Prediction of Geotechnical Parameters from DMT, CPT and PMT Tests and Formation of Design Chart

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3. List of Publication (Related to thesis)

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3) Bandyopadhyay, K., **Nandi, S.**, Scholer, P., Babu, S., & Professor, G. (2020). Prediction of settlement of high court building, Kolkata using flat dilatometer-a case study. In A. M. and E. K. Tamás Huszák (Ed.), 6th International Conference on Geotechnical and Geophysical Site Characterization. ISSMGE.

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2) **Nandi, S.**, Singh, R., & Bandyopadhyay, K. (2023). Estimation of Undrained Cohesion of Cohesive Sub-Soil in Kolkata Region using Pressuremeter Test. In J. J. Regin, Suhasini A., I. Jessy Mol, D. Judson, Shiny D. Smiline, & Illanthalir A. (Eds.), INTERNATIONAL CONFERENCE ON ADVANCES IN SUSTAINABILITY OF MATERIALS AND ENVIRONMENT (ICASME'23). St. Xavier 's Catholic College of Engineering

Abstract:

This study investigates the feasibility of utilizing in-situ tests such as DMT, CPT, and PMT to predict geotechnical parameters and sub-soil profiles, compared to conventional methods like SPT and laboratory tests, particularly in the context of rapid urbanization in India. The aim is to establish relationship between in-situ test results and conventional testing methods to streamline geotechnical investigations. Key findings suggest that undrained cohesion (Cu) estimated from DMT tests closely aligns with laboratory triaxial (UU) test results, whereas both CPT and DMT tests provide comparable estimates of angle of internal friction (ϕ) compared to laboratory direct shear tests (DS). Additionally, vertical drained constrained modulus values from DMT and CPT tests are more or less consistent. This study proposes relations between in-situ test parameters and SPT-based consistency of cohesive silty clay/clayey silt sub-soil, allowing for prediction of plasticity index (PI), plastic limit (W_P), and liquid limit (W_L). For PMT tests, typical ranges of pressuremeter modulus (E_{PMT}) and limit pressure (P_L), along with liquidity index (I_L) prediction based on E_{PMT}/P_L ratio, are suggested for cohesive sub-soil. Additionally, attempt has also been made to predict the settlement of shallow foundations on cohesive soils using CPT tests. Settlement analysis has been done by using an empirical equation based on average cone resistance (C_{KD}). This prediction is then compared with DMT-based settlement and numerical models developed using PLAXIS 2D software. Overall, the study underscores the potential of in-situ tests to streamline geotechnical investigations in urbanizing regions like India, offering insights for efficient and accurate assessment of soil parameters and settlement predictions.

