evaluate the geotechnical parameters of the soil instantaneously in the field. Ten numbers of Dilatometer tests were carried out on three selected locations up to the depth of 18 m on an average below the existing ground level.

The undrained cohesion (c_u) and vertical drained constrained modulus (M) [6, 11, 12, 13, and 14] were calculated from Eqs. (3) and (4) with the help of SDMT Elab software provided with the machine. Figure 1 illustrates the setup of the DMT machine.



(1) Dilatometer blade (2) Dilatometer rods (3)P-e cable (4) Control Box
(5) Pneumatic cable (6) Gas tank (7) Expansion of the membrane i.e., 1.1mm
(8) Two numbers sensors for seismic dilatometer tests

Fig. 1 The Flat Dilatometer equipment [13]

$$(c_u) = 0.22\sigma'_{v0} \times (0.5 \times K_D)^{1.25} \tag{3}$$

$$M_{DMT} = R_M \times E_D \tag{4}$$

$$If\ I_D \leq 0.6 \quad R_M = 0.14 + 2.36 \log K_D \tag{4.1}$$

$$If\ I_D \geq 3 \quad R_M = 0.5 + 2 \log K_D \tag{4.2}$$

$$If\ 0.6 < I_D < 3 \quad R_M = R_{M,0} + \left(2.5 - R_{M,0}\right) \log K_D \tag{4.3}$$

$$\text{where} \quad R_{M,0} = 0.14 + 0.15(I_D - 0.6) \tag{4.4}$$

$$\text{If} K_D > 10 \ R_M = 0.32 + 2.18 \log K_D \tag{4.5}$$

$$\text{If} R_M < 0.85 \text{ set} R_M = 0.85 \tag{4.6}$$

where

$K_D = \left[(p_0 - u_0)/\sigma'_{v0}\right]$ = horizontal stress index,

$I_D = (p_1 - p_0)/(p_0 - u_0)$ = material index,

$E_D = 34.7(p_1 - p_0) =$ dilatometer modulus,

p_0 = Corrected first pressure reading, p_1 = Corrected second pressure reading, u_0 = Static pore pressure or pre-insertion in situ equilibrium water pressure. σ'_{v0} = Effective overburden pressure.

Based on the values of Dilatometer Modulus (E_D) and Material Index (I_D), in situ density is estimated from the standard chart suggested by [13].

PLAXIS Software

In this study purpose, PLAXIS 2D 2016 software has been used for foundation analysis from the obtained in situ tests data [15] numerically.

Site Investigation

The type of investigations and test locations were chosen in order to evaluate the soil parameters for geotechnical analysis and design purpose. The sub-soil characteristics had to be investigated in terms of strength and deformability parameters to design a cost effective foundation for new structures. Hence, the following investigations, on the sites, were performed.

Total eight numbers (BH1, BH2, BH3, BH4, BH5, BH6, BH7, BH8) of boreholes along with SPT tests were conducted up to an average depth of 20 m at three different test locations in Kolkata (i.e. Science City, High Court and Rajarhat). Out of these BH1, BH2 and BH3 were dug at Science City site; BH4 to BH6 were dug at High Court site; BH7 and BH8 were dug at Rajarhat site. Description of stratigraphy along with the strength and stiffness

Fig. 2 Photographs showing pit and placement of ramps at High Court test location

Fig. 3 Photograph showing test set up at High Court test location

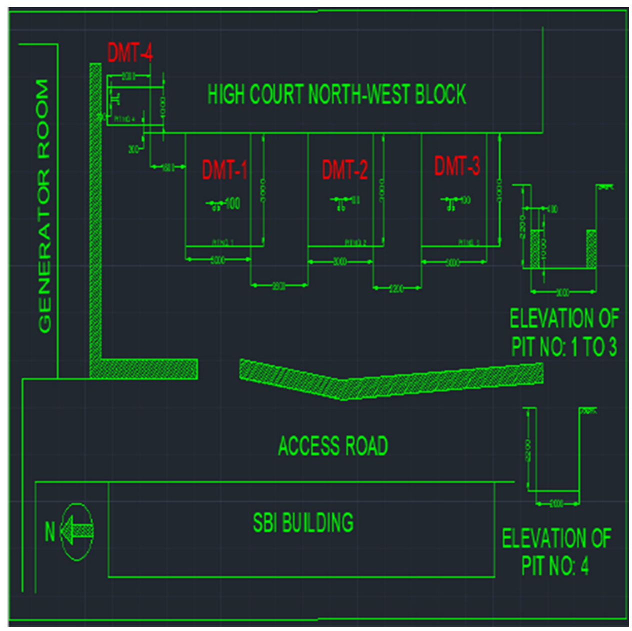


Fig. 4 High Court test locations

parameters had been evaluated on the basis of laboratory tests conducted on collected undisturbed soil sample.

Eight numbers of DMT tests, i.e. DMT1, DMT2, DMT3, DMT4, DMT5, DMT6, DMT7 and DMT8 (adjacent to afore-mentioned boreholes), were carried out by giving 500 mm spacing between the respective CPT points. DMT1 and DMT2 test locations were made at Science City site; DMT3 to DMT6 test locations were chosen at High Court site; DMT7 and DMT8 test locations were selected at Rajarhat site.

Eight numbers of CPT (CPT1, CPT2, CPT3, CPT4, CPT5, CPT6, CPT7 and CPT8) tests were carried out up to an average depth of 19.0 m below the existing ground level adjacent to DMT test locations. The CPT tests were carried out by using the attached CPT assembly provided with Pagani TG 63-150 penetrometer. The CPT test was performed at 2 cm/s penetration rate vertically downward. On every 200 mm depth interval readings were taken. CPT1 and CPT2 test locations were at Science City site; CPT3 to CPT6 test locations were at High Court site; CPT7 and CPT8 test locations were selected at Rajarhat site.

High Court Test Site

The ambience of High Court site was very challenging to conduct the field exploration by means of placing rigs and using conventional wash-boring technique with shell,

Fig. 5 Photograph showing garbage dump and TG 63 penetrometer at Science City test location

Fig. 6 Photograph showing test set up at Rajarhat test location

mainly due to insufficient space for placing the rig at each test location. To overcome this difficulty, DMT and CPT tests were recommended by the consultant experts. Since this site had a fill layer consisting of brickbats, rubbish etc., it was difficult to push the DMT balde through this layer. Subsequently, pits of about 1.5 m depth were dug to excavate the heterogeneous fill and tests were conducted starting from this depth. In order to place the heavy penetrometer, four numbers of steel ramps were placed over these excavated pits. Each ramp measured 2.72 m in length, 0.4 m in width and 0.18 m in thickness. These ramps were joined together by pairing through bolts as four numbers of shorter ramps were converted into two longer ones having length of 5.4 m as shown in Fig. 2.

