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Medusa DMT in transient silts

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ABSTRACT: This paper provides some recent updates on the interpretation of the flat dilatometer test (DMT) in transient soils with the aim of developing alternative methods for predicting geotechnical parameters. Close evaluation for drainage conditions during membrane expansion is attained by observing the response of a complete dissipation test where the *A*-pressure versus time curve was continuously monitored until a minimum pressure was identified, before expanding the membrane. With this new approach, values of p_0 and p_1 can be calculated and used to estimate the properties of transient soils. This research uses the Medusa DMT, which is an innovative device that is capable to autonomously perform dilatometer tests, providing higher quality continuous measurements of the membrane expansion. Validation also requires interrelating data from dilatometer tests and piezocone penetration tests (CPTUs) in granular soils and, for that purpose, q_c/σ'_{v0} versus K_D correlations have been reassessed. The original ϕ' - K_D correlation for uncemented sands established by Marchetti [1] has been modified, and a new a ready-to-use correlation is proposed in which ϕ' is expressed as a function of K_D and the critical state friction angle.

Keywords: Medusa DMT; Flat Dilatometer; Automated Dilatometer; Friction angle; silts.

1. Introduction

Many soils have scattered grain size distribution, and variations in mineralogy and clay content. These features have a dominant effect on soil permeability, hence also on *in situ* behaviour at given loading rates, producing geomaterials in the so called intermediate permeability range of 10^{-5} to 10^{-8} m/s. For intermediate soils, the simplest idealized approach of a broad distinction between drained (gravels and sand) and undrained (clay) conditions for the interpretation of *in situ* tests cannot be applicable since test response can be affected by partial consolidation. The present paper addresses the possible effects of partial drainage in the interpretation of DMT data and introduces a method to derive the internal friction angle in granular materials.

1.1 The Flat Dilatometer (DMT)

The Flat Dilatometer (DMT) is an in situ geotechnical instrument developed in Italy in the late seventies [1]. Today it is used in all industrialized countries and the test is coded in international standards ASTM [2], ISO[3]) and building codes (Eurocode7 [4]). A dedicated monograph was written by the ISSMGE Technical Committee TC102 (former TC16) [5], describing in detail the instrumentation, the test procedure, the data reduction formulae and the main applications for which this test is commonly employed.

The dilatometer consists of a steel blade with a thin circular steel membrane mounted on one of its sides. The blade is connected to an electro-pneumatic cable, running through the penetration rods up to a control unit at surface. The control unit is equipped with pressure gauges, an audio-visual signal and valves for regulating pressure supplied by a gas tank. A computer is connected to the control unit with a USB cable, for the automatic logging of the test data. The dilatometer may be advanced into the ground using common field machines, like static penetrometers or drill rigs. The blade is pushed into the ground and penetration is stopped at each test depth. Initially, the membrane is flat against the surrounding plane behind it, due to the horizontal pressure of the soil. The operator opens the flow valve on the control unit to inflate gas down to the DMT's membrane at depth and to take the following readings:

A: the pressure required to start the expansion of the membrane (lift-off pressure)

B: the pressure required to expand the membrane center 1.1 mm horizontally against the soil.

The optional *C* reading may be taken by deflating the pressure with the slow vent valve, just after the *B*-reading (membrane closing pressure). The blade is then advanced to the next test depth, with an increment of typically 0.20 m. The field readings are then processed using calibration constants and well established formulae, for obtaining soil parameters commonly used in geotechnical design [5].

As indicated in the standards, the *A*-reading should be taken between 10-20 seconds after penetration has stopped. The *B*-reading should be taken between 10-20 seconds after the *A*-reading. In clay soil the test is fully undrained, because the excess pore pressure Δu caused by the blade penetration has no time to dissipate appreciably during test execution. In clean sand the test occurs in drained conditions, as there is no generation of Δu.

