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# Effectiveness of an advanced fully automated in-situ test for the characterization of very soft soils

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**Abstract.** The Sarapuí II site, located on a very soft clay deposit in Guanabara Bay, Rio de Janeiro, is one of the most extensively documented geotechnical research sites in Brazil. Since 1985, it has been investigated using also with all the versions of the Marchetti Flat Dilatometer (DMT), including the conventional pneumatic and the recently developed fully automated Medusa DMT. As reported by Januzzi et al. (2015), the pneumatic DMT produced acceptable repeatability in readings $p_0$ and $p_1$, but showed significant variability in the differential pressure ($\Delta p = p_1 - p_0$), resulting in considerable scatter for all derived parameters. This variability stems from the extremely low $\Delta p$ values (~10 kPa) and limitations inherent to the pneumatic system, such as operator-dependent inflation/deflation rates and pressure differences along the pneumatic cable. Testing in such soft geomaterials requires advanced instrumentation capable of precise pressure control and accurate measurement at extremely low stress levels. The Medusa DMT addresses these issues by generating and measuring pressure directly at depth, ensuring a fully automated and repeatable membrane expansion rate. This innovation substantially improves the accuracy and precision of $p_0$, $p_1$, and also of $\Delta p$ readings in very soft soils. Comparisons of key geotechnical parameters—such as undrained shear strength ($s_u$) and overconsolidation ratio (OCR)—interpreted using standard DMT correlations with high-quality laboratory and other in situ test results demonstrate excellent agreement. These findings confirm that the Medusa DMT is highly effective to evaluate correctly geotechnical parameters and with negligible scatter very soft clays like the ones at Sarapuí II.

## 1 Introduction

The Flat Dilatometer Test (DMT) is an in-situ soil investigation technique originally developed in the late 1970s by Professor Silvano Marchetti [1]. Since its introduction, the DMT has gained widespread international acceptance and is now routinely applied in all industrialized countries worldwide. The test procedure and interpretation are standardized in major international codes and guidelines [2 – 4]. A comprehensive monograph prepared by the ISSMGE Technical Committee TC102 (formerly TC16) [5] provides detailed descriptions of the DMT equipment, test procedures and interpretation framework for deriving geotechnical design parameters. Further methodological advancements, refinements and extended applications developed over the past decade and a half have been summarized in subsequent publications [6].

The Medusa DMT represents a significant technological evolution of the traditional pneumatic dilatometer [7,8]. It is a fully autonomous, self-contained probe that performs dilatometer testing using a blade of standard geometry, eliminating the need of pneumatic cables, surface control units and gas tank required in conventional DMT systems (Fig. 1). Membrane expansion is achieved hydraulically by means of a motorized syringe controlled by an onboard electronic unit powered by rechargeable batteries. This system allows the automatic acquisition of DMT A, B and C pressure readings at each test depth, typically at 0.20 m intervals, and real time transmission of the data to the computer at surface.

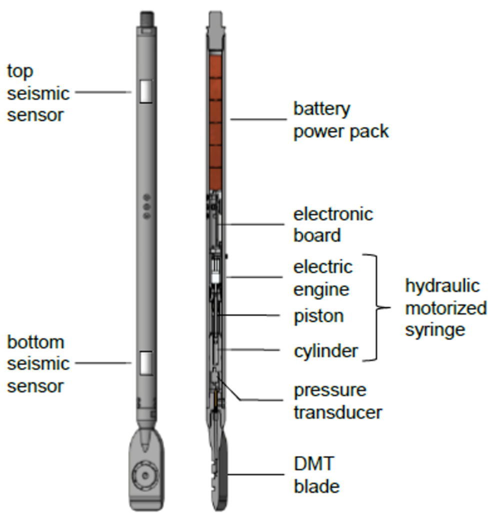


**Fig. 1.** The Medusa Seismic DMT.

The hydraulic pressurization of the membrane is volume-controlled, enabling a perfectly repeatable

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membrane expansion rate. Programmable values of $T_A$ and $T_{AB}$ allow to apply either standard or customized pressurization rates for respectively the A reading and the B reading, which are particularly useful when dealing with partially drained soils [7].