In the next step, the side of the excavated pit was cleaned and these ramps were placed horizontally above the pit. These ramps were laid parallely keeping a clearance of 200 mm in between so that the DMT blade could easily pass through this space, as shown in Fig. 2. Subsequently, penetrometer TG63-150 was placed on these ramps (Fig. 3).

Science City Test Site

It was observed from field exploration that there was a garbage and ash filling layer up to 9 m on an average at Science City test location. From the initial geotechnical test report, recommendation was made for use of pile foundation for all the high-rise structures. To reduce the cost of construction, it was recommended by the geotechnical experts to conduct DMT testing at this test site to ascertain whether or not shallow foundation could be used for some

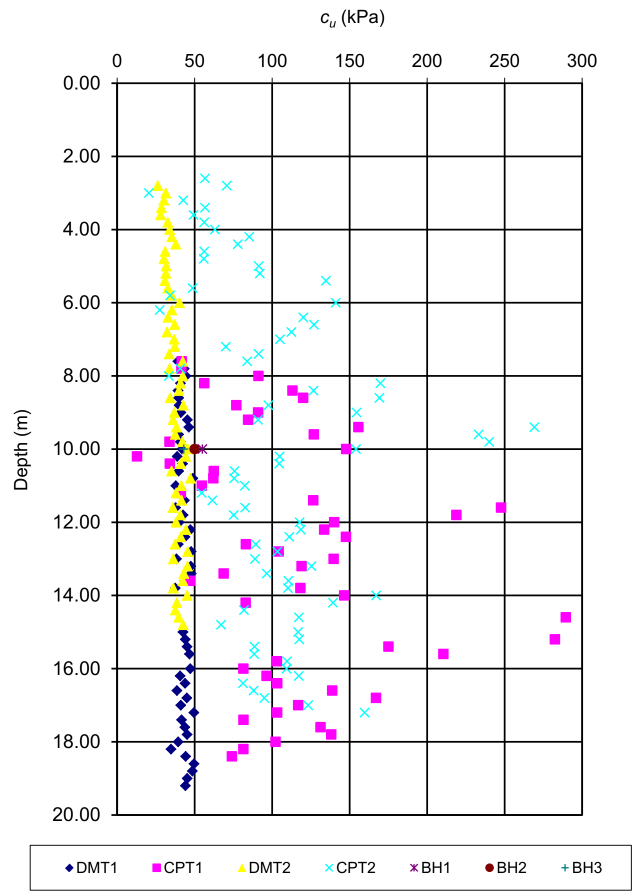


Fig. 7 Variation of undrained cohesion (c_u) with depth for DMT1, DMT2, CPT1, CPT2, BH1, BH2, and BH3 test points at Science City, Kolkata

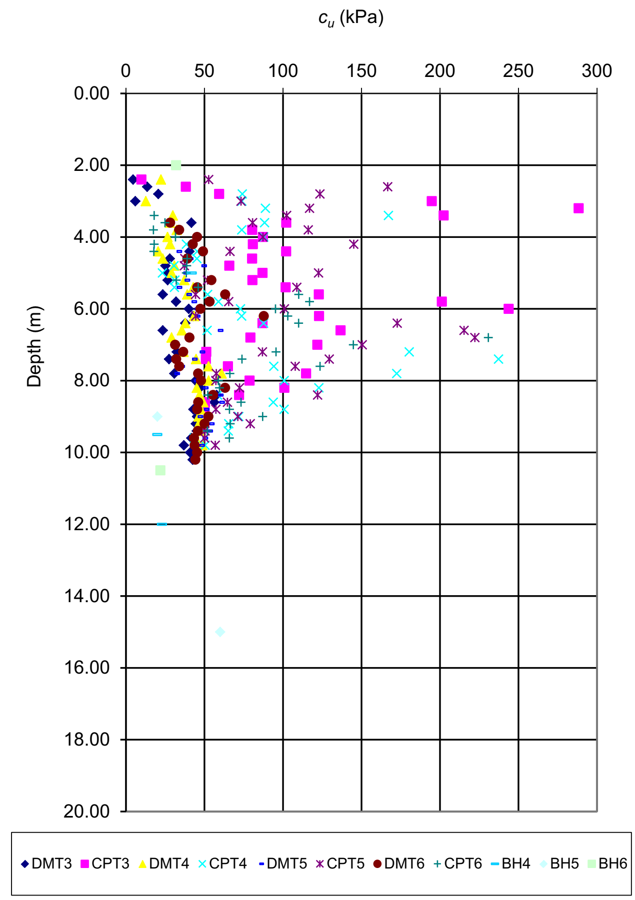


Fig. 8 Variation of undrained cohesion (c_u) with depth for DMT3, DMT4, DMT5, DMT6, CPT3, CPT4, CPT5, CPT6, BH4, BH5, and BH6 test points at High Court, Kolkata

of the low to medium-rise structures proposed to be constructed here. Figure 5 demonstrates the site location.

Rajarhat Test Site

At this location, DMT test was performed in order to compare the laboratory test results with in situ results. Figure 6 demonstrates the site location.

4. Results and Discussion

Undrained Cohesion (c_u)

Undrained cohesion (c_u) was estimated from correlations for CPT and DMT tests and compared with the laboratory triaxial *UU* test results conducted on collected undisturbed soil samples corresponding to nearest boreholes [2, 6, 8, 9, 11, 13, 16–19]. The authors had considered layer-wise weighted average of c_u value for ascertaining the safe bearing capacity of soil. The variations of results along depth are plotted in Figs. 7, 8, and 9.

The test results were found to be consistent for the laboratory triaxial *UU* tests and DMT tests in all three test locations.

With regard to CPT, some values estimated were found to be on the higher side for CPT test results. The probable reason behind this may be due to the fact that the CPT cone senses soil slightly ahead and behind of the cone tip due to the size of the influence zone. This observation is also supported by [10] who showed that the cone can sense a soil interface up to 15 times cone diameters ahead and behind, depending on the strength/stiffness of the soil and the in situ effective stresses.

The DMT results are more comparable with the conventional borelog survey results because of the effect of less disturbance of the sub-soil during the penetration of Dilatometer blade into the soil as suggested by [11].

