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Research article

Analysis of CPTu data from the North Sea region to estimate the frequency of inaccurate pore pressure measurements

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Abstract: Cone Penetration Testing with pore-pressure measurements (CPTu) is the main site characterization test because of its ability to provide stratigraphy, as well as mechanical and hydraulic properties. Malfunctioning of the piezocone equipment, as well as poor calibration and/or maintenance, can lead to poor data quality, and therefore, there are clear procedures in place to avoid such instances, which can be considered quite rare. However, saturation of the piezocone pore-pressure measuring system, which is a key to reliable results, is a significantly more common source of erroneous measurements. The great variety of saturation methods and media encountered in engineering practice is symptomatic of the empirical approaches applied to solve this type of uncertainty. We performed a systematic analysis of open-source data available from the UK, Germany, the Netherlands, and Belgium and analyzed the data to identify measurement repeatability and calculate the frequency of occurrence of inaccurate measurements in the pore pressure response based on site conditions. The analysis of pore-pressure measurements in clean sands, which was primarily based on the IJmuiden Ver wind farm in the Netherlands, showed that approximately 34% of the tests that appeared to follow a hydrostatic profile may nonetheless diverge significantly.

Keywords: pore-pressure; CPTu; piezocone; data quality

1. Introduction

Cone Penetration Testing with pore-pressure measurements (CPTu) is a main source of information in offshore projects, and in many other project types. While equipment malfunctions and poor calibration or maintenance can lead to erroneous data, these issues are relatively rare due to established procedures. In particular, considerable work has been done to establish a calibration procedure, frequency, and validation (e.g. [1]), and practitioners are increasingly aware of the related issues [2–4]. Low reproducibility of CPTu measurements cannot be explained alone by site variability (e.g. [5]), and therefore, there are unaccounted sources of uncertainty, such as preparation or testing procedures and equipment design. Studies on uncertainty [6–12] regularly mention incomplete or incorrect saturation of the piezocone's pore-pressure measuring system as a potential source of uncertainty. However, research addressing the root causes of this problem is not as widespread. DeJong et al. [13] investigated the variability in filter saturation based on materials and procedures, while De Backer et al. [14] reported a systematic study about loss of saturation during penetration, as a function of materials and procedures used. According to a survey conducted by Rocchi and Zhelezova [15], pore-pressure is perceived as being the most uncertain parameter measured in CPTus, and poor saturation of the piezocone pore-pressure measuring system is the leading reported cause for issues in the pore-pressure measurements. Despite the limited number of respondents in this survey, their geographical distributions were widespread, and some of the respondents reported as many as 90% of the tests being affected by poor pore-pressure measurements. Lunne et al. [16] compiled a database of pore pressure measurements of 546 datasets containing data from 63 onshore and offshore sites. While they mention that uncertain or poor-quality data were removed, they do not report the initial number of tests, nor the criteria used for screening. Sleeve friction measurements were also mentioned as a source of uncertainty in the survey by Zhelezova and Rocchi [15], but there seems to be more widespread effort towards solving this problem or at least raising awareness about it [5,17,18].

Uncertainties in the pore-pressure measurements can affect the overall quality of the data collected, particularly the corrected cone resistance in soft clays, the identification of the exact boundary depth between two layers, or the hydraulic parameters (e.g. [19]). Clients working in the offshore industry typically have stringent requirements for data quality, including the saturation procedure to be adopted before performing CPTus. Because of this extra care and because the water column of the sea has a positive impact on saturation due to its action as back pressure, it may be reasonable to expect no issues with lack of saturation in CPTu tests executed offshore. Nonetheless, measurements may be more prone to drift due to a buildup in temperature due to friction between the soil and the piezocone [9]. Pore pressure measurements can be validated based on their agreement with the hydrostatic profile when penetrating clean sands, responsiveness in layered stratigraphy, ability to measure negative pore pressure without cavitation, and monotonic decrease during dissipation tests in normally consolidated clays. We analyze systematically open-source offshore data from the UK, Germany, the Netherlands, and Belgium to calculate the frequency of valid pore-pressure measurements and the measurement repeatability based on the first of the above criteria. In this case, the discrepancy between the pore-pressure measurement u_2 and the hydrostatic distribution u_0 corresponds to the experimental uncertainty of u_2 because the calculated u_0 represents the true value under the assumptions of a hydrostatic distribution and fully drained penetration, which are reasonable for coarse-grained deposits offshore. The larger the distance between the measurement and the theoretical value, the lower its accuracy, even though the measurement might not necessarily be invalid. However, given that precision is usually described as consisting of two parts, a constant one and one proportional to the measurement, it is possible to identify invalid measurements based on inconsistency in the differences between u_2 and u_0 with depth, as the latter increases with depth.

