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Soil Classification Through Penetration Tests

A. H. Khan, A. Akbar, K. Farooq, N. M. Khan, M. Aziz and H. Mujtaba

Department of Civil Engineering, University of Engineering and Technology, Lahore, Pakistan. Email: ammadhk@hotmail.com

Abstract

The Newcastle Dilatometer (NDMT) developed by Akbar in 2001 has a distinctive feature that it loads the soil with a rigid piston in place of flexible membrane as in the Marchetti Dilatometer (MDMT). Based on the previous research works carried out using the NDMT in normally consolidated soils, it has been found that the material and dilatometer indices from the NDMT data can be used to classify the soils based on Marchetti and Crapps (1981) chart. However, in overconsolidated soils, the Marchetti and Crapps (1981) chart for soil classification sometimes shows disagreement with other methods in the prediction of soil type based on the NDMT data. This is also true with the Cone Penetrometer (CPT) data. These findings are based on extensive testing carried out in alluvial soil deposits at Kala Shah Kaku campus of the University of Engineering and Technology, Lahore. These testing comprised particle size analysis in the laboratory in conjunction with the NDMT and CPT testing in the field. This paper presents the data of penetration tests along with laboratory soil classifications and explores the possible causes of disagreement in the prediction of true soil type based on penetration tests in overconsolidated soils.

Key Words: Soil classification; cone penetration test; alluvial deposit; dilatometer test.

1. Introduction

Ever since the appearance of the first in situ test, engineers and scientists have continuously endeavored to improve the equipment, the test protocol and the interpretation of data to obtain more representative values of soil profiling, in-situ strength, stiffness and horizontal stress. This has led to an improvement in the analyses required for the design of various geotechnical structures.

Like other engineering techniques used in the evaluation of geotechnical design parameters, intrusive in-situ testing does disturb the ground to some extent creating difficulties in interpreting tests to obtain intrinsic design parameters. This difficulty in the interpretation of test results is primarily due to the complex behaviour of soils, together with the lack of control and choice of the boundary conditions in any field test. Therefore the results of many in situ tests are interpreted using empirical correlations with results of laboratory tests.

One of such penetration devices is the *MDMT* which is a simple and cost effective geotechnical investigation tool. Its testing procedure has been standardized as ASTM D 6635[1]. The *MDMT* is still in use as originally designed and all efforts (except the *NDMT*) improve the data quality or interpretation at the cost of increase in complexity of device. Marchetti et al. (2001) suggests that the reliability of the *MDMT* data interpretation in overconsolidated soils is uncertain [2].

The *NDMT* was developed and initially tested in the UK soils [3]. Later on, its in-situ testing & research was initiated in Pakistan [4, 5, 6, 7, 8]. The *NDMT* research work can be seen in the following references [3, 9, 10, 11, 12, 13,14].

In the *NDMT* (Figure 1), a rigid piston is moved out to load the soil through N_2 gas. The piston movement is measured electronically by a magnet and Hall Effect transducer system. The gas pressure required in moving the piston is simultaneously recorded by a pressure transducer.

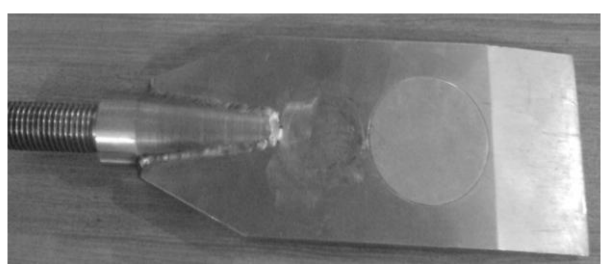

Figure 1: The *NDMT* probe

Figure 2 show a typical pressure-displacement curve obtained by constant rate of stress (CRS) method.

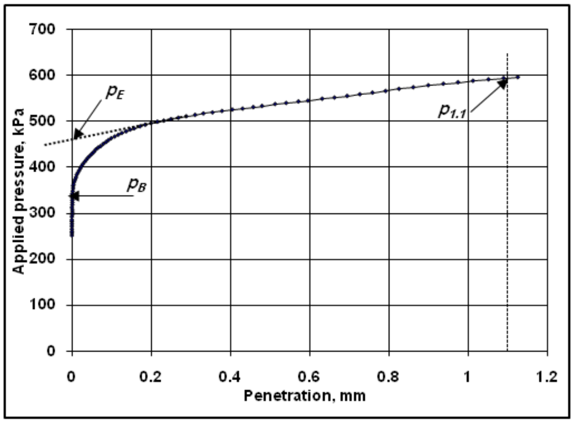

Figure 2: A typical *NDMT* pressure displacement curve using CRS method

Further details about design and testing procedure can be seen in reference [3].

2. Basic Indices of Dilatometer

The *NDMT* indices (Table 1) are based on three pressures (p_B, p_E and $p_{1.1}$) defined in Figure 2. The *MDMT* corresponding indices are based on two pressures (p_0 and p_1) defined below.

Table 1: The *NDMT* & *MDMT* indices

Index	*NDMT* [9]	*MDMT* [15]
Material index (I_D)	$(p_{1.1}–p_E) / (p_E–u_0)$	$(p_1 –p_0)/(p_0 – u_0)$
Dilatometer modulus (E_D)	$42.8\ (p_{1.1} – p_B)$	$34.7\ (p_1 – p_0)$
Horizontal stress index (K_D)	$(p_E – u_0)/ \sigma'_{v0}$	$(p_0 – u_0)/\sigma'_{v0}$

where

- p_1 = The *MDMT* pressure corresponding to 1.1 mm expansion of membrane
- p_0 = The *MDMT* lift off pressure
- $p_{1.1}$ = The *NDMT* pressure corresponding to 1.1 mm displacement of rigid piston
- p_B = The *NDMT* lift off pressure
- p_E = The *NDMT* yield pressure
- u_0 = Static pore pressure

I_D is a parameter that helps define a soil type, and a reasonable soil description in normal soils. Marchetti in 1980 presented a soil classification system based on I_D values. The system is based on the concept that slope of loading curve ($p_{1.1}$-p_E) is less in clays and more in sands [2].

