The effects of test procedure on DMT results in intermediate soils

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<td>Schnaid, F.; Federal University of Rio Grande do Sul, Civil Eng. Dep. Odebrecht, E.; UDESC, DEC; Geoforma Engenharia Ltda, Sosnoski, Jonatas; UFRGS –Universidade Federal do Rio Grande do Sul, Civil Engineering Robertson, Peter; Gregg Drilling &amp; Testing Inc.</td>
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The effects of test procedure on DMT results in intermediate soils

Schnaid, F., Odebrecht, E., Sosnoski, J. and Robertson, P.K.

Abstract
The evaluation of rate effects on the flat dilatometer test (DMT) can best be developed with some knowledge of the excess pore pressures generated during penetration, dissipation and subsequent membrane expansion. While research that include pore pressure measurements in the DMT have documented drainage conditions in clean sand and soft clay, further studies are required to determine the drainage conditions during the DMT in intermediate permeability soils, such as silts. For that purpose, a simple and inexpensive research device has been developed for monitoring pore pressures at the center of the DMT blade. Data using both a standard DMT and the modified research DMT from various tests in sand, silt and clay have been compared in a space that correlates dimensionless velocity to degree of drainage. In this space it is possible to evaluate whether partial drainage is taking place. Measurements indicate that the DMT is essentially undrained in soft clay and dominated by penetration pore pressures, is drained in clean sand and is partially drained in intermediate permeability soils, such as silt. A method is suggested to identify soils where partial drainage may influence the standard DMT results.

Keywords: DMT, rate effects, pore pressures, intermediate permeability soils, partial drainage

Introduction
The flat dilatometer test (DMT) was developed in Italy by Professor Marchetti in the 1980’s and has become popular in many parts of the world, since it is simple, robust, repeatable and economical. The flat dilatometer is a 95mm wide stainless steel blade that is 15mm thick with a 60mm diameter circular steel membrane mounted flush on one side. The test involves two readings $A$ and $B$ that are corrected for membrane stiffness, gage zero offset and feeler pin elevation in order to determine the pressures $p_0$ and $p_1$, respectively. Readings are taken every 200 mm during a pause in the penetration and the corrected pressures $p_0$ and $p_1$ are subsequently used for interpretation. The original correlations were obtained by calibrating DMT results with high quality soil parameters from several test sites in Europe (Marchetti 1980). Many of these correlations form the basis of current interpretation, having been generally confirmed by subsequent research and experience.

The interpretation evolved by first identifying three "intermediate" DMT parameters (Marchetti 1980):

Material index, $I_D = (p_1 - p_0) / (p_0 - u_0)$ (1)
Horizontal stress index, \( K_D = \frac{(p_0 - u_0)}{\sigma'_{vo}} \) \tag{2}

Dilatometer modulus, \( E_D = 34.7 (p_1 - p_0) \) \tag{3}

The key DMT design parameters are \( I_D \) and \( K_D \) and both are normalized and dimensionless. \( E_D \) can be derived from the other two. \( I_D \) is the difference between the corrected lift-off pressure \( (p_0) \) and the corrected deflection pressure \( (p_1) \) normalized by the lift-off pressure corrected for the equilibrium pore pressure \( (p_0 - u_0) \). \( K_D \) is the effective lift-off pressure normalized by the in-situ vertical effective stress. Marchetti (2001) recommended that the DMT expansion rate should be such that the test is completed in about 1 min after the stop in penetration with the A reading measured within about 15 s and the B reading after an additional 15 s. Marchetti (2001) also suggested that an optional C reading (“\( p_2 \) closing pressure”) can be taken during a slow deflation of the membrane and that this \( p_2 \) closing pressure is an approximate measure of the pore pressure on the membrane.

Previous research (e.g. Campanella and Robertson 1991) has shown that in most clay soils the DMT is essentially performed under undrained conditions and in clean sands the test is essentially performed under drained conditions. Experience has also shown that in most clays and sands current DMT interpretation methods produce reasonably accurate and realistic predictions of most geotechnical parameters, but the DMT has not been systematically evaluated for drainage conditions in intermediate soils, such as silt. In silts the degree of drainage may be a crucial factor in interpreting DMT data. However, assessment of drainage conditions from in situ tests generally requires pore pressures to be measured, which is not a standard practice in the DMT.