2. Materials and methods

Four open access databases portals were investigated as potential sources, which are presented in Table 1. However, the CPTu tests performed in Germany were discontinuous (i.e., alternated with drilling) due to the tip resistance reaching maximum capacity. Because of the significant gap in the data available, these results were not analyzed.

Table 1. Overview of CPTu tests conducted at the studied testing sites.

Location Portal	Location Portal	Number of CPTu
UK	marinedataexchange.co.uk	147
Belgium	offshore.digitaldatabase.economie.fgov.be	92
Germany	pinta.bsh.de	57
Netherlands (Ijmuiden Ver Wind Farm)	offshorewind.rvo.nl	313

The data from the UK is part of the geotechnical investigation for The Greater Gabbard Offshore Wind Farm Project. The site is approximately 26 km off the Suffolk Coast at Felixstowe/Hollesley Bay. The geological profile of the region is dominated by a thick sequence of the London Clay Formation, dating back to the Eocene epoch. This formation primarily consists of firm to stiff clay, interbedded with layers of clayey and sandy silt, along with minor occurrences of gravel. The London Clay extends beneath the site and its surrounding areas, reaching depths of over 100 m. In certain locations, the formation is exposed at the seabed surface, while in others, it is partially overlain by thin sandy deposits.

In Belgium, the dataset belongs to the geotechnical site investigation of a wind farm in the Princess Elisabeth Zone, which is approximately 40 km northwest of the Port of Zeebrugge. The site is divided into two geotechnical survey areas, the Northern zone and the Southern zone. The stratigraphy of the area consists of superficial Quaternary sediments composed of dense to very dense fine to coarse sand with shell fragments. These sediments exhibit variable thickness, being absent in some areas and reaching up to 34.5 m in the Northern Zone, with an average thickness of 7.5 m. In the Southern Zone, the Quaternary sediments reach a maximum thickness of 29 m, averaging around 7.8 m. Beneath the Quaternary sediments lies a continuous clay unit, which extends beyond the maximum depth of exploration (70m). This clay also dates to the Eocene epoch and has high to very high consistency, which increases further with depth to extremely high consistency.

The dataset from the Netherlands is associated with the geotechnical site investigation of a wind farm at the IJmuiden Ver (IJV) Wind Farm Zone, in the Dutch sector of the North Sea. The area is around 62 km off the west coast of the Netherlands. The stratigraphy consists of fine to medium sand with a gravel content below 10%, exhibiting a variable thickness from seabed level to up to 25 m depth. This is underlain by a unit of silty sand, containing interbedded clay layers, with a maximum thickness of 10 m. Beneath this, a layer of well-sorted fine sand is present, occasionally containing fine to coarse gravel, with a thickness ranging from 0 to 20 m. The deepest identified unit comprises silty clay, with a thickness varying between 0 and 15 m. The geological profile of the test site was confirmed by data from 37 deep boreholes reaching a maximum exploration depth of 100 m.

All tests were performed at a nominal constant rate of 2 cm/s using standard equipment according to ISO/DIS 19901-8:2023 [20]. The piezocone size was 10 cm^2 in the United Kingdom and Belgium and 15 cm^2 in the Netherlands, while both sizes were used in Germany. Table 1 reports the number of CPTus available at each location, where it should be noted that in the Netherlands 61 tests were performed with seismic measurements.

Since pore pressure in clean sand layers are expected to follow the hydrostatic pressure, our objective was to validate pore pressure measurements based on the difference between the pore-pressure, which was measured behind the cone tip (u_2) and the hydrostatic pressure (u_0). Even though the focus was on assessing the pore-pressure measurements, all CPTu results were interpreted in full, specifically to identify intervals relevant for analysis in the stratigraphy. The criteria used were that a minimum 2 m long continuous interval of data points, classified as clean sands based on the soil behavior type ($1.31 < I_{cn} < 2.05$), showed that u_2 followed a linear trend with depth. Because the u_2 response under the same conditions may become less reliable after the cone has penetrated intermediate or clay layers, the analysis excluded sites where the same conditions were not met from the ground surface (i.e. the seabed). Note that the criterion about a linear trend was necessary because there were instances where the soil was dilatant despite being classified as clean sand. All data meeting these criteria, which had relative density, $35\% < D_r < 85\%$, and average $D_r = 70\%$, were thereafter included in the analysis. Typically, more elaborate statistical frameworks are employed to identify outliers, which rely on the average response and the theoretical uncertainty determined theoretically based on instrumental precision (e.g., [21]). However, since the true value was known in this case (as the pore pressure must equal the hydrostatic distribution), the difference between the pore-pressure (u_2), and the hydrostatic pressure (u_0), which is referred to as drift in the figures, represents a direct estimate of the experimental measurement accuracy.