Marchetti (1980) found, from his testing experience in a variety of soils, that the material index 'I_D' is a parameter, which is related to the prevailing grain size of a soil, and is relatively independent of *OCR*. It is also independent of the degree of saturation of a soil [16, 17, 18]. Table 2 is based on the mechanical behaviour of soils (or possibly rigidity index) and, therefore, sometimes, it can misdescribe silt as clay and vice versa. An admixture of sand and clay would generally be described as silt [2].

Table 2: Soil classification based on I_D [19]

Soil type	Material index, I_D
Peat/sensitive clays	< 0.10
Clay	0.10 – 0.35
Silty clay	0.35 –0.60
Clayey silt	0.60 –0.90
Silt	0.90 –1.20
Sandy silt	1.20 –1.80
Silty sand	1.80 –3.30
Sand	>3.30

Marchetti & Crapps (1981) expanded Table 2 to produce Figure 10 which, based on dilatometer modulus and material index, can provide an estimate of in-situ unit weight of soil as well [19]. Lacasse & Lunne (1988) further reinforced Figure 3 by including the effect of *OCR* on I_D and E_D [17].

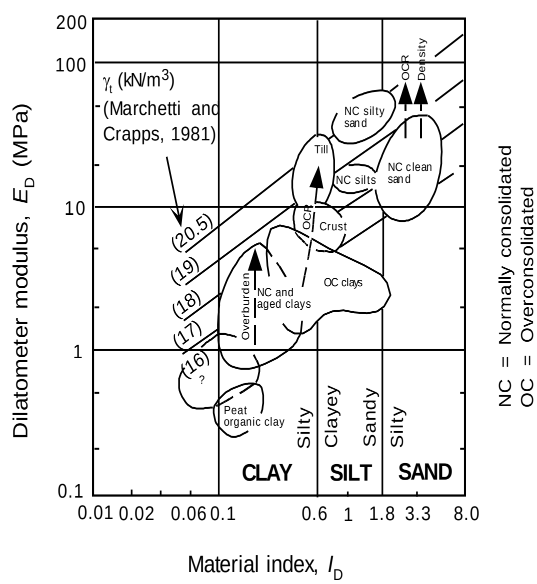

Figure 3: Classification chart for soils [17]

3. Field and Laboratory Testing

In-situ testing was carried out at the Kala Shah Kaku (KSK) campus of the University of Engineering and Technology, Lahore, Pakistan. The in-situ testing comprised the *NDMT* and the electrical *CPT* [20] soundings. These tests were performed at 10 locations (labelled TP-1 to TP-10) up to a depth of 10 m. All the test locations were kept within 1.0 m distance. The disturbed soil samples were obtained through split spoon sampler at depth interval of 0.5 m from boreholes close to the test points, for actual soil classification in the laboratory. The undisturbed block samples were collected from the test pits (dug to 3.0 m depth close to the other test points) for laboratory oedometer tests [21]. The *CPT* soundings were taken at depth interval of 1 cm. The *NDMT* tests were performed at an interval of 20 cm [15]. The ground water table was encountered at a depth of 7.5 m at all the investigated points.

4. Results and Discussion

Based on results of particle size distribution and Atterberg limits, the soil samples have been classified according to ASTM D 2487. The soil descriptions are given in Table 3.

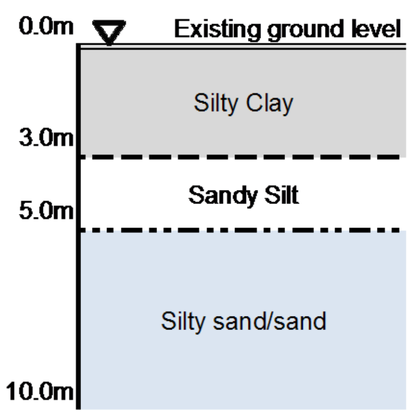

Figure 4: A generalized soil profile at the test site

Figure 4 shows a generalised soil profile at the site up to 10 m depth based on the actual soil classification tests.

The *CPT* tip resistance and friction ratio profiles are shown in Figure 5. The friction ratio (R_f) is normally used for soil classification. There are more than 25 different independent *CPT* soil classification systems in use worldwide [22]. However, Robertson (1990) soil classification chart (Figure 6) has been used in this analysis [23] and the soil descriptions are given in Table 3.

The *CPT* data has also been used to determine overconsolidation ratio (*OCR*) according to equation [24] given below:

$$OCR=[0.33(q_c-\sigma'_{vo})^m(\sigma_{atm}/100)^{1-m}]/\sigma'_{vo} \quad (1)$$

Where,

m = $0.65+1/(800\times10^{-Ic}+2.5)$
I_c = $[(3.47-\log Q_t)^2+(\log F_r+1.22)^2]^{0.5}$
Q_t = $(q_c-\sigma_{vo})/\sigma'_{vo}$
F_r = $F_s/(q_c-\sigma'_{vo})$ in %age
q_c = The *CPT* cone tip resistance in kPa
σ_{vo} = Total overburden stress in kPa
σ_{vo}' = Effective overburden stress in kPa
σ_{atm} = Atmospheric stress = 100 kPa
F_s = The *CPT* cone sleeve friction in kPa

Profiles of *OCR* from the *CPT* data and those based on Oedometer tests are shown in Figure 7.

