Comparison of Various Pressuremeter Tests for Characterizing Sensitive Lacustrine Clays

Comparaison de divers essais pressiométriques pour la caractérisation des argiles lacustres sensibles

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ABSTRACT

This contribution presents the results of an extensive in-situ testing campaign conducted at a test site near Rosenheim, southern Germany, to characterize the mechanical properties of a sensitive soft lacustrine clay. The investigation evaluates three different pressuremeter testing (PMT) technologies, including Self-boring pressuremeter (SBPM), Menard-PMT, and Pencel-PMT. Our comparison focuses on the influence of the different probe insertion methods specifically for each of the three PMT technologies on the measurements and consequently the data interpretation for deriving classical soil mechanics parameters. The PMT probe insertion processes, integral to each test, introduce varying degrees of soil disturbance. Particularly in sensitive soft soils, the disturbance associated with the boring (SBPM) and push-in process (Menard-PMT, Pencel-PMT) as well as the particular features of the probe significantly influence the soil-specific parameters evaluated from the PMT results. The interpretation of the PMT is based on the cavity expansion theory and focuses on the semi-empirical estimation of the soil stiffness, soil strength (limit pressure) and the in-situ horizontal stress. In this study, we assess the advantages and shortcomings, hence the applicability of the considered techniques for the investigation of the Rosenheim soft sensitive clays. We found that the disturbance during PMT installation and eventually the device features significantly influence the lift-off pressure and the stiffness derived from the pressuremeter curve. On the contrary, the limit pressure was similar for the three devices used in this study. Further numerical investigations with advanced constitutive models will be carried out to further understand the influence of the PMT installation on the pressuremeter results.

RESUME

Cette recherche présente les résultats d’une vaste campagne d'essais in situ menée sur un site d'essai près de Rosenheim, dans le sud de l'Allemagne, dans le but de caractériser les propriétés mécaniques d’une argile lacustre tendre et sensible. L'étude évalue trois technologies différentes d'essais pressiométriques (PMT): le pressiomètre auto-foreur (SBPM), le Menard-PMT et le Pencel-PMT. Notre comparaison étudie l'influence des différentes méthodes d'insertion de la sonde sur les mesures et sur l'interprétation des données afin d’en déduire les paramètres géotechniques. Les processus de forage et d'insertion des sondes PMT, qui font partie intégrante de chaque essai, perturbent le sol à des degrés divers. Particulièrement dans les sols mous sensibles, la perturbation du sol associée au forage, au type de sonde et aux processus d'insertion de la sonde influence de manière significative les paramètres spécifiques au sol déduits des mesures PMT. L'interprétation de ces mesures se base sur la théorie de l'expansion des cavités et se concentre sur l’estimation semi-empirique de la rigidité , de la résistance, de la pression limite et de la contrainte horizontale du sol in situ. Dans cette étude, nous évaluons les avantages et les limites, et donc l'applicabilité de chaque méthode PMT observée, en particulier pour l'évaluation des sols mous et sensibles de Rosenheim. Nous avons constaté que la perturbation pendant l'installation du PMT, et éventuellement les caractéristiques de l'appareil, influencent de manière significative la pression de décollement et la rigidité issue de la courbe du pressiomètre. En revanche, la pression limite était similaire pour les trois dispositifs utilisés dans cette campagne d’essais. D'autres études numériques avec des modèles constitutifs avancés seront menées pour mieux comprendre l'influence de l'installation de la PMT sur les résultats du pressiomètre.

Keywords: in-situ testing; sensitive soft clay; pressuremeter testing; Menard-PMT; Pencel-PMT; SBPM.

1. Introduction

The Pressuremeter Tests (PMTs) are classified based on their insertion method into three main categories: 1) Pre-boring, 2) Self-boring, and 3) Push-in methods. The applicability of the insertion method depends on site- and soil-specific conditions. PMT probes are mainly classified into two types: electrical and hydraulic. Electrical probes use sensors to measure radial membrane expansion, while hydraulic probes assess expansion by measuring the volume of the injected fluid. Hydraulic probes are further divided into Monocell (MC) and Tricell (TC) systems, with the latter featuring one measuring cell and two guard cells for enhanced accuracy (Marcil 2020).

In recent decades, researchers have sought to enhance various types of PMTs for use in cohesive soils to reduce disturbance during insertion. Benoit & Howie (2014) assert that a certain degree of soil disturbance is inevitable during probe installation. Probe insertion through pre-drilled boreholes causes unloading, leading to plastic deformation especially in soft clays and cohesionless soils hence unavoidable soil disturbance. The Self-boring pressuremeter (SBPM) was developed to minimize soil disturbance by simultaneously pushing the probe while cutting the soil with a sharp cutting shoe (Benoit & Howie 2014). Bandis & Lacasse (1986) found that Push-in PMTs caused significant soil disturbance. Other Pushed-in method, so-called Full-displacement PMTs were designed to create a uniform and repeatable soil disturbance around the expansion unit, ensuring more consistent but in regard to the soil disturbance possibly less representative test results (Benoit & Howie 2014).