3. Results

Based on a preliminary analysis, it was observed that the number of CPTus conducted in the UK with sand as the shallowest layer was limited (15 CPTus), with a maximum observed thickness of 4 meters for this unit. Because the remainder of the stratigraphy comprises clay and no dissipation tests were performed, no further analysis is presented. With regards to Belgium, even though the shallowest layer classified as sand, the presence of gravel and/or high relative density results in a pore pressure profile that seldom follows exactly the hydrostatic distribution, especially after the first few meters of test, as seen in Figure 1. Therefore, these CPTu results could not be used for further interpretation, and the subsequent analysis concentrates on the Dutch site. Figure 1 and similar subsequent figures display the profiles of cone resistance (q_c), sleeve friction (f_s), and pore pressure (u_2), alongside the estimated drift only for those intervals classified as clean sands based on the normalized soil behavior index (I_{cn}). Inset (e) shows I_{cn} throughout the test and provides the boundaries distinguishing clean sands from gravelly sands and silty sands.

Based on the pattern exhibited by the drift with depth, it was possible to identify three types of response, which were used to define categories of the piezocone response. The first category (Category 1) includes tests that, after developing a drift in the initial part of the test (1–2 m), exhibited a constant value throughout the upper sand layer (up to 10 m). This behavior may be explained by heat buildup due to friction developing in the initial part of the test. Here, it should be highlighted that the piezocone used for these tests contained a temperature sensor, which would enable us to correct the data, but temperature data were not available in the database. The second category (Category 2) comprises tests that showed an increasing drift throughout the sand layer, where the u_2 measurements exceeded the hydrostatic pressure (positive drift). Finally, the third category (Category 3) includes tests characterized by an increasing drift, with the u_2 measurements falling below the hydrostatic pressure (negative drift). Of the 313 CPTu tests analyzed, 123 tests showed a constant drift, 131 exhibited an increasing positive drift, and 48 displayed an increasing negative drift. Additionally, 11 tests were classified as not applicable due to the presence of softer or gravelly soils in the uppermost layer, which affected the pore pressure response. Figure 2 shows the spatial distribution of the different categories, where no univocal geographical distribution of the categories can be seen.

Figure 3 presents the CPTu measurements from three representative tests, one from each of the above-mentioned categories. In Figure 3(e), local divergency of u_2 from hydrostatic conditions can be attributed to I_{cn} being in proximity of different soil behavior type categories, even though the soil is classified as clean sand.