Compared with the conventional pneumatic DMT equipment, the Medusa DMT offers the following advantages:

1. The probe is 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. Components such as the gas tank, control unit with valves and pneumatic cables are no longer necessary.
3. The operator is no longer required to carefully inflate and deflate the gas pressure with pneumatic valves, because the hydraulic pressurization cycle of Medusa DMT is fully automated by the motorized syringe.
4. The membrane pressurization rates are pre-programmed and enforced with high accuracy thanks to the incompressibility of the hydraulic fluid. All uncertainties related to incorrect pneumatic inflation and deflation rates, difficult to avoid using a compressible fluid, are eliminated.
5. The motorized syringe of the Medusa DMT is able to adjust very rapidly the pressure in order to maintain the membrane in equilibrium with the soil pressure. This feature is employed to obtain continuous high resolution dissipation curves, useful for the estimation of the consolidation and permeability coefficients of the soil. The same feature also allows to acquire continuous A-readings with depth during penetration, measuring the total horizontal stress of the soil against the membrane without requiring time for pressurization ($T_A$=0).
6. 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 interchangeability 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.
7. Both pressure generation and measurement are carried out directly at the test depth, rather than at the ground surface. This feature eliminates errors in the readings related to pressure loss and lag that can occur at the opposite ends of a pneumatic cable.

## 2 Test site (Sarapui II)

The geotechnical behavior of the very soft clay deposit known as Sarapuí has attracted considerable research interest for more than half a century due to its extreme compressibility and low shear strength. The earliest systematic documentation of this deposit dates back to the pioneering work of Lacerda and coworkers [9], who first identified the presence of exceptionally soft, highly compressible clay layers in the region. These findings established Sarapuí as one of the most representative natural laboratories for the study of soft soils in Brazil.

The original Sarapuí experimental site is situated in a low-elevation, marshy plain bordering Guanabara Bay, on the left margin of the Sarapuí River, approximately 7 km from the city of Rio de Janeiro, at average coordinates latitude 22°44′41″ S and longitude 43°17′23″ W (Fig. 2). Geomorphologically, the area corresponds to a coastal plain environment formed by recent Holocene sedimentation, with a strong influence of estuarine and lagoon depositional processes.


**Fig. 2.** The study area (Google earth).

At the original Sarapuí site, an extensive program of in-situ testing and laboratory investigations was carried out. These studies included field vane shear tests (VST), high-quality sampling, oedometer and triaxial testing, and long-term monitoring of test embankments [10,11]. These early investigations provided valuable insights into the stress–strain behavior, consolidation characteristics and stability issues associated with very soft clays. A comprehensive synthesis of the geological framework, stratigraphy and engineering properties of the Sarapuí deposit was later presented by Alves [12], consolidating decades of experimental evidence.

Despite its scientific importance, the original Sarapuí site has seen limited use over the past 25 years due to increasing access restrictions and safety concerns, which constrained the execution of new field experiments. In response to these limitations, a new experimental area—designated Sarapuí II—was selected within the same geological formation. Sarapuí II is located approximately 1.5 km from the original site, ensuring geological continuity and lies within a secured Brazilian Navy facility, providing controlled access and long-term operational stability.

Since its establishment, Sarapuí II has become an active and well-instrumented field laboratory dedicated to the investigation of very soft organic clays. Numerous experimental research programs have been conducted at this site, addressing topics such as strength anisotropy, consolidation behavior, creep and soil–structure interaction [13 – 15]. At present, the site is jointly operated by the Research Center of PETROBRAS (CENPES) and the Federal University of Rio de Janeiro (UFRJ) and it is widely recognized as a worldwide reference site for soft soil research.

The subsurface profile at Sarapuí II is dominated by a very soft organic clay layer extending to a depth of approximately 8 m, underlain by a clayey silt layer of higher stiffness. The upper clay layer is characterized by high natural water content, elevated organic matter content, low unit weight and extremely low undrained shear strength, making it representative of some of the weakest naturally occurring clays encountered in practice. A detailed and systematic characterization of the Sarapuí II deposit—including geological history, index properties, mechanical behavior and chemical composition—has been presented by various researchers [16 – 19].

Profiles of key index and mechanical parameters, particularly the undrained shear strength ($s_u$) derived from VST, illustrate the pronounced softness and vertical variability of the clay deposit and are presented in Fig. 3a. These characteristics make Sarapuí II an invaluable reference site for the development, calibration and validation of constitutive models and design methodologies for very soft soils.

