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# A novel procedure for measuring the saturation of the pore-pressure system in piezocone tips

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ABSTRACT: Uncertainty in the measurement of the pore-water pressure in piezocone testing (CPTU) can be caused by an equipment malfunction, poor calibration and maintenance of sensors, but also by a lack of saturation of the piezocone. The standards allow for many different options in terms of filters, saturation fluids and methodologies. The novel device described herein aims at measuring in a very simple manner the degree of saturation of the piezocone prior to testing. Because the quality of pore-water pressure measurements can currently only be assessed a posteriori, i.e. after the test has been completed, or at best while testing, the methodology proposed herein has the potential to provide quality benchmarks for CPTU. The tool measures a parameter inspired by the well-established Skempton coefficient B, which is routinely used to estimate the sample saturation prior to laboratory testing. Furthermore, by performing the same measurement after a CPTU test, it is possible to assess whether saturation was lost during cone penetration. The paper describes a set of preliminary results that show a clear correlation between the saturation degree of filters and/or of the overall pore-pressure measurement system and the B parameter proposed, thus providing a proof of concept in laboratory settings.

**List of Notations**

| | |
|---|---|
| B | pore-pressure coefficient (Skempton, 1954) |
| $B^*$ | proposed pore-pressure parameter |
| CPTU | Cone Penetration Test with pore-water pressure measurement (piezocone testing) |
| $q_c$ | measured tip resistance |
| $u_0$ | hydrostatic pore-water pressure |
| $u_2$ | measured pore-water pressure at the shoulder position |

Keywords

Piezocone, pore pressure, in situ testing, quality control, CPTU

# INTRODUCTION

Defects in piezocone saturation are routinely listed among likely sources of uncertainty/error in CPTU measurements (e.g., Schneider et al., 2008; Löfroth et al., 2010; Ramsey, 2010; Sandven, 2010; Peuchen & Terwindt, 2014, 2015; Kardan et al., 2016). Yet evaluation of porous filters saturation (e.g., Larsson & Mulabdic, 1991; DeJong et al., 2007) and/or cavitation of the saturation fluid (e.g. Ramsey, 2010; De Backer et al., 2022) is limited. Suggested best practices are described in the standards (ASTM D5778-20; ISO/DIS 22476-1:2021; ISO/DIS 19901-8:2021), but do not necessarily result in well-defined data quality. In engineering practice, therefore, a great variety with respect to filter material, saturation fluid and saturation methodology is found, as reported in DeJong et al. (2007), and pore-water pressure, $u_2$, response remains a major uncertainty (Tonni et al., 2016).

Good saturation of the piezocone tip is paramount to obtain reliable data for soil characterization and evaluation of mechanical and/or hydraulic properties. An incorrect measurement of $u_2$ has cascading effects on the reliability of virtually all data collected, the pore water pressure being required to obtain the corrected cone resistance from raw data of $q_c$. Responsiveness in the measurements also relies on good saturation, which is particularly important in layered soil deposits.

Examples where the pore-pressure behaviour is not consistent with the expected response due to a lack of saturation are depicted in Figure 1, either because desaturation and/or cavitation occurred during penetration or because of incomplete/incorrect saturation.

This paper describes a device designed to measure a pore-pressure parameter $B^*$, associated with the degree of saturation of an assembled piezocone tip, and discusses preliminary laboratory results obtained on a tip having different initial degrees of saturation. The proposed $B^*$ parameter is inspired to the well-established Skempton's pore-pressure coefficient B (Skempton, 1954), which is routinely used in laboratory testing to assess the specimen saturation, e.g. prior to triaxial testing. By measuring it prior to and after CPTU testing, the $B^*$ parameter could be used to evaluate the reliability of pore-pressure data and the overall test quality. This matches recent suggestions to use reference readings and output stability as non-subjective diagnostic checks to classify test results with respect to quality (Lunne et al., 2017; Soage Santos, 2022).

## EQUIPMENT AND METHODOLOGY

A piezocone tip manufactured by Delft Geotechnics, with the filter in the $u_2$ position, was used in this study. The filters fitted onto the cone were 5 μm sintered stainless steel and were purchased from the supplier already saturated with 20 cSt silicon oil, which are typical in current engineering practice, as reported by De Jong et al. (2007).

