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Effects of variable penetration rate using Medusa DMT in the Australian tests site of Ballina

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ABSTRACT: In December 2024 a set of dilatometer tests was performed in the Australian test site of Ballina using the recently developed in situ testing equipment named Medusa DMT. This enhanced version of the dilatometer enables inflation of the membrane at different programmable rates and not only at the standard rate recommended for the traditional DMT test procedure. The tests were carried out with different combinations of penetration rate, in addition to the standard DMT test procedure. Piezocone penetration test (CPTu) was performed as well in the study area and laboratory data of previous test campaigns is available for comparisons. The aim of the paper is to present results obtained with all the different test procedures and to look into the effects caused by the different conditions of drainage between the faster and slower penetration-inflation rate procedures.

KEYWORDS: DMT, dilatometer, Medusa DMT, penetration rate, partial drainage

1 INTRODUCTION

Although the Medusa DMT system has been thoroughly documented in previous studies (Marchetti D 2018; Marchetti et al. 2019, 2021, 2022; Monaco et al. 2021, 2022, 2023a, 2023b; Danziger et al. 2024), a brief description is provided here for clarity. The Medusa DMT integrates a traditional flat dilatometer with an automated hydraulic actuation system, enabling fully autonomous testing. As shown in Figure 1, the system comprises an electronic board powered by a rechargeable battery, a high-precision pressure transducer, and a custom motorized syringe. The embedded firmware controls the motorized syringe, which hydraulically generates the pressure required for DMT readings, operating up to 25 MPa. Pressure applied to the membrane is measured by the transducer, while membrane contact is monitored electronically. The A, B, and C readings are obtained following the same principles as the conventional pneumatic DMT.

By hydraulically regulating membrane expansion, the Medusa DMT provides programmable, volume-controlled pressure application consistent with international testing standards (Eurocode 7, ASTM, ISO). The electronic system can also maintain near-static membrane conditions, allowing continuous measurement of total horizontal soil pressure acting on the membrane.

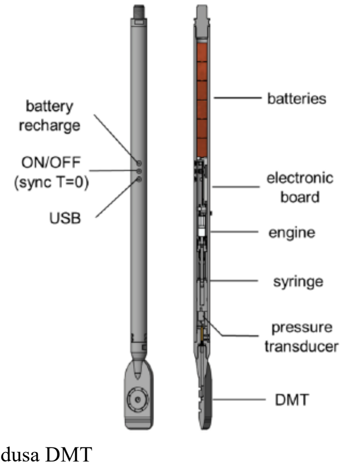


Figure 1. Medusa DMT

The Medusa DMT offers numerous advantages over conventional pneumatic dilatometer systems, particularly in terms of equipment simplification and improved measurement precision. The key benefits are summarized below:

1. The system is highly compact, with the entire setup limited to the dimensions of a standard blade and an extension rod mounted on top, resulting in a total length of approximately 1 meter.
2. Traditional components such as the gas tank, control unit, and pneumatic hoses are no longer necessary.
3. The operator is no longer required to inflate and deflate the pressure for the DMT readings, which introduces possible uncertainties in case of pressurization rates outside the recommended ranges.
4. An electric cable connecting the Medusa DMT at depth to the acquisition unit at surface provides real-time data acquisition during test execution. A CPT cable is generally employed as it allows a rapid inter changeability between DMT and CPT testing. The Medusa DMT may also perform tests in cableless memo mode, sometimes beneficial in offshore applications where cable management may be challenging.
5. Both pressure generation and measurement are carried out directly at the test depth, rather than at the ground surface. This feature eliminates the common issue of pressure loss and lag that can occur at the opposite ends of a pneumatic cable.
6. The membrane pressurization is automated and does not depend on the field operator. The motorized syringe ensures a fully-controlled membrane expansion rate, according to the recommendations of the international standards, providing highly accurate and repeatable A and B pressure readings.

This paper presents a comparative analysis of DMT results obtained at the Ballina test site using the Medusa DMT operated at different penetration rates. The primary objective is to evaluate and compare the outcomes from the different testing procedures, with particular focus on understanding the influence of drainage conditions associated with distinct penetration rates. In addition, the study includes a comparison between the DMT/SDMT results and data from piezocone penetration tests (CPTu) and previously conducted laboratory tests, to provide a comprehensive assessment of soil behavior using different testing methodologies.

2 TEST DETAILS

The Australian Research Council Centre of Excellence for Geotechnical Science and Engineering (CGSE) established a dedicated research platform to address challenges associated with soft soil environments. As part of this effort, CGSE developed the National Soft Soil Field Testing Facility (NFTF) in Ballina, New South Wales (Kelly, 2013). The facility supports improved design and construction of transport infrastructure on naturally occurring soft soils common along Australia's eastern and southern coasts. It provides comprehensive in-situ testing, long-term monitoring, and advanced laboratory investigations, all essential for improving the understanding and modeling of Australia's estuarine soft clays.