The overconsolidation ratio (OCR) profile obtained from 24-hour incremental loading oedometer tests by [19] on high-quality undisturbed samples is shown in Fig. 3b. Samples recovered between depths of approximately 4.0 m and 5.5 m contained a significant proportion of shell fragments, which affected the compression response and led to unreliable estimates of preconsolidation stress. Consequently, OCR values derived at this depth interval are considered non-representative. Excluding this depth range, the deposit exhibits a lightly overconsolidated behavior below about 3 m, with OCR values generally close to 2.

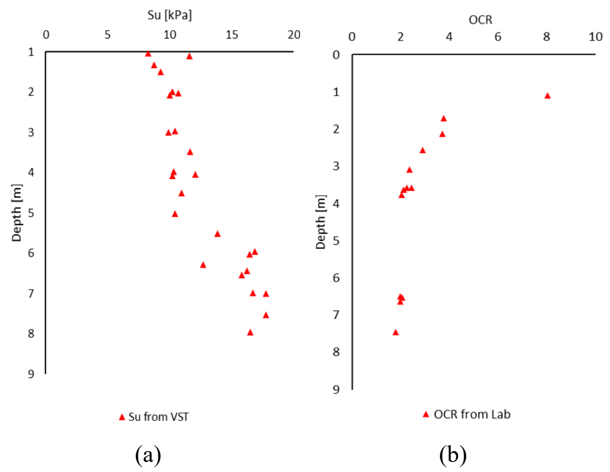



**Fig. 3.** (a) $S_u$ obtained from VST, (b) OCR from oedometer [19].

## 3 Geotechnical investigations at the study area

### 3.1 Previous tests

The development and subsequent integration of a seismic module into the Flat Dilatometer Test system, leading to the Seismic Dilatometer Test (SDMT), as proposed by [18], represented a significant advancement in in-situ soil characterization by enabling the simultaneous measurement of mechanical and small-strain dynamic properties. In response to this innovation, COPPE/UFRJ acquired its own SDMT equipment in 2011, thereby expanding its experimental capabilities at benchmark soft soil sites.

The availability of the SDMT system made it possible to conduct the third and fourth experimental testing campaigns in 2012 at the Sarapuí II research site. These investigations were performed using the same pushing rig employed during earlier testing phases, ensuring consistency in penetration procedures and minimizing equipment-related variability in the results. Field conditions are characterized by very shallow groundwater table, with the water level located on average at 0.3 m above the ground surface during the campaign, reflecting the saturated nature of the deposit and its swampy environmental setting. The testing methodology, data processing procedures, and interpretation of the results were documented in detail [18].

### 3.2 Medusa DMT tests

In September 2018 two tests were performed using the Medusa DMT equipment, developed by Studio Prof. Marchetti in 2014. As in all previous tests, the rate of 20 mm/s was used. The water table was 0.3 m above the ground level at the time of the tests (Table 1).

**Table 1.** DMT test details.

| Test name | Date | Representative name |
|---|---|---|
| SDMT 1 | 14.06.12 | SDMT 1 (14th June 2012) |
| SDMT 2 | 15.06.12 | SDMT 2 (15th June 2012) |
| SDMT 1 | 12.12.12 | SDMT 1 (12th December 2012) |
| SDMT 2 | 14.12.12 | SDMT 2 (14th December 2012) |
| Medusa DMT 1 | 05.09.18 | Medusa DMT 1 (5th September 2018) |
| Medusa DMT 2 | 06.09.18 | Medusa DMT 2 (6th September 2018) |

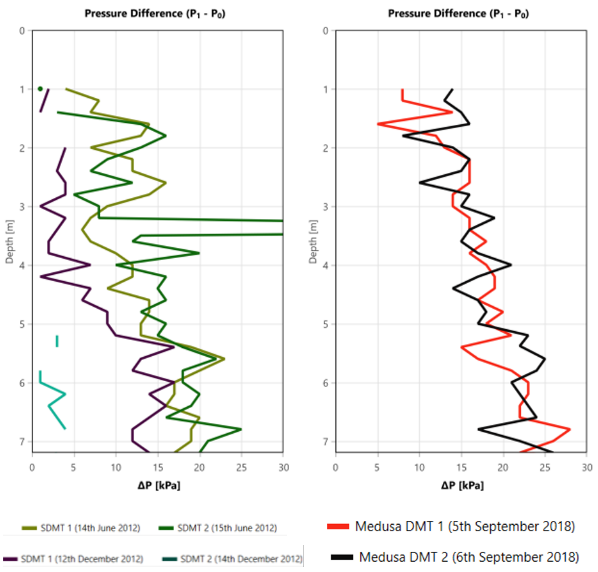
## 4 Geotechnical interpretation of the in-situ test results