This study focuses on a sensitive lacustrine clay deposit within the Rosenheim basin located approximately 80 km southeast of Munich. This region is known for foundation design challenging, sensitive lacustrine clay. The subsoil consists of quaternary young fine-grained sediments of mostly clay with a maximum depth of about 300 m (Reich (1955); Wolff 1979; Schorr et al., 2024). The inherent susceptibility of these sediments to disturbance, manifest as a reduction of their strength due to fabric and bonding degradation under both static and dynamic loading. As part of a currently ongoing research testing 12 different methods of pile foundation and soil improvement respectively at the so-called Kolbermoor test site it was decided to conduct series of PMTs. These tests were designed to assess the impact of soil disturbance from the processes of probe insertion on the measuring data from the cavity expansion. Specifically, three types of PMTs each representing a distinct length to diameter ratio (L/D) and insertion technique were investigated: 1) Menard pressuremeter, 2) Self-boring pressuremeter from Cambridge Insitu, and 3) Pencel pressuremeter. By comparing the test results, the study aims to explore how assumed in correspondence to the different PMT technologies various degrees of soil disturbance influence the accuracy and reliability of determination of geotechnical parameters. The interpretation is performed for fundamental parameters derived from PMTs, including the lift-off pressure (P_0), the deformability modulus (E_M), the limit pressure (P_L) and the undrained shear strength (c_u).

2. Rosenheim Lacustrine Clay

2.1. Site description and geology

The region around Rosenheim, in southern Germany, lies within the catchment area of the Inn River. During the last ice age, this area was part of a vast glacial valley known as the Ur-Inn, characterized by a solid ice base and a terminal moraine formed by glacial debris. As the ice age ended, the moraine-dammed the glacier's meltwater, creating the Rosenheim Lake expanding to an area of more than 420 km² (Kroemer, 2011). Over time, fluviatile sediments transported by the Inn filled the lake, depositing fine-grained soils - silt, clay, and fine sand - based on mechanical, chemical and biogenic sedimentation (Schumann, 1969). Geophysical studies estimate these deposits to be up to 80 m thick at the Kolbermoor test site (Wolff 1979).

2.2. Soil classification

To analyze the soil classification of the Rosenheim basin in the Kolbermoor test field, various sampling methods were employed, including core cutter, rotary core drilling (RCD), and Osterberg sampling. Fig. 1 presents the geotechnical characterization, indicating that most of the samples fall within the low to medium plasticity clay range.

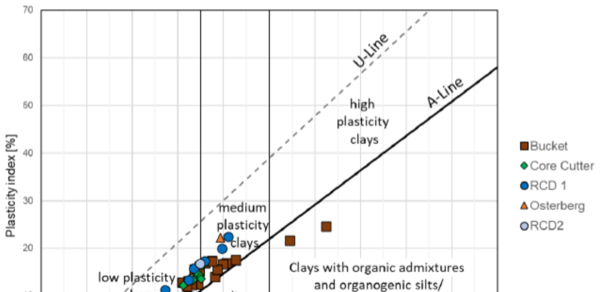


Figure 1. Plasticity of lacustrine clay at the Kolbermoor test site.

The lacustrine clay in the Rosenheim basin consists of in average 24% clay, 72% silt, and 4% sand, with no gravel present taken from samples down to a depth of 20 m. The natural water content ranges from 24% to 53%, and the samples predominantly exhibit a plastic to soft consistency. In laboratory permeability tests, the coefficient of permeability was determined from 10^{-9} to 10^{-8} m/s. The void ratio e varies between about 0.8 and

1.1. Oedometer tests indicate that the overconsolidation ratio (*OCR*) exceeds 2 at depths down to 2 m. Between 2 and 9 m, the lacustrine clay remains overconsolidated with $1 < OCR < 2$, while at greater depths, the *OCR* is at about 1. It needs to be noted that significant soil disturbance is induced by sampling and the further preparations in the laboratory in order to conduct oedometer tests. Hence, about among other parameters *e* and *OCR* are affected by a yet unknown degree of soil disturbance.

2.3. Field investigation tests results

In field investigations out of PMTs, cone penetration tests with pore pressure measurements (CPTu) (DIN EN ISO 22476-1:2012) and seismic down-hole (DH) (ASTM D7400) tests were conducted at the Kolbermoor test site.