Within this initiative, Black Insitu Testing, in collaboration with Studio Prof. Marchetti, carried out an extensive testing campaign at the Ballina site. The program included four Medusa DMTs executed at different penetration rates, one Seismic Dilatometer Test (SDMT), one DMT while penetration (DMT-WP), one Repeated A-readings DMT (DMT-RA), and one CPT. All Medusa DMTs used the standard membrane inflation durations of TA = 15 s for the A reading and TAB = 15 s for the B reading. Table 1 summarizes the penetration and inflation rates adopted for each of the four Medusa DMT

Table 1. Test Details.

Test Name	Penetration Rate	T_A (sec)	T_{AB} (sec)
MDMT 3	2 mm/sec	15	15
MDMT 1	20 mm/sec	15	15
MDMT 2	60 mm/sec	15	15
MDMT 6	140 mm/sec	15	15

Figure 2. Test Progression

3 GEOTECHNICAL CHARECTERIZATION

A detailed analysis of the subsoil profiles obtained from Medusa DMT and CPT in the Ballina site area reveals a highly plastic clay layer up to an average depth of 11.0 m in all the soundings. Below this layer a stiff clayey silt/silty clay layer is extended up to an average depth of 13.4 m, followed by a silty sand/sandy silt layer up to the termination level. Across all tests, a groundwater table was assumed at a depth of 1.00 m, based on p_2 values detected in thin sand layers.

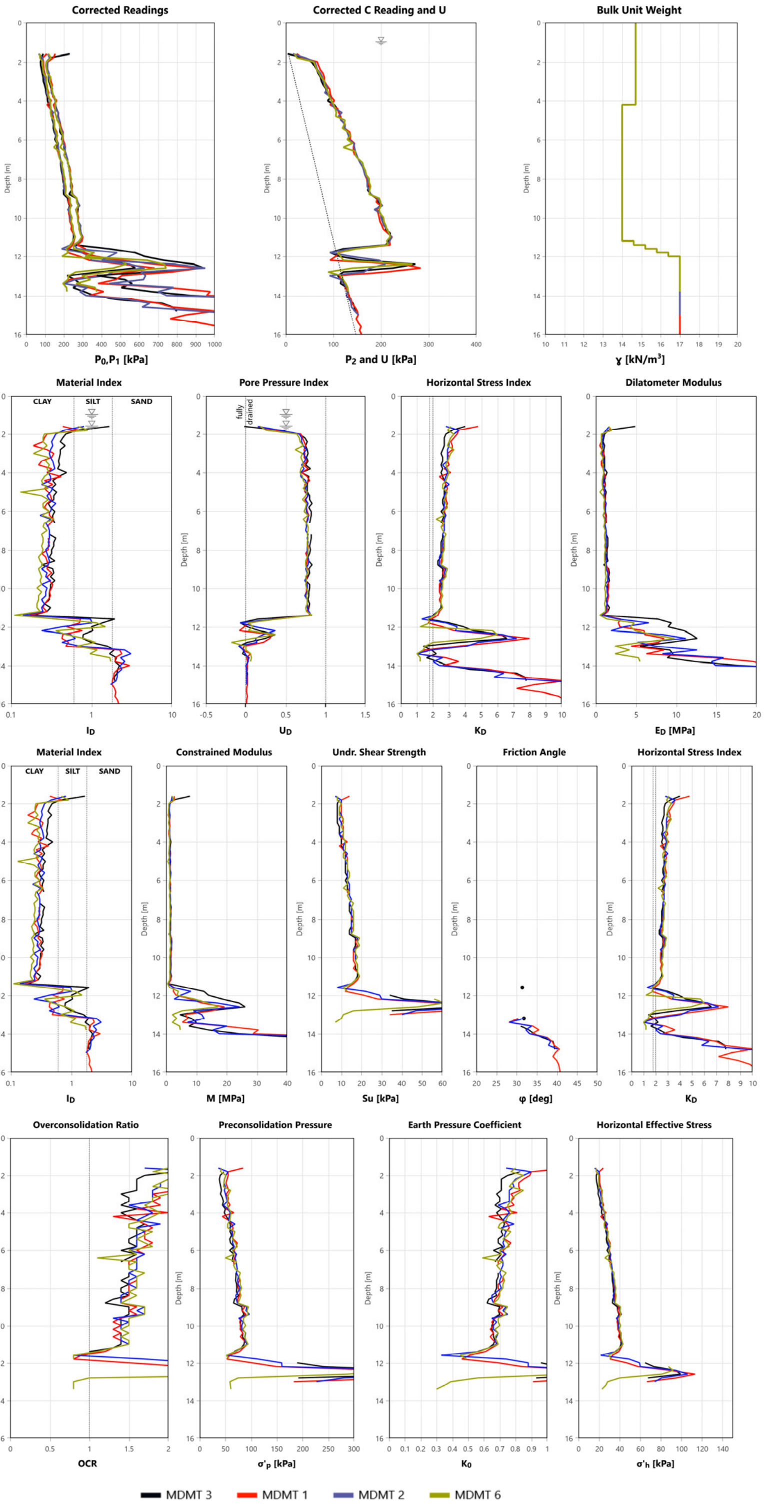


Figure 3. Results obtained by Medusa DMT using different test procedures at Ballina

