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Comparisons CPT-DMT in soft clay at Fucino-Telespazio GeoTest site

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ABSTRACT: This paper presents the comparison of results obtained from CPT/CPTU tests carried out in past investigations and from recent DMT tests carried out using the automated Medusa DMT, adopting different test procedures (standard, repeated *A*-readings, *A*-reading while penetrating), at the benchmark soft clay test site of Fucino-Telespazio, Italy. In particular, the depth profiles of the undrained shear strength s_u of the Fucino clay obtained from CPT/CPTU interpretation are compared with the s_u profiles obtained from standard DMT and from Medusa DMT using different test procedures, as well as with the s_u values obtained from field vane test (FVT), self boring pressuremeter test (SBPT) and laboratory tests available from past investigations, resulting generally in good agreement.

1 INTRODUCTION

Benchmarking is of significant importance in geotechnical engineering for testing and validating both innovative soil investigation methods and foundation solutions. The growing interest in this topic is documented by the 1st International GeoTest Site Symposium ISGTS, Oslo, 2019, aiming to promote an increasing use of benchmark test sites, selected to ensure simplicity of geotechnical conditions (i.e., relatively homogenous soil deposit) and ease of interpretation (i.e., pre-existing laboratory and field data).

Fucino-Telespazio is a well known benchmark 'GeoTest site' in Italy, constituted by a thick deposit of cemented, homogeneous soft lacustrine clay of high plasticity. The site was extensively investigated at the end of the 1980s by means of several in situ and laboratory tests carried out by various international research groups (Burghignoli et al. 1991). Earlier experimentation with the flat dilatometer (DMT) at this site was carried out in the 1970s, as reported by Marchetti (1980). Subsequently, in 2004-2005 the site was selected for validation of the seismic dilatometer (SDMT, Foti et al. 2006, Marchetti et al. 2008). More recently, in 2020 the same site was selected for experimentation with the automated Medusa DMT, ideally linking past experience and recent technological developments.

This paper presents the comparison of results obtained at Fucino-Telespazio from cone/piezocone penetration tests (CPT/CPTU) carried out in past investigations and from recent DMT tests carried out using the Medusa DMT equipment (briefly described in the next section) by adopting different test procedures. In particular, the focus in this paper is on the evaluation of the undrained shear strength s_u of the Fucino clay by different test methods.

2 MEDUSA DILATOMETER TEST

The Medusa DMT (Figure 1) is the last-generation, fully-automated version of the DMT. It is a self-contained probe able to autonomously perform dilatometer tests using a blade of standard dimensions without the pneumatic cable, the control unit and the gas tank required in the traditional pneumatic DMT configuration. A motorized syringe, driven by an electronic board powered with

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rechargeable batteries, hydraulically expands the membrane to obtain the DMT *A*, *B*, *C* pressure readings, which are acquired and stored automatically at each test depth (typically every 0.20 m). The automatic (volume controlled) hydraulic pressurization of the membrane is highly repeatable and permits to impose a programmable timing (i.e., the recommended standard timing, or different timing corresponding to variable pressurization rates) to obtain the pressure readings. The probe may operate in cableless mode, which is a significant practical advantage in the offshore industry and for deep investigations. An optional electric cable may be used to obtain real-time data during test execution.

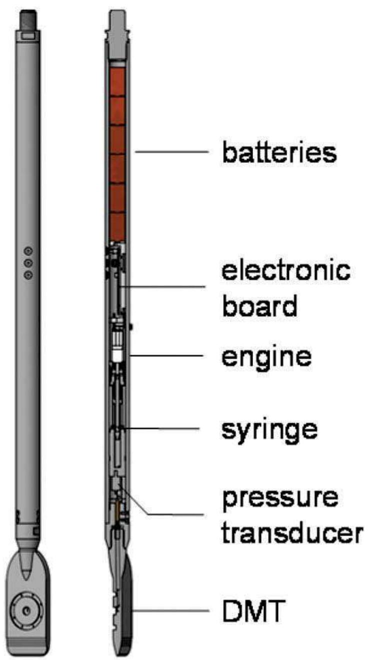

Figure 1. Main components of the Medusa DMT.