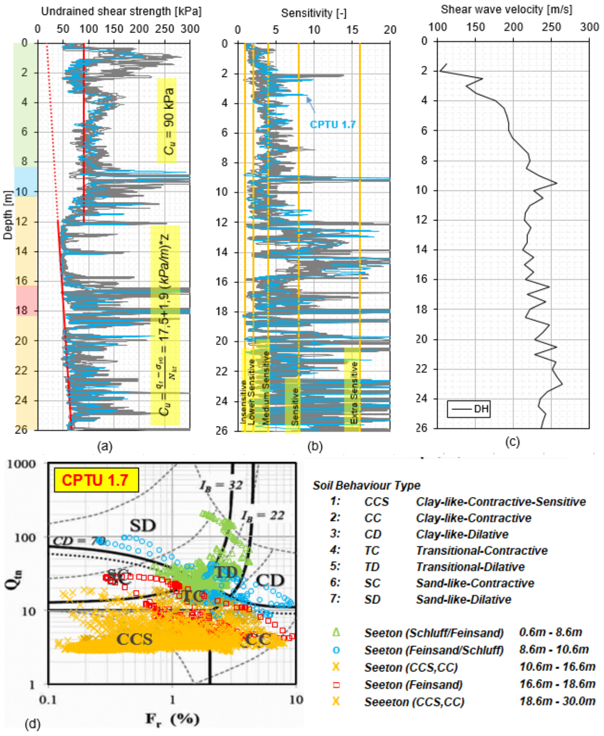


Figure 2. Results from CPTu tests for a) Undrained shear strength c_u, b) Sensitivity according to Robertson 2016, c) Shear wave velocity V_s by DH measurements in depth and d) SBT evaluation based on Robertson 2016.

Fig. 2(a-b) presents the undrained shear strength (c_u) and sensitivity profiles derived from seven CPTu tests across the site, while Fig. 2d illustrates the soil behavior type (SBT) classification based on Robertson (2016). In this figure, CPTU 1.7 is shown with the blue color as it is closest at a distance of maximum 6 m apart from the PMTs investigated in section 3 of this paper. In this study, the cone factor (N_{kt}) is assumed 13 to estimate c_u. The CPTu results indicate that the soil profile consists of two main layers: upper clay (0.6–8.6 m) and lower clay (10.6–30.0 m). The upper clay has an average c_u of 90 kPa, ranging from medium sensitive to sensitive, whereas the lower clay exhibits lower c_u values that increase with depth (as shown in Fig. 2a) and has higher sensitivity than the upper layer. According to SBT classification, the upper clay (marked with green Δ in Fig. 2d predominantly falls within the transitional-contractive and transitional-dilative (TC and TD) zones. The correspondingly decreasing values of *OCR* from laboratory tests support this conclusion, indicating that Transitional Contractive (TC) soils generally correspond to slightly overconsolidated ($OCR < 2$) to normally consolidated soils ($OCR \approx 1$) which was determined down to 9.0 m depth and hence the upper clay layer respectively. Additionally, the upper layer (down to 2 m depth) classified as Transitional Dilative (TD) soils in the SBT framework are typically associated with moderately to highly overconsolidated clays and silts, with an *OCR* range of approximately 2 to 4 or higher. In contrast, the lower clay (marked with yellow X) corresponds to clay-like contractive with sensitive behavior (CCS and CC). Additionally, two fine sand-like layers are present between the upper and lower clay. Fig. 2c presents the shear wave velocity (V_s) profile down to a depth of 26 m, measured through downhole (DH) testing at 0.5 m intervals by the use of the SDMT. The results indicate that V_s increases within the upper clay, ranging from 100 to 200 m/s with depth, while the lower clay exhibits V_s values between 200 and 270 m/s.

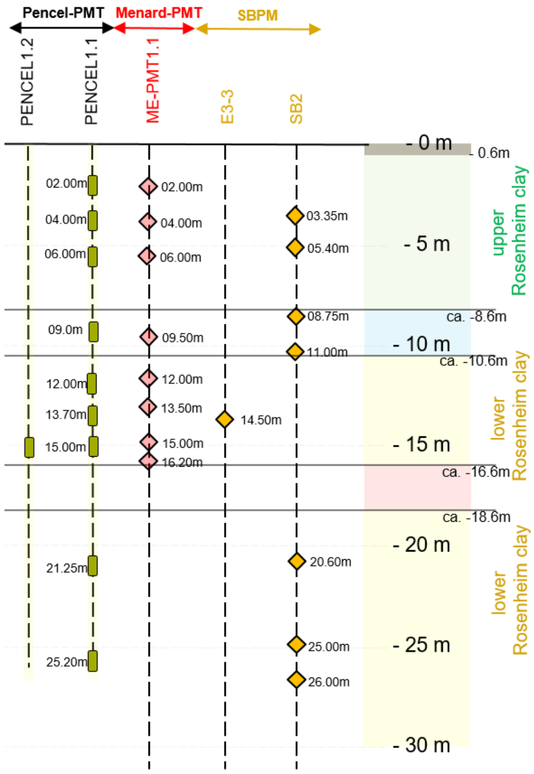


Figure 3. Investigated PMTs at Kolbermoor test site.

3. PMT apparatuses tested in lacustrine clay

The in-situ testing campaign, including PMTs, was carried out to investigate the characteristics of sensitive lacustrine clay deposit at the Kolbermoor site. Using SBPM, Menard-, and Pencel-PMTs, respectively, three different PMT technologies were employed featuring two insertion methods, namely the self-boring and the push-in technique. Fig. 3 illustrates the depth profiles of the different PMT tests, with all methods planned to be conducted up to 26 m depth. For the further investigations, the primary PMTs, including PENCEL1.1, SB2, and ME-PMT1.1, are positioned comparably close to each other to evaluate their performance under identical conditions, with a maximum distance of 15 m. At PENCEL1.2 one Pencel-PMT was performed at a depth of 15 m and at E3-3 a single SBPM has been carried out.