1. Literature Study:

The Flat Dilatometer (DMT) is an in-situ soil testing device, developed by Prof. Marchetti in Italy in 1980. It consists of a stainless steel blade, 15 mm thick and 96 mm long, with a single-sided circular membrane of 60 mm diameter. The blade is connected to a control unit via a nylon cable, allowing gas pressure and electric circuit connections. During testing, the membrane is initially seated against the blade, completing an electrical circuit and activating a buzzer. As the membrane is inflated, the circuit breaks, deactivating the buzzer. When the membrane reaches its maximum deflection of 1.1 mm, the circuit reconnects, and the buzzer activates again. The DMT blade is pushed into the ground at 200 mm intervals using a penetrometer (e.g., CPT rig). At each test depth, the membrane is inflated to measure the pressure readings A and B, corrected to p_0 and p_1 respectively. The original correlations were explained by Marchetti based on the available data obtained from eight numbers test sites, mostly in Italy (Marchetti 1980). The test sites comprised of variable sub-soil conditions ranging from cohesive to cohesionless soil with different stress history (Baldi et al. 1986; Marchetti et al. 1986, 1991; Konrad 1988; Marchetti and Totani 1989; Burghignoli et al. 1991). The basic three parameters of Dilatometer i.e., I_D, K_D and E_D were obtained from those sites. These values were compared and empirically correlated to the laboratory results. The summerised correlations were proposed by Totani (Totani et al. 2001). The material index parameter (I_D) merely indicates the type of soil and closely related to its grain size distribution(Iwasaki et al. 1991) (Kamei and Iwasaki 1995). Increasing or decreasing value of (I_D) mainly depends on presence of fine contents within the soil mass irrespective of the soil stress history (Iwasaki et al. 1991; Kamei and Iwasaki 1995). The increasing amount of fine content sharply decreases the value of I_D and vice versa (Marchetti 1980; Powell and Uglow 1988; Iwasaki et al. 1991; Smith and Houlsby 1995). However, it cannot provide detail information on grain size distribution (Iwasaki et al. 1991). In this context, the value of I_D was considered as a function of the mechanical properties of the soil which depends on grain size as a whole (Powell and Uglow 1988; Lutenegger 1990a; Iwasaki et al. 1991; Smith and Houlsby 1995; Marchetti et al. 2001). It was proposed that the Material Index is to be estimated as the ratio of soil stiffness (the difference of p_1 and p_0) and soil strength (as estimated by $p_0 - u_0$) (Marchetti 1980, 2015; Schmertmann 1986a; Marchetti et al. 2001; Penna 2006). These two independent variables (i.e., soil stiffness and soil strength) depict wide range of ID reflecting the soil behavioural qualities having different grain size. However, there was no correlation or range found between the plasticity index (PI) and Material Index (I_D). Further a chart was developed by Marchetti and Crapps (Marchetti and Crapps 1981) for predicting bulk unit weight corresponding to the soil type identified from the value of I_D and E_D. The aim behind to prepare this chart, was to predict the average value of unit weight for "normal soil". This was used to calculate the effective stress (σ'_v) and not to estimate accurate unit weight. The value of effective stress was used in the correlation suggested by Marchetti (Marchetti and Crapps 1981; Schmertmann and Marchetti 1981). Following the original work by Marchetti (1980), many research works had been carried out in the various part of world. The main focus of those studies were given to compare the DMT based test results with the conventional test results(Gabr and Borden 1988; Schmertmann 1988a, 1989, 1991; Baldi et al. 1989; Mayne and Bachus 1989; Borden 1991; Tanaka and Tanaka 1998; Cruz et al. 1999; Mayne and Liao 2004; Mayne 2006b, c, d, 2015; Nuno Cruz et al. 2006; Aykin et al. 2010; McNulty and Harney 2010)(Nandi et al. 2022)(ASTM International 1986; Schmertmann 1986b; Robertson 1988; Roque et al. 1988; Sanglerat 2012).There have been few studies carried to compare the material index (I_D) to other conventional soil classification tests. Also, there are limited resources available on the comparison of soil unit weight as predicted from Dilatometer test. However, the Building Research Establishment (BRE) in the UK, attempted to establish a comparison of the DMT results with the known soil properties obtained from various test sites throughout the

UK (Powell and Uglow 1988). As a part of that research work, material index, (I_D) and the dilatometer modulus (E_D) for the various types of soils were plotted on the Marchetti density chart (Powell and Uglow 1988). It was found that some of the soil types were accurately identified by the chart (mainly silty clays/clayey silts). Whereas, the soil more than 60% clay contents, were found to be scattered. It was concluded that the very high degree of over consolidation and relative age of those soils might affect the value of material index (I_D)(Mayne and Martin 1998). Besides, mixed responses were found in the comparison of unit weight. The predicted value from the chart indicated lower values for the majority of soil. However, for certain soil types, there was a good agreement, indicating a trend of variation.