There have been some published results showing pore pressure measurements during the DMT and these have tended to be in either soft clay or clean sand (Robertson et al. 1988; Lutenegger 1988; Campanella and Robertson 1991). The experience accumulated in the late 1980s was recently extended to include varved clay (Benoit & Stetson 2003) and efforts have also been made to improvement the equipment (Akbar & Clarke 2001; Lui et al. 2013; Stetson et al. 2003). A fully instrumented DMT with automatic data acquisition system would, in principle, enhance the understanding of standard procedures and interpretation methods. However, a fully instrumented DMT complicates both the equipment and test procedure and would significantly reduce the simplicity and robustness of the test and equipment, both of which are major advantages of the basic DMT.

Both \( p_0 \) and \( p_1 \) are total stress measurements and are affected by both penetration and possible pore pressure dissipation taking place before and during membrane expansion. The penetration rate is usually 20 mm/s, similar to the cone penetration test (CPT), but rates from 10 to 30 mm/s are also acceptable (Marchetti 2015). This recommendation may hold for the drained conditions observed in clean sand or the undrained conditions observed in most soft clay, but may induce errors due to partial drainage in some intermediate soils (e.g. silts). In the permeability range of most silts the coefficient of
consolidation may be sufficiently high so that penetration at the standard rate may not be sufficient to ensure fully undrained or completely drained soil response and therefore pore pressure dissipation is observed during penetration as well as before and during DMT membrane expansion. The objective of this paper is to evaluate rate effects during the DMT based on pore pressure measurements with a focus on identifying the range of soils where partial drainage may influence DMT results. A series of field tests have been carried out in different soils, ranging from sand to clay, as well as a silt-sand tailings, using both a standard DMT and modified pore pressure instrumented DMT blade developed to record pore pressures.

**Pore pressure instrumented flat dilatometer**

Campanella & Robertson (1991) attached a pore pressure sensor and a small porous element to the DMT membrane to measure the pore pressures generated during penetration and membrane expansion. Given the fragility of the expandable membrane, alternate devices have been constructed with different pore pressure systems. Akbar & Clarke (2001) replaced the flexible membrane with a rigid piston and placed a porous element and differential pressure transducer at the center of the piston. Recently developed devices have recorded pore pressure using transducers mounted nearby the membrane, allowing for easier fabrication requirements but lacking somewhat in precision by not measuring pressures at the center of the membrane or blade (Benoit & Steton 2003; Steton et al. 2003; Lui et al. 201; Shen et al. 2015).

The instrumented flat dilatometer used in this study allowed pore pressures to be recorded at the center of the blade during penetration and with time during any dissipation from the end of penetration. The instrumented device used a modified Marchetti flat dilatometer blade where the circular steel membrane was replaced by a fixed porous element connected to a pressure transducer, as shown in Figure 1. The 38mm diameter and 2mm thick porous filter was made of sintered bronze with an average pore size of about 10 µm. The cavity between the porous filter and the pore pressure sensor (placed immediately behind the filter) is small and was fluid-filled. Saturation of the filter element and cavity was accomplished using a silicone oil bath under vacuum for a period of 24h (as illustrated in Figure 1c). The pressure transducer is connected to an electrical system using hardware and software specially adapted for this study. International reference test procedures for the calibration of pore pressure sensors adopted for cone penetration tests with pore pressure (CPTu – piezocone, IRTP, 1989) were followed for the saturation of the modified DMT blade.

Since the membrane has been replaced by a porous element, the DMT A and B pressures are recorded separately using a standard DMT carried out adjacent to the modified DMT, but pore pressure variation during membrane expansion is not measured. With this set up a complete set of results can only be attained by pushing two probes (standard DMT and the instrumented pore pressure blade) side
by side, about 1m apart, allowing a ‘DMTu’ profile to be obtained. Tests are reported here for clay, sand and tailings.

**Test Sites**

Tests reported here have been carried out at three different locations in Brazil: the Tubarão clay site, the Araquari sand pile site and the *Fazenda Brasileiro* tailing dam. The site locations are shown in Figure 2. CPTu (piezocone tests) were also performed close to the DMTu’s for comparison and additional evaluation of geotechnical conditions.