Fig. 5 illustrates the profiles of the DMT intermediate parameters $I_D$ (Soil behaviour type index), $K_D$ (horizontal stress index) and $E_D$ (dilatometer modulus) obtained from all test series. A pronounced scatter is observed in the $I_D$ and $E_D$ profiles, as well as in $K_D$ values derived from the pneumatic DMT tests. In contrast, the profiles obtained from the automated Medusa DMT display a noticeably reduced dispersion and a smoother vertical trend, indicating improved repeatability and measurement consistency.

The increased variability associated with the pneumatic DMT is particularly evident in this very soft soil deposit, where the lift-off pressure ($p_0$) and the expansion pressure ($p_1$) are often very close in magnitude. Under such conditions, even small deviations in membrane inflation rate can lead to significant relative errors in the determination of the intermediate parameters. Moreover, when using the pneumatic DMT equipment, the membrane expansion and deflation rates cannot be actively controlled to strictly satisfy the recommended reading times $T_A$ and $T_{AB}$, which are critical for ensuring standardized stress application and pore pressure dissipation conditions. As a result, the derived DMT parameter profiles may exhibit local discontinuities and non-physical fluctuations, providing misleading soil characterization.

This uncertainty in soft soils is overcome by the Medusa automated DMT, as it allows precise control of the membrane expansion rate and enforces constant and reproducible reading times in accordance with standard testing recommendations. By eliminating operator-dependent variability and ensuring consistent membrane pressurization rates, the Medusa system significantly enhances the reliability of the $I_D$, $K_D$ and $E_D$ parameters. This improvement is especially critical in very soft soils, where the sensitivity of DMT measurements to testing procedure is inherently high. Consequently, the automated Medusa DMT provides more continuous and representative parameter profiles, leading to a more robust characterization of the subsoil.

When the pressure difference, $\Delta p = p_1 - p_0$, is plotted (Fig. 4a), the results from the pneumatic DMT show a pronounced scatter. The variability in $\Delta p$ propagates into the intermediate parameters $I_D$, $K_D$, and $E_D$ which are directly computed from $p_0$ and $p_1$, any variability in $\Delta p$ propagates into these indices and, consequently, into the derived geotechnical design parameters. This effect becomes particularly critical in very soft soils, where $p_0$ and $p_1$ are intrinsically close in magnitude. Under such conditions, even minor fluctuations in pressure application or reading translate into disproportionately large relative variations in $\Delta p$, amplifying inconsistencies in the interpreted soil profile (Fig. 5).




(a) (b)