The Medusa DMT has several advantages over the traditional DMT equipment in terms of test automation, field productivity and increased accuracy (Marchetti 2018, Marchetti et al. 2019). It also provides the possibility of performing additional measurements, not feasible with the traditional DMT, including continuous measurement of the total horizontal pressure against the membrane with time at a stationary test depth, to obtain information on soil response in terms of fully drained/partially drained/undrained behavior, or during probe penetration, to obtain information on the in-situ stress state. Due to the increased accuracy of pressure measurements and controlled pressurization rate, the Medusa DMT is particularly useful for testing soils which are usually difficult to characterize using common in-situ techniques, such as very soft or even nearly liquid soils (Marchetti et al. 2021), mine tailings and intermediate soils (Monaco et al. 2021).

3 THE FUCINO-TELESPAZIO BENCHMARK TEST SITE

The Fucino-Telespazio test site is located in the Fucino basin, central Italy, about 80 km east of Rome. In 1986 the site was selected as a national benchmark test site and investigated by means of a joint effort of a number of Italian and international research groups. The primary aim of the investigation was to carry out comparative in situ and laboratory tests in a suitable soft clay deposit. The choice fell on the Fucino-Telespazio site due to its marked spatial homogeneity and apparently simple geological history. The site is constituted by a thick deposit of soft, homogeneous, highly structured $CaCO_3$ cemented clay of lacustrine origin (Fucino clay). The experimental activity, which lasted more than two years (1986-88), was documented in several research reports and papers. In particular, the data shown in this paper are taken from Burghignoli et al. (1991), who presented a comprehensive description of the in situ and laboratory testing program and a detailed geotechnical characterization of the Fucino clay.

The in situ testing program included boreholes with undisturbed sampling, cone/piezocone penetration tests (CPT/CPTU), self boring pressuremeter tests (SBPT), flat dilatometer tests (DMT), field vane tests (FVT), seismic cone tests (SCPT), cross-hole tests (CH), down-hole tests (DH), surface wave tests (SASW) and piezometer measurements.

Laboratory tests were carried out on a large number of undisturbed samples, including determination of index properties, incremental loading (IL) and constant rate of strain (CRS) oedometer tests, unconsolidated undrained (UU), isotropically consolidated drained (CID) and undrained (CIU) triaxial compression tests, direct simple shear tests (DSS-CK_0U), laboratory vane tests (VT), resonant column tests (RC) and cyclic torsional shear tests (CTS).

To minimize the influence of spatial variability of the clay properties, the field investigations were concentrated in an area of 10 × 40 m^2, to a depth of about 40 m. The superimposed profiles of the cone resistance q_c measured from four CPTs performed at the corners of the area (Figure 2) show a fair homogeneity of the site, both in vertical and horizontal directions: the soil stratigraphy is virtually identical at all test locations, with thin sandy layers identified at the same depths by all tests. Similar results were found in three CPTUs carried out in the same area.

The Fucino clay is characterized by high plasticity (plasticity index *PI* mostly between 40 and 70%, natural water content *w* between 60 and 120%). Despite its relatively recent deposition, the clay is highly structured and cemented. The calcium carbonate