Figure 1. Pore pressure instrumented DMT a) instrumented blade compared to a standard Marchetti blade, b) details of instrumented blade and (c) saturation of pore pressure element

Figure 2. Location of testing sites is Brazil

**Tubarão clay site**

A comprehensive site investigation was carried out in a clay deposit at the Tubarão experimental test site in southern Brazil that comprised; seismic DMT (SDMT), CPTu, field vane shear tests (FVT) and standard penetration tests (SPT) to identify soil type and stratigraphy (e.g. Mantaras et al. 2014). Sediments in the upper 20m are predominantly normally consolidated, formed during the last 8,000 years in the Holocene period after the most recent glaciation (Schnaid 2015 and Odebrecht). Typical CPTu and DMT profiles, showing: corrected CPT cone resistance, $q_t$, and pore pressure, $u_2$, DMT $p_0$, $p_1$, $I_d$, $E_D$, $K_D$ and penetration pore pressures (CPTu and DMT), are presented in Figure 3. The CPTu pore pressures were measured behind the cone in the $u_2$ location and the DMT pore pressures ($u$) were measured using the modified instrumented DMT blade. Figure 3 shows that the soils below a depth of about 6m are soft, essentially normally to lightly overconsolidated clay. The clay below a depth of 6m has an average plasticity index (PI) of 55%. The water table at the site is about 0.6m below ground level and the piezometric profile is approximately hydrostatic. The DMT pore pressure ($u$) acting on the blade during penetration are high and comparable (but slightly lower) to those measured behind the cone tip in the CPTu.

Figure 3. Typical soil profile at the Tubarão clay site showing main CPTu and DMT results

**Araquari sand site**
Site characterization of the Araquari Site, located in southern Brazil, began in 2014 and supported by ISSMGE was carried out primarily to study the behaviour of pile foundations. Araquari is part of sedimentary deposits formed along the coastline of Brazil mainly as a product of the general eustatic sea level variations over the last 1 million years, during the Quaternary Period. Sediments from the upper 20m layers were predominantly from transgression integrated bay-lagoon sedimentary systems formed behind a transgressive barrier during the last 8,000 years in the Holocene maximum flooding (Angulo et al. 2006; Giannini et al. 2007). The site investigation comprised SPT, CPTu, SDMT as well as some laboratory testing. Details of the site investigation can be found at http://www.ufrgs.br/araquari-ets/. Typical CPTu and DMT profiles, showing: CPT q_t and u_2; DMT p_0, p_1, I_D, E_D, K_D and penetration pore pressures (CPTu and DMT), are presented in Figure 4. The pushing equipment available was unable to push the standard DMT through the upper dense sand between depths of about 4 to 11m due to a buildup of resistance during the pause to perform the standard DMT measurements (A and B), hence there is no standard DMT data in that depth range shown in Figure 4. However, the pushing equipment was able to push the modified DMT blade since there were few pauses in penetration.

The soil conditions at the Araquari site are mostly composed of sandy soils with about 11m of dense fine sand overlaying about 3m of clayey fine sand (PI = 6%, fines content, FC < 32%) then about 4m of silty fine sand (non-plastic NP, FC < 20%), 4m of soft sandy clay (PI ~17% and FC ~70%), over silty sand and sand to about 30m (NP, FC < 10%). The water table at the site is about 2m below ground level and the piezometric profile is approximately hydrostatic. The CPTu and DMTu penetration pore pressures are approximately hydrostatic in the upper 11m of sand indicating predominantly drained penetration and the DMT p_0 and p_1 readings correspond to a fully drained test, similar to that observed by Campanella &and Robertson (1991) for clean sand. Below 11m, some pore pressures are generated during CPT (and DMT) penetration that is common in some silty sands. As discussed later, these pore pressures dissipate very quickly after halting penetration and the DMT p_0 and p_1 readings are essentially drained and the p_2 closing pressure corresponds to hydrostatic conditions, similar to that observed by Campanella &and Robertson (1991) for clean sand.

Figure 4. Typical profile at the Araquari sand site showing main CPTu and DMT results.

Fazenda Brasileira tailings site
SDMTu and CPTu tests were carried out at the *Fazenda Brasileira* tailings disposal site in Bahia State, northeast Brazil. The tailings were derived from mining operations for gold. Since 2005, the site has been used for research by the Federal University of Rio Grande do Sul (e.g. Bedin et al. 2012; Schnaid et al. 2013).