However, there are soils in which the coefficient of consolidation is such that partial dissipation occurs during the *A*-reading and continues during membrane expansion before obtaining the *B*-reading. The partial drainage effect influences the pressure values of each reading. Furthermore, the difference in the amount of partial drainage strongly decreases the homogeneity between the *A* and *B* readings. These two effects may cause ambiguous interpretation in parameters derived with the commonly used DMT reduction formulae [6]. Although, this inconvenience occurs only in a very narrow subset of silt soils ("niche silts"), several tailings and semiliquid silts appear to be part of this soil family, thus there is considerable interest in looking into possible improvements for testing these special soils. As a further uncertainty, the above mentioned acceptable time interval for the *A* and *B* readings introduces further variability, due to the amount of partial drainage related to the effective time for each reading. When performing DMT tests in the niche silts, clearly the missing control variable is time.

1.2 The Medusa DMT

The Medusa DMT is an enhanced dilatometer able to autonomously perform DMT tests [7,8]. An electronic board, powered by rechargeable batteries, activates a motorized syringe for hydraulically expanding the membrane. The blade has the same dimensions of the original standard dilatometer. The device may operate as cableless (MEMO mode), which is a practical option especially in offshore projects at large depths (> 100 m). It may also operate with a standard electric cable, similar to the CPT cable, to obtain real time results during test execution. Fig. 1 shows the main components of the Medusa DMT.

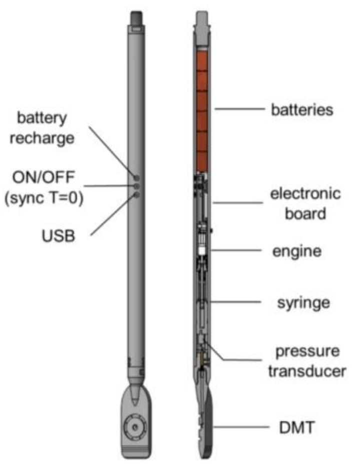


Figure 1. Main components of the Medusa DMT [7,8].

Validations with the traditional pneumatic DMT equipment have shown good agreement in several sand and clay soils. The repeatability of the Medusa DMT pressure readings is very high, due to the automated replication of membrane inflation and deflation. The incompressibility of the liquid used in the motorized syringe enables to set the timing for the *A* and *B* readings with considerable accuracy. In addition, the Medusa DMT may also be programmed to perform rapid consecutive *A*-readings to monitor, without membrane displacement, the total horizontal stress with time.

The *A*-reading may thus be obtained at any desired time after penetration has stopped, including at the origin (0 seconds), or it is also possible to record repeated DMT *A*-readings with time. On the other hand, the expansion to *B* requires the motorized syringe to inject a non-negligible amount of oil, which requires at least 4-5 seconds.

This paper presents the first research program conducted in Brazil at the Araquari experimental testing site using the Medusa DMT. In these tests the reading of *A* was performed continuously at each depth, waiting for the time required for excess pore pressure generated by the insertion of the blade to be fully dissipated, before proceeding to reading *B*.

2. Friction angle in sand

Two methods are currently used for estimating the internal friction angle (ϕ') of sands from DMT [9,10]. The first method provides simultaneous estimates of ϕ' and the in situ coefficient of lateral earth pressure (K_0) derived from the combination of the horizontal stress index K_D and penetration resistance q_D or q_c, being q_D the dilatometer penetration resistence and q_c the cone penetration resistence. The second method provides a lower bound estimate of ϕ' based only on K_D.

The first approach developed by Schmertmann [11,12] is iterative and allows for the assessment of both K_0 and ϕ'. The method expressed as a function of 2 variables (K_D and K_0) requires 2 equations for solving the mathematical system. In the first empirical equation, obtained from calibration chamber tests, K_D is expressed as a function of K_0 and ϕ'. The second equation was proposed by Durgunoglu and Mitchell [13] to estimate ϕ' as a function of q_c and K_0. To avoid the iterative process, Marchetti [9] introduced a graphical representation of the proposed solution. It requires first deriving K_0 from q_c and K_D and, on a subsequent stage, using the chart in Fig. 2 to estimate ϕ' from K_0 and q_c.