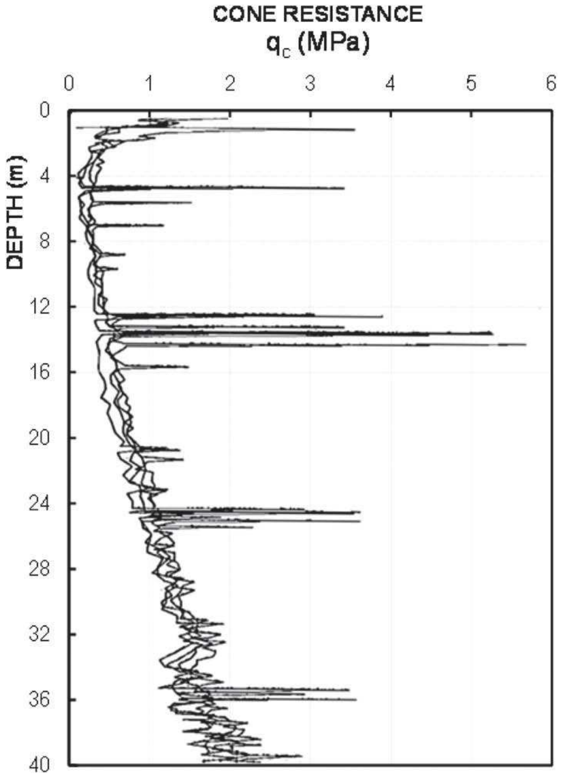

Figure 2. CPT results from past investigations at Fucino-Telespazio (Burghignoli et al. 1991).

$CaCO_3$ content was found to range between 10 and 30% in the upper 25 m, increasing to an average value of about 60% below this depth. The clay deposit is geologically normally consolidated. However both laboratory and in situ tests indicated a light overconsolidation, which was attributed mostly to diagenetic interparticle bonding due to $CaCO_3$ cementation. Burghignoli et al. (1991) pointed out that structure and cementation have a dominant influence on stress history, compressibility, consolidation and shear strength properties of the Fucino clay.

4 MEDUSA DMT TESTS AT THE FUCINO-TELESPAZIO BENCHMARK TEST SITE

An experimental program at the Fucino-Telespazio test site, including three Medusa DMT soundings and one traditional pneumatic DMT sounding carried out using the SDMT equipment, was completed in September 2020. All soundings were performed at close mutual distance, to a depth of 30 m.

The Medusa DMT soundings were carried out using three different test procedures (see Monaco et al. 2022 for details), which differ essentially for the technique adopted for measuring the *A*-pressure.

4.1 *Standard DMT procedure (STD)*

The STD procedure is the same procedure of the traditional pneumatic DMT test. As soon as the test depth is reached, the penetration is stopped and the DMT test cycle starts. The activated motorized syringe gradually increases the hydraulic pressure to the membrane. When the internal oil pressure equals the external soil pressure, the membrane lifts-off from its seat and starts to expand laterally. When the membrane has expanded of 0.05 mm at its centre, the *A*-pressure is recorded. After the *A*-reading, the motorized syringe continues to increase the pressure until the membrane displacement at the centre equals 1.10 mm. At this instant the second pressure reading *B* is recorded. As soon as the *B*-reading is obtained, the motorized syringe starts decreasing the oil pressure. If the *C*-pressure reading is requested, the motorized syringe applies a gradual and controlled depressurization after the *B*-reading and the membrane slowly returns to its initial position against the sensing disc. At the instant in which the contact reactivates, the corresponding pressure is recorded as the *C*-pressure reading. In the STD procedure the pressurization rate is regulated by the motorized syringe so that the *A*-pressure reading is obtained 15 s after start of pressurization and the *B*-pressure reading 15 s after the *A*-pressure reading, in accordance with existing standards of the pneumatic DMT (ASTM D6635-15, ISO 22476-11:2017(E)). The *C*-reading is typically obtained 30 s after start of depressurization following the *B*-reading.

