Comparison of settlement of various shallow foundations estimated from DMT

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Abstract. Thorough geotechnical investigations are required to properly identify and characterize sub-soil profiles. In this regard Standard Penetration Test and collection of undisturbed soil samples are age-old common techniques. But from the last decades, a new trend of in-situ soil testing has been emerged. In- situ tests (e.g., Cone Penetration Test (CPT), Flat Dilatometer Test (DMT) etc.) are fast, economical and highly informative. 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. This paper describes about the usefulness of DMT for the prediction of settlements along with the sub-soil properties from different test sites in West Bengal. An attempt is also made to draw a comparison between the calculated settlement from DMT settlement software with the values obtained from model simulation using PLAXIS 2D. Apart from this, the undrained cohesion (c_u) and vertical drained constrained modulus (M) are obtained from Dilatometer tests and the values have been compared with other field and laboratory test results from different test sites in West Bengal.

Keywords: DMT; Triaxial UU; primary settlement; comparison; M_{DMT}; Mohr Coulomb model; PLAXIS 2D; DMT settlement software.

1. Introduction

Standard Penetration Test (SPT) and collection of undisturbed soil samples are one of the most used techniques. An inclination towards in-situ testing instead of collecting samples from conventional borehole or drill hole had been observed recently. In situ tests (e.g., Cone penetration test (CPT), Flat Dilatometer test (DMT) etc.) are fast, economical, and highly informative. The Standard Penetration Test (SPT) was initially introduced during the beginning of 1920s [1].

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 [1].

Important soil parameters such as undrained cohesion (c_u), angle of internal friction (φ), vertical drained constrained modulus (M) can be estimated by the Flat Dilatometer test. 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 [1].

In this paper an attempt has been made to draw a comparison between the calculated settlement from DMT settlement software with the values obtained from model simulation using PLAXIS 2D. Apart from this, the undrained cohesion (c_u) and vertical drained constrained modulus (*M*) are obtained from Dilatometer tests and the values have been compared with other field and laboratory test results from different test sites in West Bengal (i.e. Sonarpur, Burdwan, and Kolkata)

2. Introduction

1.1 Conventional Boring Approach

In this study, bore holes were dug within the proposed site up to an average depth of 20 m. The undisturbed samples were collected at every 3.0 m depth interval. Laboratory triaxial tests (*UU*) were conducted on collected undisturbed samples as per [2, 3] to estimate the undrained cohesion (c_u).

1.2 Cone Penetration Test

CPT test is done by pushing the cone (Begemann Bit) vertically into the ground surface at a constant strain rate (≈2 cm/s). Three numbers of readings namely, R_p, R_p+R_L and R_T are recorded during the penetration 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 [1, 4, 5, 6, 7, 8, 9].

The vertical drained constrain modulus (*M*) are calculated based on the correlations on corrected cone resistance (q_c) [1, 4, 5, 7, 8, 9, 10] as per equations (1) below.

$$M = 8.25\times(q_c - \sigma'_{v0}) \tag{1}$$

Where,
q_t= corrected cone resistance (q_c) for CPT tests without piezocone,
σ_v= total overburden pressure (i.e., $\Sigma Z_i \times \gamma_i$),
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 [11].
$\sigma/_{v0}$ = effective overburden pressure,
q_c =corrected cone resistance,

1.3 Flat Dilatometer Test

The Flat Dilatometer Test (DMT) is used to evaluate the compressibility characteristics and shear strength parameters of the soils within very short time. The flat dilatometer consists of a steel blade with size of 95 mm x 200 mm x 15 mm, having one side consisting of an expandable steel membrane. The gas (nitrogen gas) pressure is used to expand the membrane. During the expansion of the membrane, 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.