In the year 1991, another research work was carried out by Iwasaki on soft alluvial clays in Japan (Iwasaki et al. 1991). It was revealed an average relationship between the fines content and the material index, I_D. It was found that the fifty percent (50%) fine content lies within the I_D of 1.8. The Cone Penetration Test (CPT) is a mechanical in-situ test used in geotechnical engineering, first introduced in the Netherlands in 1930 (Vermeiden 1948; Schmertmann 1988b; Jamiolkowski et al. 1988; Baldi et al. 1989; Mayne and Bachus 1989; Danziger and Velloso 1995; Kaplan et al. 2004; Been et al. 2010; Presti and Meisina 2019; Bandyopadhyay et al. 2022a). Initially, the test utilized a 35mm diameter cone attached to a smaller inner rod within a 35mm diameter hollow pipe. The cone was pushed through the outer pipe at depth intervals of 150mm (Campanella et al. 1983, 1985; Robertson and Campanella 1983a, b; Robertson 1986a; Robertson and Cabal 2015). The outer casing and inner rod, along with the cone, were then pushed downward to the next test depth. The test was further improved by Vermeiden, who added a conical part above the cone to prevent soil particle entry between the casing and rods (Vermeiden 1948) (Holtrigter 2010). In 1953, Begemann modified the instrument by adding an 'adhesion jacket' behind the cone, leading to the development of the 'Dutch cone test' (Mayne and Bachus 1989; Holtrigter 2010; Robertson and Cabal 2015). Two types of cones, the Begemann cone and the Vermeiden cone, are still used in various parts of the world. In 1965, Fugro designed an electric cone, and an add-on device for predicting pore water pressure during the test was introduced, known as the piezocone (de Ruiter 1971; Campanella et al. 1985; Bihs et al. 2010). The pore water pressure was estimated through a porous filter placed in the probe, with the most common position being just behind the cone (Fonseca 2010). Piezocones of varying sizes are available, but a size of $10cm^2$ is considered standard for all ground conditions (Robertson and Cabal 2015).The CPT probe is attached to the extension in the same manner for conducting the test.The CPT process involves pushing the assembly into the ground at a steady rate, with load cell data providing continuous resistance readings. These readings are recorded at 200mm intervals and used to calculate cone resistance (q_t), sleeve friction (f_s), and total thrust (Q_T). Corrections for pore water pressure are applied to estimate corrected cone resistance (q_t) (Mayne and Bachus, 1989; Kulhawy and Mayne, 1990; Mayne, 2006a, 2007; Robertson and Cabal, 2015; Rocscience Inc., 2016; Sakleshpur et al., 2022). While CPT can offer insights into soil behavior types, its accuracy in predicting soil types based on physical characteristics is limited. However, it provides valuable guidance on mechanical characteristics. Various charts and equations have been proposed to predict soil unit weight, soil behavior type index (I_C), undrained shear strength (C_u), and constrained modulus (M_{CPT}). The cone factor (N_{kt}) is influenced by factors like plasticity index (PI), soil sensitivity, and pore pressure ratio (B_q) (Aas, 1986; Holtrigter, 2010). Correlations between cone resistance and parameters like undrained shear strength and internal friction angle have been proposed, along with CPT-SPT correlations for different soil types (Robertson, 1990; Lunne et al., 2002).It's worth noting that correlations between cone resistance and SPT N values are often site-specific, and there's currently no specific correlation for cohesive soils in the Indian context (Nandi et al., 2022; Das et al., 2022; Bandyopadhyay et al., 2022b, a).The Pressuremeter (PMT) apparatus, pioneered by Louis Menard in 1954 in France, builds upon

Kogler's concept from 1953 (Winter, 1986). Evolving into a fundamental in-situ test, PMT involves cavity expansion to measure soil pressure-deformation relationships (Baguelin et al., 1978; Cestari Ferrucio, 2012). The probe, designed to maintain length during radial expansion, records volume change as pressure increases (Baguelin et al., 1978; Hughes and Robertson, 1985). Initially, evaluation methods were unknown, but after research spanning over two decades, the significance of installation disturbance and borehole formation effects on results became evident (Baguelin et al., 1978; Amar et al., 1991; Clarke, 1996; Briaud, 2013).PMT tests can be stress-controlled or strain-controlled, typically employing 7 to 10 pressure or volume increments (Singh, 1981; British Standard, 1997; ASTM International, 2000b). The test continues until the cavity volume doubles or reaches the working range of the volumeter (Baguelin et al., 1978). Calibration is essential to adjust for pressure and volume losses (Baguelin et al., 1978; Clarke, 1996; British Standard, 1997; ASTM International, 2000b). The limit pressure (PL), corresponding to doubled cavity volume, defines soil failure pressure (Baguelin et al., 1978). Indirect methods, like the inverse volume method, are sometimes used to determine P_L to avoid probe damage (Singh, 1981; Cestari Ferrucio, 2012).The pressuremeter modulus (E_{PMT}) and net limit pressure (P_{Ln}) are key parameters, reflecting soil behavior and failure pressure, respectively (Baguelin et al., 1978; Clarke and Wroth, 1989; Cestari Ferrucio, 2012). PMT delineates in-situ boundaries and stress-strain relationships more accurately than other tests like SPT and CPT (Lutenegger, 1990b; Benoît and Lutenegger, 1992; Mayne, 1995). PMT's versatility spans all soil and rock types (Nayak, 1979, 2001; Amar et al., 1991; Clarke, 1994; Terzaghi et al., 1996; Bowles, 2001; Salgado, 2006; Cestari Ferrucio, 2012; Narimani et al., 2018). Correlations between PMT and SPT are less explored but gaining attention. Various studies have proposed correlations between P_L/E_{PMT} and SPT N values for different soil types (Yagiz et al., 2008; Kayabasi, 2012; Cheshomi and Ghodrati, 2015; Balachandran et al., 2015, 2017; Anwar, 2018; Özvan et al., 2018; Ramaswamy et al., 2021).

These correlations cater to different soil conditions and provide valuable insights for geotechnical engineering practices.