4.2 *DMT repeated A-readings procedure (DMT-RA)*

The DMT-RA procedure differs from the STD procedure only in the first part of the measurement sequence, before membrane expansion, while the *B*- and *C*-pressure readings are taken exactly in the same way. As previously described, in the STD procedure the *A*-reading is taken when the membrane centre has expanded horizontally 0.05 mm against the soil, replicating exactly the same procedure implemented in the traditional pneumatic DMT test. The motorized syringe of the Medusa DMT, driven by the electronic board, is also able to maintain the membrane in equilibrium with negligible horizontal displacement of the membrane. The DMT-RA procedure makes use of this capability. The initial stage of the DMT test cycle with the DMT-RA procedure, before penetrating to the next test depth, consists in maintaining the membrane in equilibrium with the soil pressure. This state is obtained with very rapid pressure corrections operated by the motorized syringe, with negligible membrane displacement. In this situation the membrane is in equilibrium at 0.05 mm distance from the sensing disc. When the new test depth is reached, the test cycle starts (t = 0) and repeated sequential *A*-readings are taken with time during the rapid pressure corrections of the motorized syringe, monitoring the total horizontal soil pressure against the membrane with time. All the sequential A-readings are obtained without any displacement of the soil, because the blade is advanced to the test depth with the membrane already at 0.05 mm displacement from the sensing disc. Such DMT-RA procedure is characterized by the duration (T_{diss}) of the sequential A-readings taken with time (dissipation), before concluding the DMT test cycle with the standard B and C readings. The parameter T_{diss} is selected and pre-programmed before starting the test cycle, so that the membrane expansion will be activated after the time T_{diss} has elapsed. At Fucino-Telespazio T_{diss} was set equal to 15 s, to comply with the standard timing adopted in the STD procedure. The procedure and timing for taking the B and C readings are the same as in the STD procedure.

4.3 *DMT A-reading while penetrating procedure (DMTA-WP)*

The capability of the Medusa DMT to maintain the membrane in equilibrium with negligible horizontal displacement enables to obtain continuous measurements of the total horizontal pressure of the soil against the membrane during penetration of the probe. The DMTA-WP procedure consists in performing repeated A-pressure measurements (equivalent to A-pressure reading at $t = 0$ instead of the standard time of $t = 15$ s) recorded during penetration of the Medusa DMT at a constant rate. The sequence of A-readings is generally taken over depth intervals of 1 m, corresponding to the typical length of push rods. Almost all penetrometers require to stop penetration every meter to add a push rod, during which B and C pressure readings may be taken without employing additional time. A constant penetration rate of 20 mm/s, as in the standard test procedure, is generally adopted. The current Medusa DMT equipment does not include instrumentation to measure the penetration depth during the readings. Most penetrometers include an encoder (for CPT measurements) and may output a time versus depth file, helpful for accurately associating the A-readings to the corresponding depth at which they were taken. When such information is missing, the time-depth relation may be estimated assuming an average speed of penetration, estimated by measuring the time for penetrating a 1-meter rod. The average speed and the time from the start of penetration enables to estimate the depth of each A-reading. Although not as accurate as with an encoder, the error is reasonably limited in terms of % error, since each measuring interval is maximum 1 m long.

4.4 *Comparison of results obtained by different test procedures*

Figure 3 shows the comparison of the results obtained by Medusa DMT using the three different test procedures (STD, DMT-RA, DMTA-WP) and the results obtained by traditional DMT. The test results obtained from Medusa DMT were processed using the same data reduction and interpretation formulae used for the traditional DMT test (ISSMGE TC16 Report, Marchetti et al. 2001). In particular, Figure 3 shows the depth profiles of the corrected pressure readings p_0, p_1, p_2 (A, B, C corrected with the calibration offsets ΔA, ΔB to account for membrane stiffness), as well as of the derived parameters material index I_D and horizontal stress index K_D. For the DMT-RA sounding, the A-pressure reading used in data processing is the last value obtained from the A-dissipation series, i.e. the A-pressure recorded 15 s after start of pressurization. In the processing of data from all soundings the groundwater table was assumed at a depth of 0.60 m below the ground surface, as indicated by the p_2 values observed in the very few thin sand layers.