The main purpose of the DMT test was to evaluate the geotechnical parameters of the soil instantaneously in the field. Sixteen 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) [1, 8, 10, 12, and 13] were calculated from the following equations (2), (3) with the help of SDMT Elab software provided with the machine. Figure 1 illustrates the setup of the DMT machine.

$$(c_u) = 0.22\sigma'_{v0} \times (0.5 \times K_D)^{1.25} \tag{2}$$

$$M_{DMT} = R_M \times E_D \tag{3}$$

If $I_D \leq 0.6$

$$R_M = 0.14 + 2.36 \log log\, K_D \tag{3.1}$$

If $I_D \geq 3$

$$R_M = 0.5 + 2 \log log\, K_D \tag{3.2}$$

If $0.6 < I_D < 3$

$$R_M = R_{M,0} + (2.5 - R_{M,0}) \log log\, K_D \tag{3.3}$$

Where $R_{M,0} = 0.14 + 0.15\,(I_D - 0.6)$ (3.4)

If $K_D > 10$ $\quad R_M = 0.32 + 2.18 \log log\, K_D$ (3.5)

If $R_M < 0.85$ set $R_M = 0.85$ (3.6)

Where,

$K_D = [(p_0 - u_0)/\sigma'_{v0}]$ = 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 [14]

Fig. 1. The Flat Dilatometer equipment [14]

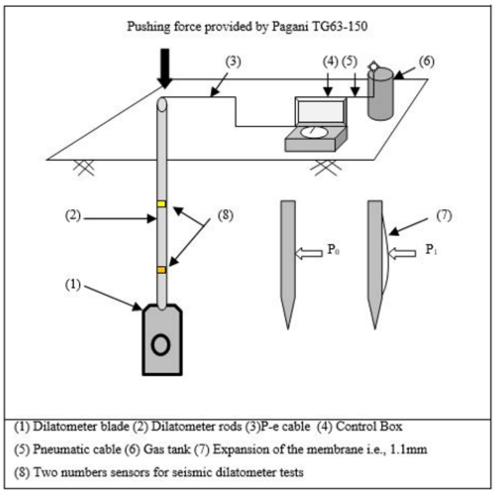
1.4 PLAXIS software

In this study purpose, PLAXIS 2D 2016 software has been used for foundation analysis from the obtained in-situ tests data [1, 15] numerically.

3. Site Investigation

Total fifteen numbers (BH1 to BH15) of boreholes along with SPT tests were conducted up to an average depth of 20 m at three different test locations in West Bengal (i.e., Sonarpur, Burdwan, and Rajarhat). Out of these BH1 to BH6 were dug at Sonarpur site; BH7 to BH12 were dug at Burdwan site; BH13to BH15 were dug at Rajarhat site. Description of stratigraphy along with the strength and stiffness parameters had been evaluated on the basis of laboratory tests conducted on collected undisturbed soil sample.

Sixteen numbers of DMT tests (DMT1 to DMT16) (adjacent to afore-mentioned boreholes) were conducted up to an average depth of 20 m at three different test locations in West Bengal (i.e., Sonarpur, Burdwan, and Rajarhat). Out of these DMT1 to DMT6 test locations were at Sonarpur site; DMT7 to DMT12 test locations were at Burdwan site; DMT13to DMT16 test locations were at Rajarhat site.



Eight numbers of CPT tests (CPT1 to CPT8) (adjacent to afore-mentioned boreholes and DMT points) were conducted up to an average depth of 20 m at three different test locations in West Bengal (i.e., Sonarpur, Burdwan, and Rajarhat). Out of these CPT1 to CPT6 test locations were at Sonarpur site; CPT7 to CPT18 test locations were at Kolkata (Rajarhat) site.

Figure 2, Figure 3 and Figure 4 demonstrate tests being conducted at these sites.

Fig. 2. Photograph showing test set up at Sonarpur test location

Fig. 3. Photograph showing test set up at Burdwan test location

Fig. 4. Photograph showing test set up at Kolkata (Rajarhat) test location

4. Results and Discussion

3.1 Undrained cohesion (c_u)

Undrained cohesion (c_u) was estimated from correlations for DMT tests and compared with the laboratory triaxial UU test results conducted on collected undisturbed soil samples corresponding to nearest boreholes[1, 7, 9, 10, 11, 12, 16, 17, 18, 19, 20]. 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 Figure 5, Figure 6, and Figure 7.

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

The DMT results are more comparable with the conventional bore log survey results is because of the effect of less disturbance of the sub-soil during the penetration of Dilatometer blade into the soil as suggested by [1].