The Marchetti Dilatometer Test (MDMT) serves as a significant tool for predicting shallow foundation settlement (Fabius, 1985). Marchetti et al. (1997) proposed a model based on one-dimensional consolidation theory for settlement prediction from MDMT (Fabius, 1985; Borden et al., 1986; Schmertmann, 1986b; Chang, 1987; Kalteziotis et al., 1991; Marchetti et al., 2001; Monaco et al., 2006). Numerous comparisons between settlements predicted from DMT tests and other methods showed good agreement (Schmertmann, 1986b; Hayes, 1986; Marchetti et al., 2001). In India, Bandyopadhyay et al. (2022b, a) conducted case studies comparing settlements calculated using MDMT with observed settlements, finding them comparable. Similarly, Das and Nandi (2022) (Das et. al. 2022) observed similar results in a study on sub-soil parameters and settlement estimation in Kolkata.

For settlement prediction from Cone Penetration Test (CPT), Meyerhof (1965, 1974) used CPT cone resistance (q_c), finding CPT-based settlements to be conservative, ranging from 1.2 to 1.5 times field settlements (Sargand et al., 2003). De Beer (1965) proposed a refined method for CPT-based settlement prediction, resembling consolidation settlement of cohesive soils, but resulting in predicted settlements twice those observed (Sargand et al., 2003). Schmertmann et al. (1988b) introduced another method based on linear elastic theory for cohesionless soil, showing realistic results compared to laboratory models and finite element methods (Sargand et al., 2003). In Indian standards (IS 8009 Part-1), a method is described to find settlement based on average cone resistance (C_{KD}) from CPT tests for cohesionless soils (Indian Standards, 1985). Bandyopadhyay et al. (2022a) conducted a case study applying this method to predict settlement of shallow foundations on cohesive soils, finding the predicted settlements to closely align with observed settlements as well as those estimated from finite element-based software.

2. *Need for the Present Study:*

In Eastern India, the use of CPT, DMT and PMT tests is limited, and research on these tests is still very scanty. A side-by-side comparison of geotechnical parameters from DMT, CPT, and PMT tests with conventional tests is needed. To bridge the gap between conventional laboratory and in-situ test results, a design chart needs to be developed. Additionally, there is a necessity to analyse the efficacy of average cone resistance from CPT tests in predicting the settlement behavior of shallow foundations on cohesive soils within the Indian context.

2.1. Objectives of the Study:

- To determine fundamental geotechnical parameters obtained from the cohesive subsoil in the coastal regions of West Bengal (WB) and Odisha (OR) using three distinct in-situ tests viz., DMT, CPT and PMT.
- To develop design charts based on parametric relations done by regression analyses of the outcomes of DMT, CPT, PMT, and SPT tests, particularly focusing on silty clay/clayey silt soil in the coastal regions of WB and OR.
- To determine the settlement of shallow foundation placed on cohesive soil within the coastal region of West Bengal and Odisha, using average cone resistance (C_{KD}) from the CPT test and comparing it with DMT-based settlement data along with a numerical analysis based settlement.

2.2. Scopes of the Study:

1. Conduct 29 DMT and 25 CPT tests adjacent to conventional boreholes at various sites in WB and OR.

2. Perform 48 PMT tests in 12 NX size (≈76mm diameter) boreholes adjacent to conventional SX size (≈150mm diameter) boreholes.

3. Predict sub-soil profiles from DMT and CPT tests and compare with profiles from conventional boreholes.

4. Measure shear strength parameters (undrained cohesion and angle of internal friction) from DMT and CPT tests and compare with laboratory results.

5. Estimate compressibility characteristics (vertical drained constrained modulus) from CPT tests and compare with DMT values.

6. Estimate limit pressure (P_L) and pressuremeter modulus (E_{PMT}) from PMT tests.

7. Develop regression-based relations between Dilatometer modulus (E_D) and vertical drained constrained modulus (M_{DMT}) from DMT tests and observed SPT blow count (N_{ob}) for cohesive soil.

8. Create regression-based relations between E_D and M_{DMT} with plastic limit (W_P) and plasticity index (PI) from laboratory tests.

9. Establish regression-based relations between cone penetration resistance (q_c), sleeve friction (f_s), and vertical drained constrained modulus (M_{CPT}) from CPT tests with observed SPT blow count (N_{ob}) for cohesive soil.

10. Establish regression-based relations between qc and M_{CPT} with W_P and PI from laboratory tests.

11. Develop regression-based relations between limit pressure (P_L) and E_{PMT} with observed SPT blow count (N_{ob}) for cohesive soil.

12. Create regression-based relations between E_{PMT}/P_L ratio from PMT tests and liquidity index (I_L) from laboratory tests.