The profiles of p_0 obtained by Medusa DMT using the three different test procedures are very similar, despite the different techniques adopted for measuring the A-pressure, and in good agreement with the profile of p_0 obtained by traditional DMT.

The profiles of p_1 and p_2 obtained by Medusa DMT (all test procedures) and traditional DMT are nearly coincident. The values of p_1 and p_2 obtained by the DMTA-WP procedure are discontinuous, because in this case the B and C pressure readings are performed at depth intervals of 1 m, instead of 0.20 m as in the STD and DMT-RA procedures.

The profile of the material index I_D, which depends on the difference ($p_1 - p_0$), shows some inconsistency between the values obtained by different test procedures. In particular, the values of I_D calculated from p_0 and p_1 data acquired by the DMTA-WP procedure appear significantly lower than the I_D values provided by the STD and the DMT-RA procedures. This discrepancy could be due to the fact that in the DMTA-WP procedure the A-pressure is measured at $t = 0$ instead of $t = 15$ s, resulting in lower values of the difference ($p_1 - p_0$), and for low I_D values such incongruity is amplified by the logarithmic scale. The values of the horizontal stress index K_D, which depends only on p_0, do not seem influenced by the adopted test procedure.

5 EVALUATION OF THE UNDRAINED SHEAR STRENGTH FROM CPT/CPTU AND DMT

As described by Burghignoli et al. (1991) and Soccodato (2003), the shear strength characteristics of the Fucino clay were determined by means of a variety of in situ and laboratory tests carried out in the 1987 investigation. In particular, the undrained shear strength s_u was obtained from CPT and CPTU interpretation with the usual relationships, respectively:

$$s_u = \frac{q_c - \sigma_{v0}}{N_k} \qquad (1)$$

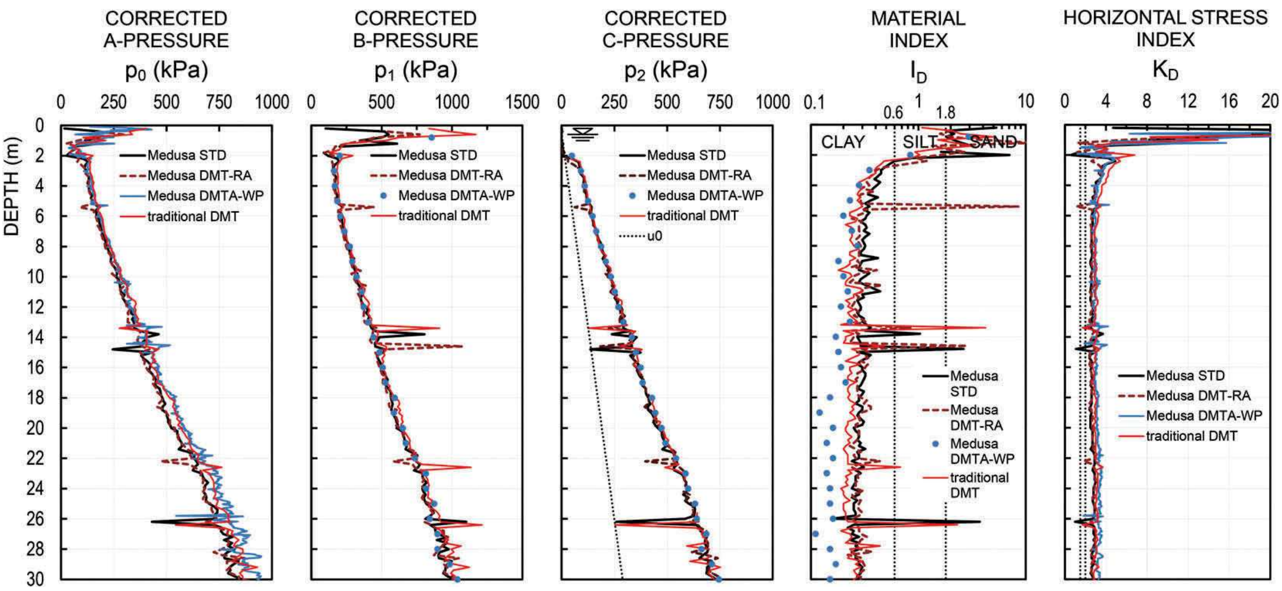

Figure 3. Results obtained by Medusa DMT using different test procedures and by traditional DMT at Fucino-Telespazio.