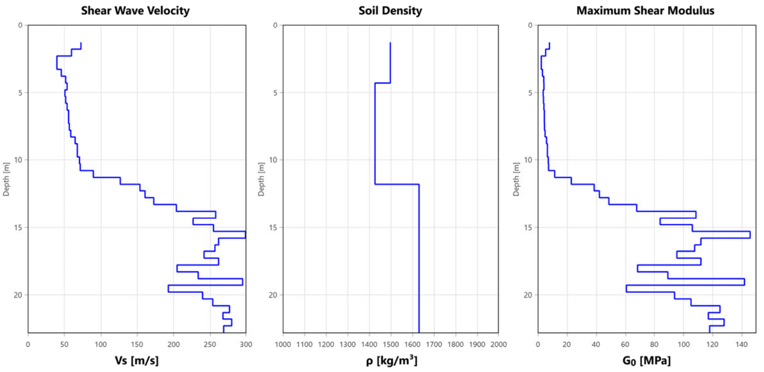


Figure 4. Results obtained by SDMT test procedures at Ballina

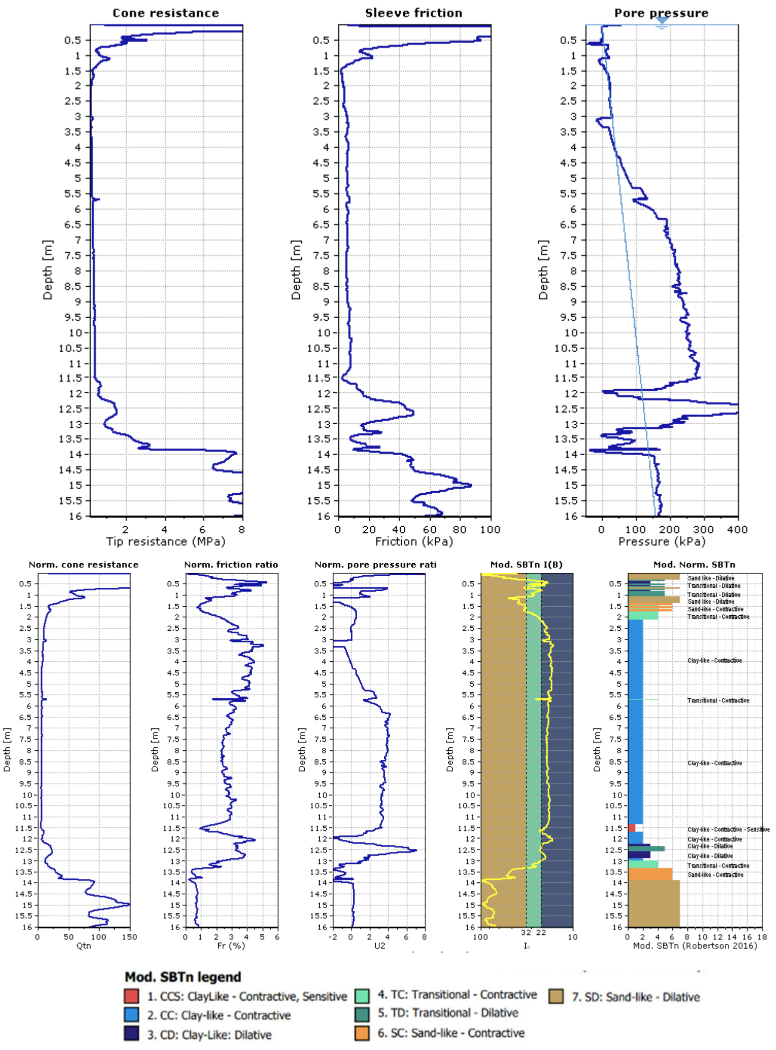


Figure 5. Results obtained by CPT test procedures at Ballina

4 COMPARITIVE ANALYSIS OF THE MEDUSA DMT, DMT-WP, DMT-RA RESULTS

The DMT-RA procedure differs from the standard (STD) method only in the initial phase, before membrane expansion begins; the B and C readings are collected exactly as in the STD test. In the standard procedure, the A-reading is taken when the membrane has expanded 0.05 mm. With the Medusa DMT, the electronically controlled motorized syringe can hold the membrane in equilibrium with negligible horizontal movement. The DMT-RA method uses this capability by maintaining the membrane at pressure equilibrium with the surrounding soil at the start of each test cycle. At each depth ($T = 0$), multiple A-readings are recorded as the syringe continuously compensates for external pressure variations, providing a non-disturbing measurement of total horizontal soil pressure. This produces a dissipation curve of duration Tdiss, set to 15 s in the Ballina tests to match standard DMT timing. After dissipation, the test continues with the usual B and C readings.