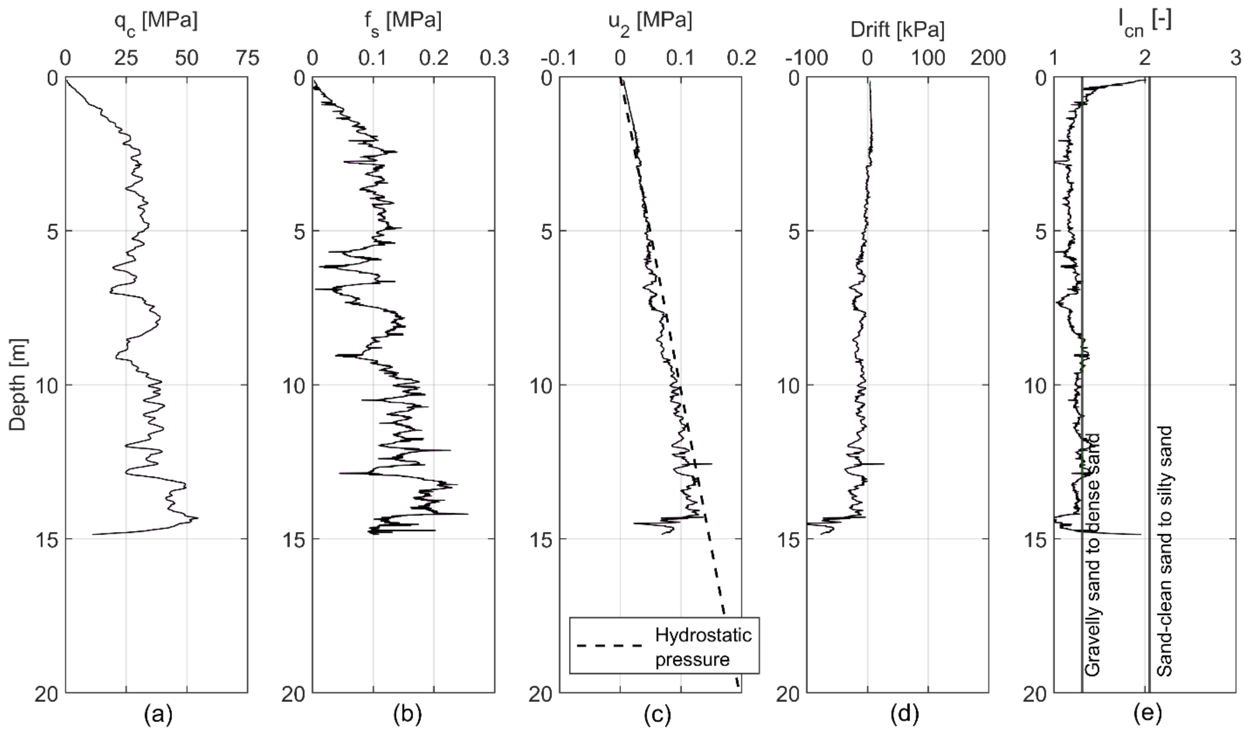

Figure 1. Representative CPTu profile from the Belgium testing site, showing cone resistance (q_c), sleeve friction (f_s), pore pressure (u_2), estimated drift, and the normalized soil behavior index (I_{cn}), with I_{cn} boundaries for gravelly to dense sands and clean to silty sands.

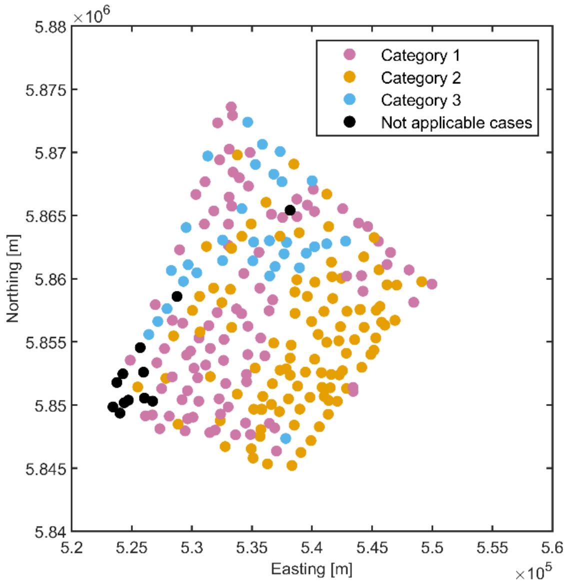

Figure 2. Location of CPTus on the Dutch site across categories of behavior.