$$s_u = \frac{q_t - \sigma_{v0}}{N_{kt}} \quad (2)$$

where q_c = cone resistance (CPT), q_t = corrected cone resistance (CPTU), σ_{v0} = total overburden stress, N_k and N_{kt} = cone bearing capacity factors for CPT and CPTU respectively, which were assumed to range between 14 and 22.

The undrained shear strength s_u was estimated from DMT results, both obtained by traditional pneumatic DMT and by Medusa DMT in the 2020 investigation, using the original correlation proposed by Marchetti (1980):

$$s_u = 0.22\sigma'_{v0}(0.5K_D)^{1.25} \quad (3)$$

Figure 4 shows the comparison of the depth profiles of the undrained shear strength s_u obtained at Fucino-Telespazio from different in situ and laboratory tests in past investigations and in the 2020 Medusa DMT campaign. In particular, the s_u profiles from the 1987 investigation shown in Figure 4 (data from Burghignoli et al. 1991) were obtained in situ from several CPT and CPTU tests, field vane tests (FVT), self boring pressuremeter tests (SBPT), DMT tests, and in the laboratory from direct simple shear tests (DSS-CK$_0$U), unconsolidated undrained triaxial compression tests (UU) and laboratory vane tests. For CPT and CPTU only the lower- and upper-bound trend lines, corresponding to the average s_u estimated from Eqs. 1 and 2 by assuming N_k and N_{kt} equal to 22 and 14 respectively, are plotted in Figure 4. The values of s_u from FVT in Figure 4 are not corrected for strain rate and anisotropy effects.

Figure 4 shows an overall agreement between the s_u values obtained from different in situ and laboratory tests. With reference to the various field tests results obtained in 1987, Burghignoli et al. (1991) observed that, below an upper desiccated crust, there is a fair agreement between the s_u values resulting from FVT and DMT. The SBPT provided values of s_u significantly higher than those resulting from other in situ and laboratory tests. Soccodato (2003) suggested that low values of N_k for CPT are needed in order to match the data, while N_{kt} = 15 seems to