The typical trends of some of the *NDMT* pressure and displacement curves observed in various soils are shown in Figure 8. The profiles of I_D are shown in Figure 9. Soil descriptions based on Marchetti and Crapps (1981) chart [19] are given in Table 3. Figure 10 presents the I_D and E_D data plotted on Marchetti and Crapps (1981) chart.

Based on the data from all sources, following discussion can be made:

- The soil classification tests results indicate that the top 2.0 m to 3.0 m thick deposit comprises cohesive soils consisting of lean clay (CL) and silty clay (CL-ML) followed by non plastic sandy silt (ML), silty sand (SM) to poorly graded sand (SP/SP-SM). The liquid limit and plasticity index values for the cohesive soils vary between 24 & 34 and 3 & 12 respectively. The cohesive soils contain traces of cementation also and are nearly dry with natural moisture content varying between 0.25% and 2.08 %. The liquidity index of cohesive soils varies between -7.38 & -1.62 indicating highly overconsolidated soil deposit. The SM, SP/SP-SM soils are mainly passing sieve # 40 with variable amount of non plastic silt. The natural moisture content in these soils varies between 0.28% and 7.25 % up to the ground water table.

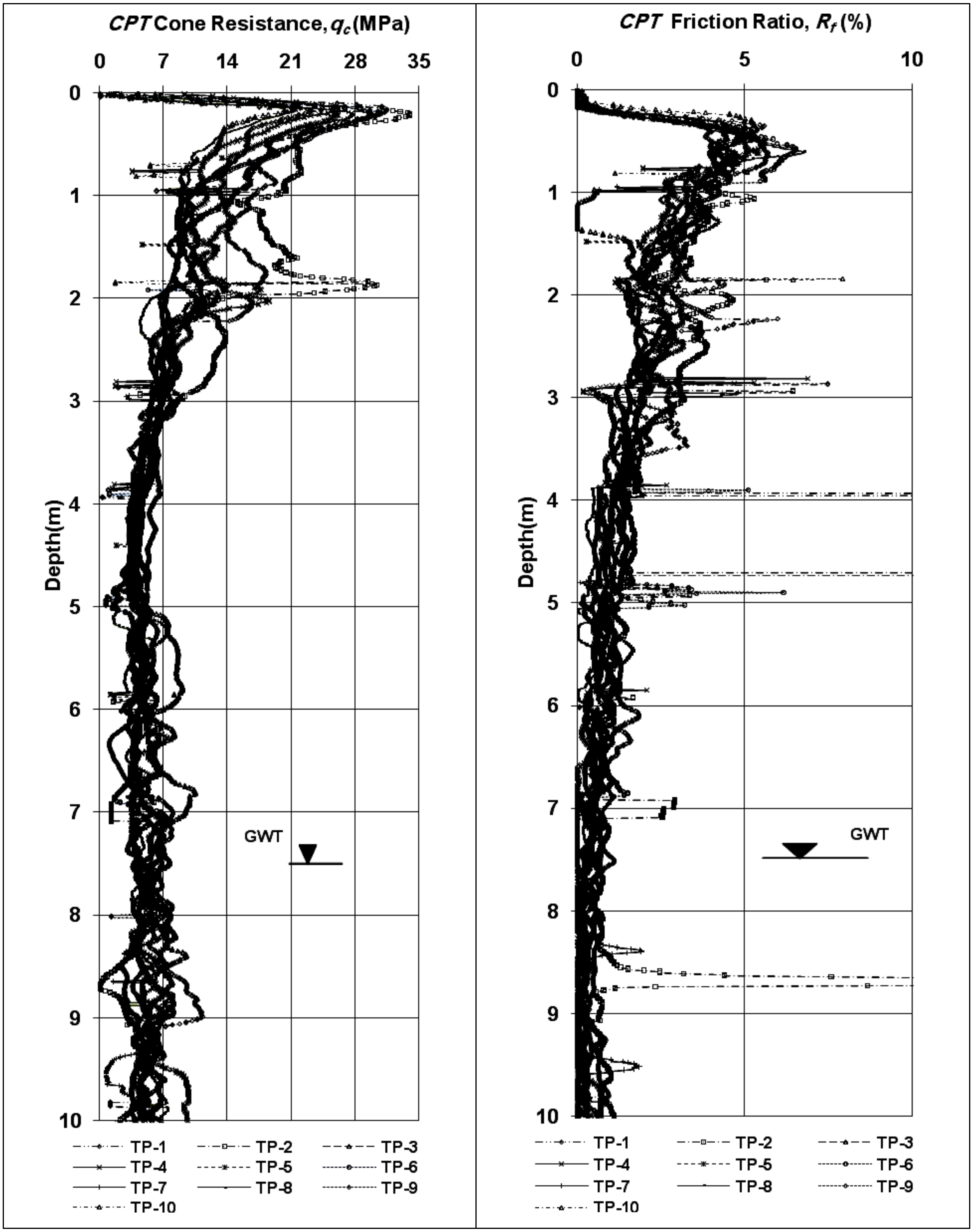

Figure 5: The *CPT* cone resistance (q_c) and friction ratio (R_f) profiles

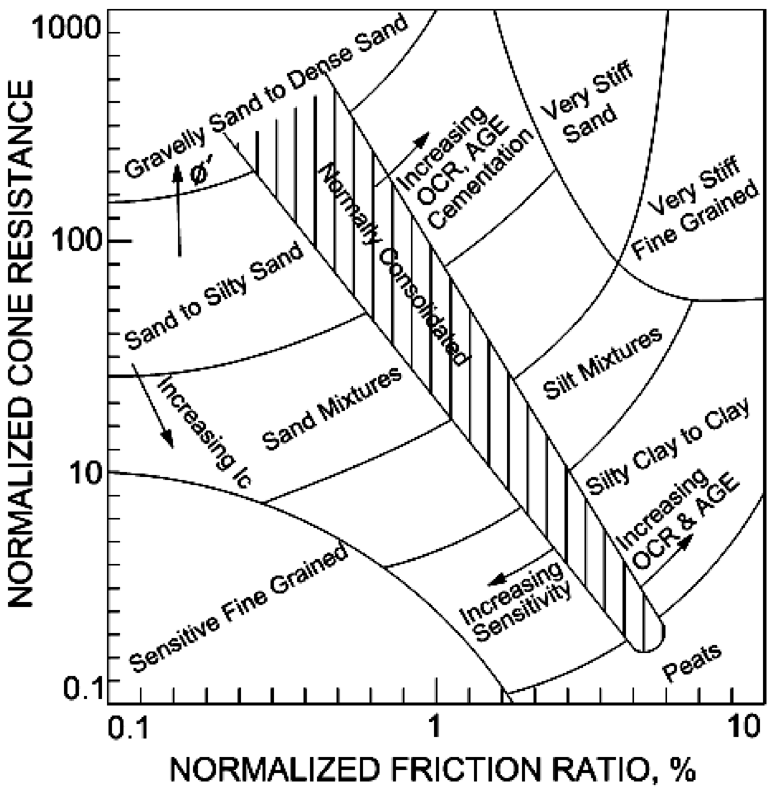

Figure 6: *CPT* soil behavior type chart [23]