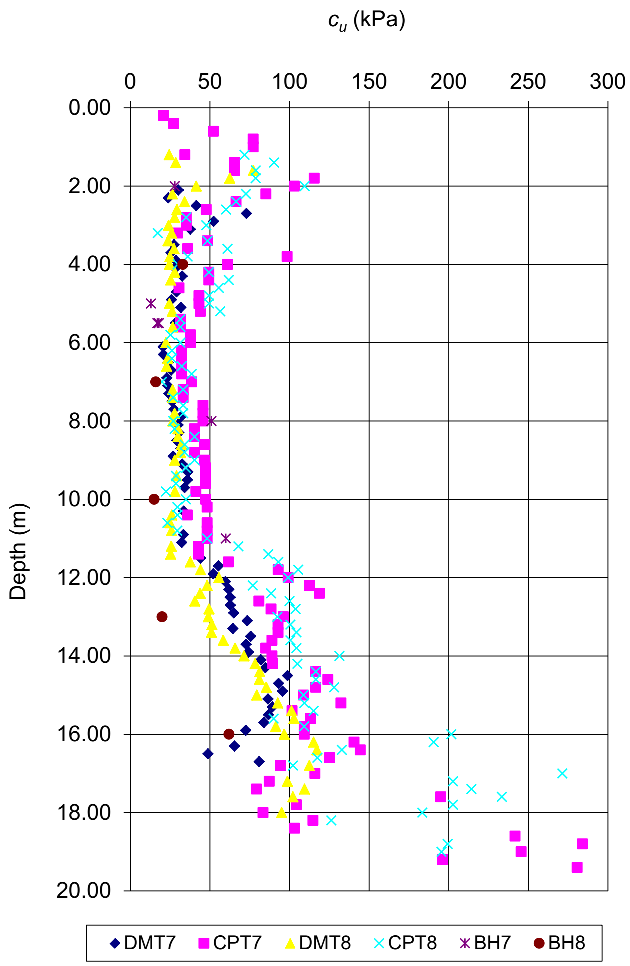


Fig. 9 Variation of undrained cohesion (c_u) with depth for DMT7, DMT8, CPT7, CPT8, BH7, and BH8 test points at Rajarhat, Kolkata

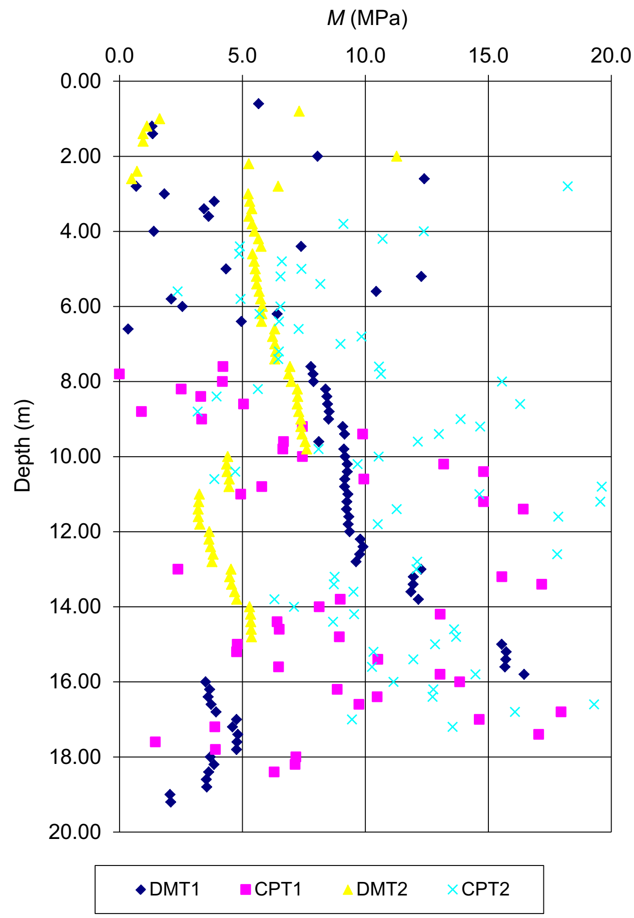


Fig. 10 Variation of vertical drained constrained modulus (*M*) with depth for DMT1, DMT2, CPT1, and CPT2 test points at Science City, Kolkata

Vertical Drained Constrained Modulus (M)

By using Eqs. (2) and (4–4.6), vertical drained constrained modulus had been calculated from CPT and DMT tests, respectively. Figures 10, 11 and 12 show the variation of (*M*) values with depth for Science City, High Court, and Rajarhat test locations, respectively.

The test results were found to be consistent for the CPT tests and DMT tests in all three test locations. However, some values estimated were found to be on the higher side for CPT test results.

Sub-soil Profile

Science City test site

It was observed that the top layer, namely Layer I, consists of garbage materials and ash filling having an average thickness of 9.0 m below ground level. This top layer is followed by light bluish/ brown, grey silty clay/clayey silt (Layer II) with an average depth of 10.40 m. For DMT 2, test point there is layer of sandy silt/silty sand (Layer III) below Layer II having a depth of 2 m. Figure 13 demonstrates the sub-soil profile of Science City test location.

Here, no foundation will be placed on the MSW fill layer. The foundation depth of 2.8 m has been considered from the bottom of the fill layer. Before placing the foundation, the entire MSW fill of about 8 m will be excavated and removed to open the actual ground level below which the virgin soil exists. Further excavation will be made in the virgin soil to the tune of (2.8 m + 1.6 m), i.e. 4.4 m. The bottom 1.6 m will be filled with compacted sand above which the foundation will be placed. Hence the overall foundation depth works out to be about 11 m (8 m of fill + 2.8 m) from the top of the MSW fill or so to say the existing ground level. In Fig. 13, all these levels are clearly marked. Due to the presence of this huge fill layer, pile foundation was initially recommended.

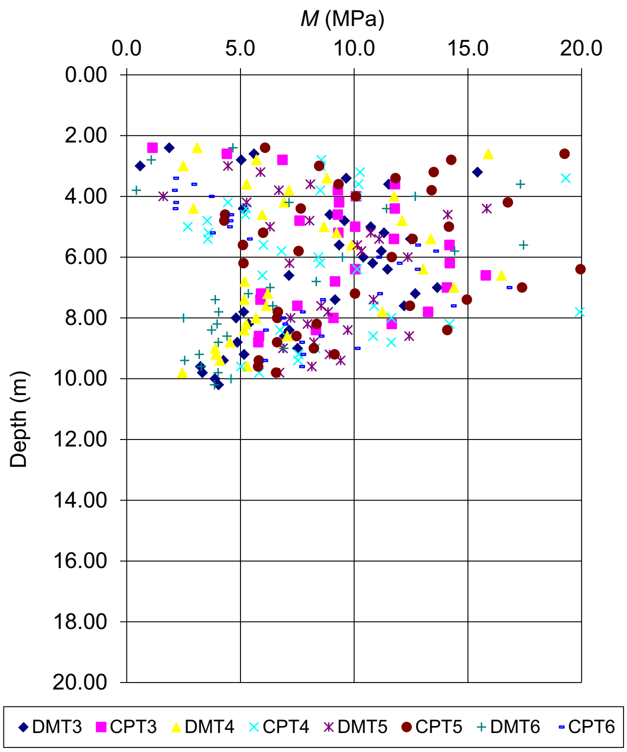


Fig. 11 Variation of vertical drained constrained modulus (*M*) with depth for DMT3, DMT4, DMT5, DMT6, CPT3, CPT4, CPT5, and CPT6 test points at High Court, Kolkata