3.1. Menard-PMT

The Menard-PMT is an in-situ testing device used to assess soil and rock stress-strain behavior. It involves inserting a cylindrical probe into a pre-drilled borehole or pressing the probe into the ground and then inflating a flexible membrane to apply controlled radial pressure on the surrounding soil. This test best suits firm clays, mixed grained soils owning significant cohesion and soft rocks where boreholes can be drilled without collapsing. A pre-drilled borehole leads to some disturbance to the surrounding soil, which reduces the horizontal stress and influences test results.

Figure 4. Menard control unit and Tri-cell pressuremeter probe Type G-AX with and without slotted tube.

In this study, Menard Company conducted various PMT tests (see Fig. 3) up to a depth of 16.0 m using a Tri-cell G-type probe (Fig. 4). For insertion at the Kolbermoor test site, the probe was driven / pushed in with a slotted tube (DST) without pre-boring using a cone-shaped attachment connected to the slotted tube. The probe has a 60 mm diameter and a total length of 600 mm, including upper and lower guard cells, with a 370 mm long expandable section. In this investigation, the instrument is calibrated prior to the PMTs to account for pressure losses. The wall rigidity of the probe is assessed by measuring pressure losses during calibration. This process ensures that the actual pressure applied to the soil is determined to take into account the compensating for membrane resistance. During calibration, the probe is inflated in 25 kPa increments, with each pressure level held for 1 minute to record the corresponding volumes. A calibration curve is then established to adjust the PMT pressure readings. In soft soils, volume loss correction is considered negligible (DIN EN ISO 22476-4:2021).

3.2. Self-boring pressuremeter (SBPM)

SBPM was independently developed with French and English research groups (Baguelin et al., 1972; Wroth & Hughes, 1972) on the purpose of reducing disturbances due to probe insertion. Unlike the prebored pressuremeter, SBPM advances by simultaneously pushing and cutting soil, which enters through a sharp cutting shoe. This cutting mechanism breaks the soil into small fragments, transported to the surface by a flushing fluid, typically water. With no external flushing, assumed minimal in-situ stress alterations make SBPM ideal for testing soft clays, silts and sands. Since the probe creates the borehole, according to Silvestri, (2003) soil disturbance is minimized. The probe advances through self-boring and, once in position, inflates its cylindrical membrane. Six equally spaced displacement transducers measure the radial expansion of the membrane, while an internal pressure transducer records the applied pressure. From the literature, this method should offer advantages by a compared to other PMT techniques more adequate soil parameter estimation suitable for indirect design methods. However, to the application of the SBPM in field is rather challenging and has depth limitations.

Figure 5. SBPM probe equipment used at Kolbermoor test site.

At the Kolbermoor test site, the SBPM tests were conducted by Cambridge Insitu Ltd. This study focuses on borehole SB2 (Fig. 3), where seven tests were performed at depths ranging from 3.3 m to 26.0 m. The SBPM probe, with a diameter of 88.1 mm and a length of 1.2 m, was positioned about 1.5 m above the actuel testing position using a rotary drilling rig. The mechanism of self-boring was used for the final insertion of the apporximately 1.5 m as mentioned above. The lower probe area could expand using dry nitrogen gas, with radial expansion limited to 15%. The SBPM setup used in Rosenheim clay had a cutting arrangement that creates a hole about 1 mm larger than the expanding section. The probe equipped with six displacment measuring arms recorded radial deformations. Fig. 3 illustrates the used SBPM probe.

3.3. Pencel-PMT

In this study, the Pencel-PMT from ROCTEST, Canada, was utilized. The Pencel-PMT was developed to simplify pressuremeter testing by eliminating the need for pre-boring or self-boring, reducing time and equipment demands (Messaoud et al., 2024). The probe is designed to be used together with lightweight drilling equipment (Roctest Ltd, 2023). The drilling equipment bores a hole down to a depth close to the testing depth and then inserts the Pencel probe by push-in to the actual position of testing. The Pencel-PMT evolved from the pavement evaluation tool developed by Briaud & Shields (1979), which was also pushed into position for testing. These instruments were designed to ensure a uniform and repeatable degree of soil disturbance. A key benefit of this approach is its higher production rate compared with other PMTs (Benoit & Howie, 2014). Fig. 3 illustrates the depths of ten PMT tests conducted using the Pencel probe. According to Roctest Ltd, 2023 the Pencel-PMT mono-cellular probe has a total length of 580 mm, whereas the expandable section is 240 mm long, and a maximum deflated diameter of 32.1 mm, slightly smaller than a standard cone penetration test CPT. The maximum working capacity is of 2.500 kPa and the maximum recommended volume injectable is 90 cc. However, the volume limit was exceeded and volumes of up to 110 cc were injected without damaging the membrane. Thus, the maximum radial strains reached was 25%.