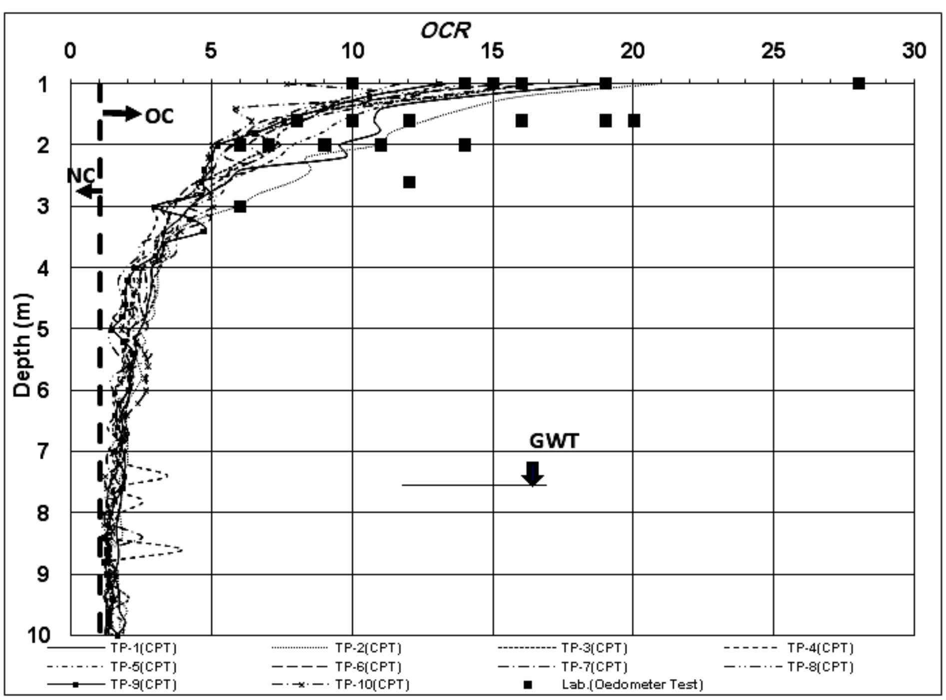

Figure 7: The *OCR* profile by *CPT* and laboratory oedometer tests

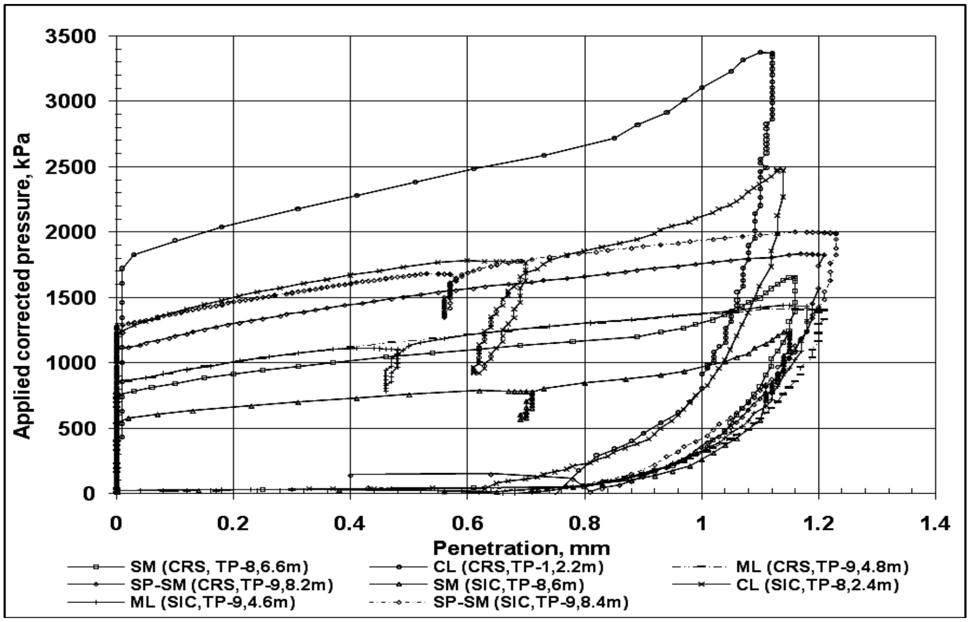

Figure 8: The typical *NDMT* curves at the site

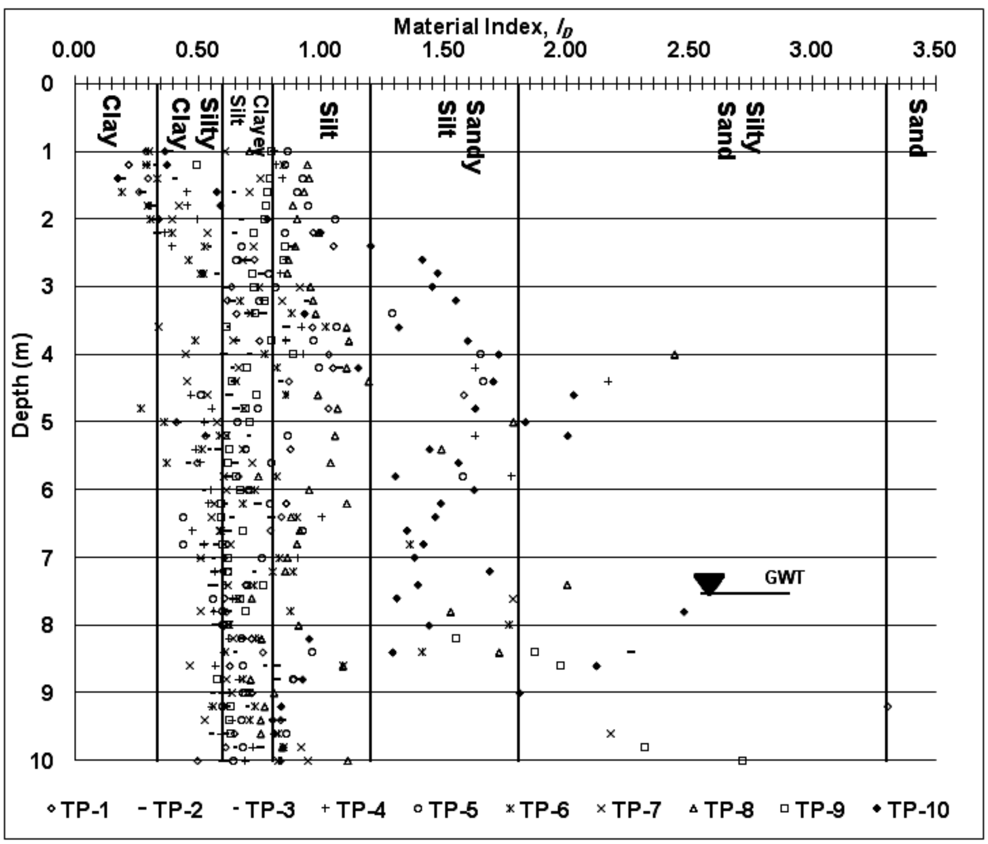

Figure 9: Profiles of material index (I_D)