High Court Test Site

For High Court test location, it was observed that the top layer, namely Layer I consists of rubbish and brickbats with an average depth up to 3.0 m below ground level. This top layer is followed by soft/ firm brownish grey silty clay/clayey silt (Layer II) with an average depth of 3.0 m. Layer III starts from 6 m below the ground level with soft dark grey silty clay/clayey silt along with organic matter and decomposed vegetation having average depth of 9.0 m. This layer is underlain by light bluish/ brown, grey silty clay/clayey silt with an average depth of 8.0 m (Layer IV). This layer is finally followed by medium dense/ dense brownish grey silty fine sand with mica extending up to the termination depth, i.e. 25.60 m (Layer V). Figure 14 demonstrates the sub-soil profile.

Rajarhat Test Site

For Rajarhat test location, it was observed that the top layer, namely Layer I consists of rubbish with an average depth up to 1.5 m below ground level. This top layer is followed by soft/ firm brownish grey silty clay/clayey silt (Layer II) and silty clay/clayey silt with calcareous nodules (Layer III) with an average depth of 12.00 m. The next layer (i.e. Layer IV) is underlain by silty clay/clayey silt with an average depth of 4.0 m below Layer II & III. This layer is finally followed by stiff silty clay (Layer V) and fine sand/sandy silt (Layer VI) with an average depth of 3.0 m. Figure 15 demonstrates the sub-soil profile.

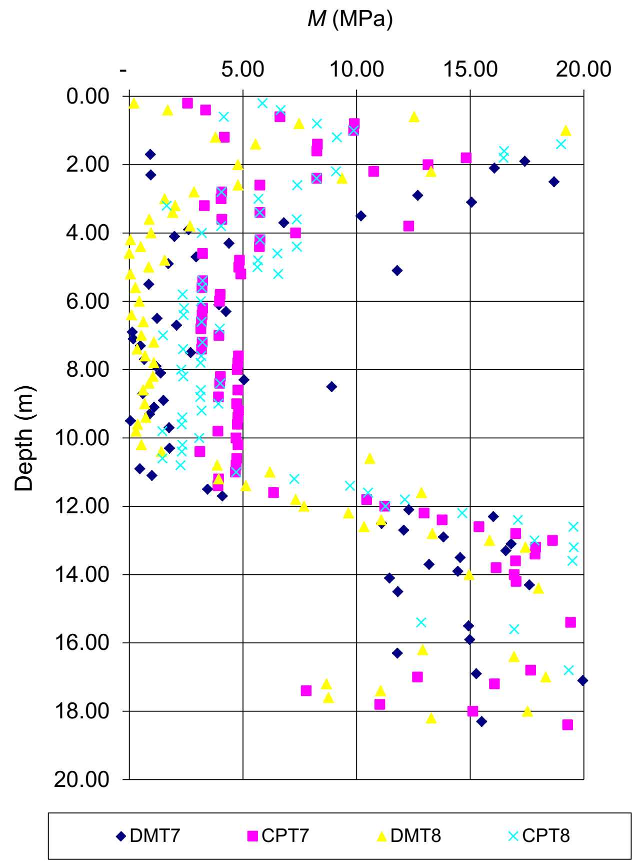


Fig. 12 Variation of vertical drained constrained modulus (*M*) with depth for DMT7, DMT8, CPT7, CPT8 test points at Rajarhat, Kolkata