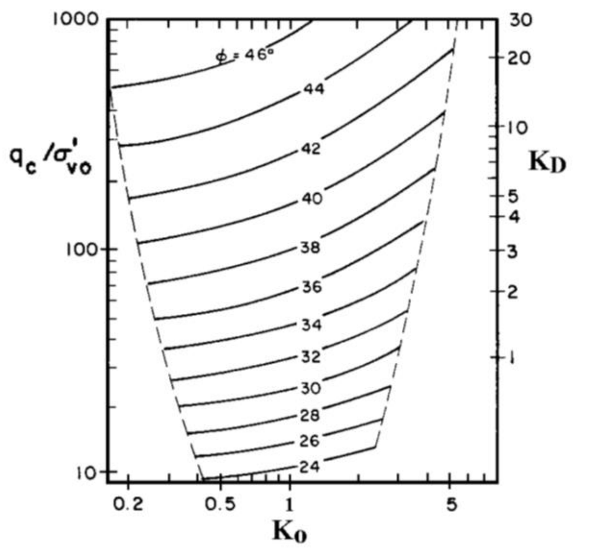


Figure 2. Chart q_c-K_0-ϕ' - graphical equivalent of Durgunoglu & Mitchell theory (worked out by Marchetti, [9]).

Alternatively, a simple direct method for assessment of the friction angle in sand was proposed by Marchetti [10] in which ϕ' is obtained directly from K_D, as outlined in Fig. 3. The approach was supported by a correlation proposed by Robertson and Campanella [14] where the ratio of cone tip resistence (q_c) and vertical in situ effective stress (σ'_{v0}) is expressed as a direct function of K_D (q_c/σ'_{v0} = 33.33K_D) indicated in the left vertical axis in Fig. 2). Several lines are outlined in Fig. 3: a top curv established from $K = K_{0,nc} = 1 - sen\phi'$ (dotted line), an intermediate condition for $K = 1$ (dashed line) and an 3rd from top curv for $K = \sqrt{K_p}$ (continuous line). After comparisons against predictions from other test results, the author adopted a conservative strategy for estimating ϕ' by establishing a new lower bound indicated by the thick line in Fig. 3 (the corresponding equation is also shown in the Fig. 3).

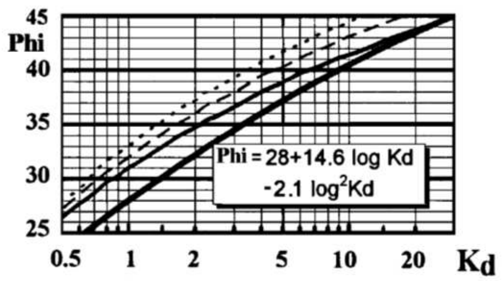


Figure 3. The ϕ' - K_D correlation derived from Fig. 2 [10].

The applicability of these methods for soils in which partial drainage prevails during the test (intermediate permeability silty soils) has been investigated in the present work from testing data gathered in different sites and soils.

3. Araquari experimental testing site

The Araquari Testing Site located in Southern Brazil was set primarily to study the behaviour of pile foundations. Comprehensive site investigation comprising SPT, CPTU, SDMT as well as laboratory testing revealed 12m of fine dense sand underlain by 12m of fine sandy-silty soils and clean dense sand to about 30m. Results are compared with data collected in other locations, which requires interrelating K_D from dilatometer tests and q_c/σ'_{v0} from piezocone penetration tests.

3.1. The q_c/σ'_{v0} versus K_D correlation in sand

The DMT correlation q_c/σ'_{v0} = 33.33K_D has been endorsed by modern DMT practice after the work from Campanella and Robertson [14] based on calibration chamber tests in Ticino sand and field test in McDonalds Farm sand. The database established from this early work has been extended by using additional data and work locations (Fig. 4). This figure summarizes the results from uncemented silica sand from (a) laboratory calibration chamber tests in Ticino sand and Hokksund sand and (b) field tests from Treporti and Balneário Camboriu sand. Clearly the q_c/σ'_{v0} versus K_D relationship is linear but yields a gradient of about 23, lower than the value of 33.33 established from previous studies.

Included in Fig. 4, sand iron tailings characterized by CPT and DMT tests produced very similar trends when compared to silica sand, also yielding a gradient of 23 for the q_c/σ'_{v0} versus K_D relationship.