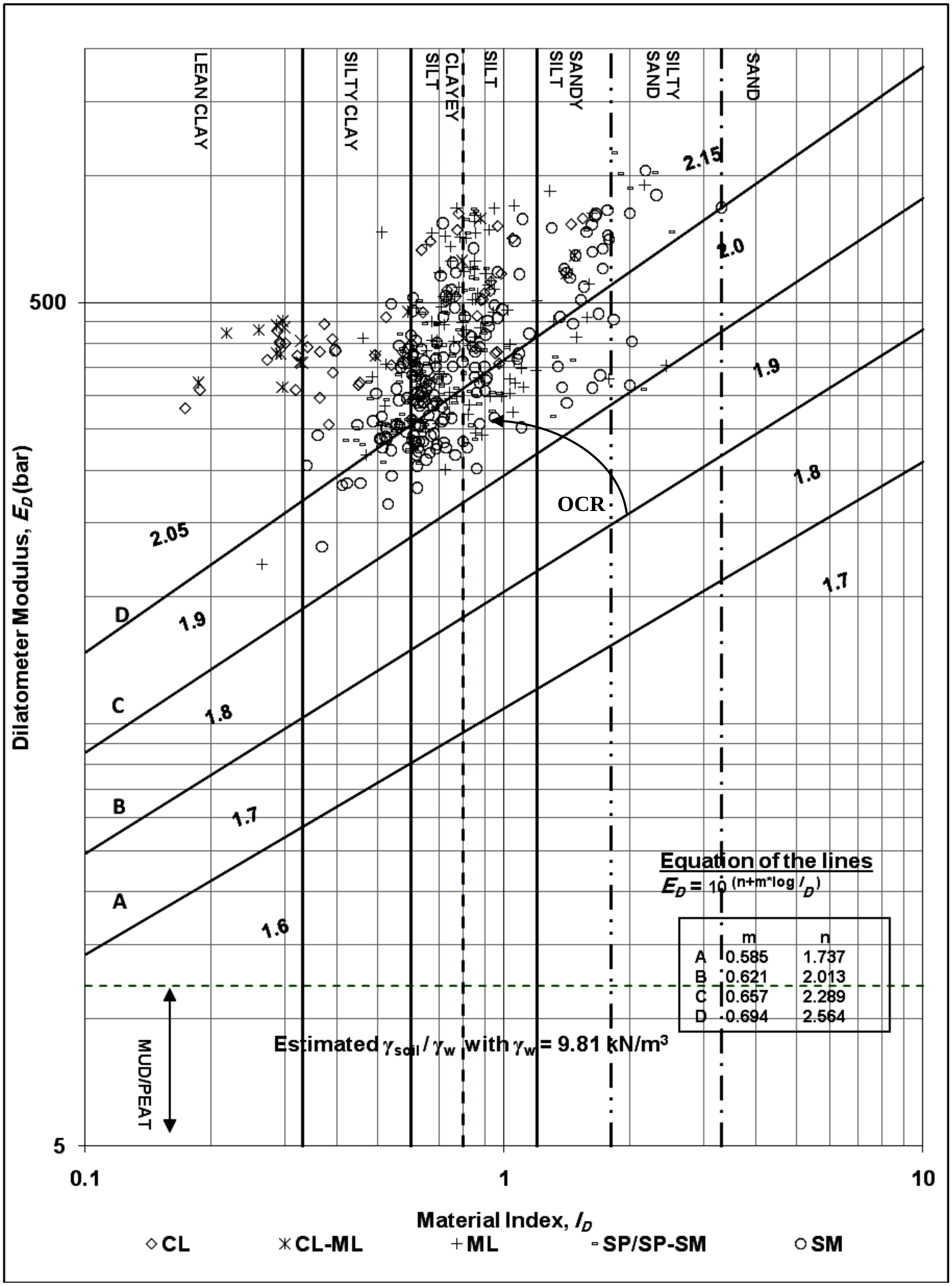

Figure 10: The *NDMT* based I_D and E_D plotted on Marchetti and Crapps (1981) chart

Table 3: A comparison of actual soil classification with the *CPT* and the *NDMT* (Sheet 1 of 2)

Depth (m)	**Soil classification based on different sources**														
	TP-1			**TP-2**			**TP-3**			**TP-4**			**TP-5**		
	*	**	***	*	**	***	*	**	***	*	**	***	*	**	***
1.0	Silty Clay	Silty sand	Clay	Silty Clay	Silty Sand	Silty clay	Silty Clay	Silty Sand	Silty clay	Sandy Silt	Silty Sand	Silt	Sandy Silt	Silty Sand	Silt
1.5	Silty Clay	Silty sand	Clay	Silty Clay	Silty Sand	Clay	Silty Clay	Silty Sand	Silty clay	Silty Clay	Silty Sand	Silt	Sandy Silt	Silty Sand	Silt
2.0	Silty Clay	Silty sand	Silty clay	Silty Clay	Silty Sand to Sandy Silt	Clay	Silty Clay	Silty Sand	Silty clay	Silty Clay	Silty Sand	Silty clay	Sandy Silt	Silty Sand	Silt
2.5	Sandy Silt	Silty sand to sandy silt	Silty clay	Sandy Silt	Silty Sand to Sandy Silt	Silty clay	Sandy Silt	Silty sand to sandy silt	Silty clay	Sandy Silt	Silty Sand to Sandy Silt	Silty clay	Sandy Silt	Silty Sand to Sandy Silt	Silt
3.0	Silty Sand	Silty sand to sandy silt	Clayey silt	Silty Sand	Silty Sand to Sandy Silt	Clayey Silt	Sandy Silt	Silty Sand	Silt	Sandy Silt	Silty Sand	Silt	Sandy Silt	Silty Sand to Sandy Silt	Silt
3.5	Silty Sand	Silty sand to sandy silt	Clayey silt	Silty Sand	Silty Sand to Sandy Silt	Clayey silt	Sandy Silt	Silty Sand	Silt	Sandy Silt	Silty Sand	Silt	Silty Sand	Silty Sand to Sandy Silt	Silt
4.0	Sandy Silt	Silty sand to sandy silt	Silt	Silty Sand	Silty Sand to Sandy Silt	Clayey silt	Sandy Silt	Silty Sand to Sandy Silt	Silt	Sandy Silt	Silty Sand to Sandy Silt	Silt	Silty Sand	Silty Sand	Clayey silt
4.5	Sandy Silt	Silty sand to sandy silt	Silt	Silty Sand	Silty Sand to Sandy Silt	Clayey silt	Sandy Silt	Silty Sand to Sandy Silt	Silt	Sandy Silt	Silty Sand to Sandy Silt	Silt	Sandy Silt	Silty Sand to Sandy Silt	Sandy silt
5.0	Silty Sand	Silty sand to sandy silt	Silt	Sand with silt	Silty Sand to Sandy Silt	Clayey silt	Silty Sand	Silty Sand to sandy silt	Silt	Silty Sand	Silty Sand to sandy silt	Silt	Silty Sand	Silty Sand to Sandy Silt	Silt