13. Predict reference range of E_D and M_{DMT} from DMT tests for cohesive soil with different SPT-based consistency.

14. Predict liquid limit (W_L) and plastic limit (W_P) from E_D and M_{DMT} values from DMT tests.

15. Predict reference range of qc, fs, and M_{CPT} from CPT tests for cohesive sub-soil with different SPT-based consistency.

16. Predict liquid limit (W_L) and plastic limit (W_P) from q_c and M_{CPT} values from CPT tests.

17. Predict reference range of P_L and E_{PMT} for cohesive sub-soil with different SPT-based consistency.

18. Predict reference range of E_{PMT}/P_L ratio for cohesive sub-soil with different liquidity indices.

19. Estimate settlement of shallow foundations on cohesive soil using average cone penetration resistance (C_{KD}) from CPT tests and M_{DMT} values from DMT tests.

20. Determine settlement using a numerical model in PLAXIS 2D and compare with results from DMT and CPT tests.

2.3. Organization of Thesis:

The thesis is structured into eight chapters as follows:

Chapter 1: Introduces the problem, need for research, scope, objectives, and organization of the thesis.

Chapter 2: Provides a detailed literature review on data interpretation from DMT, CPT, and PMT tests, geotechnical parameter assessment, prediction of settlements, and site-specific correlations.

Chapter 3: Discusses procedures for conducting DMT, CPT, and PMT tests, data interpretation methods, design chart preparation, and methodology for predicting settlement of shallow foundations on cohesive soil.

Chapter 4: Presents detailed location plans of the study area and descriptions of individual sites.

Chapter 5: Offers a comparative overview of subsoil characteristics from conventional boreholes and DMT, CPT, and PMT tests, including depth-wise variations of key parameters and comparative analysis of shear strength parameters and cone penetration resistance methods.

Chapter 6: Compares basic parameters from DMT, CPT, and PMT tests with observed standard penetration blow counts, presents a design chart for cohesive soil, and predicts index properties using parameters from in-situ tests.

Chapter 7: Predicts settlement of shallow foundations using average cone penetration resistance (C_{KD}) and M_{DMT} from DMT tests, includes numerical analysis using Plaxis 2D software, and compares settlement values from different approaches.

Chapter 8: Summarizes the study, presents conclusions, and discusses limitations and future scope.

Additionally, the thesis includes a list of references and appendices providing detailed comparisons of DMT, CPT, and PMT test parameters with conventional borehole data, as well as sample calculation for settlement prediction.

3. *Methodology:*

To establish relationships between geotechnical parameters, in-situ tests (CPT, DMT, PMT) were conducted alongside conventional boring and SPT tests at eleven project sites in West Bengal (WB) and Odisha (OR). The project sites are: Site-1 (HC) at Highcourt Site, Kolkata, WB: 22.5645°N, 88.3476°E, Site-2 (PB) at Panchayet Bhaban site, Kolkata, WB: 22.5701°N, 88.4011°E, Site-3 (RJ) at Rajarhat CA94, Kolkata, WB: 22.5868°N, 88.4799°E, Site-4 (HA) at Haldia Petrochem, Haldia, WB: 22.0555°N, 88.0787°E, Site-5 (DH) at Dhamra, OR: 20.9511°N, 86.6570°E, Site-6 (SN) at Sonarpur, South 24 Parganas, WB: 22.4147°N, 88.4347°E, Site-7 (LK) at Laketown project, Kolkata, WB: 22.6191°N, 88.4052°E, Site-8 (BD) at Burdwan, Purba Bardhaman, WB: 23.2394°N, 87.8650°E, Site-9 (VT) at Victoria, Kolkata, WB 22.5483° N, 88.3432° E , Site-10 (PT) at Park Street, Kolkata, WB: 22.5170° N, 88.3459° E, Site-11 (ES) at Esplanade, Kolkata, WB: 22.5653° N,88.3519° E. Tests were conducted at the same Reduced Level as adjacent boreholes or assumed at +100.0 m if not available. DMT and CPT tests were conducted by using Pagani TG63-150 penetrometer (max. capacity 150 kN), and PMT tests were carried out by using pre-bored Menard Pressuremeter (max. capacity 80 Bar). DMT and CPT tests estimated parameters along with shear strength were compared with the field SPT blow counts (N_{ob}) and laboratory estimated values. Besides, PMT estimated parameters i.e., P_L and E_{PMT} were compared with field SPT N value (N_{ob}). The relationships were established between DMT, CPT, PMT parameters with, N_{ob} and laboratory estimated values. Settlement of shallow foundations was evaluated using an empirical equation based on C_{KD} from CPT tests. This estimated settlement was compared with M_{DMT} based settlement (using DMT-based settlement software) and numerical model (created on Plaxis 2D ver. 16) based on the geotechnical parameters obtained from DMT , CPT and boreholes. Focus was given on cohesive silty clay/clayey silt sub-soil, across project sites with varying geological conditions. Some representative photographs are given in Fig. 1a – Fig. 1d.