Settlement Analysis of all the Project Sites

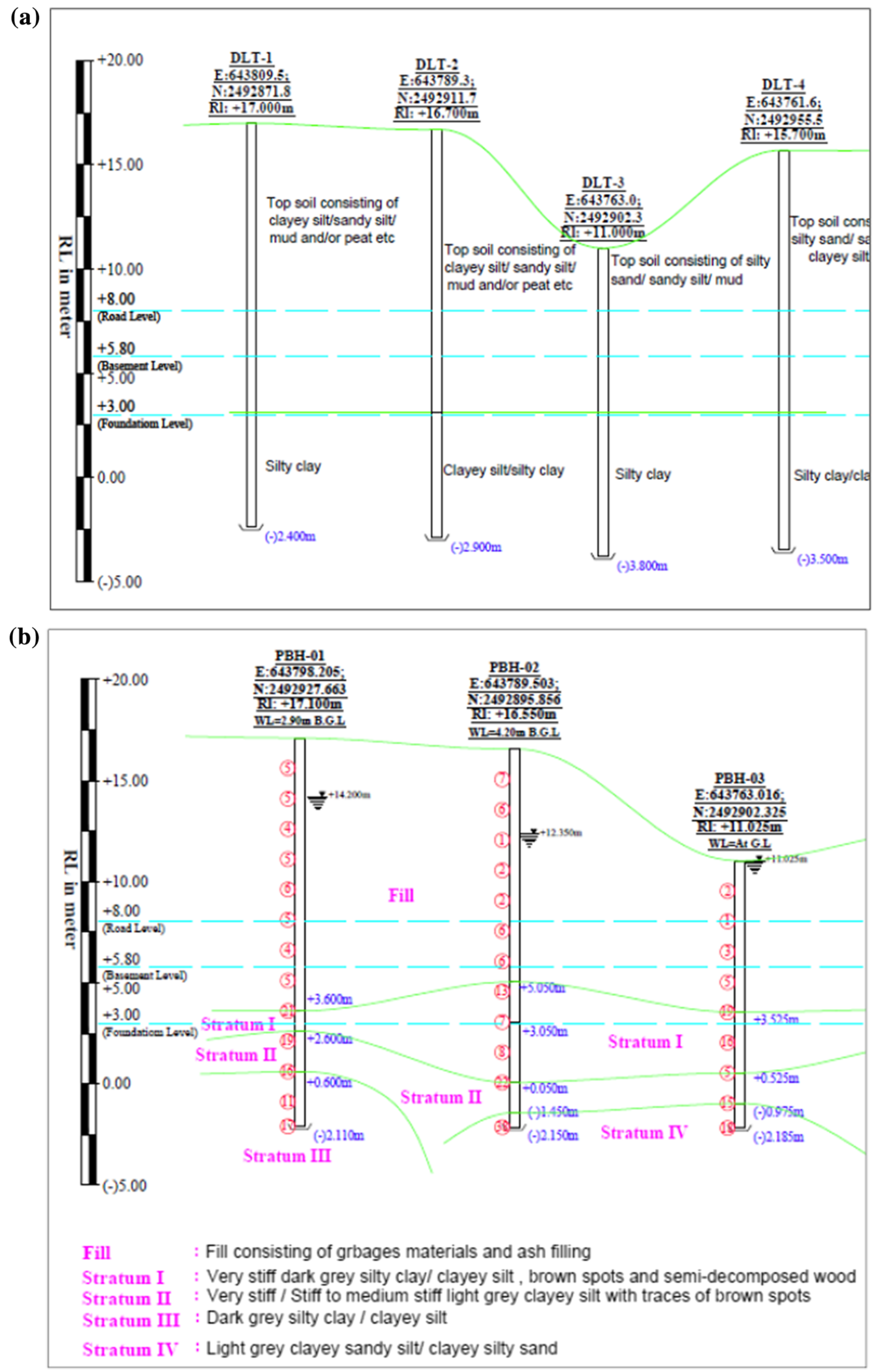
Science City Test Location

The proposed structure near Science city site is a medium-rise building, constructed for commercial purpose.

For settlement prediction, DMT data software was used, namely DMT settlement provided with the DMT machine. This software is based on the one-dimensional elastic theory. PLAXIS 2D 2016 was also been used for settlement prediction numerically.

For calculation purpose, the depth of foundation was assumed at R.L + 2.8 m. The foundation of the building has been assumed to be consisting of isolated footing with varying length by width of 6.4 m × 6.4 m, 5 m × 5 m, 3 m × 3 m and 2.55 m × 2.55 m. Total design load intensity on the footing was assumed as 150 kPa, and 155 kPa for afore-mentioned test points.

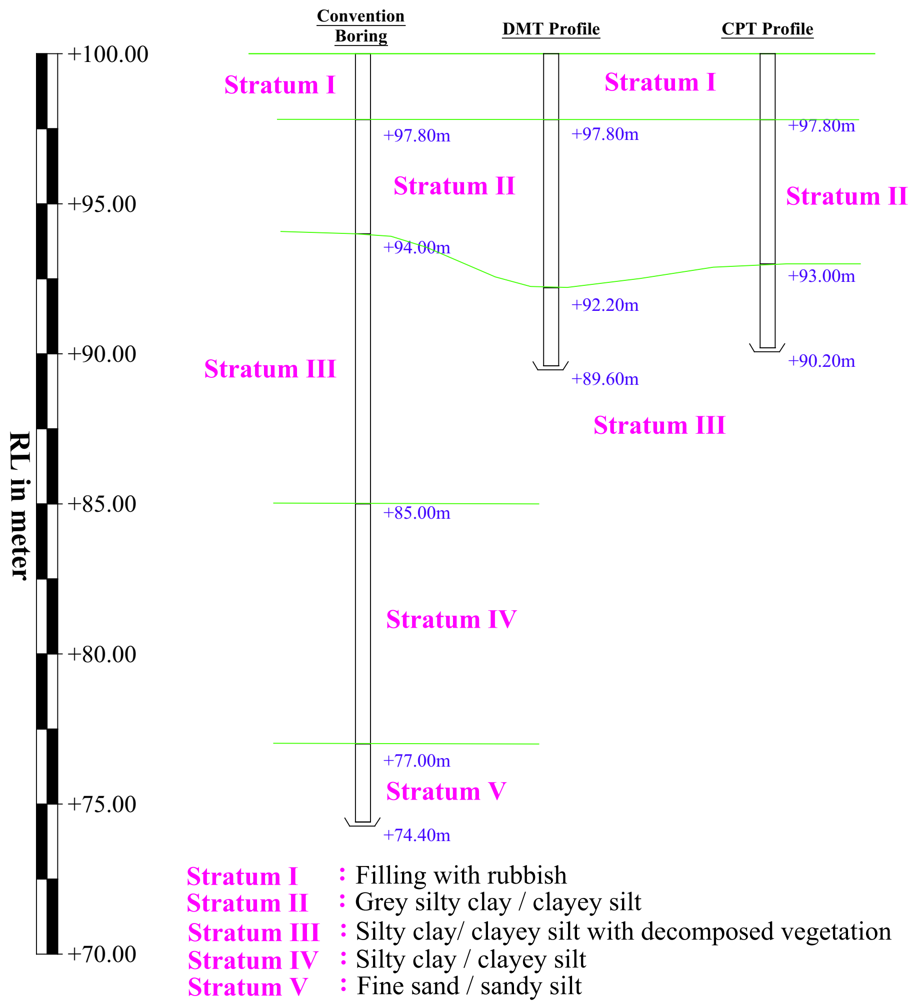
Fig. 13 (**a**) Sub-soil profile of the Science City test location obtained from DMT test, (**b**) Sub-soil profile of the Science City test location obtained from borelog data



The MSW fill up to the depth of 8.0 m will be excavated and removed during the time of construction for each location of the foundation. Subsequently foundations will be placed on the virgin soil at a depth of 2.8 m below the excavated actual ground level.

Settlement Calculation from DMT Settlement software The settlement was calculated considering four different sizes of footings proposed to be placed at each of DMT test locations. Two cases (i.e. Case 1 and Case 2) were considered for the settlement calculation. In "Case 1," foundation was placed without sand layer and "Case 2," foundation was placed on a 1–6-m-thick sand layer followed by original sub-soil. The total settlements were calculated to the centre of the footing. The calculation of the settlements was done by taking the thickness of each

Fig. 14 Sub-soil profile of the High Court test location



soil layer as 20 cm. The settlement of the foundation was calculated by the one-dimensional consolidation theory. The vertical stress increment was calculated by using Boussinesq's equation. The main parameters to calculate the settlement are vertical drained constrained modulus (M) and vertical stress increment ($\Delta\sigma$). The calculated settlements were obtained using the interpretation formulae and the calculation method as recommended in [13].

Settlement Calculated from PLAXIS 2D PLAXIS 2D 2016 also been used for settlement calculation numerically using the shear parameters obtained from DMT, CPT and SPT tests. PLAXIS results have been used as a supplementary tool to compare those of actual analysis by DMT software. Use of PLAXIS 2D for similar cases is also cited [20].

Load intensity and the size of the foundation remain same as per 4.4.1. A plate had been assumed to be placed on the soil having d_{eff} (effective depth =) 150 mm, with varying lengths of 6.4 m, 5 m, 3 m and 2.55 m and width equal to 1 m. Here EA of the plate was calculated as 4.108E^6 kN/m and EI = 7702 kN m^2/m.

where. E = Young's modulus of foundation plate, A = area of the foundation plate, I = moment of inertia of foundation plate.

Table 1 shows the comparison between the settlement analysis of DMT settlement software and PLAXIS 2D.