The photo in Figure 2a provides a view of the overall setup, whereas the diagram in Figure 2b shows the operating principle of the whole arrangement devised to check the saturation of the piezocone pore-pressure sensing system. The key-component is an annular chamber placed around the piezocone filter (Rocchi et al., 2017), with an inner flexible impermeable membrane separating the device from the piezocone (Fig. 2c). An indicative sketch of the device is provided in Figure 2d. The chamber is pressurized instantaneously with a single stroke of a hand pump, while an external pressure sensor and the pore water pressure transducer installed in the piezocone tip are both logged through the same acquisition system.

In order to perform the measurement, the same procedure can be adopted regardless of when the saturation check is performed (i.e. before or after piezocone testing) and the saturation method, filter or fluid employed. After positioning the device on the already assembled piezocone, a pressure impulse is applied and the increment recorded by the pore-pressure sensor placed inside the piezocone is compared to that recorded by the external independent pressure transducer. The pore-pressure parameter $B^*$ is thus defined as the ratio of the two increments. This closely mimics what is typically done in the saturation phase of a triaxial test, where an isotropic increment of total stress (i.e. cell pressure) is applied in undrained conditions and the response in terms of pore-water pressure is monitored. Assuming a closed hydraulic system disconnected from the specimen, if the system is not compliant (i.e. infinite stiffness), an isotropic increment of stress must result in an equal increment in the fluid pressure, which corresponds to the pore-water pressure in the soil specimen. Compliance may arise from deformability of the hydraulic system, soil grains or fluid. However, assuming air as the only relevant source of compliance, the two increments are the same for a saturated system, i.e. $B \sim 1$. Similarly, in the proposed device, air in the porous element or elsewhere in the system is assumed to be the only relevant source of compliance and therefore targeted values of $B^* \sim 1$ are sought to assess full saturation of the tip.

The tests were performed after saturation of the piezocone in silicon oil by the methods later described. The device was slid on the piezocone and a 50 kPa was applied to the device chamber.

Subsequently, a series of pressure impulses, ranging from 50 to 300 kPa, was applied in steps, each equal to a 50 kPa nominal increment. Increments were applied within a 1 s interval and kept for 30 s before proceeding to the following step. Continuous data logging of both the piezocone and the device was performed during the process.
Saturation was performed before the filters and the seals were mounted onto the tip and the cone was tightened, by using either methods recommended by ISO/DIS 22476-2021a; these consist in (1) injecting silicon oil in the piezocone chamber connecting the pore-pressure transducer to the filter, with a syringe (also in ASTM D5778-20), or (2) placing the piezocone under a 85 kPa vacuum in a silicon oil bath together with the seals for 15 min, which is the minimum time recommended by the standards. Furthermore, the results obtained applying a combination of the two methods were also evaluated. Note that for method (2), the tip was assembled while immersed in silicon oil and the device was slid on the piezocone while still in the oil bath. This avoided entrapping air during the process. Furthermore, a small pressure (<5 kPa) was applied to the device chamber to hold the device in place.
In order to test the different components of the piezocone system, either the filters or the chamber connecting the pore-pressure sensor in the tip to the filters were purposely desaturated. In particular, ahead of saturation 1ml air was injected with a syringe inside the just mentioned chamber. The tests were then performed using saturated filters. Additionally, the filters were tested under two reference unsaturated conditions. Desaturation was obtained by placing the filters either under vacuum in air for 24 hours or pressurizing them with air at 600 kPa for 1 hour, leading to 90% and 5% saturated filters, respectively, based on the weight loss recorded. When testing desaturated filters, the saturation procedure was kept the same and corresponded to the combination of the methods described above. Note that compared to Rocchi et al. (2022), the preliminary injection of air in the system guaranteed comparable initial conditions and therefore improved repeatability.