Fig.1(a) Representative photograph of Pagani TG63-150

Fig.1(b) Representative Photographs of Begemann Cone and DMT blade

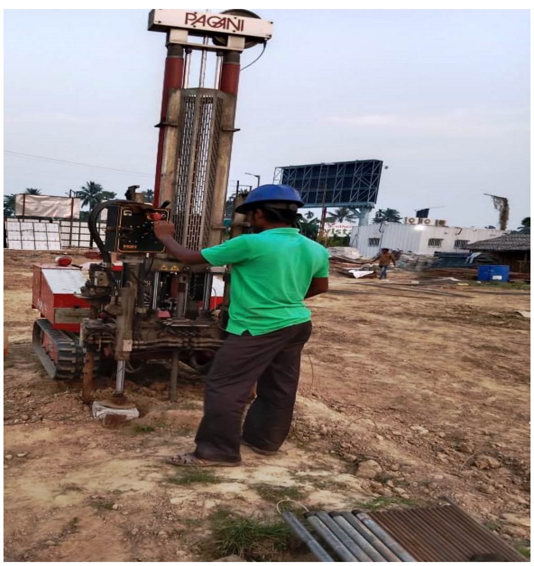

Fig.1(c)Representative photograph of CPT/DMT test

Fig.1 (d) Representative photograph of PMT test

In accordance with TC16 2001(Marchetti et al. 2001), DMT tests were conducted at 20cm depth intervals with a penetration rate of 2cm/s using the 'SDMT Elab' computer program. A total of 29 numbers of DMT tests (within the eight sites (Site-1 (HC) to Site8(BD)) were performed adjacent to boreholes at respective locations. Besides, 25 numbers of CPT tests (within the eight sites (Site-1 (HC) to Site8(BD)) were conducted using the 'Pagani TG63-150' penetrometer assembly as per Indian Standard 4968 Part III (1976) and manufacturer's instructions. Cone assembly (Begemann cone) was pushed vertically into the ground at 2cm/s, with readings recorded every 20cm depth intervals to calculate cone resistance (q_c) and frictional resistance (f_s). The PMT tests were conducted using a 'Prebored Menard Pressuremeter' with a maximum capacity of 80 Bar and a 74mm probe diameter (NX size). The total 48 numbers of PMT tests were carried out inside 12 NX size boreholes at 5m depth intervals up to an average depth of 20m at three different sites (Site-9 (VT), Site-10 (PT) and Site-11 (ES) adjacent to boreholes. Some representative photographs of the tests are given below Fig.2.

Figure: 2.0 Representative Photograph of DMT, CPT and PMT tests at site-3 (RJ), Site-4 (HA) and Site-9 (VT) respectively

4. *Determination of Geotechnical Parameters and Comparison of the Same from Different tests:*

In this section, emphasis is given on the site-wise test results obtained from DMT, CPT, and PMT tests. Additionally, the results from adjacent conventional boreholes, including field SPT N values (N_{ob}), shear parameters, and index properties (liquid limit, plastic limit) from undisturbed samples, are presented. Sub-soil profiles from DMT, CPT, and PMT are compared with those predicted from conventional boring. Shear strength parameters, vertical drained constrained modulus, sub-soil behavior type index, Dilatometer modulus, cone penetration resistance, sleeve friction, and SPT N values (N_{ob}) are determined along depth. For PMT tests the limit pressure and Pressuremeter modulus are compared with N_{ob}. Design charts are proposed based on field and laboratory test comparisons, including relationship with conventional SPT N values (N_{ob}). Settlement analysis of shallow foundations on cohesive soil is conducted by using an empirical equation (based on average cone resistance i.e., C_{KD} from CPT tests), M_{DMT} from adjacent DMT tests, and numerical modelling (created on Plaxis 2D software). The estimated settlement predicted by using C_{KD} , are compared with other methods.

Here are the key points which are summarised below.