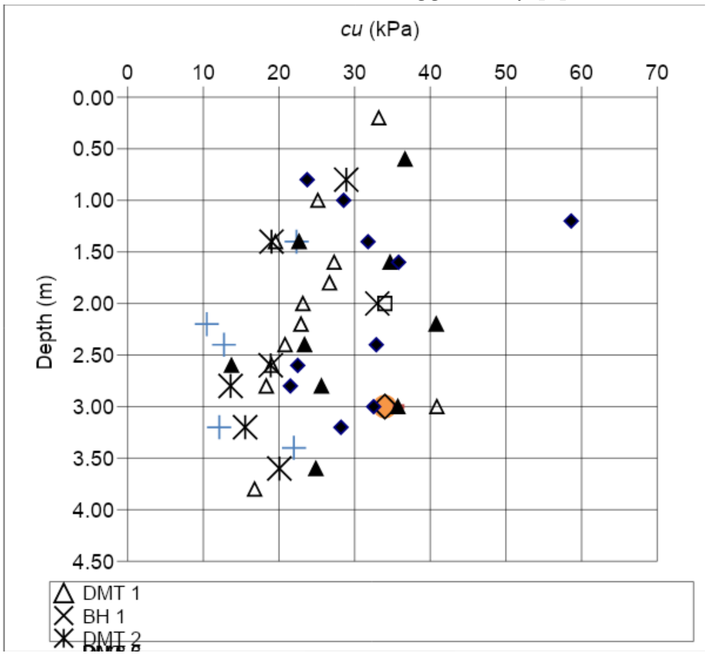


Fig. 5. Variation of undrained cohesion (c_u) with depth for DMT1, DMT2, DMT3, DMT5, DMT6, BH1, BH2, BH4, BH5, and BH6 test points at Sonarpur, Westbengal.

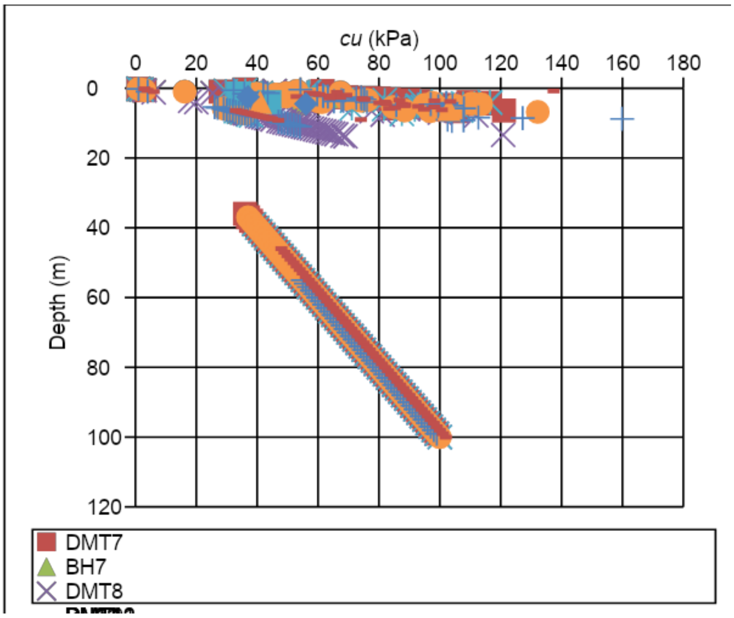


Fig. 6. Variation of undrained cohesion (c_u) with depth for DMT7, DMT8, DMT9, DMT10, DMT11, DMT12, BH7, BH8, BH9, BH10, BH11, and BH12 test points at Burdwan, Westbengal.