Typical CPTu and DMT profiles, showing: CPT \( q_t \) and \( u_2 \); DMT \( p_0, p_1, I_D, E_D, K_D \) and penetration pore pressures (CPTu and DMTu), are presented in Figure 5. The site is composed of young hydraulically placed interlayered silt and sand tailings. The water table at the test location is about 2.5m below ground level and the piezometric profile is approximately hydrostatic. Figure 5 shows that the penetration pore pressures in both the CPTu and DMTu are high in the fine-grained tailings with large excess pore pressures greater than hydrostatic. The penetration pore pressures measured using the modified DMT blade are generally almost the same as those measured during the CPTu, similar to the observations made by others in soft fine grained soils. Campanella & Robertson (1991) noted that they are closer to CPTU \( u_3 \) position pore pressures (i.e. behind the friction sleeve). Also included in Figure 5 are the \( p_2 \) closing pressure values that are significantly smaller than the penetration pore pressures (either CPT or DMT) and are closer to hydrostatic values \( (u_o) \) below a depth of about 5m, indicating an almost drained conditions after about 60s in the DMT.

Figure 5. Typical profile at the *Fazenda Brasileira* tailings site showing main CPTu and DMT results

**Standard testing rate**

This section describes CPTu and DMTu carried out at the standard penetration rate of 20mm/s, followed by DMT pressure readings within the recommended 1min time interval.

Figure 6 show results of pore pressure dissipation tests at selected depths from the Tubarão clay site for both the CPTu and the modified DMT. The time for 50% dissipation \( (t_{50}) \) from the CPTu tests was between 150 to 1000s. Robertson (2012) had suggested that when CPTu \( t_{50} \) values were greater than about 30s, the CPT penetration was likely undrained (based on 1000 mm² cone at 20mm/s penetration rate). DeJong and Randolph (2012) had suggested a slightly larger value of \( t_{50} \) greater than 50s to ensure undrained CPT penetration. The results in Figure 6 indicate that both CPT and DMT penetration at the Tubarão clay site are predominately undrained. The dissipation data in the DMT show a predominately monotonic response over time, whereas the CPTu dissipation data show a slight dilatant response were the pore pressures rise slightly before dissipating over time. This is a common feature observed in soft clays along the Brazilian coast and also at the Tubarão testing site, despite the fact that Tubarão is a normally consolidated deposit as demonstrated by the paleoenvironmental reconstruction of the lagoon system combined with carbon and nitrogen measurements from peat, wood and organic matters retrieved from the ground.
During the 1min interval required for the standard DMT test, pore pressure measurements from the modified DMT blade (without expansion of the membrane) exhibit minimal dissipation, supporting the general assumption that in soft clay the CPT and DMT are predominantly undrained. These results support early findings (e.g. Campanella & Robertson 1991) indicating that in soft clay the measured DMT total stresses $p_0$ and $p_1$ are strongly controlled by the high penetration pore pressures.

Figure 6. CPT and DMT pore pressure dissipation tests in at the Tubarão clay site
In clean sand (e.g. upper sand at the Araquari site) no excess penetration pore pressures are generated and the CPT and DMT are essentially drained. In the silty fine sand layers of the Araquari site the CPT and DMT penetration generates some excess pore pressure that dissipates rapidly ($t_{50} < 5s$) after halting penetration, as illustrated in Figure 7, and DMT readings at about 15s, 30s and 60s correspond to essentially drained conditions.

Figure 7. Pore pressure during DMT dissipation tests in silty fine sand at the Araquari site.
A CPTu was carried out at the Fazenda Brasileira tailings site where pore pressure dissipation tests were carried out every 200mm between depths of 2.5 to 9m (additional details are given later). The $t_{50}$ values varied from 5s to 150s. Based on the criteria suggested by Robertson (2012) the CPTu penetration was changing from undrained to partially drained. Typical DMT dissipation test results in the silty tailings at the Fazenda Brasileira are presented in Figure 8. Included in Figure 8 are repeated DMT $A$-readings with time, as suggested by Marchetti and Totani (1989) as a form of dissipation test. Figure 8 shows similarity between the pore pressure dissipation using the modified blade (u) and the repeated $A$-readings and that there is significant pore pressure dissipation within the 1min time period recommended to take the standard DMT readings. DMT readings taken at 15s, 30s and 60s would all be partially drained and would change with time due to the dissipation of the excess pore pressures around the blade. In the silt tailing at the Fazenda Brasileira site, the recommendation of taking the $A$-reading in about 15 s is inadequate to ensure undrained conditions. Even if the partial drainage effects occurring during penetration are disregarded, any estimate of undrained shear strength, $s_u$ from standard DMT measurements would require taking the $A$-reading in about 2 to 3s after halting the probe in order to ensure approximately undrained conditions, but this rate of DMT expansion is not feasible. An alternative approach would be to slow-down the test to allow 100% pore pressure dissipation, but this would conflict with ISSMGE TC16 (2001) recommended test procedure, and would introduce further uncertainty in the interpretation.