**Fig. 4**. DMT pressure differences (a) Pneumatic DMT results (b) Medusa DMT results.

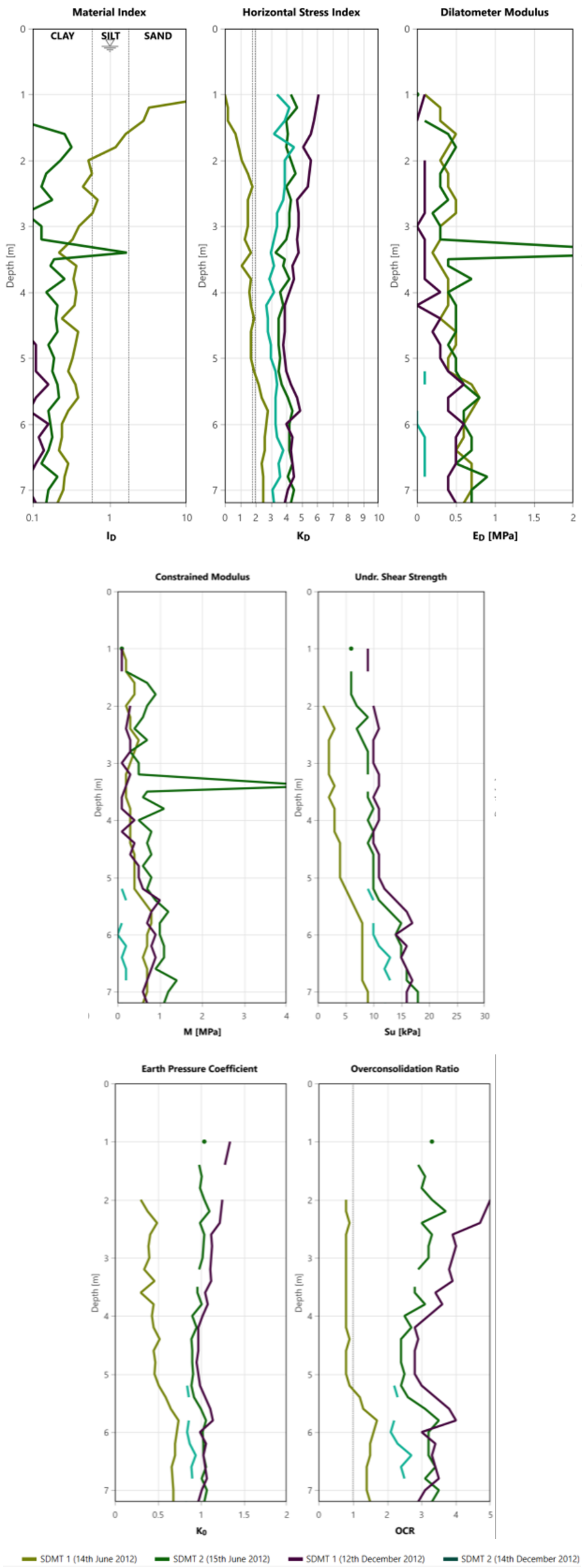



**Fig. 5**. Pneumatic DMT intermediate and geotechnical results.

A primary source of this scatter in pneumatic DMT testing is the rapid gas pressurization transmitted through a long pneumatic line. During inflation, transient pressure gradients may develop between the surface control unit and the membrane at depth. As a result, the pressure measured at the surface may not instantaneously or accurately represent the true gas pressure acting on the membrane. These pressure losses and time lags are further influenced by hose length, compressibility of the gas, and operator-controlled inflation rate. The combined effect is a non-uniform and sometimes unstable membrane expansion process, which introduces measurement noise and discontinuities in Δp and in the associated intermediate and geotechnical parameters.

In contrast, the Medusa automated DMT exhibits a markedly reduced scatter in Δp (Fig. 4b), producing smoother and mechanically consistent intermediate parameter profiles. The improvement stems from its volume-controlled hydraulic pressurization system, which eliminates the need for a surface gas cylinder and long pneumatic transmission lines. Because pressurization is generated and regulated hydraulically with precise control of expansion rate and timing, pressure losses along the line are minimized and transient gradients between surface and membrane depth are substantially reduced. Consequently, the pressure applied at the membrane corresponds closely to the recorded value, ensuring stable Δp measurements.

This enhanced pressure control results in greater repeatability, reduced measurement dispersion, and improved fidelity of both intermediate and derived parameters, particularly in extremely soft soils where accurate resolution of small pressure differences is essential for reliable subsoil characterization.

As a result, the Medusa system reliably reproduces Δp even in soils with extremely low stiffness and strength, producing intermediate parameters that are continuous and representative of the actual subsoil behavior.

This observation highlights a key advantage of automated DMT systems: in very soft soils, where conventional pneumatic methods are prone to artifacts and non-physical discontinuities, the automated approach provides robust, high-fidelity measurements, improving both the reliability of intermediate parameters and the subsequent design calculations based on DMT-derived soil properties (Fig. 6).

## 5 Comparison of the geotechnical design parameters

Undrained shear strength ($s_u$) and overconsolidation ratio (OCR) are among the most critical geotechnical parameters for the design and stability assessment of soft soil deposits. Their accurate estimation is essential for predicting settlement, assessing bearing capacity, and modeling soil–structure interaction under both static and dynamic loading conditions. To evaluate the performance and reliability of the Medusa automated DMT, a comparative analysis of these parameters was carried out using data from [19], conventional pneumatic DMT and the automated Medusa DMT.