5.5	Silty Sand	Silty sand to sandy silt	Silt	Sand with silt	Silty Sand to Sandy Silt	Clayey silt	Sand with silt	Silty Sand to sandy silt	Clayey silt	Silty Sand	Silty Sand to sandy silt	Clayey silt	Silty Sand	Silty Sand to Sandy Silt	Clayey silt
6.0	Sand with silt	Silty sand to sandy silt	Clayey silt	Sand with silt	Silty Sand to Sandy Silt	Clayey silt	Sand with silt	Silty Sand	Silt	Poorly Graded Sand	Silty Sand	Silty clay	Sand with silt	Silty Sand	Clayey silt
6.5	Sand with silt	Silt mixtures	Silt	Sand with silt	Silty clay to clay	Clayey silt	Poorly Graded Sand	Silty Sand	Clayey silt	Sand with silt	Silty Sand to Sandy Silt	Silt	Poorly Graded Sand	Silty Sand	Clayey silt
7.0	Silty Sand	Silty sand	Silt	Sand with silt	Silty sand	Silt	Sand with silt	Silty Sand	Clayey silt	Silty Sand	Silty Sand to Sandy Silt	Silt	Poorly Graded Sand	Silty Sand	Clayey silt
7.5	Silty Sand	Silty sand	Clayey silt	Sand with silt	Silty Sand	Clayey silt	Poorly Graded Sand	Silty Sand	Clayey silt	Silty Sand	Silty Sand to Sandy Silt	Clayey silt	Sand with silt	Silty Sand	Clayey silt
8.0	Silty Sand	Silty sand	Silt	Sand with silt	Silty Sand	Clayey silt	Poorly Graded Sand	Silty Sand	Silty clay	Silty Sand	Silty Sand	Silt	Poorly Graded Sand	Silty Sand	Silty clay
8.5	Sand with silt	Silty sand	Clayey silt	Sand with silt	Silty Sand to Sandy Silt	Silt	Poorly Graded Sand	Silty Sand	Clayey silt	Sand with silt	Silty Sand	Clayey silt	Sand with silt	Silty Sand	Silt
9.0	Silty Sand	Silty sand	Clayey silt	Sand with silt	Silty Sand to Sandy Silt	Clayey silt	Sand with silt	Silty Sand	Clayey silt	Silty Sand	Silty Sand	Silt	Sand with silt	Silty Sand	Silt
9.5	Silty Sand	Silty sand	Silt	Sand with silt	Silty Sand	Silt	Poorly Graded Sand	Silty Sand	Clayey silt	Sand with silt	Silty Sand	Clayey silt	Poorly Graded Sand	Silty Sand	Clayey silt
10.0	Sand with silt	Silty sand	Silt	Sand with silt	Silty Sand to Sandy Silt	Clayey silt	Sand with silt	Silty Sand	Silt	Silty Sand	Silty Sand to Sandy Silt	Silt	Sand with silt	Silty Sand	Clayey silt