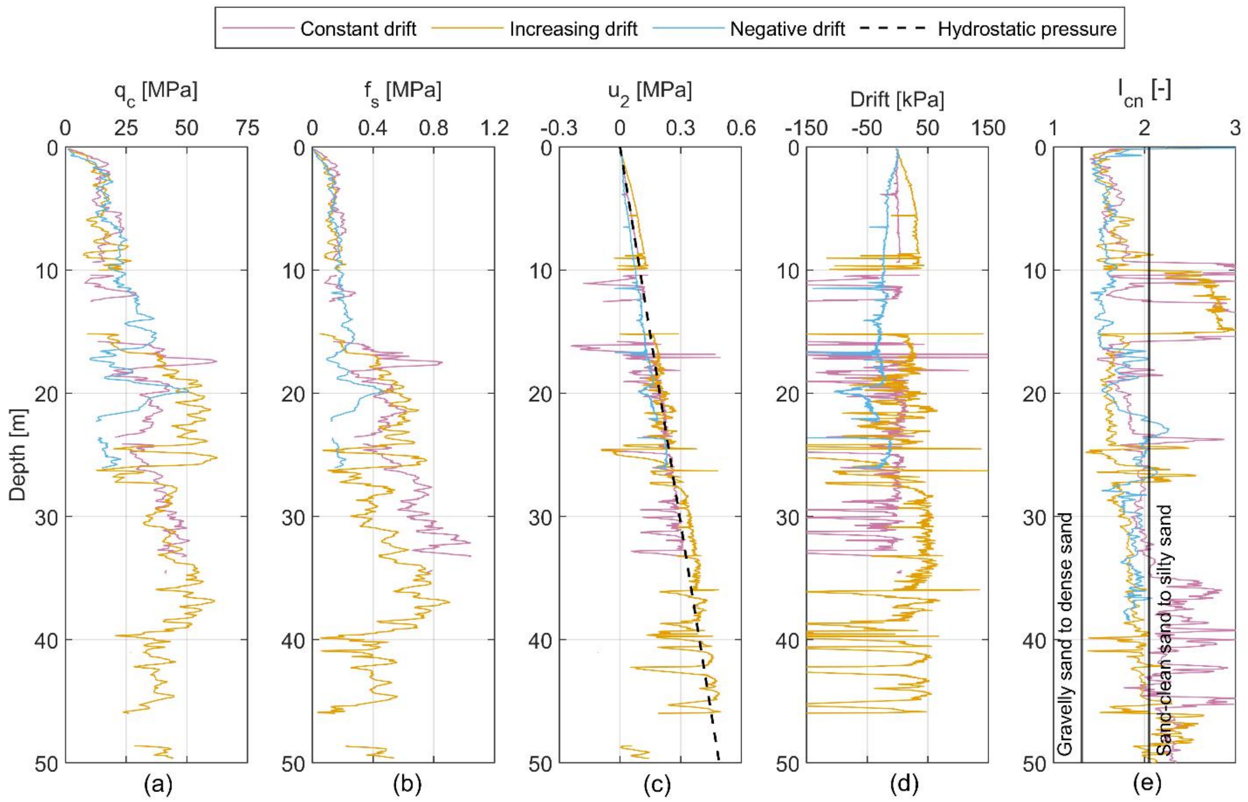

Figure 3. Representative CPTu profiles for each drift category, showing cone resistance (q_c), sleeve friction (f_s), pore pressure (u_2), estimated drift, and the normalized soil behavior index (I_{cn}), with I_{cn} boundaries for gravelly to dense sands and clean to silty sands.

Based on the pore-pressure response, the measurements were further evaluated in accordance with the three application classes defined by ISO 19901-8: 2023. The standard defines application classes based on the zero-measurement difference before and after the test and specifies the allowable minimum difference as 10 kPa for Application Class 1, 25 kPa for Class 2, and 50 kPa for Class 3. In this analysis, the same criterion was applied during the test, based on the physical constraint that pore-pressure response in clean sand layers must follow the hydrostatic profile. The drift identified by the two procedures may not necessarily be the same because further drift, or presumably drift in the opposite direction, could occur during the piezocone retraction. Table 2 summarizes the number of tests exhibiting the different drift categories identified and their distribution across each application class. Table 2 shows that for most of the tests (62%), the drift observed was within the limits for Application Class 1 measurements, and an increasingly smaller number was found moving toward lower classes, regardless of the drift behavior. As may be expected, with a continuously increasing drift (either in a positive or negative direction), the frequency of tests in lower application classes increased. Among the 131 CPTu tests behaving according to Category 2 (continuously increasing positive drift in the uppermost sand layer), the drift continued in the lower sand layer (up to 20m depth) for 13 tests, leading to a drift beyond that applicable to Class 3. Overall, 8% of tests drifted beyond Application Class 3. An example of CPTu measurements for a test exhibiting such behavior is presented in Figure 4. Further evaluation of the pore-pressure measurements identified 27 tests where loss of saturation in the pore-pressure measurement system occurred during penetration following cavitation and/or after penetration of layers with a high fines content, accounting for 56% of tests within Category 3. Two such examples are presented in Figure 5. In one of these tests, it is evident that even though the u_2 responded immediately to the change in stratigraphy and the trend remained consistent with the hydrostatic pressure, a noticeable offset was introduced.

To assess whether drift categories determine the distribution of data points across class levels, a Chi-Square test for independence was performed. The results yielded a very low p-value ($p < 0.0001$), indicating that the drift category has a substantial effect in determining the likelihood of data points falling within a particular application class. In other words, the application class is not random but is influenced by the underlying trend in drift. Therefore, if one could elucidate the reason behind the different drifts, the application class could be improved.