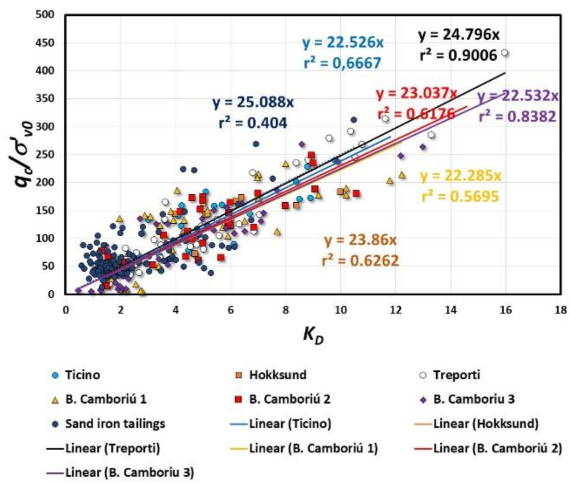


Figure 4. Relationship between K_D and normalized CPT tip resistance (q_c/σ'_{v0}) for different sands.

An independent assessment of the q_c/σ'_{v0} versus K_D coefficient is provided by the Araquari testing site results. The upper very dense, preconsolidated fine sand shown in Fig. 5 shows some scattered data with an average coefficient of about 15.6 (much lower than the accepted 33.3 value).

Data from the Araquari testing site measured at 12 to 19m depth are characteristic of silty-sand or sandy-silt soils. Results from a series of conventional DMT and Medusa DMT are summarized in Fig. 6. It should be noted that DMT tests were carried out according to ASTM D6635-15[2] without accounting for any drainage conditions taking place around the membrane. On the other hand, in the Medusa DMT the response of the complete *A*-pressure versus time dissipation curve was continuously monitored, until a minimum pressure was identified, before expanding the membrane. In this set of tests the q_c/σ'_{v0} versus K_D coefficient is 15.5 for the DMT and 11.8 for the Medusa DMT.

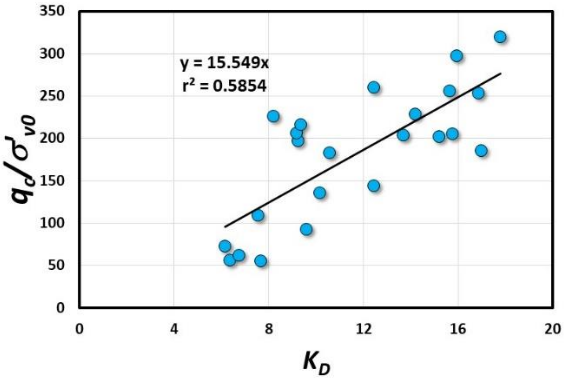


Figure 5. Relationship between K_D and normalized CPT tip resistance q_c/σ'_{v0} for the Araquari Testing Site (upper very dense sand layer from 2 to 7m depth).

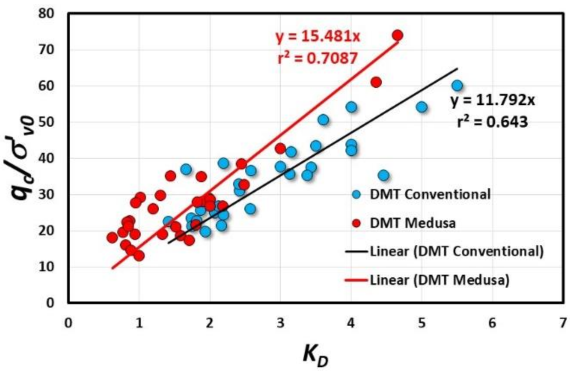


Figure 6. Relationship between K_D and normalized CPT tip resistance (q_c/σ'_{v0}) for the Araquari Testing Site (silty-sand and sandy-silt soils from 12 to 19m depth).

Based on the above database, it can be concluded that the q_c/σ'_{v0} versus K_D is not unique: for clean sands the coefficient is in the order of 23, and for silt sands it is even lower.

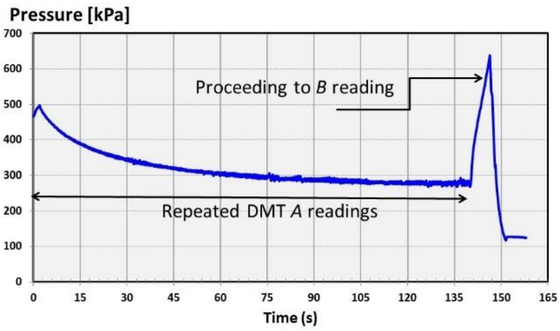
4. Results

The new methodology conceived to perform tests in transient soils was tested at Araquari. Focus is given to silty sand layers that have been identified between 12m and 19m depth.