Figure 8. DMT pore pressure and repeated $A$-reading dissipation tests in Fazenda Brasileira tailings
Figure 9 presents a summary of the above DMT pore pressure dissipation tests at the three test sites in terms of normalized pore pressure dissipation $U$, in percentage, defined as:

$$U\% = \left( \frac{u_i - u_0}{u_{\text{max}} - u_0} \right) 100$$  \hspace{1cm} (4)

where $u_{\text{max}}$ is the maximum penetration pore pressure generated at the testing depth; $u_i$ the pore pressure at any time after stopping penetration (e.g. 15 seconds for $A$ reading and 30 seconds for $B$ reading and about 60 seconds for an optional $C$ reading) and $u_0$ is the hydrostatic pore pressure at the testing depth. As seen in Figure 9, within the 60s required for the DMT readings the test is essentially undrained in soft clay (Tubarão), drained in sand (Araquari) and partially drained in silt (Fazenda Brasileira silt tailings). A challenge for the standard DMT is how to produce a unified interpretation criterion that allows drainage conditions to be identified or (even better) to be controlled.

Figure 9. Summary of typical normalized DMT pore pressure dissipation at the test sites.

**Rate effects**

Rate effects in the DMT are related to both penetration and membrane inflation rates (unlike CPT measurements that reflect penetration rate only). To further evaluate rate effects in the DMT, a series of tests were carried out at the Fazenda Brasileiro tailings site under a number of different procedures:

a) Standard tests: 20mm/s penetration rate, $A$ reading at 15s, $B$ reading at 30s and $C$ reading at 60s after halting the blade;

b) Tests at faster and slower penetration rates (relative to the standard 20mm/s);

c) Variable tests: different procedures and different time intervals after halting the blade at a given depth.

In summary this set of tests has three variables, corresponding to penetration rate, membrane inflation rate and time delay before membrane. The membrane expansion is displacement controlled and the inflation rate is defined by the rate of gas flow to pressurize the membrane (typically 15s for $A$-readings and a further 15s for $B$-readings) and to ensure that the pressure gauge at the surface is reading the correct pressure in the membrane. The recommended procedure for standard DMT is for minimum time delay (1 to 2s) between stopping penetration and starting membrane inflation.
Figure 10 summarizes the test profiles of 3 tests at the *Fazenda Brasileira* tailings site with different rates in terms of $p_0$ and $p_1$ pressure measurements and intermediate parameters $I_D$, $E_D$ and $K_D$. Two profiles were carried out at penetration rates of either 20 or 58mm/s with standard membrane inflation rates ($A$ and $B$-readings recorded in about 15s and 30s, respectively). One profile was carried out at variable penetration and inflation rates (labeled ‘variable’) and a summary of the rates are included in Figure 10. Tests carried out at penetration rates of 20mm/s and 58mm/s and standard inflation rate, show generally similar results indicating that an increase in penetration rate by a factor of close to 2 had little influence on the measured readings. Reducing the penetration rate by a factor of about 100 to 0.17mm/s reduced considerable the measured $p_0$ and $p_1$ values and reduced the resulting values of $E_D$ and $K_D$ and increased $I_D$ (see variable tests from 4.2m and 5.0m). Increasing the delay time before inflating the membrane by a factor of about 10, to a time of 240s before reading $A$ and 300s to reading $B$, (see variable tests from 3.2 to 4.0m) induced some consolidation that resulted in reduced values of measured $p_0$ and $p_1$ as well as smaller values of $K_D$ but increased values of $I_D$.

Increasing the delay time before inflating the membrane by only 40s (variable tests from 2.2 to 3.0m and from 5.2 to 10.0m) to perform 5 repeated $A$ readings (every 8s) also induced some consolidation that resulted in reduced values of $p_0$ and $p_1$ as well as $K_D$, but less noticeable changes in $I_D$ and $E_D$.