Figure 6. Control unit and mono-cellular probe of the Pence-PMT.

The probe insertion was done by firstly pre-drilling to a depth 1.5 m above the testing depth and finally pushing the probe to testing depth. The tests were conducted volume controlled in steps of 5 cc. The pressure and volume change were recorded 15 seconds after the injection of the 5 cc increment, allowing for pressure equalization in the system. This is required as the pressure measurement is done at the surface and thus includes the flow resistance through the tubing. The measured raw data was corrected for membrane stiffness and volume calibration. The membrane stiffness correction was conducted by inflating the probe in the air. A maximum membrane resistance of 150 kPa at 120 cc was measured. The volume calibration was conducted by inflating the probe in a calibration steel tube. The results showed a system stiffness of around 1000 kPa per 4 cc. Fig. 6 presents the Pencel-PMT equipment used in this research.

4. Comparison of PMT-measured results

PMT data typically depict the relationship between the change of the radial pressure and change of the volume during expansion. Wroth (1982) noted that when PMT installation minimizes soil disturbance, the lift-off pressure (P_0) aligns with the in-situ total lateral pressure at rest (σ_{h0}). However, different probe insertion methods introduce varying degrees of disturbance. Fig. 7 illustrates schematic curves from PMT for three insertion methods. The S-curve starts with a pressure rise to until the probe and membrane respecively is in contact to the soil wall. Expansion pressure and its change with increasing cavity strain certainly varies with soil type, borehole/probe size, drilling quality, and operator skill (Benoit & Howie, 2014). As shown in the figure, prebored tests allow soil relaxation and consequently convergance of the bore hole before pressure increases until the in situ-stress. In self-boring it is assumed that in-situ stresses remain largely unchanged during the process of insertion, making the first inflection of the PMT curve representative of the determination of the lateral soil stress at rest. In contrast PMT with full displacement probes, being pushed in, may start with stress higher than the in situ stress at rest (Fig. 7c).

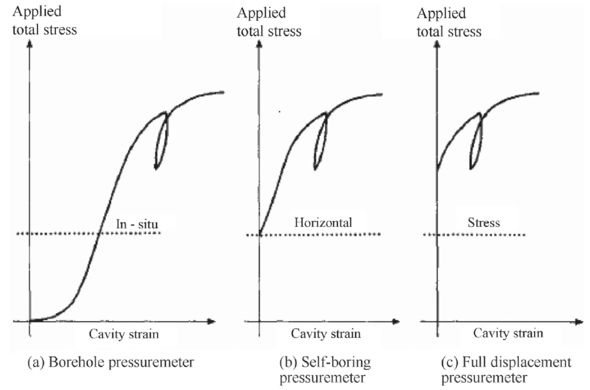


Figure 7. Schematic stress-strain curves affected by different PMT installation procedures (Clayton et al. 1995)

4.1. PMT methods performed in Kolbermoor

Fig. 8 presents the measured data from all PMTs discussed by this study as already highlighted by Fig 3, in which the curves of radial pressure-volume and – volumetric strain change were obtained. Volumetric strain is expressed as $\Delta V/V_0$ representing the ratio of the measured change in volume ΔV to the initial volume of the probe V_0. In the SBPM method, expansion is assumed to occur within a cylindrical zone corresponding to a length of 50 cm. For Menard-PMTs (see Fig. 8a), testing was conducted at eight different depths, with a single expansion phase performed at each depth. The results indicate that inclination of the curve at a given depth is influenced by the soil stiffness. At all depths, after the mobilisation of pressure with increasing volume termed in the literature as elastic phase a so-called plastic phase used for the determination of the limit pressure is clearly observable. The curves demonstrate an overall increase of the pressure needed to inflate the pressiometer with depth in both the upper and lower clay formations. Here the test at 8 m depth is evaluated as an outlier. This particular test exhibits a higher limit pressure, likely due to its proximity to a layer of silty sand, which as well corresponds to significantly higher values of q_c from CPTu.

The Pencel-PMTs at the location of PENCEL1.1 illustrated by Fig 8b were conducted at nine different depths, with a single cycle of loading and unloading performed. The results indicate that at depths of 2–9 m and 25.2 m, the curves exhibit both elastic and plastic zones. In contrast, tests conducted between 12–21.2 m show completely linear results. The very low stiffness may be a result of significant disturbance in the surrounding soil during probe insertion. The high sensitivity of these layers influences this disturbance (see Fig. 2b) compared to other, less sensitive layers.

Additionally, SBPM tests were conducted at seven different depths at SB2. The pressure-volume curves for each of the SBPM tests include multiple unloading-reloading cycles (Fig. 8c), allowing for the estimation of the unloading-reloading modulus of soils at various stress levels. The results show that the lift-off pressure is increasing by increasing depth.