The footing size of 6.4 m × 6.4 m is meant for a single column of a medium rise building.

Here, bearing capacity of 150 kN/sq.m. is calculated for the virgin soil at a depth of 2.8 m below the bottom of the landfill.

The existing overburden pressure was not considered in the calculation of settlement, since the MSW fill up to the depth of 8–12 m will be excavated and removed during the time of construction. Subsequent foundations will be placed at a depth of 2.8 m below the excavated ground level.

The experimental results were compared with estimated values from different software, and it was noticed that these were coherent in nature, except some minor

Fig. 15 Sub-soil profile of Rajarhat test location

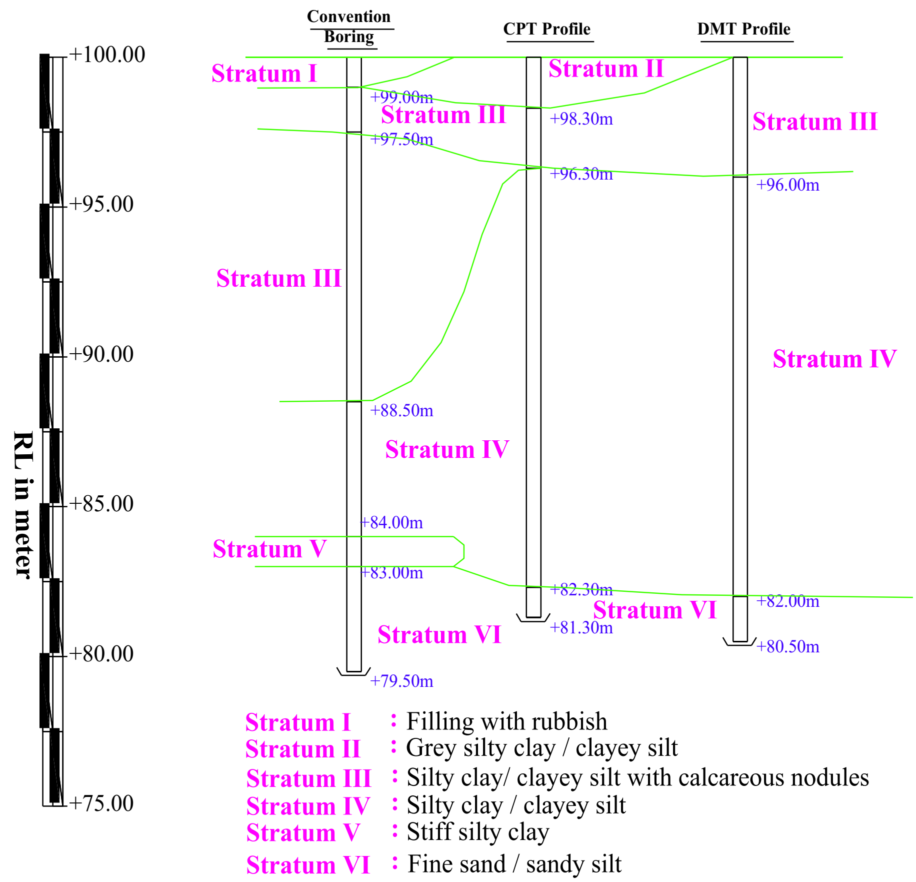


Table 1 Settlement Analysis of Science City test location

SETTLEMENT CALCULATIONS								
Test Points	DMT1		DMT2		CPT1	CPT2	BH1	BH2
Load(kN/m^2)	150		155		150	155	150	155
Specification of settlement calculation process	Plaxis (mm)	DMT settlement Software (mm)	Plaxis (mm)	DMT settlement Software (mm)	Plaxis (mm)	Plaxis (mm)	Plaxis (mm)	Plaxis (mm)
Size Of Foundation								
5 m × 5 m								
Without sand layer	56	46	30	28	69	77	78	82
With sand layer (1.6 m)	47	27.9	27	23.8	53	72	66	74
2.55 m × 2.55 m								
Without sand layer	43	37.1	22	21	51	60	68	76
With sand layer (1.6 m)	39	20	21.7	17.3	46	42	47	55
3 m × 3 m								
Without sand layer	44	39.3	23	22.7	52	62	58	69
With sand layer (1.6 m)	40	21.9	22	18.9	49	45	46.7	63.5
6.4 m × 6.4 m								
Without sand layer	61	48.3	32	29.8	74	84	79	86
With sand layer (1.6 m)	51	30.4	30	25.8	59	66	65.7	70.8