Fig. 7 a, b, c presents the comparison of $s_u$ and OCR profiles obtained from the three sources. The results highlight several important observations. First, the values derived from the pneumatic DMT exhibit a considerable scatter, particularly in the very soft clay layer, reflecting the sensitivity of intermediate parameters to the proximity of $p_0$ and $p_1$ in soft soils and to operator-dependent variations in membrane inflation.

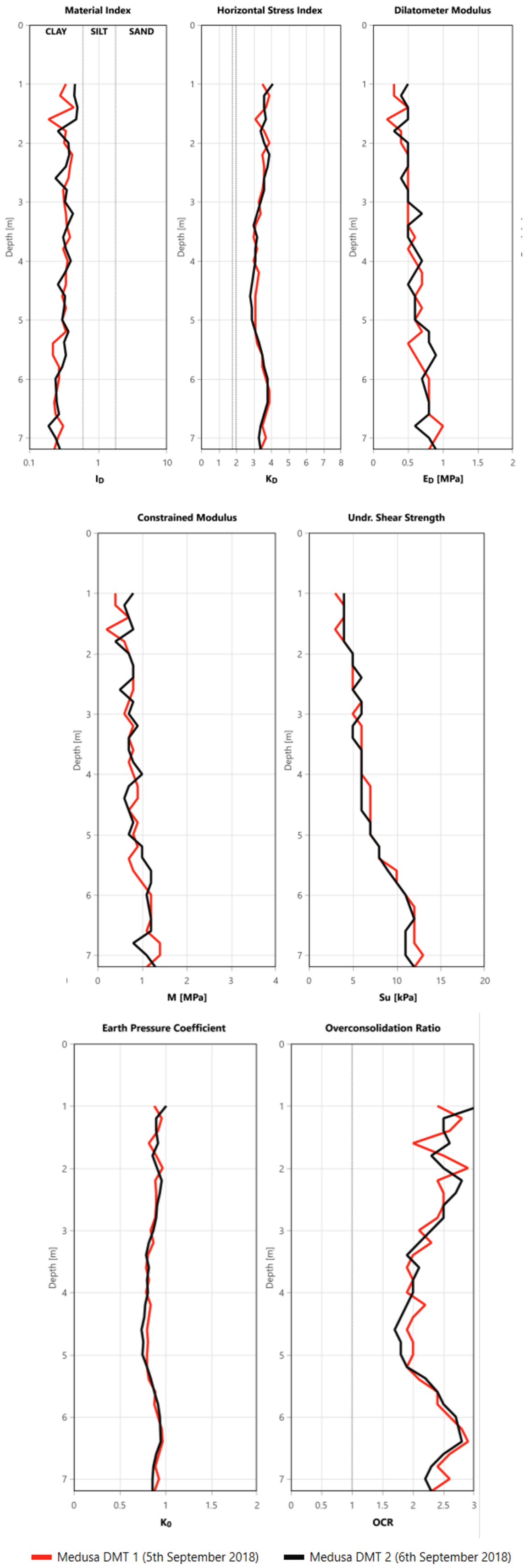
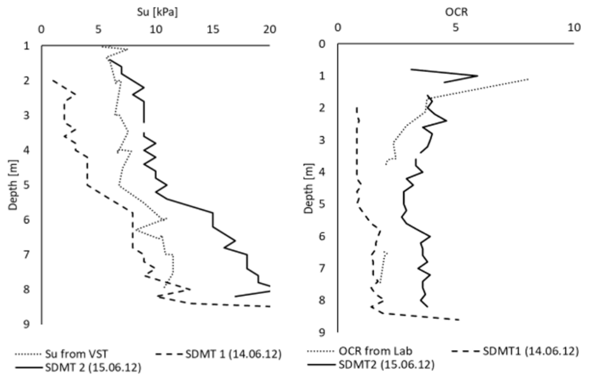
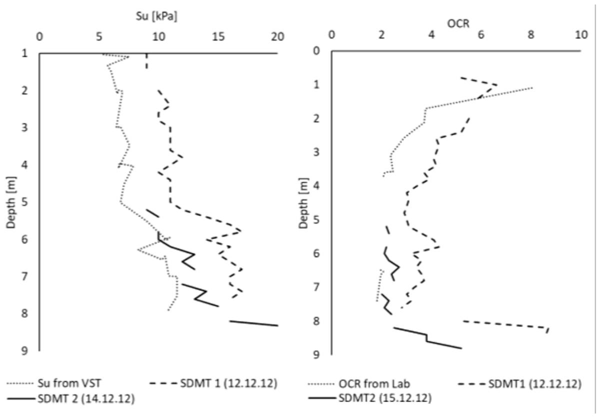