The same equilibrium capability also enables the DMT-WP procedure, where successive A-readings are taken during probe advancement at a constant penetration rate. These A-values correspond to $t = 0$ rather than the standard $t = 15$ s. The other two DMT readings are normally collected every 1 m, aligning with rod additions, during which B and C pressures can be taken without increasing test time. A penetration rate of 20 mm/s is generally used. Although the Medusa DMT does not internally record depth, many penetrometers include CPT-style encoders that can generate a time–depth profile. If unavailable, depth can be estimated from the average penetration rate over each 1-m push, providing adequate accuracy for these short intervals.

Figure 6 presents a comparison of the results obtained using the Medusa DMT with its three testing modes: STD, DMT-RA, and DMTA-WP. The data were processed using the same interpretation framework and reduction methods applied in the traditional flat dilatometer test, as outlined in the ISSMGE TC16 Report (Marchetti et al., 2001). Specifically, Figure 6 illustrates the depth-wise distribution of corrected pressure readings—p_0, p_1, and p_2 (corresponding to the A, B, and C readings adjusted using calibration offsets ΔA and ΔB to account for membrane stiffness)—along with the derived parameters: material index (I_D) and horizontal stress index (K_D).

For the DMT-RA tests, the A-pressure reading used in the interpretation corresponds to the final value of the dissipation series, recorded at 15 seconds from the start of membrane pressurization. Across all tests, a groundwater table was assumed at a depth of 1.00 m, based on p_2 values detected in thin sand layers.

The p_0 profiles obtained from all three Medusa DMT procedures show strong agreement, despite variations in the method of capturing the A-reading within the highly plastic clay layer. Similarly, the p_1, p_2 profiles derived from each procedure are nearly identical. However, in the DMT-WP mode, the p_1 and p_2 values appear more segmented due to the B and C pressure readings being taken at 1-meter intervals, unlike the 0.20-meter intervals used in the STD and DMT-RA tests.

The I_D profiles, which are influenced by the difference between p_1 and p_0, exhibit consistency across the three methods within the highly plastic clay layer. However, noticeable differences arise in the stiff clayey silt or silty clay zones, where I_D values obtained from the DMT-WP method are significantly lower than those from the STD and DMT-RA tests. This reduction stems from the timing of the A-reading in DMT-WP, taken at $T_A = 0$ rather than the standard 15 seconds, while the B-reading is taken at the standard T_{AB}=15 seconds. As a result of this timing mismatch, the difference ($p_1 – p_0$) is reduced, and due to the logarithmic nature of the I_D calculation, this leads to amplified discrepancies, especially when the values are low.

The horizontal stress index K_D, which depends solely on the p_0 reading, remains consistent regardless of the testing method employed, showing no sensitivity to the procedure across the highly plastic clay layers. However, noticeable differences arise in the stiff clayey silt or silty clay zones, where K_D values obtained from the DMT-WP method are significantly lower than those from the STD and DMT-RA tests. This variation likely stems from the timing of the A-pressure measurement in DMT-WP, which is taken at $t = 0$ rather than the standard 15 seconds. However, in sandy layers, similar to negative U values from CPT, the depression due to penetration may cause these lower values of A and K_D compared to the ones of the standard procedure taken with the blade not moving.

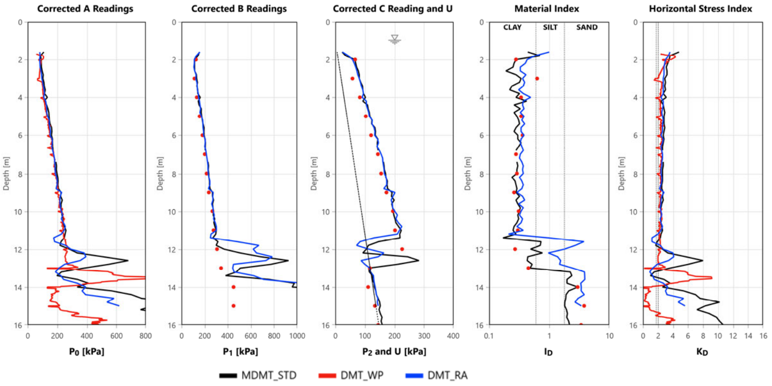


Figure 6. Results obtained by MDMT-STD, DMT-WP and DMT-RA at Ballina

5 COMPARITIVE ANALYSIS OF THE MEDUSA DMT RESULTS WITH VARIOUS PENETRATION RATE

5.1 *DMT readings*

It is observed that when the subsoil is very soft (especially in the clay up to 11.0 m) the rate of penetration does not affect the DMT readings P_1 and P_2. However, P_0 and therefore ΔP is influenced by the penetration rate; a slower penetration rate tends to result in a larger pressure difference, while a faster rate leads to a smaller difference, due to dissipation of pore water pressure with time. (Figure 7)