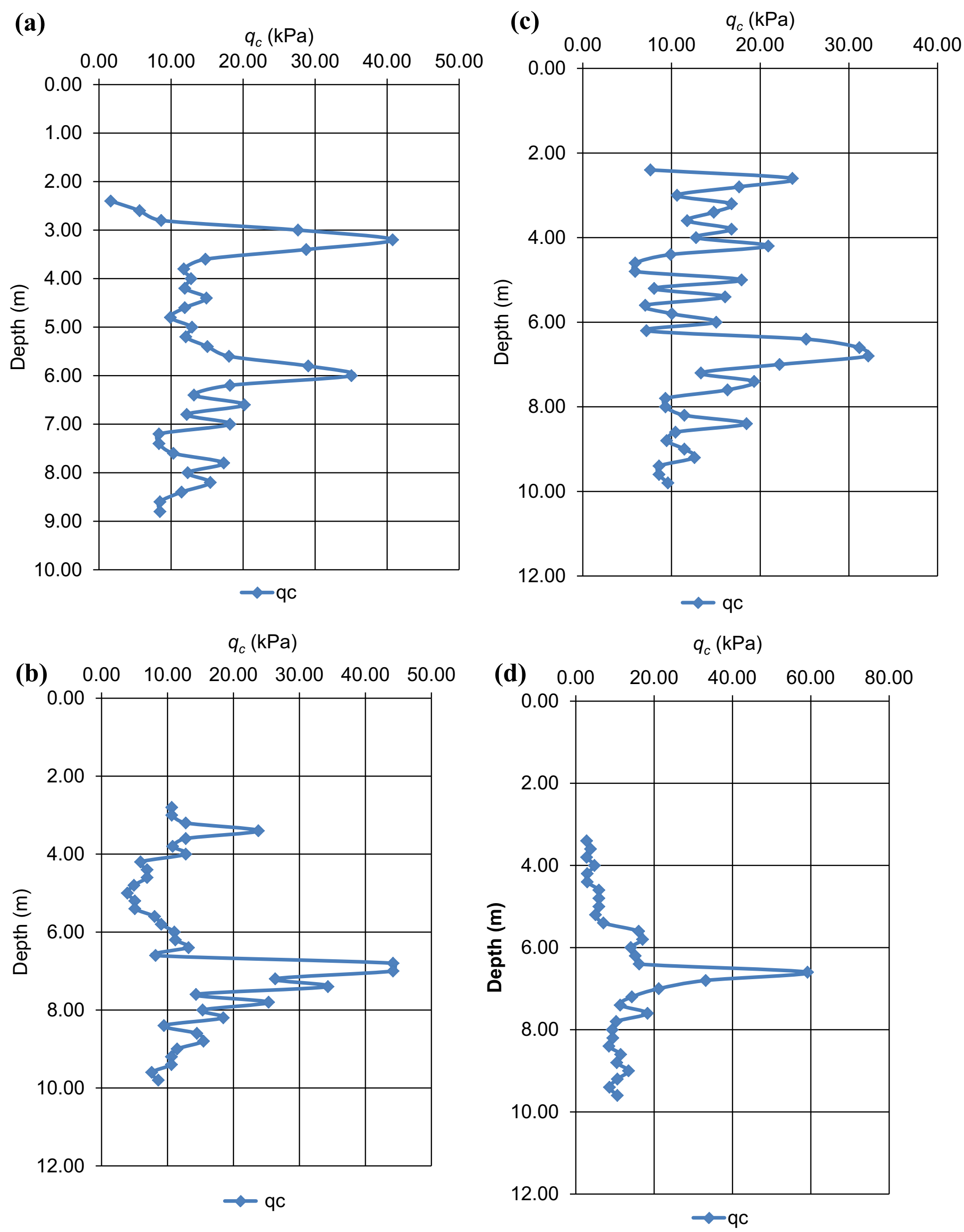


Fig. 16 Variation of cone resistance (q_c) with depth for CPT3 test point at High Court test location, Variation of cone resistance (q_c) with depth for CPT4 test point at High Court test location, Variation of cone resistance (q_c) with depth for CPT5 test point at High Court test location, Variation of cone resistance (q_c) with depth for CPT6 test point at High Court test location

differences. Here, the type of experiment conducted was the laboratory UU tests on undisturbed samples.

It was observed that the values of settlement calculated from DMT were on conservative side with respect to CPT and borehole data. When 1.6 m of sand layer is placed underneath the foundation, all the settlement values calculated from DMT, CPT and borehole data came within the range of 75 mm as per [21].

High Court Test Location

For settlement prediction, DMT settlement software, PLAXIS2D 2016, and conventional method had been used for this site. Since the foundation depth of the existing building is 1.9 m, for calculation purposes the depth of foundation was assumed the same below the ground level. The foundation of the existing building was strip footing (length, $L = 21$ m and width, $B = 2.13$ m). Total load intensity (Q) on the footing was assumed as 200 kPa.

The width of the strip footing used in High court is 2.13 m, and the reduced stress at the foundation level is calculated as:

$\Delta p = \frac{QXBXL}{(L+z)X(B+z)} = 98$ kPa as per 2:1 dispersion method, where $z = 1.95$ m mid depth of compressible layer.

where. Δp = increase in vertical pressure, Q = total load intensity, B = width of the foundation, L = length of the foundation,

Depth / RUN (m)		Length (m)	Nature of Sampling	SPT : No. of blows					Description
From	To			0-15 cm	15-30 cm	30-45 cm	45-60 cm	N' Value	
0.00									Top soil consisting
0.50	-	-	D	-	-	-	-	-	of grey silty clay with traces of roots and kankars
1.00	1.45	0.45	P/D	2	2	3	-	5	
2.00	2.50	0.50	U	-	-	-	-	-	1.00m
2.50	2.95	0.45	P/D	1	1	2	-	3	Firm grey silty clay
4.00	4.45	0.45	P/D	1	1	2	-	3	2.50m
5.00	5.50	0.50	U	-	-	-	-	-	Soft grey silty clay / clayey silt with
5.50	5.95	0.45	P/D	1	2	2	-	4	varying percentage of decomposed
7.00	7.45	0.45	P/D	1	2	2	-	4	wood; plenty of wood observed at
8.00	8.50	0.50	U	-	-	-	-	-	11.0m depth

Fig. 17 Typical borelog of Rajarhat Site

z = mid-depth of compressible layer.

Settlement analysis from conventional boring approach.

To predict settlement from the conventional boring data Eq. 5 has been used.

$$\textit{Primary consolidation Settlement} = m_v \times \Delta p \times H \qquad (5)$$

where m_v = coefficient of volume change or volume compressibility = 4.08×10^{-4} m^2/kN.

Δp = increase in vertical pressure = 98 kN/m.^{2}

H = initial thickness of clay layer up to influence zone, $2B$ = 4.26 m.

Incorporating all these values the consolidation settlement was calculated as 170 mm.

Bearing capacity of a 2.13 m wide strip footing placed at a depth of 1.9 m below ground level worked out to be 79 kPa, and the corresponding settlement was calculated as 71.4 mm. This settlement was calculated against the bearing capacity of 79 kPa, and the consolidation settlement of 170 mm was calculated against the revised structural load of 200 kPa.

Settlement Calculation from DMT Settlement software The total settlements were calculated to the centre of the footing. The calculation of the settlements was done by taking the thickness of each soil layer as 20 cm. The settlement of the foundation was calculated by the one-dimensional consolidation theory. The vertical stress increment was calculated by using Boussinesq's equation. The main parameters used to calculate the settlement are vertical drained constrained modulus (M), and vertical stress increment ($\Delta\sigma$).

Settlement Calculated from PLAXIS2D A plate had been assumed to be placed on the soil having d_{eff} (effective depth) = 150 mm, length = 21.3 m and breadth = 2.13 m., where EA of the plate was 53,015.61 kN/m and EI = 99.36 kN m^2/m. On that plate, a load of 200 kPa has been applied and the settlement of the soil profile has been recorded.

where.

E = Young's modulus of foundation plate,

A = area of the foundation plate,

I = moment of inertia of foundation plate.