**Fig. 6.** Medusa DMT intermediate and geotechnical results.

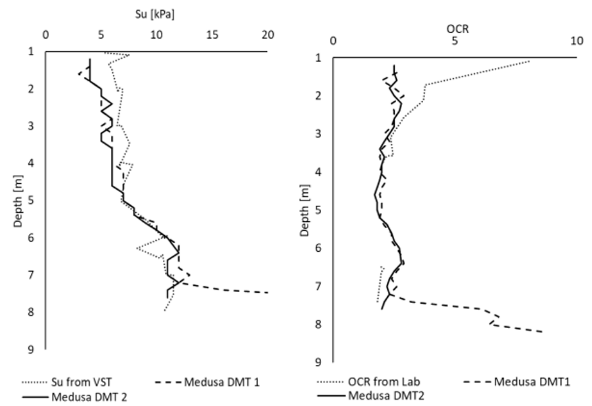
This scatter propagates into the estimated su and OCR values, leading to less reliable representations of the subsoil's mechanical state.




(a)




(b)




(c)

**Fig. 7.** Comparison of (a) $s_u$ with VST, OCR with oedometer and Pneumatic DMT results of June, 2012, (b) $s_u$ with VST, OCR with oedometer and Pneumatic DMT results of December, 2012 (c) $s_u$ with VST, OCR with oedometer and Medusa DMT results.

In contrast, the Medusa automated DMT shows a marked reduction in variability for both $s_u$ and OCR profiles. The automated control of membrane expansion, along with precise adherence to repeatable reading times, ensures that the intermediate parameters ($I_D$, $K_D$, $E_D$) are consistently measured.

Previous investigations [19] reported that the OCR values obtained from laboratory oedometer tests within the depth range of 4.0 to 6.5 m were unreliable, primarily due to sample disturbance during retrieval and handling. The presence of shell fragments and the extreme softness of the clay likely compromised sample quality, leading to non-representative preconsolidation stress estimates at these specific depths. In contrast, the OCR profile derived from the Medusa DMT (Fig. 7c) shows a consistent trend throughout the deposit. Notably, the OCR values predicted by the Medusa system above 4.0 m and below 6.5 m closely match the reliable laboratory results outside the disturbed interval. This agreement supports the validity of the Medusa-derived OCR estimates. Furthermore, within the 4.0 – 6.5 m depth range—where laboratory results are questionable—the Medusa DMT provides a smooth and mechanically consistent OCR profile, suggesting that the in-situ automated measurements may offer a more realistic representation of the stress history in this interval.

This, in turn, produces more continuous and physically representative estimates of $s_u$ and OCR, closely aligning with the reference data of [20]. Notably, the automated system effectively captures the lightly overconsolidated nature of the deposit below 3 m depth, with OCR values around 2 and reproduces the very low undrained shear strengths typical of this soft clay.

## 6 Conclusion

The investigation of the Sarapuí II soft clay using both pneumatic DMT and the automated Medusa DMT, supported by laboratory data, highlights the clear advantages of automated testing. The pneumatic DMT shows significant scatter in $I_D$, $K_D$, and $E_D$, especially in very soft layers where $p_0$ and $p_1$ are close, leading to unreliable and discontinuous soil profiles. In contrast, the Medusa DMT, with controlled membrane expansion and consistent reading times, produces smooth, reproducible parameters and more reliable estimates of key properties of soft soils such as su and OCR. The $\Delta p$ comparison further confirms the improved measurement fidelity of the Medusa system, which minimizes operator influence and ensures consistent results even in extremely soft clays. The reduced variability and strong repeatability demonstrate its high accuracy and robustness, enabling continuous and mechanically consistent soil profiling and more reliable characterization of both strength and stress-history parameters.

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