Figs. 9 illustrate the pressure-volume response and volumetric strain of the probes behavior at specific depths, including 4 m, 6 m, and 15 m. The results indicate that the maximum volume strain observed in the SBPM is greater than that in the Menard-PMT and Pencel-PMT, with the Pencel-PMT showing the least expansion. This difference can be attributed to variations in probe size and insertion methods. As shown in Fig. 8c and Fig. 9 (d-f), SBPM tests did not exceed 30% volumetric strain. In contrast, Menard-PMT and Pencel-PMT exhibited volumetric strains exceeding 50% (see Figs. 8 (a-b)) to achieve the same pressure levels.

In upper clay at depths of 4 m and 6 m (see Fig. 9), the maximum pressures recorded in the Pencel-PMT and Menard-PMT are higher than those in the SBPM. However, at higher stress levels, the slope of the volume strain versus pressure curves remains similar across all three methods of PMTs. This suggests that in the upper clay, the soil exhibits comparable behaviour while interacting with all of the different PMT methods at least in the phase of failure (plastic behavior). A notable difference is observed in the lower clay at a depth of 15 m, where the stiffness during first loading of the Pencel-PMT is seemingly different from the results of the SBPM, which may indicate significant soil disturbance during the process of insertion. This disturbance likely affected the test, causing the probe to reach its maximum expansion limit prematurely. Consequently, the maximum pressure recorded in the Pencel-PMT at this depth is the lowest among the three methods.

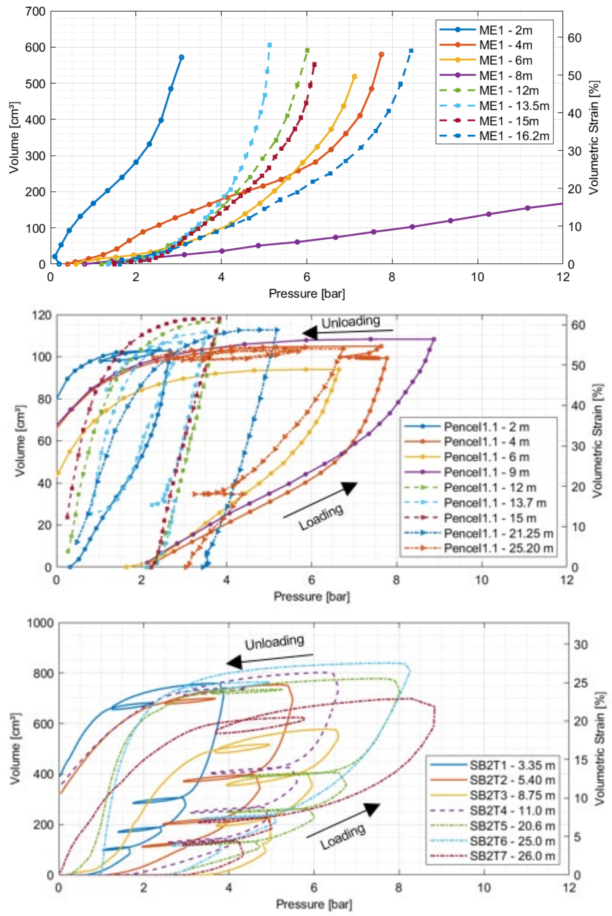


Figure 8. Results from a) Menard-PMT, b) Pencel-PMT and c) SBPM.

5. Comparison of interpreted results

From a conventional PMT, the stress-strain response provides essential geotechnical parameters, including lift-off pressure (P_0), deformability modulus (E_M), limit pressure (P_L), and undrained shear strength (c_u) for clay. This section presents an interpretation of these parameters based on the three different PMT techniques investigated in this study.

The lift-off pressure (P_0) refers to the pressure at which the membrane gets in full contact with the soil at the wall of the borehole, indicating the initiation of cavity expansion. It is commonly interpreted as the total horizontal pressure in the soil at rest (Fig. 10c). In this figure, the theoretical total horizontal pressure profiles with depth are shown as black dashed lines for two earth pressure at rest coefficients (k_0) of 0.5 and 0.6. The calculations assume a soil unit weight of 20 kN/m³ and a groundwater table at 1 m depth. Overall, P_0 increases with depth across all PMT methods, ranging from 20 kPa at 2 m depth to 320 kPa at 26 m depth. As shown in Fig. 10c, the Menard-PMT exhibits lower P_0 values compared to the other methods, which could be attributed to the disturbance caused by the push-in insertion method, especially given its larger probe diameter relative to the Pencel.