Figure 10. DMT results at the *Fazenda Brasileira* tailings site performed at different rates

Previous research has shown that drainage conditions during penetration testing (e.g. CPT) can be identified by accounting for probe size, penetration rate and soil consolidation characteristics (e.g. Randolph and Hope 2004; Schnaid 2005; Lunne et al. 2014). Normalization of penetration results can be represented by an analytical backbone curve of either penetration resistance or penetration pore pressures against normalized penetration velocity $V_h$ defined as follows:

$$V_h = \frac{v d}{c_h},$$  \hspace{1cm} (5)

where $v$ is the penetrometer velocity, $d$ is the probe diameter/thickness and $c_h$ is the horizontal coefficient of consolidation (in this case an operational value obtained from CPTu dissipation tests). These concepts are adopted here by plotting penetration pore pressure, dissipation pore pressure and DMT soil type $I_D$ versus normalized velocity, $V_h$.

Based on frequent CPTu dissipation tests (every 200mm), a profile of $c_h$ values with depth is shown in Figure 11 from the *Fazenda Brasileira* tailings site. The $c_h$ values were obtained using the Teh and
Houlsby (1991) method based on a soil rigidity index (I_R) of 300 (blue line) as well as values corrected based on the method proposed by DeJong and Randolph (2011) that accounts for the effects of partial drainage (red line). Corrected and uncorrected c_h values indicate that the CPT penetration between a depth of 3.2 to 4.8m is undrained, whereas the CPT penetration below 5m is mainly partially drained (where t_{50} < 30s).

Figure 11. Profile of coefficient of consolidation in the horizontal direction (c_h) based on CPTu dissipation tests at the Fazenda Brasileira tailings site (blue line based on Teh and Houlsby 1991; red line based on DeJong and Randolph 2011)

Penetration pore pressure data generated from the modified DMT presented early in Figure 10 are somewhat scattered and require some processing prior to the examination of general trends. In the present analysis measurements are averaged over 100mm intervals with data spikes due to localized variable soil conditions removed. Figure 12 shows the DMTu penetration pore pressure data using the modified DMT at the Fazenda Brasileira tailings site plotted in V_h versus U space, where U is the percentage pore pressure that correlates measurements recorded during probe penetration to maximum and minimum values (eq. 4). Despite the scatter, it is possible to identify a region characterized by normalized velocities V_h in the range of about 5 to 100 where partial drainage appears to occur during DMT penetration. The c_h values used to generate the data points in Figure 12 were those shown in Figure 11 from the adjacent CPTu dissipation tests. The U values in Figure 12 were derived by taking (u_{max} – u_o) values from the DMT measured excess pore pressures and u_{max} from tests carried out at 58mm/s.

In addition, the V_h versus U space was also adopted to interpret drainage effects during pore pressure dissipation, after stopping penetration, corresponding to the time required for p_0 and p_1 readings. However, in this space, u_{max} is the maximum pore pressure generated during penetration and u_i is the pore pressure at either 15s (u_{15}) or 30s (u_{30}) during dissipation. Figure 13 shows the normalized dissipation pore pressure (U) versus normalized velocity (V_h) using the modified DMT at all three test sites, as well as previous published data. Figure 13 shows that drained response is attained in less than 30s for V_h less than about 8. Partial drainage is characterized by an intermediate region where the rate of consolidation is relatively fast producing considerable scatter in pore pressure measurements, until the onset of undrained response for V_h greater than about 100. Published data from the McDonalds
Farm clay (Campanella & Robertson (1991) and the Zelazny Most Dam sand tailings (Tschuschke 2014) are shown for comparison and support the observed dissipation patterns from the three sites in this study.

Discussion

Marchetti (2001) had suggested that in most “genuinely normally consolidated soils (no aging, structure, cementation) the value of $K_D$ is close to 2.0”. This appears to apply to the DMT data collected at both the Tubarao clay site and the Araquari sand site, but does not apply to the tailings, where the $K_D$ values are less than 2.0 below a depth of 2m and significantly less than 2.0 below a depth of 5m. $K_D$ values less than 2.0 result in estimated values of over-consolidation ratio ($OCR$) less than 1.0. These very low values of $K_D (< 2)$ can sometimes be an indication of partial drainage effects during the standard DMT tests. However, observed $K_D$ values less than 2 may not be sufficient on their own to warn of possible partial drainage issues.