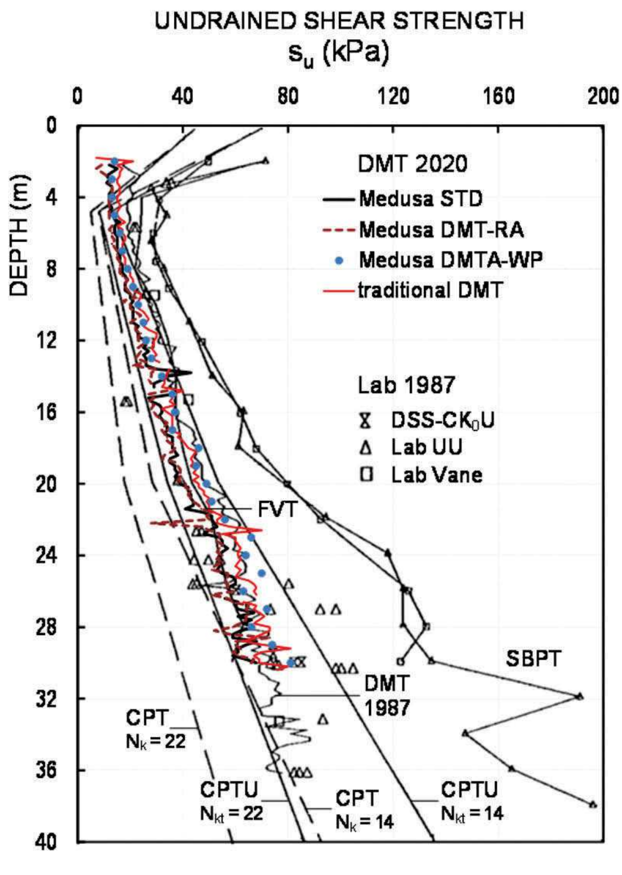

Figure 4. Undrained shear strength s_u at Fucino-Telespazio from recent DMT tests vs. s_u from CPT/CPTU and other in situ and laboratory tests obtained in the 1987 investigation (modified from Burghignoli et al. 1991).

be appropriate for CPTU. As to laboratory tests, the values of s_u resulting from UU and from DSS-CK$_0$ U tests show a marked increase below a depth of about 25 m, reflecting the increase of $CaCO_3$ content with depth. This feature is not reflected by the results of the in situ tests with the exception of the SBPT, which provided a different trend of s_u below 24-25 m of depth. Burghignoli et al. (1991) commented that in highly structured soft clays, like the Fucino clay, the results of push-in in situ testing techniques, such as CPT/CPTU and DMT, can be hampered by the destructuration of the tested soil induced by the insertion of the probe, which may partially obliterate the effect of diagenetic bonds on the inferred s_u.

In Figure 4 the profiles of s_u estimated by Eq. 3 from the results of the three Medusa DMT tests carried out adopting different test procedures (STD, DMT-RA and DMTA-WP) and from the traditional DMT carried out in the 2020 campaign are superimposed to the profiles obtained by all test methods in past investigations. As already noted with reference to the K_D profiles (Figure 3), which are used to estimate s_u by Eq. 3, the s_u values are not practically influenced by the adopted test procedure. The s_u values obtained from Medusa DMT and the traditional pneumatic DMT are almost coincident, and also in very good agreement with the s_u obtained from DMT tests carried out in 1987. In general, the profiles of s_u obtained from all DMTs plot in between the s_u profiles determined by other in situ and laboratory tests. This finding is in line with previous experience. In fact, as described in the TC16 DMT Report (Marchetti et al. 2001), the s_u estimated from DMT by Eq. 3 has generally been found to be in an intermediate position between the s_u estimated from other tests, as presented by various researchers in different clays (e.g., Nash et al. 1992 at the National Research Site of Bothkennar, UK).

6 CONCLUSIONS

Benchmark GeoTest sites, such as the Fucino-Telespazio soft clay test site, prove to be of paramount importance for testing and validating innovative soil investigation methods. In this respect, the recent experimental program at Fucino-Telespazio with Medusa DMT (the last-generation, fully-automated version of the DMT) could uniquely benefit of the availability of an existing large and consistent data set obtained in past investigations from a variety of high-quality in situ and laboratory tests.

Due to the increased accuracy of pressure measurements and controlled pressurization rate, the Medusa DMT is particularly useful for testing very soft soils, in which the measured pressures are typically very small. Moreover, its technical features permit to implement alternative test procedures (repeated *A*-readings, *A*-reading while penetrating), besides the 'standard' DMT procedure. The comparison of the results obtained at Fucino-Telespazio indicate a substantial consistency of measurements provided by Medusa DMT adopting different test procedures and by traditional pneumatic DMT.

The interpretation of Medusa DMT test results in terms of soil parameters takes advantage of the wide experience available for the traditional pneumatic DMT test, and essentially shares the same set of established soil property correlations available in literature. The profiles of s_u obtained from both Medusa DMT and traditional DMT in Fucino clay are found in an intermediate position between the s_u profiles determined by other in situ and laboratory tests, in particular by CPT/CPTU tests. This finding is in agreement with other comparisons of s_u estimated from DMT and from other tests, available from several soft clay test sites.

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