Benoit & Howie (2014) emphasize that the commonly termed pressuremeter modulus is more accurately referred to as the modulus of deformation. Here, the deformability modulus (E_M) is generally defined as the slope after reaching the pressure of P_0 sometimes interpreted as a quasi-linear portion of the stress – strain curve. In this study, the modulus for Menard-PMT and Pencel-PMT are determined from a straight-line portion in the initial curve based on the theory of linear elasticity (Gambin *et al.,* 1996) in Eq. (1):

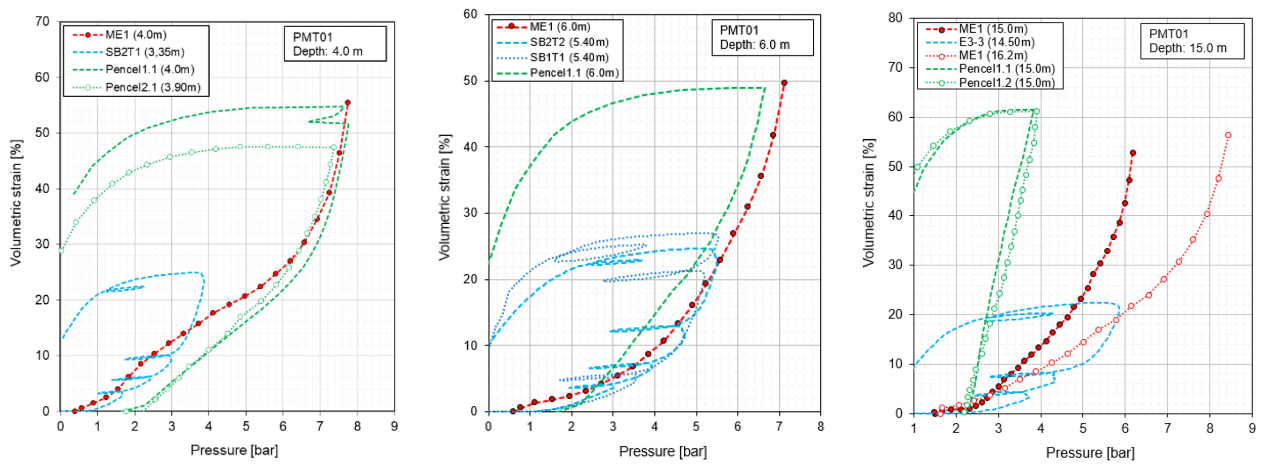
$$E_M = 2(1+\upsilon)\left[V_c + \left[\frac{V_1+V_2}{2}\right]\right]\frac{(P_2-P_1)}{(V_2-V_1)} \quad (1)$$

where the Poisson's ratio is assumed to be ν = 0.33 and V_c is volume of initial cavity; ΔV and ΔP are volume and pressure increase in straight-line portion of test curve, respectively. For SBPM, the modulus is estimated by Mair and Wood (1987) as follows:

$$E = (1+\upsilon)\cdot\left(\frac{\Delta P_c}{\Delta \varepsilon_c}\right) \quad (2)$$

where ΔP_c is pressure increase corresponding to $\Delta\varepsilon_c$ cavity strain increase. For ensuring comparison in Eq. (2) $E = E_M$.

Fig. 10d presents the estimated modulus of deformability E_M from all PMTs, highlighting variations of E_M with depth. According to Gambin et al. (1996), the slope of the curve used to derive the modulus E_M is influenced by several factors, including the coefficient of earth pressure at rest, soil stiffness, the length-to-diameter ratio of the pressuremeter probe, borehole wall disturbance, and the strain rate providing the cavity expansion. In this study, the results as presented by Fig. 10d indicates that investigated PMT techniques have a notable impact on the derived deformability modulus.



(a) (b) (c)

Figure 9. Comparison of PMT results: (a-c) volumetric strain at depths of 4.0 m, 6.0 m, and 15.0 m, respectively.

The limit pressure (P_L) is conventionally defined as the pressure leading to the doubling of the initial volume of the probe which can be measured by direct measurement or determined using extrapolation methods. In this study, P_L is determined using the Eq. (3) assuming a double hyperbolic curve proposed to match to entire pressuremeter curve (DIN EN ISO 22476-4:2021-12):

$$V = A_1 + A_2 p + \frac{A_3}{A_4 - p} + \frac{A_5}{A_6 - p} \quad (3)$$

To estimate P_L, an iterative process was applied for obtaining the parameters A_i, assuming that the limit pressure approaches an infinite value in Eq. (3). The fitted curves are expected to reach a constant value as the pressure tends toward infinity of the volume. From the presented investigations, Fig. 10e shows that the limit pressures are generally similar for all three PMT techniques. The main distinction is that the SBPM exhibits a lower limit pressure than the other methods in the upper clay layer, which can be also observed by analysing the data in Fig. 9(a-b) at depths of 4 m and 6 m.

Various empirical, analytical, and numerical methods based on pressuremeter tests have been developed to assess undrained shear strength c_u and stress-strain behavior. In this study, the semi-empirical approach proposed by Menard (1957) is utilized to determine the undrained shear strength.

$$c_u = (P_L - P_0)/5.5 \quad (4)$$

Fig. 10a illustrates that the values of c_u of PMTs derived from semi-empirical approach match well to CPTu results

In addition to the semi-empirical methods, the c_u can also be derived from SBPM data using the nonlinear elastic/perfectly plastic framework proposed by Bolton and Whittle (1999). The relationship between pressure and undrained shear strength is defined in Eq. (5).

$$p_c = p_L + c_u ln(\gamma_c) \quad (5)$$

It was demonstrated that c_u and P_L can be determined from the slope and intercept of a plot of pressure versus the natural logarithm of the current shear strain (γ_c). In Fig. 10a, the analytical results for c_u are shown and named as SB2-analytic (unfilled triangles). The comparison between the semi-empirical and analytical values of c_u shows that, although the analytical results are slightly lower, both approaches are suitable for practical applications.