## RESULTS

Preliminary results in Figure 3 provide clear evidence that filter saturation degree (100, 90 and 5%) affects the measured pore-water pressure parameter $B^*$. Each data point corresponds to the average value obtained performing the test 3 times, each time using the same procedure but a different filter, while the associated error bars represent the minimum and maximum values measured. The results indicate a relatively good degree of repeatability within the pressure range investigated, regardless of the filter conditions. When testing fully saturated conditions, i.e. saturated filters following saturation, the values are high, relatively unaffected by the pressure at which the test is performed, and are comparable with those required in the laboratory according to ASTM D7181-20 (i.e. $B > 0.95$-$0.97$ for sands and $B > 0.97$-$0.99$ for clays). Inducing slight desaturation to the system, obtained by employing 90% saturated filters, results in a considerable difference in the incremental values of measured pressure, within the range investigated. These differences gradually reduce as the applied pressure is increased during the test, because air bubbles in the tip are compressed and the system becomes stiffer, thus its compliance is reduced. Similarly, the pore-water pressure readings measured by a poorly saturated piezocone in the field generally improve at great depth below the groundwater level. Indeed, only at the high end of the pressure range investigated, the values recorded match those prescribed for laboratory testing of saturated soils. When the filters are almost fully desaturated (5% saturation), it is still possible to obtain a response even though the $B^*$ values measured 1 s after the application of the pressure impulse are extremely low. As shown in Figure 4, the $B^*$ value increases with time for 5% saturated filters. However, the increase is not significant and stabilizes relatively fast due to the undrained conditions applied by the device. Tests on 90% saturated filters instead show a slight decrease with time, possibly due to relaxation of the system. Even though values after 30 seconds were used to calculate $B^*$ for 5% saturated filters, this still would reduce at increasing pressure applied, as shown in Figure 4, where measurements after 1 s were used for calculation. Such reduction with increasing pressure could possibly be explained by air progressing further into the pore-pressure measuring system of the piezocone.

Tests on non-saturated piezocone tip/system, though with saturated filters, were also carried out and the relevant data points are also displayed in Figure 3. In this case, the measured values of $B^*$ can be compared with the results plotted in Figure 5, which were obtained by employing different saturation methods. Again, each data point corresponds to the average value obtained on three tests, each performed with the same procedure but a different saturated filter. The associated error bars are seemingly larger compared to Figure 3, because of the smaller interval adopted for the vertical axis. When comparing $B^*$ with and without saturation of the inner piezocone chamber (both performed with saturated filters), it is clear that the procedures recommended in the standards are highly effective in achieving saturation of the system when employed in laboratory conditions.

Finally, the summary plot in Figure 6, based on the B* values measured at 50 kPa under all conditions tested, highlights that all components must be fully saturated to achieve a satisfactory outcome.

## CONCLUSIONS

The article presents a set of preliminary results, obtained using an innovative device, that correlate a newly defined $B^*$ parameter of the pore-pressure measuring system of an assembled piezocone tip with its overall saturation degree, either before or after the test. The range investigated (50 to 300 kPa) is typical of routine testing conditions in the field. However, the measured correlation is nonlinear and therefore the method proposed loses in applicability when testing at stresses significantly beyond this range, where the relationship enters a tail zone.

The parameter is suggested to be ultimately used as an objective quantitative assessment of data quality in CPTU testing. In applications where the data quality required is particularly high, proceeding to testing could be made conditional to achieving a certain threshold in the $B^*$ measured. After the proof of concept herein presented, the results should be confirmed using a range of piezocones, which despite being standardized differ in the fine details of their hydraulic system. Subsequently the most suitable saturation processes and media can be investigated by comparing their outcome in terms of $B^*$ at the laboratory scale. In particular, this is required because the exact $B^*$ value measured is a function of the relative stiffness of the fluid and the porous medium. Furthermore, field measurement of $u_2$ in a same uniform stratigraphy, obtained using the same piezocone having a range of saturation conditions (as assessed by the methodology proposed) is required to verify the correlations obtained in the laboratory. Finally, the quality of CPTU field measurements in different stratigraphic conditions should be investigated to identify threshold values suitable for reliable testing.