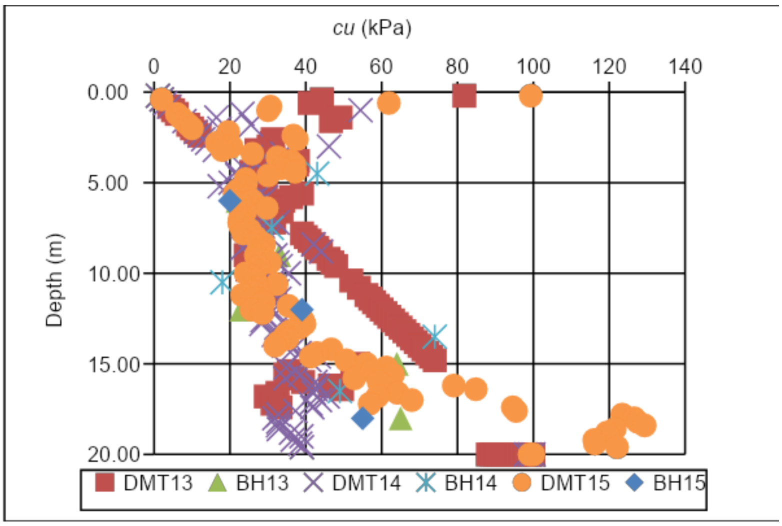


Fig. 7. Variation of undrained cohesion (c_u) with depth for DMT13, DMT14, DMT15, BH13, BH14, and BH15 test points at Kolkata (Rajarhat), Westbengal.

3.2 **Vertical drained constrained modulus (M)**

By using equation (1) and (3 to 3.6), vertical drained constrained modulus had been calculated from CPT and DMT tests respectively. Figure 8, Figure 9 shows the variation of (M) values with depth for test sites.

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.

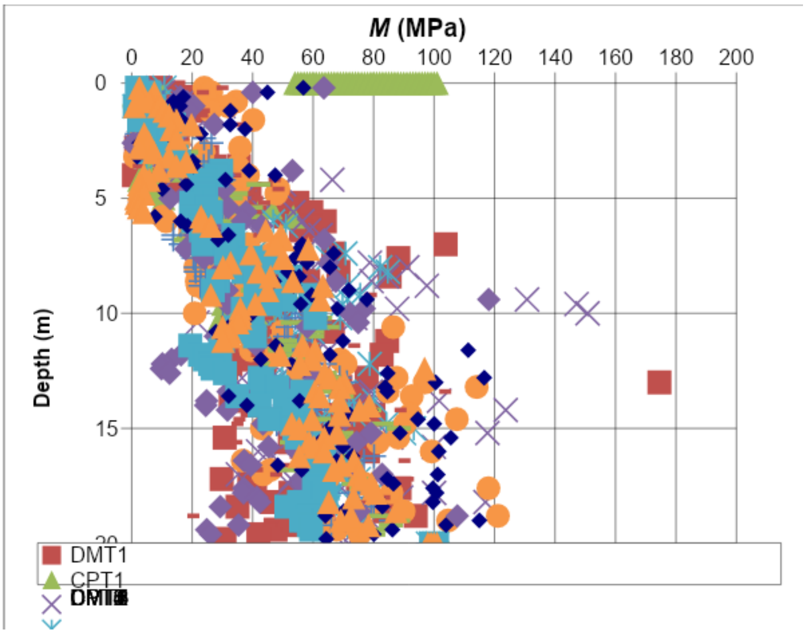


Fig. 8. Variation of vertical drained constrained modulus (*M*) with depth for DMT1, DMT2, DMT3, DMT4, DMT5, DMT6, CPT1, CPT2, CPT3, CPT4, CPT5, and CPT6 test points at Sonarpur, Westbengal.

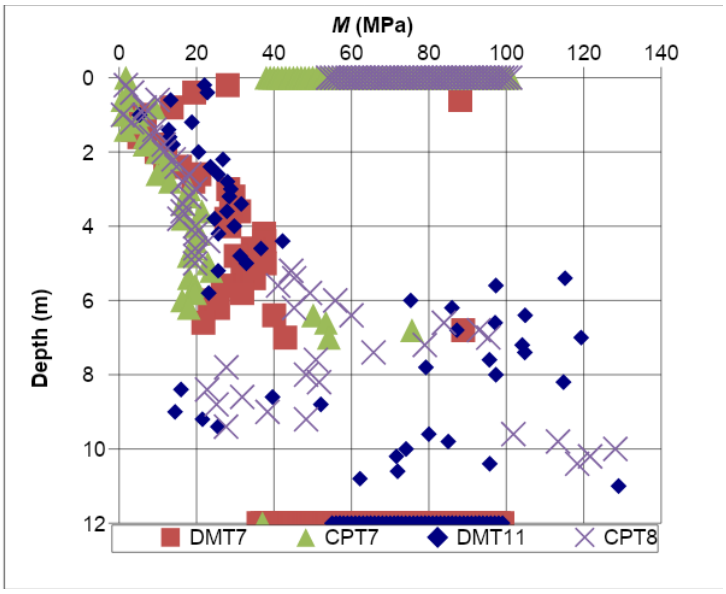


Fig. 9. Variation of vertical drained constrained modulus (*M*) with depth for DMT7, DMT11, CPT7, and CPT8 test points at Burdwan, Westbengal.