Table 2. Summary of CPTu tests by drift behavior and corresponding percentage of u_2 measurements within ISO 19901-8:2023 application class accuracy limits in the uppermost sand layer. Category 1 (constant drift), Category 2 (positive drift), Category 3 (negative drift).

	Category 1	Category 2	Category 3	Number of tests [-]
Class 1	107	56	24	187
Class 2	5	37	18	60
Class 3	2	25	4	31
Beyond Class 3	9	13	2	24
Number of tests [-]	123	131	48	302

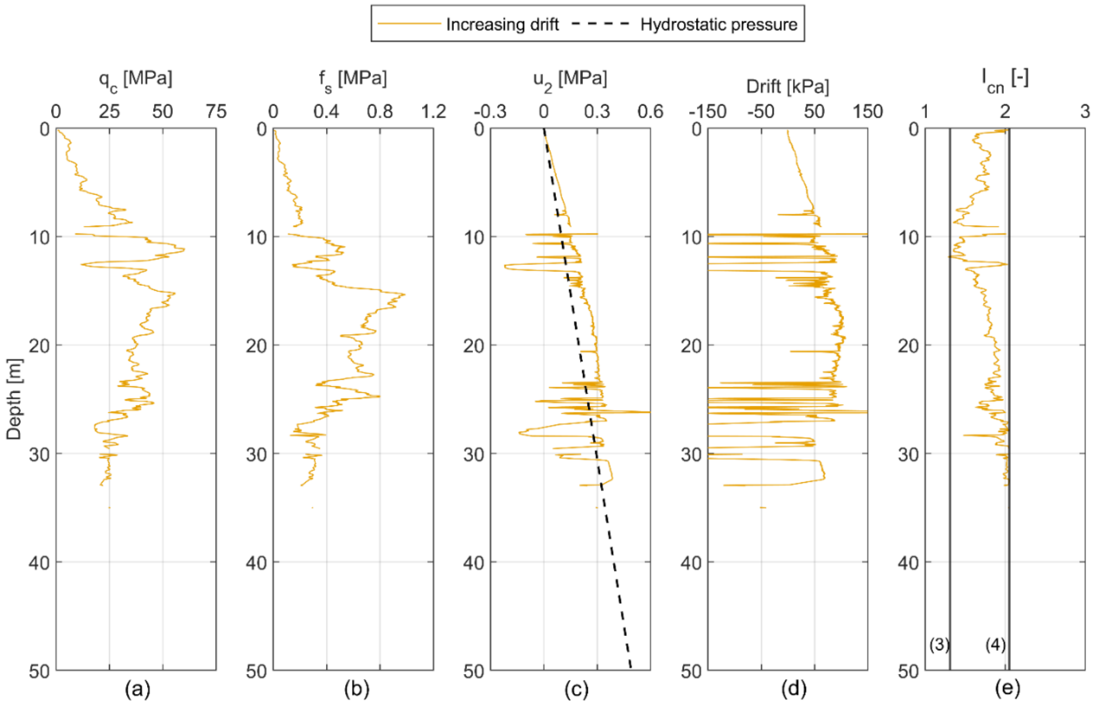

Figure 4. Example of CPTu showing continuously increasing drift with depth.