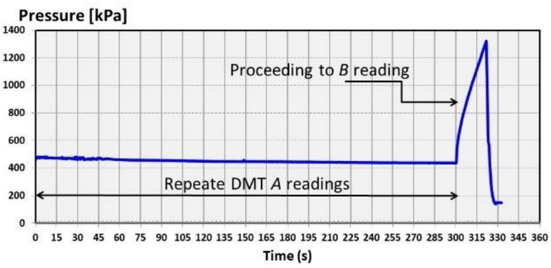
Typical results using the Medusa DMT are shown in Fig. 7, comparing data from sands (test carried out at 18.0m) and silty (test carried out at 15.8m). In this figure the repeated DMT *A*-reading is plotted against the elapsed testing time which is a form of dissipation test (e.g. [15,16]). In sand the DMT readings show very little variation indicating that the 15, 20 and 60s readings are all drained (Fig. 7b). On the other hand, in silts the DMT readings show considerable variation with time because the pore pressure is continuously dissipating during approximately 150s.

Even if partial drainage effects occurring during penetration are disregarded, any estimation of soil properties from standard DMT measurements would require accounting for pore pressure dissipation after halting the blade (Fig. 7a). After completion of pore pressure dissipation, at the minimum lift-off pressure *Af*, the membrane is inflated to measure the *B*-pressure at 1.1mm displacement.

Implications of allowing for full dissipation on DMT test data interpretation is clearly identified when inspecting DMT profiles. Fig. 8 shows the results of the corrected lift-off pressuer p_0 and the expansion pressure p_1 for the standard DMT and for the Medusa DMT. Since both p_0 and p_1 are total stress measurements, they are affected by the pore pressure regime taking place during penetration and membrane expansion and, consequently, the two tests yield different results, as indicated in the expanded plot on the right in Fig. 8 (from 11m to 21m depth**)**. The material index I_D changes considerably in the silty layer and corresponds to sand type after full dissipation.



a) Test in the 15.8m depth silty layer.



b) Test in the 18.0m depth sand layer.

Figura 7. Typical Medusa DMT tests.