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**Figures Caption List**

Figure 1. Examples of unreliable pore-water pressure measurements: (a) time lag caused by cavitation following penetration of dilative sands in Sleipner clay, North Sea (data by Lunne et al., 2014), (b) unreliable measurements caused by desaturation after leaving the piezocone in dry sand as measured at the Zwijnaarde test site in Belgium (data by De Backer et al., 2022), (c) increase in pore-water pressure with time during a dissipation test in a normally consolidated contractive clay (Po river plain, unpublished data).

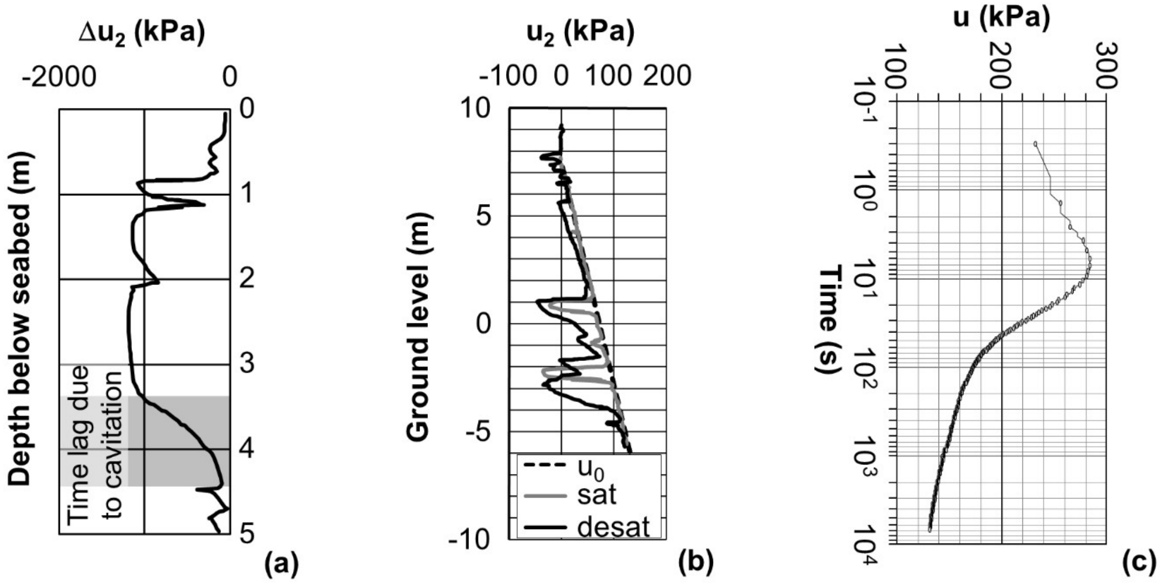
Figure 2. (a) Picture of the experimental setup, (b) close up picture of the key component, (c) schematic diagram of the setup and (d) cross section sketch of the prototype of the device. 1 device, 2 hand pump, 3 external pressure sensor, 4 data logging system, 5 piezocone, 6 oil bath for saturation, 7 annular chamber, 8 piezocone filter, 9 impermeable membrane.

Figure 3. Influence of the filter degree of saturation on the pore-pressure parameter measured after saturation of the piezocone by oil injection + vacuum.

Figure 4. Time evolution of the pore-pressure measured by a piezocone assembled with filters having different degrees of saturation when applying a pressure impulse starting at 50 kPa external pressure applied. Note the difference in the initial values measured by the piezocone pore-pressure sensor is due to air affecting the recordings.

Figure 5. Influence of saturation method on the pore-pressure parameter measured on piezocone assembled with saturated filters.

Figure 6. Relative importance of the saturation degree of the different components in the pore-pressure measuring system of the piezocone by comparison of the pore-pressure parameter measured at the minimum pressure increment.