- DMT's estimation of undrained cohesion (C_u) tends to be more consistent compared to CPT.
- Both DMT and CPT effectively estimate the angle of internal friction, aligning closely with laboratory direct shear test outcomes.
- The compressibility characteristics, as indicated by the vertical drained constrained modulus (M), exhibit remarkable similarity between DMT and CPT tests.
- The variations in M_{DMT} and M_{CPT} strongly relates with the N_{ob} across the study area.
- Dilatometer Modulus (E_D) and parameters from CPT, such as cone penetration resistance (q_c) and sleeve friction (fs), exhibit close correspondence with N_{ob}.

- The findings reveal a remarkable resemblance between the subsoil profiles predicted from DMT or CPT tests (based on I_D and I_C values) and those derived from conventional borehole investigations.
- In PMT tests, the variations in Limit pressure (P_L) and Pressuremeter modulus (E_{PMT}) align well with the N_{ob}, contingent upon the subsoil consistency.
- Notably, the presence of decomposed wood particles in the subsoil significantly influences the outcomes of DMT, CPT, and PMT tests.
- In certain instances, there's a discrepancy between subsoil classifications obtained from DMT/CPT and conventional methods, likely due to the presence of decomposed wood. This discrepancy leads to higher values of M_{DMT} or M_{CPT} compared to situations where silty clay/clayey silt soil is predominant.

These insights offer a comprehensive understanding of the reliability and comparability of different testing methodologies and underscore the importance of considering site-specific conditions for accurate geotechnical assessment and design.

5. ***Design Chart Based on Parametric Comparison:***

This section focuses on comparing basic parameters such as E_D, M, q_c, f_s, P_L, and E_{PMT} with observed SPT N values from adjacent conventional boreholes at each test location. Subsequently, a design chart is developed to predict these parameters for cohesive soil (silty clay/clayey silt) based on observed SPT N values (N_{ob}). Additionally, efforts are made to predict the index properties of cohesive soil using parameters obtained from DMT, CPT, and PMT tests.

For individual in-situ tests (DMT, CPT, and PMT), relationships are established by comparing test results with adjacent borehole data, focusing on cohesive sub-soil. Good-quality data, excluding scattered values, are utilised.

In this study, the Chi-square value is estimated using ten observed data points from two different locations (out- side from study area) and compared with the predicted values from proposed relationships. In this context the calculated value of Chi-square for the proposed relationships is less than the critical value, confirming their significance.

Key findings include:

- In DMT tests for silty clay/clayey silt soil, E_D and M_{DMT} values depend on consistency of cohesive soil.
- Presence of decomposed wood particles affects DMT, CPT, and PMT results.
- M_{DMT}/E_D ratio relates linearly with plasticity index and plastic limit for silty clay/clayey silt soil.
- In CPT tests, q_c, M_{CPT}, and fs values are dependent on the consistency of cohesive soil.
- q_c/PI and q_c/W_P ratios linearly relate with M_{CPT}.
- In both DMT and CPT tests, the calculated values of Chi-square for all the predicted relations fall well within the critical values at the 0.05 significance level

- In PMT tests, P_L and E_{PMT} relate linearly with N_{ob}.
- The E_{PMT}/P_L ratio decreases with increase in liquidity index, exhibiting a power-law behavior.

6. Cpt-Based Predictive Model for Shallow Foundation Settlement on Cohesive Soil:

This chapter focuses on estimating the settlement of shallow foundations on cohesive soil, primarily using CPT cone resistance and comparing it with other methods. Settlement analysis is carried out using an empirical equation based on average cone resistance (C_{KD}), M_{DMT} from DMT tests, and conventional Mohr's Coulomb model in PLAXIS 2D software. To carry out settlement analysis, Indian standards typically recommend use of this empirical equation (based on average cone resistance (C_{KD})) for cohesionless soil. Basis Bandyopadhyay et al. 2022, it had already been shown that this formula is well suitable for cohesive soil as well. Hence, in this study the same empirical equation is used for finding settlement of cohesive soil from CPT test. The estimated values of settlements are compared with settlement estimates from other methods, including M_{DMT} and PLAXIS 2D modelling.

Settlement values based on M_{DMT} from DMT tests and average cone resistance (C_{KD}) from CPT tests are nearly equal for various types of foundations on cohesive soil.

Key findings include:

• Settlement values obtained from numerically modeled PLAXIS 2D (using Mohr's Coulomb model) based on laboratory (UU) tests, CPT, and DMT shear parameters tend to be lower. Therefore, settlement values estimated from M_{DMT} and C_{KD} are more conservative.

• Settlements predicted on using average cone resistance (C_{KD}) for foundations on cohesive soil closely match those from other methods (i.e., DMT Settlement software and PLAXIS 2D).