Marchetti and Totani (1989) had suggested that in certain soils an equivalent DMT dissipation test can be carried out by repeating the $A$ readings over time (with no $B$ reading). Example DMT dissipations tests using the repeated $A$ reading method are shown in Figure 8 from the Fazenda Brasileira tailings site at depths of 6 and 9m. Figure 8 shows that in the silt tailings the dissipation is rapid and only 5 readings were obtained between 10s and 60s after stopping blade penetration. The resulting ‘dissipation test’ is somewhat crude (readings every 5s) compared to the actual DMT pore pressure measurements (readings every 1s) but does indicate considerable changes in the $A$ readings with time that suggest rapid pore pressure dissipation. However, as noted by Marchetti (2001) DMT dissipations tests (i.e. repeated $A$ readings) “can be time consuming and are generally performed only when information on flow properties is especially valuable”.

Marchetti (2015) suggested that in ‘niche’ silts where partial dissipation during the DMT may be an issue, the $B$ reading maybe too low compared to the $A$ reading resulting in very low values of $I_D$ ($I_D = 0.1$ to 0.2) and that these very low values of $I_D$ maybe a ‘signature’ feature to identify these niche silts. Unfortunately, the standard DMT results at the Fazenda Brasileira tailings site do not show this ‘signature’ since $I_D$ values are mostly larger than 0.2 (see Figure 5), even though rapid dissipation occurs within the 30s required to obtain the DMT readings (see Figure 8). Marchetti (2015) also suggested that in niche silts the measured values of $K_D$ maybe acceptable. However, the DMT data from the Fazenda Brasileira tailings site suggest that the $K_D$ values are not acceptable (too low with $K_D < 2.0$) due to the significant dissipation that occurs within the first 15s after stopping penetration (see Figure 8). The low $K_D$ values produce values of engineering parameters such as $OCR$ and “undrained” shear strength ($s_u$) that are also too low. The consequences of disregarding partial
drainage effects are illustrated in Figure 14, in which the calculated $s_u$ values, based on the original correlation proposed by Marchetti (1980), are plotted against depth for the Fazenda Brasileira tailings site. Figure 14 also includes a profile of $s_u$ values estimated from the nearby CPT using a cone factor $N_{kt} = 15$ for comparison and shows that the DMT values are significantly smaller than those estimated from the CPT. The soil response induced by either the CPT or the DMT may not represent predominately undrained conditions in intermediate soil types. When partial drainage occurs the undrained strength calculated from the CPT can overestimate the true undrained shear strength value whereas the DMT can underestimate the true undrained value.

Figure 15 shows the normalized velocity $V_h$ plotted with the corresponding DMT soil behaviour type $I_D$ to evaluate if drainage conditions can be inferred directly from $I_D$. Although there appears to be a general trend of increasing $V_h$ with decreasing $I_D$, the scatter in results is considerable. In the range where partial drainage may influence the DMT results ($-8 < V_h < 100$), the range in measured $I_D$ is considerable. The variable rate tests performed at the Fazenda Brasileira tailings site show that the $I_D$ values are influenced by possible partial drainage and become a less reliable indicator of soil behavior.

Figure 12. Normalized penetration pore pressure ($U$) versus normalized velocity ($V_h$) using the modified DMT at the Fazenda Brasileira tailings site

Figure 13. Normalized dissipation pore pressure ($U$) versus normalized velocity ($V_h$) using the modified DMT at all three test sites as well as previous published data

Figure 14. Variation of calculated “undrained” shear strength ($s_u$) with depth at the Fazenda Brasileira tailings site based on standard DMT and CPT interpretation (disregarding partial drainage)

Figure 15. Soil behaviour type, inferred from DMT $I_D$ values, versus normalized velocity $V_h$

To identify if partial drainage is influencing the DMT results may require several steps. Based on the results from this study one indicator of possible partial drainage during the DMT, at least in young,
uncemented essentially normally consolidated soils, are $K_D$ values less than 2.0. Unfortunately, very low $K_D$ values can also be the result of other features (e.g. low horizontal stresses, incorrect soil unit weights, etc.). Marchetti (2001) suggested that in soils where partial drainage may be of concern, repeated $A$ readings can be performed to estimate the rate of change of readings with time, however, this can be time consuming. An alternate approach is to carry out adjacent CPT (or CPTu) and compare the DMT and CPT results for consistency. Marchetti (2015) has suggested that companion CPT and DMT can provide valuable in-sight into soil behavior and improve test interpretation and suggested that the ratio of $M_{DMT}/q_t$ (where $M_{DMT}$ is the 1-D constrained modulus calculated from the DMT) maybe a useful parameter to compare the two tests. Marchetti (2015) suggested that $M_{DMT}/q_t = 5$ to 10 in most normally consolidated uncemented sands and $M_{DMT}/q_t = 12$ to 24 in most over consolidated uncemented sands. For the companion standard DMT and CPT at the Fazenda Brasileira tailings site the ratio $M_{DMT}/q_t$ was less than 1 and in places $M_{DMT}/q_t < 0.1$, below a depth of 5m where partial drainage effects are the most prominent. These very low values of $M_{DMT}/q_t$ would appear to be a helpful indicator of unusual response that should encourage further investigation (e.g. repeated $A$ readings, etc.).