*Actual Soil classification based on ASTM D 2487
**Soil classification based on the *CPT* [23]
***Soil classification based on the *NDMT* [19]

Table 3: A comparison of actual soil classification with the *CPT* and the *NDMT* (Sheet 2 of 2)

Depth (m)	Soil classification based on different sources														
	TP-6			TP-7			TP-8				TP-9				TP-10
	*	**	***	*	**	***	*	**	***	*	**	***	*	**	***
1.0	Silty Clay	Silty Sand	Clay	Silty Sand	Silty Sand	Clayey silt	Sandy Silt	Silty Sand	Silt	Silty Clay	Silty Sand	Clay	Silty Clay	Dense Sand	Silty clay
1.5	Silty Clay	Silty Sand	Clay	Silty Sand	Silty Sand	Clayey silt	Silty Clay	Silty Sand	Silt	Silty Clay	Silty Sand	Silty clay	Silty Clay	Silty Sand	Clay
2.0	Silty Clay	Silty Sand	Clay	Silty Sand	Silty Sand	Clayey silt	Silty Clay	Silty Sand to Sandy Silt	Silty clay	Sandy Silt	Silty Sand	Silt	Sandy Silt	Silty Sand	Silt
2.5	Sandy Silt	Silty Sand to Sandy Silt	Silty clay	Sandy Silt	Silty Sand to Sandy Silt	Clayey silt	Silty Clay	Silty Sand to Sandy Silt	Silty clay	Sandy Silt	Silty Sand	Silt	Silty Clay	Silty Sand	Silt
3.0	Sandy Silt	Silty Sand	Silt	Silty Sand	Silty Sand	Clayey silt	Silty Clay	Silty Sand	Silty clay	Silty Clay	Silty Sand	Silty clay	Silty Clay	Silty Sand to Sandy Silt	Clay
3.5	Sandy Silt	Silty Sand to Sandy Silt	Silt	Silty Sand	Silty Sand to Sandy Silt	Clayey silt	Sandy Silt	Silty Sand to Sandy Silt	Silty clay	Sandy Silt	Silty Sand to Sandy Silt	Silty clay	Sandy Silt	Silty Sand to Sandy Silt	Clay
4.0	Sandy Silt	Silty Sand to Sandy Silt	Silt	Silty Sand	Silty Sand to Sandy Silt	Clayey silt	Sandy Silt	Silty Sand	Silt	Sand with silt	Silty Sand to Sandy Silt	Clayey silt	Silty Sand	Silty Sand to Sandy Silt	Clayey silt
4.5	Sandy Silt	Silty Sand to Sandy Silt	Silt	Silty Sand	Silty Sand to Sandy Silt	Clayey silt	Sandy Silt	Silty Sand to sandy silt	Silt	Sandy Silt	Silty Sand to sandy silt	Clayey silt	Silty Sand	Silty Sand to Sandy Silt	Sandy silt
5.0	Silty Sand	Silt Mixtures	Clayey silt	Silty Sand	Silty Sand to Sandy Silt	Silt	Sandy Silt	Silty Sand to Sandy Silt	Silt	Silty Sand	Silty Sand	Silt	Silty Sand	Silty Sand	Silt
5.5	Silty Sand	Silty Sand to sandy silt	Clayey silt	Silty Sand	Silty Sand to Sandy Silt	Clayey silt	Sandy Silt	Silty Sand to Sandy Silt	Silt	Silty Sand	Silty Sand to sandy silt	Clayey silt	Silty Sand	Silty Sand to Sandy Silt	Sandy silt
6.0	Silty Sand	Silty Sand to Sandy Silt	Clayey silt	Silty Sand	Silty Sand to Sandy Silt	Silt	Silty Sand	Silty Sand	Silt	Silty Sand	Silty Sand to Sandy Silt	Silt	Silty Sand	Silty Sand to Sandy Silt	Silt
6.5	Silty Sand	Silty Sand to Sandy Silt	Silt	Silty Sand	Silty Sand to Sandy Silt	Clayey silt	Silty Sand	Silty Sand to Sandy Silt	Silt	Sand with silt	Silty Sand to Sandy Silt	Clayey silt	Silty Sand	Silty Sand to Sandy Silt	Sandy silt
7.0	Sandy Silt	Silty Sand	Silt	Silty Sand	Silty Sand to Sandy Silt	Silt	Silty Sand	Silty Sand to sandy silt	Silt	Silty Sand	Silty Sand to sandy silt	Silt	Silty Sand	Silty Sand to sandy silt	Sandy silt
7.5	Silty Sand	Silty Sand	Silt	Silty Sand	Silty Sand	Clayey silt	Silty Sand	Silty Sand	Silt	Silty Sand	Silty Sand to sandy silt	Clayey silt	Sand with silt	Silty Sand	Sandy silt
8.0	Silty Sand	Silty Sand	Silt	Silty Sand	Silty Sand	Silt	Silty Sand	Silty Sand	Silt	Sand with silt	Silty Sand	Clayey silt	Sand with silt	Silty Sand	Clayey silt
8.5	Silty Sand	Silty Sand	Sandy silt	Sand with silt	Silty Sand	Clayey silt	Silty Sand	Silty Sand	Sandy silt	Sand with silt	Silty Sand	Clayey silt	Sand with silt	Silty Sand	Silt
9.0	Sand with silt	Silty Sand	Clayey silt	Silty Sand	Silty Sand	Silt	Silty Sand	Silty Sand	Silt	Silty Sand	Silty Sand	Silt	Sand with silt	Silty Sand	Clayey silt
9.5	Sand with silt	Silty Sand	Clayey silt	Silty Sand	Silty clay to clays	Clayey silt	Sand with silt	Silty Sand	Clayey silt	Silty Sand	Silty Sand	Clayey silt	Sand with silt	Silty Sand	Silt
10.0	Sand with silt	Silty Sand	Silt	Silty Sand	Silty Sand to sandy silt	Silt	Silty Sand	Silty Sand	Silt	Sand with silt	Silty Sand	Clayey silt	Sand with silt	Silty Sand	Clayey silt