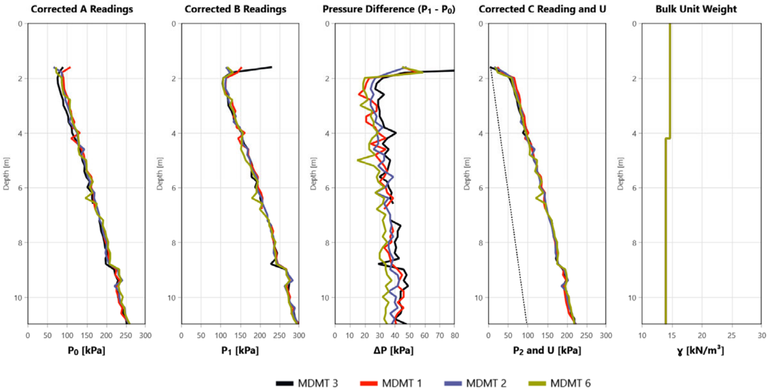


Figure 7. DMT readings obtained by Medusa DMT using different test procedures at Ballina (highly plastic clay layer)

When subsoil is silt from 12.0 m to 13.0 m it is not evident whether the rate of penetration affects DMT readings (i.e., p_0, p_1, p_2). However, the ΔP in silt is also influenced by the penetration rate; a slower penetration rate tends to result in a larger pressure difference. (Figure 8)

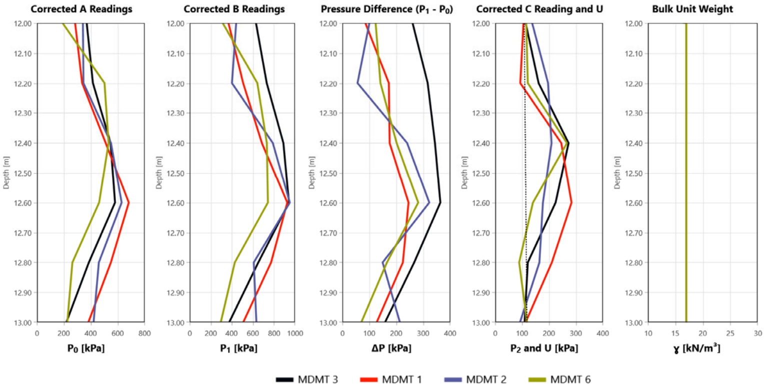
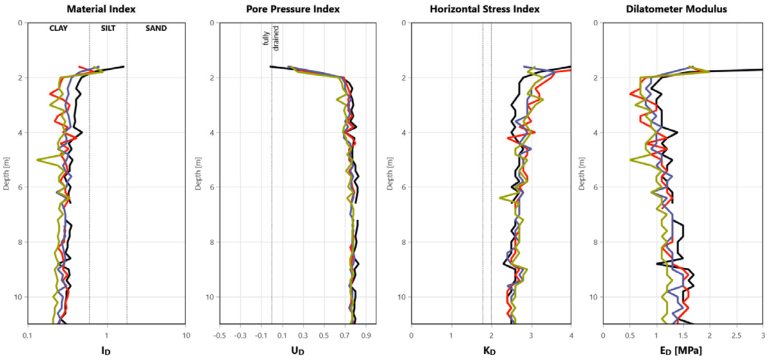


Figure 8. DMT readings obtained by Medusa DMT using different test procedures at Ballina (silt layer)

5.2 *DMT intermediate parameters*

The overlay plots of Figure 9 indicate that in the very soft clay up to 11.0 m, the rate of penetration does not affect the overall intermediate and geotechnical design parameters (i.e., I_D, U_D, K_D, E_D, M_{DMT}, S_u, K_0, OCR).