Conclusions

The intent of this study was to assess the influence of rate effects and partial drainage from the flat dilatometer test (DMT) using pore pressure measurements. The influence of rate effects on penetration and dissipation pore pressures was studied by using a modified dilatometer blade with a porous element at the center of the blade. DMT data from various tests in sand, silt and clay have been compared in a space that correlates dimensionless velocity to degree of drainage. In this space it is possible to evaluate whether partial drainage is taking place. Measurements indicate that the DMT is essentially undrained in soft clay and dominated by penetration pore pressures, is drained in clean sand and can be partially drained in intermediate permeability silty soils. The potential for partial drainage in some silts can influence the subsequent interpretation that can result in incorrect interpretation of geotechnical parameters. Very low $K_D$ values ($K_D < 2.0$) maybe an indicator of possible partial drainage effects, but may be limited to only young, uncemented essentially normally consolidated soils. An alternate approach is to perform adjacent CPT (or CPTu) and compare the DMT and CPT results for consistency.

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References


Figure Captions

Figure 1. Pore pressure instrumented DMT a) instrumented blade compared to a standard Marchetti blade, b) details of instrumented blade and (c) saturation of pore pressure element

Figure 2. Location of testing sites is Brazil

Figure 3. Typical soil profile at the Tubarão clay site showing main CPTu and DMT results

Figure 4. Typical profile at the Araquari sand site showing main CPTu and DMT results.

Figure 5. Typical profile at the Fazenda Brasileira tailings site showing main CPTu and DMT results

Figure 6. CPT and DMT pore pressure dissipation tests in at the Tubarão clay site

Figure 7. Pore pressure during DMT dissipation tests in silty fine sand at the Araquari site.

Figure 8. DMT pore pressure and repeated A-reading dissipation tests in Fazenda Brasileira tailings

Figure 9. Summary of typical normalized DMT pore pressure dissipation at the test sites.

Figure 10. DMT results at the Fazenda Brasileira tailings site performed at different rates

Figure 11. Profile of coefficient of consolidation in the horizontal direction ($c_h$) based on CPTu dissipation tests at the Fazenda Brasileira tailings site

(Blue line based on Teh and Hounsby, 1991; red line based on DeJong and Randolph, 2011)

Figure 12. Normalized penetration pore pressure ($U$) versus normalized velocity ($V_h$) using the modified DMT at the Fazenda Brasileira tailings site

Figure 13. Normalized dissipation pore pressure ($U$) versus normalized velocity ($V_h$) using the modified DMT at all three test sites as well as previous published data

Figure 14. Variation of calculated “undrained” shear strength ($s_u$) with depth at the Fazenda Brasileira tailings site based on standard DMT and CPT interpretation (disregarding partial drainage)

Figure 15. Soil behaviour type, inferred from DMT $I_D$ values, versus normalized velocity $V_h$
Pore Water Pressure (kPa)

Time (s)

GWL = -2.00 m

\( u_{\text{equi}} \) -16.80m = 148 kPa
\( u_{\text{equi}} \) -17.00m = 150 kPa
\( u_{\text{equi}} \) -17.20m = 152 kPa
(1-U) (%) vs Time (s)

- A reading
- B reading
- C reading

- Blue: Sand (ID>3)
- Red: Silt (0.6<ID<3.0)
- Green: Silt (0.6<ID<3.0)
- Purple: Clay (ID<0.6)
v = 20 mm/s

v = 58 mm/s

v = Variable

A and B readings at 15s

Membrane inflate time delay 240s and 300s before A and B

A reading 5 times every 8s before A reading

A reading 5 times every 8s before B reading

P0 20 mm/s

P1 58 mm/s

P0 Variable

P1 Variable

u0

u0

E_s (MPa)

K_s

v = 0.17 mm/s

v = 20 mm/s

v = 58 mm/s

P0

P1

u0

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\[ V_h = (v \cdot d/c_h) \]
\[ V_h = \left( \frac{v \cdot d}{c_h} \right) \]