Settlement analysis from Cone Penetration Test (CPT) The settlement was calculated for the four numbers of pits based on CPT test data conforming to [21]. Though this code recommends calculation of settlement in cohesionless soil, the calculation of settlement for cohesive soils also has been made following this code as no other code is available for Indian conditions. This is done in order to check how the values compare with other test results. As per clause number 9.1.2 of [22], a curve has to be plotted corresponding to the variation of cone resistance (q_c) along depth for a particular test. This graph consists of several broken part. The average cone resistance (C_{kd}) is to be calculated by virtue of the average line drawn through the similar type broken part of the curve. This value (C_{kd}) is then considered to calculate compression index (c) as given in Eq. (6), and then settlement (S_t) of each layer is calculated as per Eq. (7). Figure 16a, b, c and d shows variation of cone penetration resistance (q_c) along with the depth for

Table 2 Comparison of the Results of Settlement Analysis at High Court test location

Settlement calculations

Load = 200 (kN/m^2)

Specification of settlement

Method of tests	Test points	Settlement calculated from PLAXIS	Settlement calculated from volume compressibility (m_v)	Settlement calculated from vertical drained constrained modulus (M) obtained from DMT tests	Settlement based on average cone resistance of CPT as per IS 8009 Part I	Observed settlement from settlement sensors
		mm	mm	mm	mm	mm
Conventional boring		190.6	170	–		–
DMT	DMT3	158.3	–	108.3		–
	DMT4			118.3		
	DMT5			72.4		
	DMT6			155.7		
CPT	CPT3	125.6	–	–	151.7	–
	CPT4				103.24	
	CPT5				103.43	
	CPT6				167.09	
Settlement sensors	DMT3					101.63
	DMT6					153.42
	DMT5					78.55
	CPT6					234.91
	CPT4					41.49

four numbers of test points i.e. CPT3, CPT4, CPT5, and CPT6, respectively, and the average cone resistance (C_{kd}) of each layer along with the primary settlement was calculated. Next, total settlement corresponding to each test point was calculated by summation of each layer settlement and noted accordingly. The vertical stress increment (Δp) was calculated from Boussinesq's equation [23].

$$S_t = 2.303 \frac{H_t}{c} \log\left[\frac{\overline{p_0} + \Delta p}{\overline{p_0}}\right] \tag{6}$$

$$c = \frac{3}{2}\frac{C_{kd}}{\overline{p_0}} \tag{7}$$

where.

S_t = settlement,

H_t = thickness of soil layer,

$\overline{P}_0$ = initial effective overburden pressure at mid height of the layer,

Δp = vertical stress increment,

c = constant of compressibility,

C_{kd} = average static cone resistance.

During the time of testing at HIGH COURT site, it was observed that there was a fill of brickbats and other filling materials up to a depth of 2 m to 3.45 m. This may be the reason behind the non-uniformity of results up to this depth. Below this depth when the cone of CPT penetrates virgin soil the results are more or less uniform in nature.

Table 2 shows the comparison between the settlement values obtained from conventional boring approach, CPT test, DMT test as well as settlement sensors.

It was observed that the values of settlement calculated from DMT, CPT, borehole data and settlement sensors are more or less consistent in nature; in particular, DMT values tallied more with the observed settlement values.

Since CPT cone can sense a soil interface up to 15 times cone diameter ahead and behind, depending on the strength/stiffness of the soil and the in situ effective stresses, the soil parameters might be overestimated than the other two tests. On the other hand, the disturbance of the soil stratum is less for DMT tests. That's why the authors recommend the DMT test results to be more reliable.

Rajarhat Test Location

The structure at Rajarhat site is a G + 3 storied residential building. For settlement prediction, numerical analyses by DMT settlement software and PLAXIS2D 2016 had been used at this site. For calculation purpose, the depth of

Table 3 Settlement Analysis of Rajarhat test location

Settlement calculations								
Load(kN/m^2)	40							
Test points	DMT7		DMT8		CPT7	CPT8	BH7	BH8
Specification of settlement calculation process	Plaxis (mm)	DMT Settlement Software (mm)	Plaxis (mm)	DMT Settlement Software (mm)	Plaxis (mm)	Plaxis (mm)	Plaxis (mm)	Plaxis (mm)
Size Of Foundation								
3 m × 3 m	12	39.6	44.7	73.2	49	39	24	22
2 m × 2 m	29	26.3	36.9	40.8	41	35	20	20
1.5 m × 15 m	24	45.1	32.5	77.3	34	28	18	18
2.5 m × 25 m	36	68.3	42.5	84.5	44	35.2	21	19.7

foundation was assumed as1.5 m below the ground level since the existing building had this as the foundation depth. The foundation of the building has isolated footing and strip footing with varying sizes of 3 m × 3 m, 2 m × 2 m, 1.5 m × 15 m, and 2.5 m × 25 m. Total design load intensity on the footing was assumed as 40 kPa.

A typical borelog of Rajarhat Site up to 8 m depth is provided below.

Settlement Calculation from DMT Settlement software The total settlements were calculated to the centre of the footing. The calculation of the settlements was done by taking the thickness of each soil layer as 20 cm. The settlement of the foundation was calculated by the one-dimensional consolidation theory. The vertical stress increment was calculated by using Boussinesq's equation. The main parameters to calculate the settlement are vertical drained constrained modulus (M), and vertical stress increment ($\Delta\sigma$).

Settlement Calculated from PLAXIS 2D Two types of plates had been assumed to be placed on the soil. The properties of the plates are given below.

d_{eff} (effective depth) = 150 mm,

EA = 4,107,919.18 kN/m for isolated footing and 410,791.91 kN/m for strip footing,

EI = 7702.3 kN m^2/m for isolated footing and 770.23 kN m^2/m for strip footing,

where. E = Young's modulus of foundation plate, A = area of the foundation plate,

I = moment of inertia of foundation plate.

On these plates a load of 40 kPa has been applied and the settlement of the soil profile has been recorded.

Table 3 shows the comparison between the settlement values.

Here depth factor, rigidity factor, etc., have not been considered for calculation of settlement. This is because the calculated settlement values remained well below the permissible limits without applying these.

It was observed that most of the values of settlement calculated from DMT, CPT, and borehole data were within the range of 75 mm as per [21] and were more or less consistent in nature. Only for the strip footings, the results exceeded permissible values. As a consequence, pile foundations were finally recommended for this building.

Conclusions

- From the present investigation, it was observed that the soil profile obtained from Dilatometer tests were more or less similar in nature to those obtained from other in situ tests for all the three test sites.
- Secondly, it was also noticed that the undrained cohesion obtained from DMT tests was slightly on the conservative side in comparison with the values obtained from laboratory triaxial *UU* test.
- It was also observed that DMT gives more acceptable values of the undrained cohesion than conventional boring approach and other in situ tests for the given design criteria.
- The settlement values for all the cases are found to be well within permissible limits of all the DMT test locations.
- Estimated value of vertical drained constrained modulus portrayed good compatible results with values obtained from other tests.
- By conducting DMT tests, it had been successfully shown that use of piles at the Science City site was not essential as shallow foundations proved to be adequate for low to medium-rise buildings. Thus cost of the project could be brought down to a great extent.
- It was also found that the values of settlement calculated from DMT, CPT, borehole data and observed

settlement from settlement sensors at High Court site were more or less consistent in nature; in particular, DMT values tallied more with the observed settlement values. Thus this case study portrayed a classic example for the comparison of DMT-predicted settlement vs. observed settlement at site.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Informed Consent Informed consent was obtained from all individual contributors involved in this study.

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