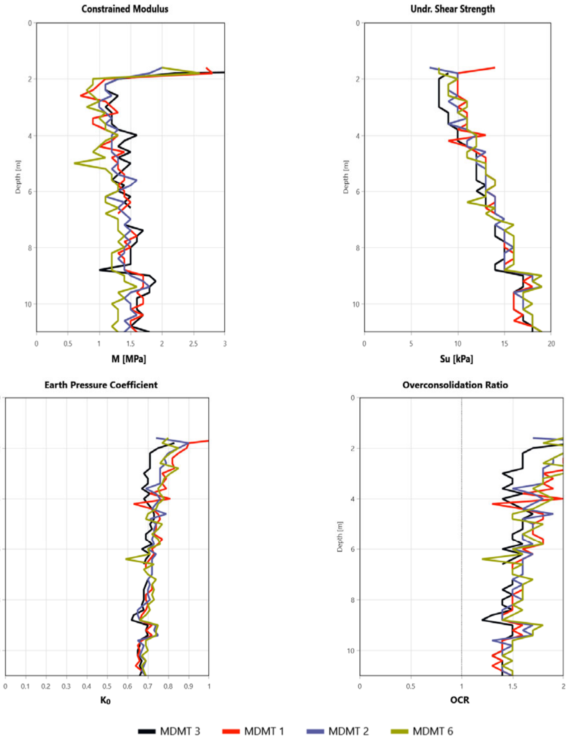


Figure 9. DMT intermediate parameters obtained by Medusa DMT using different test procedures at Ballina (highly plastic clay layer)

Figure 10 shows that when the subsoil is silt from 12.0 m to 13.0 m the geotechnical design parameters are more scattered than in clay but the parameters like E_D and M_{DMT}, associated with ΔP, show a similar trend of higher values with slower penetration.

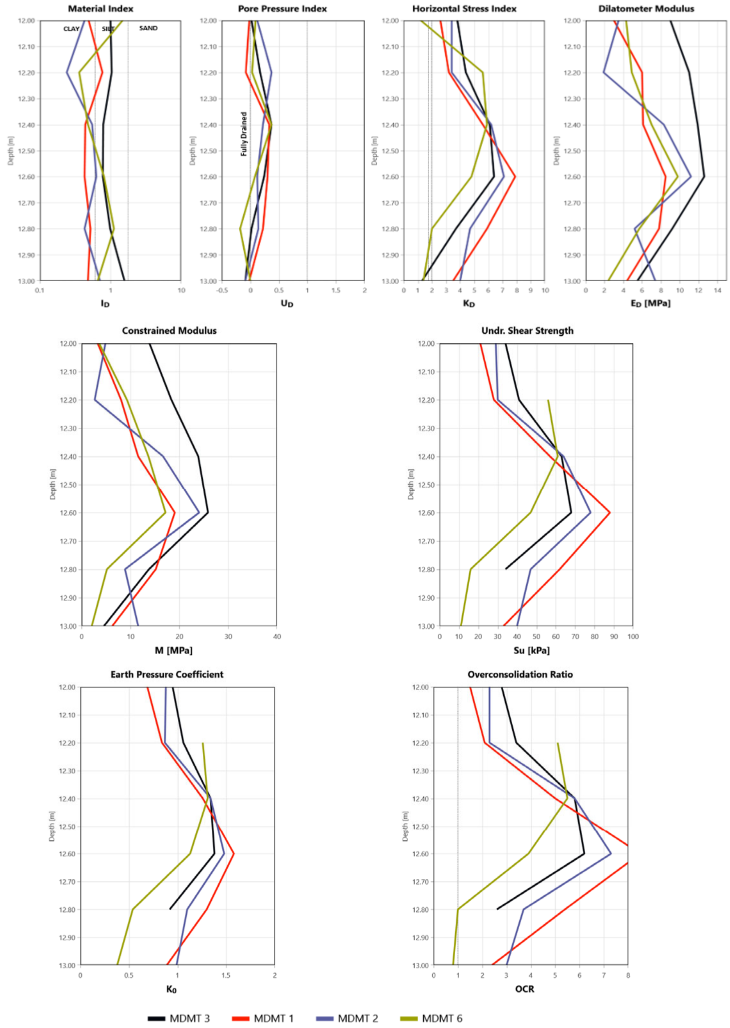


Figure 10. DMT intermediate parameters obtained by Medusa DMT using different test procedures at Ballina (silt layer)

In the top clay layer, the faster penetration rate of MDMT 6 provides a slightly lower I_D, indicating a somewhat more "clay-like" response, perhaps motivated by the reduced time for drainage around the membrane, compared to the slower penetration rate tests.

In contrast, both MDMT 3 (slowest) and MDMT 6 (fastest) show in Figure 11 similar U_D values (≈0.7–0.8), suggesting that the considerable long time required for the C-readings hides the effects of the different penetration rates on U_D.

Figure 11 also shows that a slower penetration rate corresponds to a higher E_D, which derives from the same trend already observed for the pressure difference ΔP.