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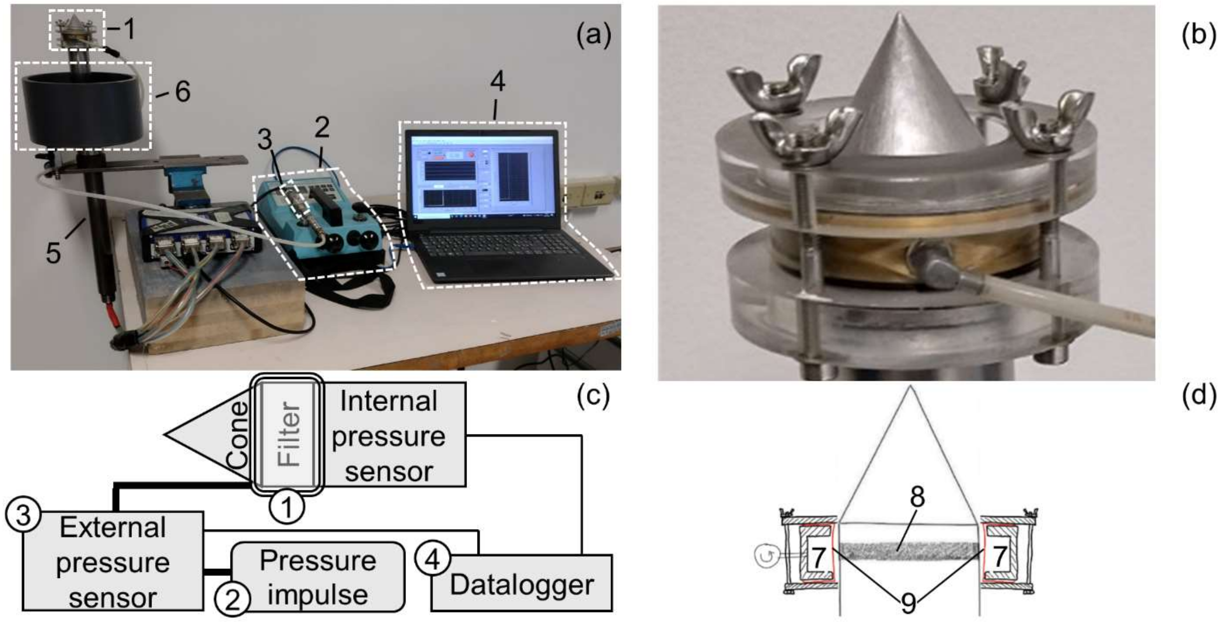


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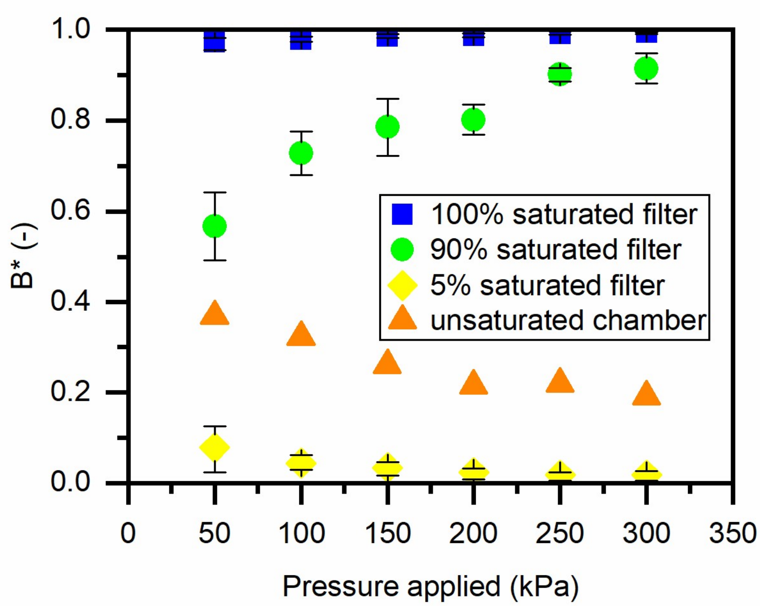