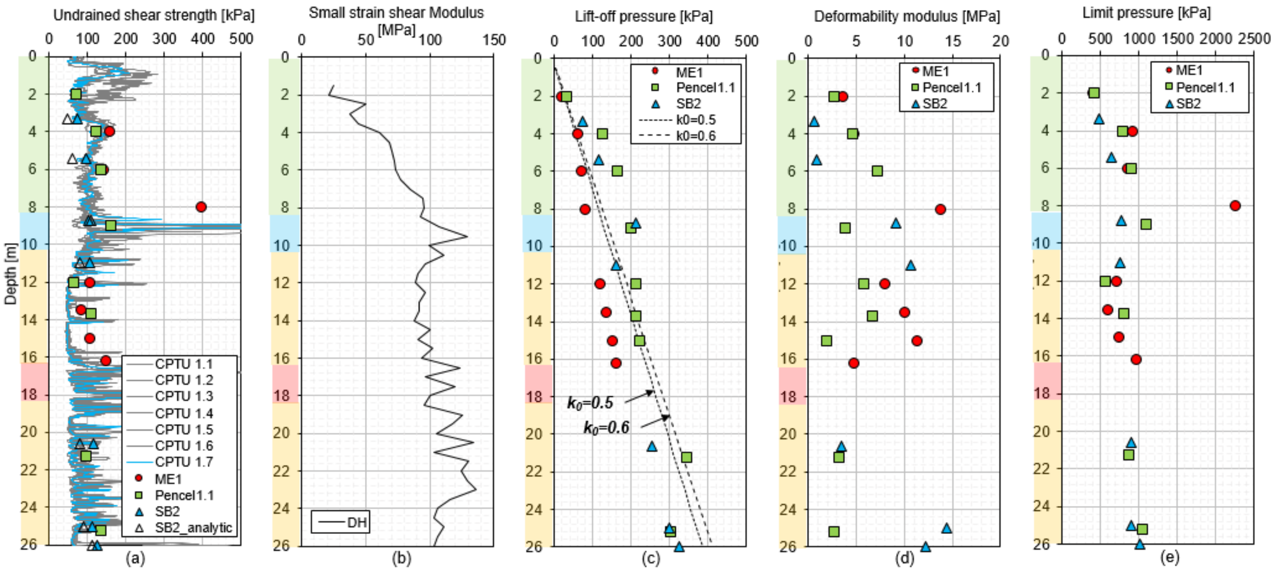


Figure 10. Profile of a) undrained shear strength c_u b) shear modulus from V_s measured by seismic DH tests and c-e) results of PMTs.

6. Conclusion

This study investigates the applicability of three different PMT techniques in assessing geotechnical properties of Rosenheim clay generally characterized as a sensitive soft soil deposit. Beside the different types of PMT devices, the research focuses on evaluating the impact of probe insertion methods on soil disturbance and the reliability of derived geotechnical parameters. Three PMT types namely Menard-PMT, SBPM, and Pencel-PMT were utilized, each with distinct insertion methods and probe dimensions. Pencel-PMT and SBPM were carried out from a pre-drilled borehole bottom while Menard-PMT is inserted with DST method. While SBPM creates a borehole by the PMT probe until the actual testing position is reached the Menard-PMT and Pencel-PMT is pushed towards the testing position.

The findings highlight the significant influence of the PMT techniques on the interpretation of the PMT-results. The lift-off pressure P_0 commonly linked to the total earth pressure at rest condition is observed to increase with depth, with variations between PMT-methods due to probe installation effects. The Menard-PMT exhibit lower P_0 values, likely influenced by DST method for a higher diameter probe compared to Pencel-PMT. E_M was derived by analytical approaches, showing that the different PMT techniques produce significant variations in soil stiffness estimates. P_L was determined through a double hyperbolic curve fitting method, revealing similar values across all PMT techniques, though SBPM exhibit slightly lower P_L in the upper clay layer. Finally, c_u derived from all investigated PMT techniques aligned well with CPTu results in the less sensitive soft soil layers (above 12 m) and slightly overestimated the CPTu values in the more sensitive soil layers (below 12 m).

Until now a conclusive evaluation of the influence of the different PMT techniques on the measurement of parameters characterizing the mechanical behavior of the investigated sensitive soft clay deposit is not possible. To further analyze the capability of conducted PMTs to realistically capture the undisturbed properties of the Rosenheim soft clay, extensive laboratory tests on high-quality soil samples are being planned. The sampling quality will be quantified by comparing V_s in the field and in the laboratory. Based on numerical simulations of the PMTs featuring advanced constitutive models, which are calibrated by the results of laboratory tests and in addition by full-scale loading tests at the Kolbermoor test site, the influence of soil disturbance on the test results will be analyzed for the different PMT insertion techniques.

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