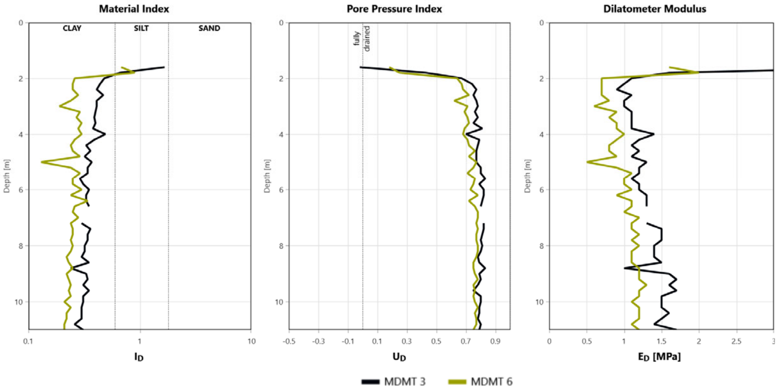


Figure 11. DMT intermediate parameters obtained by Medusa DMT using different test procedures at Ballina (highly plastic clay layer)

In silt the faster penetration MDMT 6 (fast) shows more variation and lower I_D values at several depths compared to MDMT 3 (slow). Faster penetration likely preserved more excess pore pressure, leading to lower I_D (more "clayey" response)

U_D values are mostly near zero or slightly negative, for both MDMT 3 and MDMT 6, indicating that this layer behaves closer to fully drained, as expected for silty soils. The small differences between the curves suggest minimal rate sensitivity for U_D in this specific soil.

In silt a slower penetration rate also tends to result in a larger pressure difference and as a result at higher ED due to dissipation of pore water pressure with time. (Figure 12)

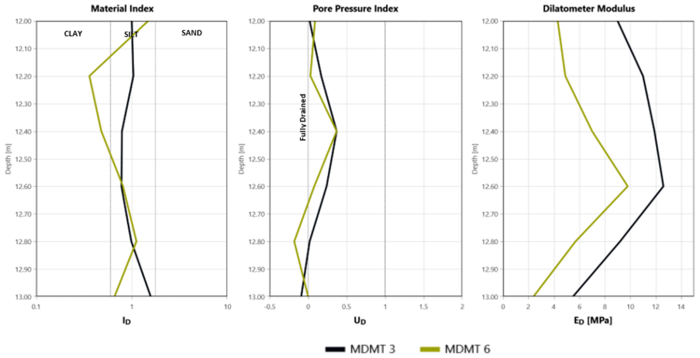


Figure 12. DMT intermediate parameters obtained by Medusa DMT using different test procedures at Ballina (silt layer)

6 COMPARITIVE ANALYSIS OF THE MEDUSA DMT, CPT AND LABORATORY TEST RESULTS

6.1 *Undrained shear strength (s_u)*

The s_u obtained from both CPTu and DMT have been compared with triaxial test results as per Pineda JA et al. (2016) (Figure 13) for Ballina clay. N_{kt} = cone bearing capacity factors for CPTu, were assumed to range between 14 and 17. It is observed that both the in-situ test results are in line with the laboratory test results.

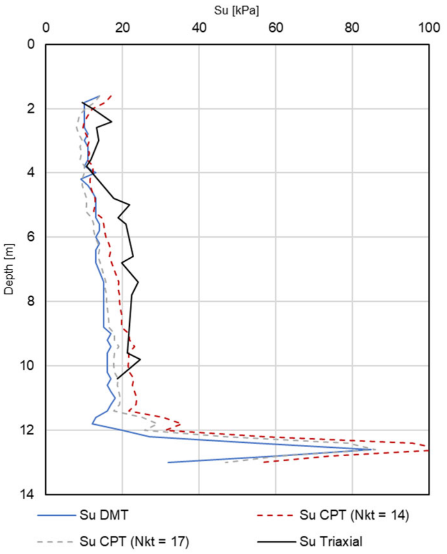


Figure 13. Results obtained by Medusa DMT using different test procedures at Ballina (silt layer)

6.2 *K_0 and OCR*

The Coefficients of lateral earth pressure (K_0) and Overconsolidation ratio (OCR) obtained from DMT are compared with the upper and lower OCR limits obtained from lab-based s_u as per Paul W. Mayne 1988 work on determination of OCR in clays from the available laboratory test results.

$$(1.82\, s_u/\sigma'_{vo})^{1.43} \le OCR \le (4\, s_u/\sigma'_{vo})^{1.43} \tag{1}$$

$$K_0 = \sin\varphi\,(OCR)^{\sin\varphi} \tag{2}$$

Figure 14 shows that the values of K_0 and OCR derived from DMT consistently fall within the mid-range of these established limits.