*Actual Soil classification based on ASTM D 2487
**Soil classification based on the *CPT* [23]
***Soil classification based on the *NDMT* [19]

- The *OCR* values from the Oedometer and the *CPT* are about 20% near the surface and decrease with depth. The high values near the surface are probably due to desiccation effects. However, the values remain more than 1.0 up to 10.0 m depth indicating that the deposit to 10 m depth as overconsolidated.
- The soil classification based on the *CPT* data indicates the soil deposit comprising silty sand to sandy silt from the ground surface to 10.0 m depth.
- The soil classification based on the *NDMT* data and using Marchetti and Crapps (1981) chart shows soil deposit up to about 3.0 m depth comprising mainly clay and silty clay. From about 3.0 m down to 10.0 m depth, the soil deposit is categorised as silt and clayey silt with sandy silt at places.
- A comparison of soil classification by different sources is presented in Table 3. It can be observed that the *NDMT* based classification compare well with actual in the top cohesive layer of about 3.0 m thickness. From 3.0 m down to 10.0 m depth, the *NDMT* data describe the silty sand and sand as silt or clayey silt due to lesser values of I_D. In overconsolidated soils, the I_D values decrease. As a result the data points on the Marchetti and Crapps (1981) chart are shifted towards left resulting in disagreement with the actual soil type. The possible reason for this disagreement is that all these soils (silty sand, sand, silt and clayey silt) have very narrow range of particle size distribution and the *NDMT* loading is unable to distinguish between them. Another reason for lesser values of I_D is the increase in yield pressure values which could be due to overconsolidated condition of the deposit.
- The disagreement of the *CPT* based classification with the actual is more pronounced in the top 2.0 to 3.0 m (CL and CL-ML layers) which is highly overconsolidated. Below this depth, classification from the *CPT* data compare reasonably well with the actual.
- The dissimilarity in the prediction of soil type from the *NDMT* or the *CPT* is probably not due to the limitation in the in-situ testing instruments or soil classification methodology. It indicates the mechanical response of soil which is the function of *OCR* and natural moisture content.

5. Conclusions

The actual soil classification has been compared with that from the *CPT* and the *NDMT* data. The following conclusions have been drawn from the comparison:

1. The mechanical response of soils during penetration tests is function of *OCR* and natural moisture content. It also depends on whether soil is containing any cementation or not.
2. The *NDMT* is unable to differentiate between fine sands and silt. Fine sands are usually mis-described as silts based on Marchetti classification system.
3. When soils are highly overconsolidated and dry, the *CPT* data interpretation may describe clays as silty sand to sandy silt.
4. The comparison between various soil classification methods presented in this paper is based on soil samples at the same level but from different locations. These locations, though kept close to each other, do not guarantee of exactly similar soils. A comparison of actual soil classification from different locations indicates horizontal as well as vertical variation of soil types.

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