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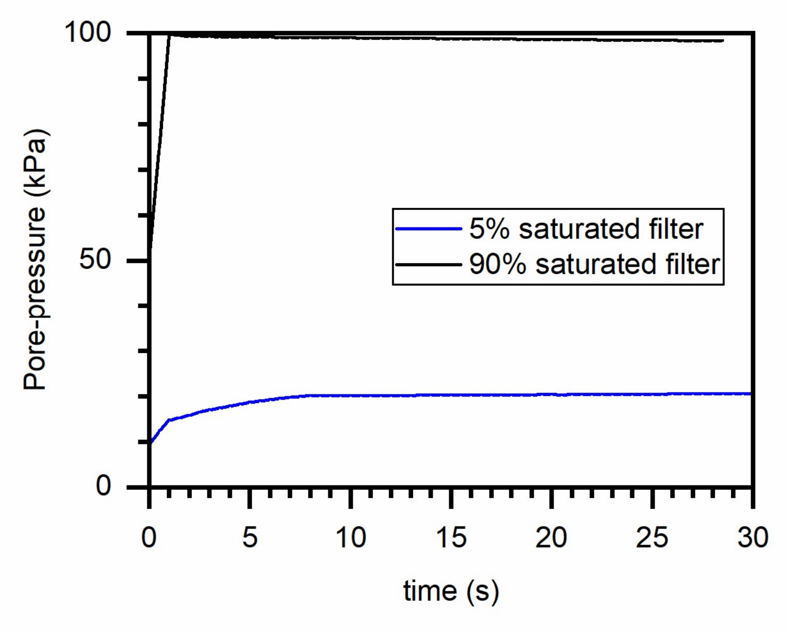


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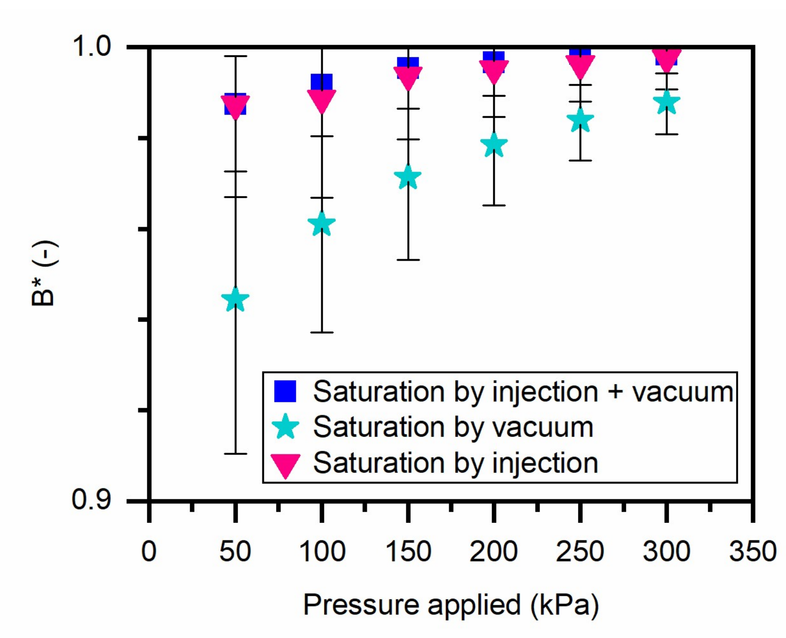


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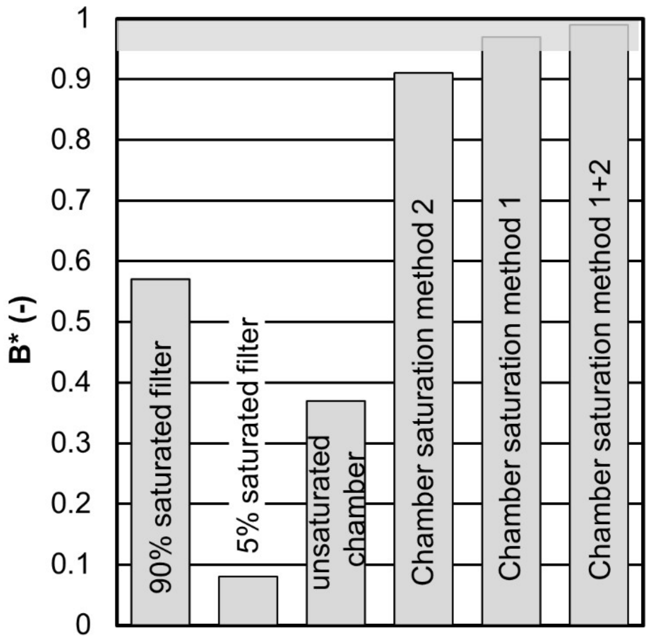


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