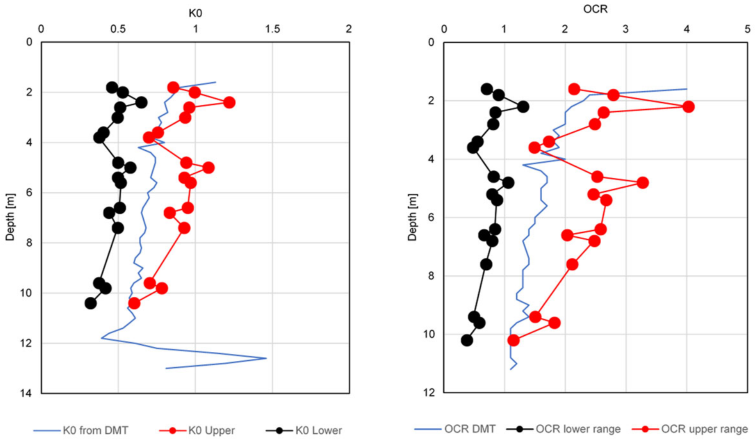


Figure 14. K_0, OCR obtained by Medusa DMT compared with lab results

6.3 *Constrain Modulus (M)*

M obtained from both in-situ tests CPTu and DMT has been compared with the constrained modulus obtained from Constant Rate of Strain consolidation test (CRS) by Pineda JA et al. (2016) (Figure 15). It was observed that the modulus obtained from DMT (M_{DMT}) closely matches the modulus from the Constant Rate of Strain test (M_{CRS}), whereas the modulus derived from CPT (M_{CPT}) tends to be significantly lower with $\alpha_m = 8$.

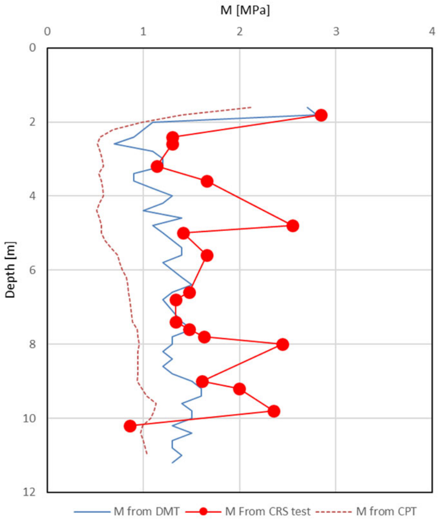


Figure 15. Constrained modulus (M) obtained by Medusa DMT, CPTu and CRS

6.4 *Shear wave velocity (V_s)*

V_s obtained from SDMT has been compared (Figure 16) with the obtained Vs from CRS test by Pineda, J. A. et al. (2016). It was observed that the V_s obtained from both these tests are in good agreement with each other. The Vs-(CRS)/Vs-(IN-SITU) ratio is between 0.77 and 1.50, suggesting very good to excellent sample quality, as per Lunne et al. (1997) criteria.

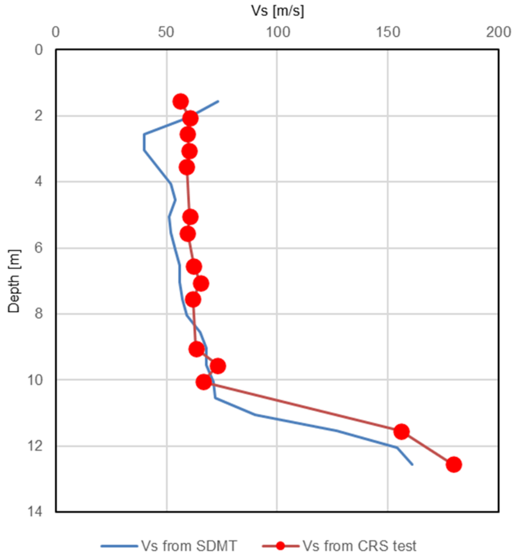


Figure 16. V_s obtained by SDMT and CRS

7 CONCLUSIONS

The Ballina soft clay benchmark site is well established for evaluating advanced soil investigation methods, supported by a comprehensive database of high-quality in situ and laboratory results. The recent Medusa DMT campaign at this site benefited greatly from this existing dataset. With its high-precision pressure measurement and controlled pressurization, the Medusa DMT is particularly effective in very soft soils where low pressures must be measured accurately. Its design also enables alternative procedures—Repeated A-readings (DMT-RA) and A-readings during penetration (DMT-WP)—in addition to the standard method. The Ballina results show strong consistency across all three procedures, even under different penetration rates.

The comparison of test results obtained with different penetration rates provides clear and consistent trends. A slower penetration rates results in a higher-pressure difference between the DMT readings (ΔP) and consequently also in all parameters derived from such difference. Particularly for I_D, this trend matches that concept that a faster penetration rate tends to shift the soil classification towards a finer geomaterial with undrained behavior.

Interpretation of Medusa DMT data relies on well-established correlations developed for the traditional pneumatic DMT. The undrained shear strength (s_u) profiles obtained from Medusa DMT align well with those from CPTu and laboratory tests. Similarly, estimates of K_0 and OCR from Medusa DMT fall within the range of values derived from lab-based correlations. The constrained modulus (M) and shear wave velocity (Vs) from Medusa DMT and SDMT, respectively, also show strong agreement with previous laboratory results.

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