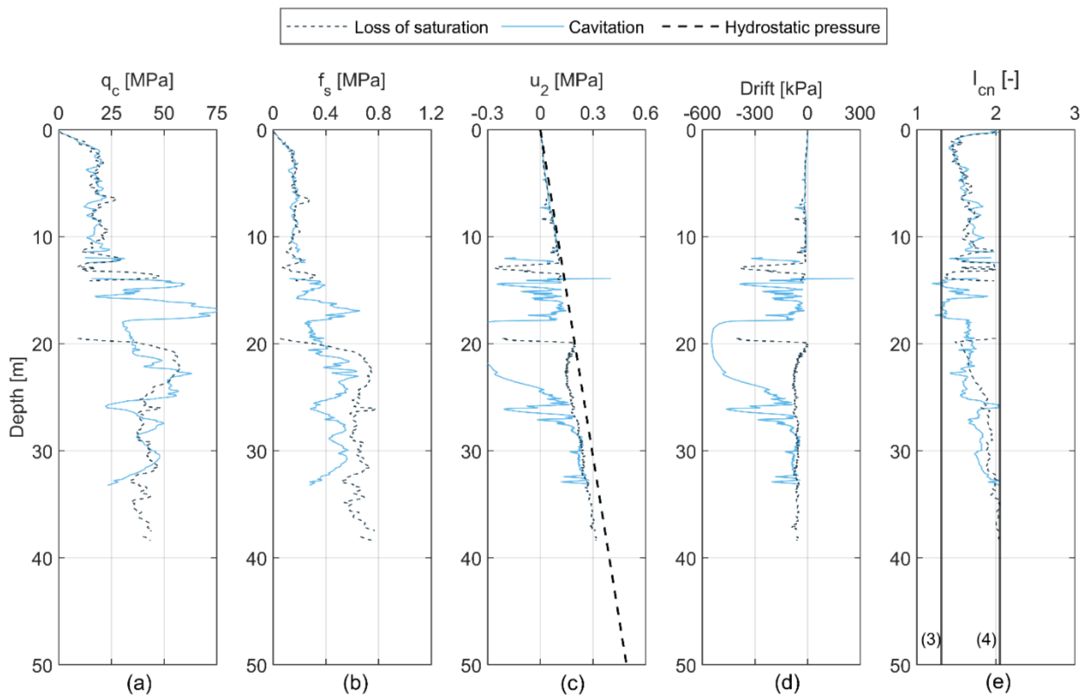

Figure 5. Example of CPTu showing loss of saturation due to cavitation, and subsequent negative drift.

4. Conclusions

We analyzed a large open-source database of offshore CPTus (530 tests) to identify overall data quality regarding pore-pressure measurements. The consistency between the hydrostatic distribution and the pore-pressure measurements was used to validate these measurements, limiting this analysis to uppermost layers that, according to the normalized soil behavior index, were classified as clean sands and exhibited a linear tendency in the u_2 distribution. First, we found that of 4 potential sites, only 1 stratigraphy enabled us to meaningfully apply these criteria (313 tests). For most tests, the drift either stabilized after a few meters (41%) or continued building up throughout the test (43%), while in 16% of tests, a similar behavior was identified but in the opposite direction. For this last category, 56% of tests had pore-pressure measurements that followed a hydrostatic trend but developed a negative shift only after experiencing cavitation (accounting for 9% of overall tests). No clear correlations were found between the trend in drift and specific areas of the site, time of investigation, or piezocone used, based on the information provided. For tests in Category 1, where the drift stabilized, 87% of CPTu at the end of the test had drifted less than 10kPa. This led to 36% of tests being classified as most accurate, given the limited discrepancy, and that the values recorded were significantly less than 1MPa. Assuming this discrepancy was due to heat buildup, the accuracy could be further improved by correcting for temperature effects. For tests with a continuously increasing drift in either direction, only 50–60% of the tests performed similarly well. Finally, a drift beyond 50 kPa was found for almost 18% of tests. As the CPTu extended less than 40 m, the drift had a rate of 1 kPa/m for the most uncertain tests. Because of the statistical significance in the correlation between application class and drift category, we conclude that to improve the application class, one must elucidate the reasons behind the different drift categories. Any explanation would be highly speculative at this stage because the representativeness of the analysis presented is limited by the fact that only 1 site was analyzed, which is essentially uniform with respect to stratigraphic sequence. A limited insight into the effects of soils having dilative behavior can be drawn based on the fact that the only tests where a change in the type of drift was observed were those experiencing cavitation (specifically changing from Category 1 to Category 3). However, this was observed only in about half the tests where cavitation occurred. Finally, because all tests were performed using the same piezocone type, size ($15cm^2$), and preparation procedure, analysis of additional data is required to identify whether these may impact the drift category.

Author contributions

Efthymios Panagiotis: Writing–original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. Alena Zhelezova: Writing–review & editing, Conceptualization. Irene Rocchi: Writing–review & editing, Methodology, Formal analysis, Conceptualization, Project administration, Funding acquisition.

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Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The Authors do not declare any conflict of interest.