3.3 Settlement analysis of all the projects

For settlement prediction, DMT data software was used namely DMT settlement provided with the DMT machine. The total settlements were calculated at the center 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 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 [14].

PLAXIS 2D 2016 was also been used for settlement prediction numerically using the shear parameters obtained from DMT 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 [21, 22, 23, 24].

At Sonarpur test site for calculation purpose the depth of foundation was assumed at 5.25 m below the existing ground level. The foundation of the tower has been assumed to be consisting of raft foundation with length by width of 52.0 m x 24.0 m. Total design load intensity on the footing was assumed as 249 kPa.

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

Table 1. Settlement Analysis of Sonarpur test location.

Location	Size of foundation (m x m)	Depth of Foundation below G.L (m)	Net allowable bearing capacity (kPa)	Settlement (mm) DMT	PLAXIS
DMT1,2,3	52.0 m x 24.0 m	5.25	219	67.90	105.50
DMT4,5,6	52.0 m x 24.0 m	5.25	172	69.80	103.90

At Burdwan test site for calculation purpose the depth of foundation was assumed at 2.0 m below the existing ground level. The foundation of the tower has been assumed to be consisting of raft foundation with length by width of 48.6 m x 18.0 m. Total design load intensity on the footing was assumed as 219 kPa, 172 kPa, 206 kPa, 213 kPa, 197 kPa, and 195 kPa for DMT7 to DMT12 respectively.

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

Table 2**.** Settlement Analysis of Burdwan test location.

Location	Size of foundation (m x m)	Depth of Foundation below G.L (m)	Net allowable bearing capacity (kPa)	Settlement (mm) DMT	PLAXIS
DMT7	18.8 m x 48.6 m	2.0	219	18.8	10.1
DMT8	18.8 m x 48.6 m	2.0	172	23.1	15.0
DMT9	18.8 m x 48.6 m	2.0	206	19.9	10.4
DMT10	18.8 m x 48.6 m	2.0	213	17.2	8.7
DMT11	18.8 m x 48.6 m	2.0	197	21.1	17.9
DMT12	18.8 m x 48.6 m	2.0	195	19.7	12.5

At Kolkata (Rajarhat) test site for calculation purpose the depth of foundation was assumed at 5.15 m below the existing ground level. The foundation of the tower has been assumed to be consisting of raft foundation with length by width of 62.0 m x

28.0 m. Total design load intensity on the footing was assumed as 72 kPa, 45 kPa, 63 kPa, and 40 kPa for DMT13 to DMT16 respectively.

Table 3 shows the comparison between the settlement analysis of DMT settlement software and PLAXIS 2D

Table 3. Settlement Analysis of Kolkata (Rajarhat) test location.

Location	Size of foundation (m x m)	Depth of Foundation below G.L (m)	Net allowable bearing capacity (kPa)	Settlement (mm)	
				DMT	PLAXIS
DMT13	28.0 m x 62.0 m	5.15	72.0	46.0	65.0
DMT14	28.0 m x 62.0 m	5.15	45.0	66.2	66.4
DMT15	28.0 m x 62.0 m	5.15	63.0	67.9	69.1
DMT16	28.0 m x 62.0 m	5.15	40.0	66.2	56.8

5. Conclusion

- From the present investigation, it was observed 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.
- Settlement values obtained from DMT settlement software and PLAXIS 2D was more or less equal in nature.
- The settlement values for all the cases are found to be well within permissible limits of all the DMT test locations expect at Sonarpur test site.
- Estimated value of vertical drained constrained modulus portrayed good compatible results with values obtained from other tests.
- By conducting DMT tests, it had been suggested for the raft foundations at Sonarpur site, the settlement values exceed the permissible limit (75 mm) [23] and as such placing these foundations directly on the underlying soil with this extent of loading intensity may prove counter-productive. This is why it is advised that before placing the raft foundations, some form of ground improvement measures be adopted in order to improve the shear strength and compressibility properties of the underlying soil

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