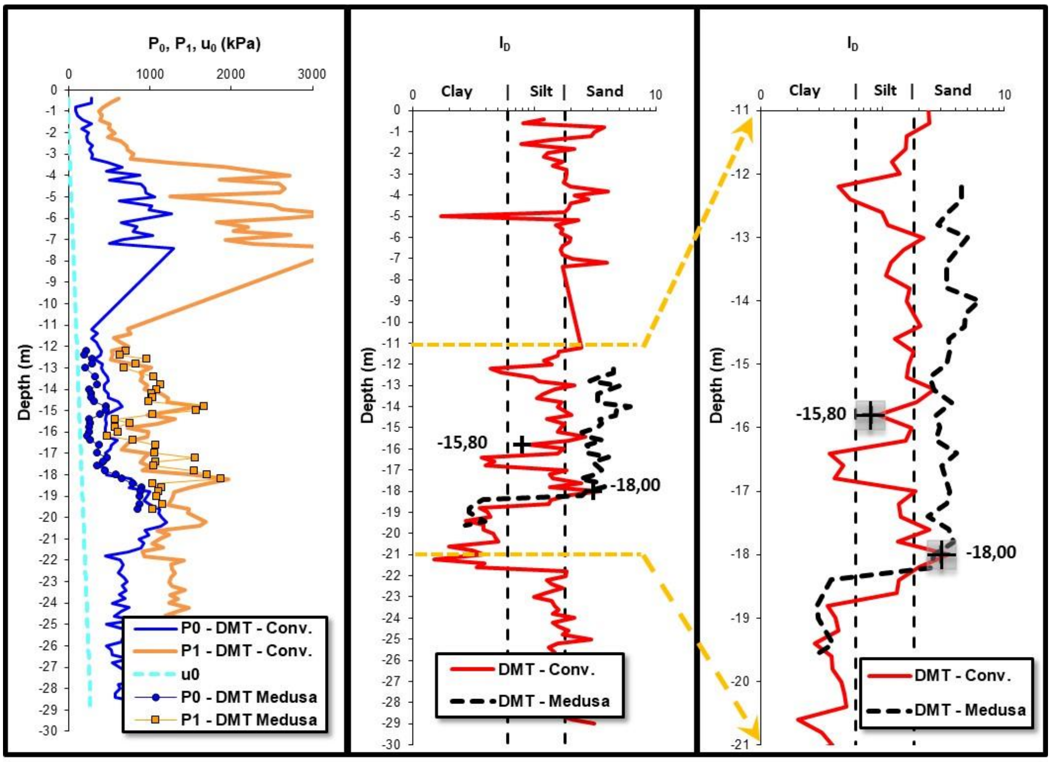


Figure 8 Typical soil profile for the Araquari testing site.

It is than assumed that, after full dissipation, A_f pressure has approached drained conditions (any excess pore pressure variation for expanding the membrane from p_0 to p_1 is disregarded) and as a consequence p_0 can be used to estimate the effective internal friction angle ϕ'. For that purpose, the original ϕ' - K_D correlation for uncemented sands established by Marchetti [10] has been modified, and a new correlation is proposed in which ϕ' is expressed as a function of K_D and the critical state friction angle ϕ'_{cv}:

$$\phi' = \phi'_{cv} + \alpha \cdot \log(K_D) \quad (1)$$

Validation of Eq. 1 to estimate ϕ' is made by comparisons with values estimated from piezocone tests using the correlation proposed in [14] and plotted in the q_c/σ'_{v0} versus *tan* ϕ' (Fig. 9). For the Araquari Testing Site the coefficient correlating q_c/σ'_{v0} and K_D was calibrated as 15 for the 11m to 21m soil layer depth. Taking the critical state friction angle measured in triaxial compression CIU and CID tests as 28^0 and assuming α as 14, values ϕ' can be calculated from DMT data (Eq. 1). The predicted DMT and CPTU friction angles ϕ' showed similar trends at Araquari. Although the predicted values are consistent with early published results, partial drainage is very likely to have occured during standard CPTU and DMT penetration which may introduce errors in the analysis of both tests.

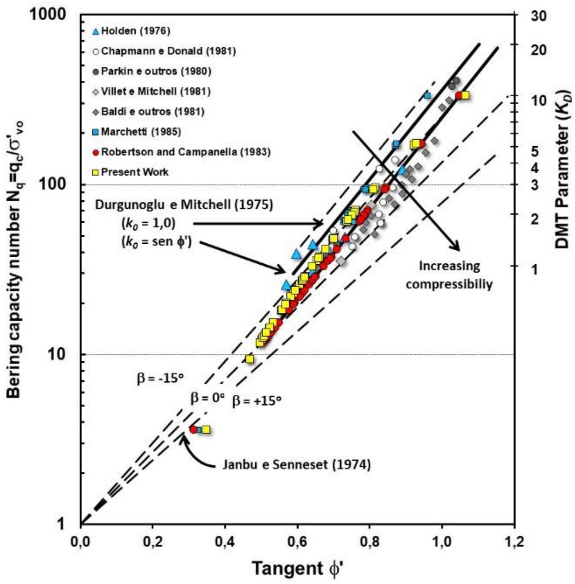


Figure 9. Standard DMT and Medusa DMT testing data.

5. Conclusion

The present paper discusses some recent updates on the interpretation of the flat dilatometer test (DMT) in transient soils, including a new correlation to estimate the effective internal friction angle ϕ'. The new equation modifies the original ϕ' - K_D correlation for uncemented sands, established by Marchetti [10], by expressing ϕ' as a function of K_D and the critical state friction angle ϕ'_{cv}.

The approach considers that drainage conditions during penetration and membrane expansion are fully drained, requiring a dissipation test where the *A*-

pressure versus time curve is continuously monitored until a minimum pressure is identified, before expanding the membrane. High quality data was gathered by using the Medusa DMT, which is an innovative device that is capable to autonomously perform dilatometer tests, providing accurate continuous measurements of the membrane expansion. Validation of the proposed approach was provided from tests carried out at the Araquari Testing Site in Brazil.

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