References

1. Santos RS, Meyer EG, Peuchen J, et al. (2022) Calibration of cone penetrometers according to International Organization for Standardization requirements. *Cone penetration testing 2022,* USA: CRC Press, 121–126. https://doi.org/10.1201/9781003308829-26
2. McConnell A, Chapman M (2024) Does CPT reference value drift really inform CPT correctness? *7th International Conference on Geotechnical and Geophysical Site Characterization (ISC 24)*, Barcelona, Spain.
3. Parasie N, Sinjorgo G, Virelink L, et al. (2024) The importance of calibration laboratories in in-situ test methods. *7th International Conference on Geotechnical and Geophysical Site Characterization (ISC 24)*, Barcelona, Spain.
4. Scholey G (2024) Technical Note on Calibration for Cone Penetration Testing in Soft Soils. *7th International Conference on Geotechnical and Geophysical Site Characterization (ISC 24)*, Barcelona, Spain.
5. Paniagua P, Lunne T, Gundersen A, et al. (2018) CPTU results at a silt test site in Norway: effect of cone penetrometer type. *IOP Conference Series: Earth and Environmental Science*, 710: 012010. https://doi.org/10.1088/1755-1315/710/1/012010
6. Schneider JA, Randolph MF, Mayne PW, et al. (2008) Analysis of factors influencing soil classification using normalized piezocone tip resistance and pore pressure parameters. *J Geotech Geoenviron Eng* 134: 1569–1586. https://doi.org/10.1061/(ASCE)1090-0241(2008)134:11(1569)
7. Ramsey N (2010) Some issues related to applications of the CPT. *2nd International Symposium on Cone Penetration Testing, CPT'10*, Huntington Beach, CA, USA, 47–69.
8. Sandven R (2010) Influence of test equipment and procedures on obtained accuracy in CPTU. *2nd International Symposium on Cone Penetration Testing, CPT'10*, Huntington Beach, CA, USA, 1–26.
9. Peuchen J, Terwindt J (2014) Introduction to CPT accuracy. *3rd international symposium on cone penetration testing CPT'14*, USA, CRC Press, 1–45.
10. Peuchen J, Terwindt J (2015) Measurement uncertainty of offshore cone penetration tests. *Frontiers in Offshore Geotechnics III: Proceedings of the 3rd International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2015)*, Taylor & Francis Books Ltd., 1209–1214. https://doi.org/10.1201/b18442-182
11. Kardan C, Viking K, Nik L, et al. (2016) Influence of operator performance on quality of CPTu results. *Proceedings of the 17th Nordic geotechnical meeting. Challenges in Nordic geotechnics*, Reykjavik, Iceland: Icelandic Geotechnical Society, 153–158.
12. Santos RS (2022) Uncertainties associated with COT data acquisition. *Cone Penetration Testing 2022,* CRC Press, USA, 121–126. https://doi.org/10.1201/9781003308829-4
13. DeJong JT, Yafrate NJ, DeGroot DJ (2007) Design of a Miniature Piezoprobe for High Resolution Stratigraphic Profiling. *Geotech Test J* 30: 292–302. https://doi.org/10.1520/GTJ100592

14. De Backer G, Verastegui-Flores RD, Vervaele W, et al. (2022) Evaluation of parameters inducing desaturation of a piezocone: saturation liquid viscosity and exposure to dry sand. *Cone Penetration Testing 2022,* CRC Press. https://doi.org/10.1201/9781003308829-10
15. Rocchi I, Zhelezova A (2024) Survey study of the engineering practice of piezocone devices with regards to saturation conditions. *Nordic Geotechnical Meeting*.
16. Lunne T, Ghanekar RK, Tucker GW, et al. (2022) The revival of multiple pore pressure measurements in the cone penetration test. *Cone penetration testing 2022,* CRC Press, USA, https://doi.org/10.1201/9781003308829-20
17. Di Buò B, d'Ignazio M, Lånsivaara T, et al. (2022) Issues related to piezocone sleeve friction measurement accuracy in soft sensitive clays. *Cone Penetration Testing 2022*, CRC Press, USA, https://doi.org/10.1201/9781003308829-12
18. McConnell AJ, Wassenaar EJC (2022) An innovative new 3MPa CPT—to detect and measure very small fs values. *Cone Penetration Testing 2022*, CRC Press, USA. https://doi.org/10.1201/9781003308829-22
19. Rocchi I, Tonni L, Gottardi G (2024) Quantitative Assessment of Tip Saturation for High Quality Piezocone Testing, *Conference Proceedings Edited by CIMNE.* https://dx.doi.org/10.23967/isc.2024.207
20. International Organization for Standardization, ISO/DIS 19901-8:2023: Petroleum and natural gas industries—specific requirements for offshore structures—part 8: marine soil investigations. Geneva, Switzerland: International Organization for Standardization, 2023. Available from: www.iso.org
21. Joint Committee for Guides in Metrology, Evaluation of measurement data—Guide to the expression of uncertainty in measurement, International Bureau of Weights and Measures (Sèvres, France), 2008.