7. *Conclusions*

The major conclusions made from the present study are as follows

- The sub-soil profiles predicted from Dilatometer and Cone Penetration tests closely resemble those from conventional soil exploration boreholes at eight test locations.
- DMT tests provide better comparison with laboratory triaxial (UU) tests for undrained cohesion, while CPT tests often yield higher values. Further research on predicting cone factor (N_{kt}) for alluvial deposits is needed.
- M_{CPT} and M_{DMT} variations along depth are similar, allowing accurate prediction of sub-soil compressibility characteristics.
- The variation of Dilatometer modulus (E_D) along depth depends on sub-soil consistency, showing uniformity in cohesive sub-soils but scattering in the presence of decomposed wood particles or silty sand/sandy silt.
- E_D and M_{DMT} variations align well with N_{ob} along depth.
- Relationships between SPT blow count, DMT estimated E_D, and M_{DMT} allow predicting cohesive sub-soil consistency.
- Plasticity index, plastic limit, and liquid limit can be predicted based on relationships between M_{DMT}, E_D/PI, and E_D/W_P.
- Cone resistance variation with depth is influenced by sub-soil consistency, showing uniformity for silty clay/clayey silt but scattering for sandy silt/silty sand.
- Variation of q_c, f_s, and M_{CPT} with depth aligns well with N_{ob} for cohesive sub-soil, allowing prediction of SPT-based consistency.

- Ratio of M_{CPT} to q_c effectively represents PI and W_P, enabling prediction of plasticity index, liquid limit, and plastic limit.
- Limit pressure (P_L) and pressuremeter modulus (E_{PMT}) are higher for silty sand/sandy silt soil and influenced by decomposed wood particles.
- Variation of P_L and E_{PMT} with depth is comparable to N_{ob} for cohesive sub-soil, allowing prediction based on N_{ob}.
- E_{PMT}/P_L ratio can predict liquidity index (I_L) for cohesive sub-soil.
- Predicted settlements using C_{KD} are similar to those using M_{DMT}.
- Settlements estimated using M_{DMT} and C_{KD} for cohesive soil are more conservative than those from PLAXIS2D.
- Recommended methods to estimate the settlement from CPT test for cohesionless soil, when used for cohesive soil also present values well comparable with those obtained from numerical analyses and field observed values.

7.1. Limitation of the Study:

- Incorporating more DMT tests with a wider range of material index (I_D) values would enhance the study's effectiveness for analyzing silty clay/clayey silt sub-soil.
- The proposed relation for predicting SPT based consistency from DMT tests is valid within the range of SPT blow counts observed (2 to 23).
- A versatile range of plasticity index and plastic limit values would improve the effectiveness of studying relationships for predicting soil properties from DMT tests.

- The proposed relations for predicting liquid limit, plastic limit, and plasticity index from DMT tests are valid for the sub soil having similar or comparable properties i.e., coastal east zone cohesive soil.

- Increasing the number of CPT tests with a wider range of cone resistance (I_C) values would enhance the study's effectiveness for analyzing silty clay/clayey silt soil.

- The proposed relation for predicting SPT based consistency from CPT tests is valid within the observed range of SPT blow counts (2 to 21).

- A broad range of plasticity index and plastic limit values is crucial for establishing relations to predict W_L, W_P, and P_I from CPT tests.

- Utilizing a larger dataset of PMT tests would be more beneficial for the study.

- Relations are focused on cohesive soil profiles, particularly silty clay/clayey silt, with I_L, values ranging from 0.18 to 0.75 and N_{ob} between 3 to 18.

- The relations can be applied to soils of similar deposits in different geographic locations, but the presence of decomposed wood should be considered.

- In numerical model (created in PLAXIS 2D ver. 2016) based on the CPT test results, the cohesion values from CPT test (generally which is on higher side) is used for the settlement analysis. It is obvious, that more comparable value of undrained cohesion estimated from CPT tests, may be more useful for the study.

- In majority of study locations, CPT based settlement has not been compared with the observed settlement due to the scarcity of data. It is obvious that comparing the estimated settlements (from all methods) with the observed settlement will make the study more accurate.

*7.2. **Recommendations For Further Study:***

- Conduct more DMT, CPT, and PMT tests across various locations within the region.
- Revise the cone factor (N_{kt}) used in CPT tests to estimate undrained cohesion in cohesive sub-soils in the study area.
- Develop a range of limit pressure and pressuremeter modulus for silty sand/sandy silty deposits in Kolkata region.
- Analyse more case studies to compare predicted settlement of shallow foundations (on cohesive soil) from CPT and DMT tests with observed settlement.