AIMS Geosciences

AIMS Geosciences, 11(4): 1007–1022.
DOI: 10.3934/geosci.2025044
Received: 29 April 2025
Revised: 01 September 2025
Accepted: 09 October 2025
Published: 10 December 2025

https://www.aimspress.com/journal/geosciences

Research article

On the effect of using different penetrometers on CPTU test results on AMU-Morasko test site

Jędrzej Wierzbicki[1,*], Katarzyna Stefaniak[1], Waldemar Wołyński[2], Łukasz Smaga[2] and Dawid Matusiak[3]

[1] Institute of Geology, Adam Mickiewicz University Poznań, Poland
[2] Faculty of Mathematics and Computer Science, Adam Mickiewicz University Poznań, Poland
[3] Grunt-Test, Poznań, Poland

* **Correspondence:** Email: jwi@amu.edu.pl; Tel: +48 604912848.

Abstract: Investigations were conducted at the test site of Adam Mickiewicz University in Poznań. The test site is located in the northern part of Poznań, within the marginal zone of the Poznań Phase of the Weichselian (*Vistulian*) glaciation. The subsoil consists of glacial till from the Vistulian glaciation, separated by fluvioglacial sandy sediments, and is covered with fine and medium sands with single grains of gravel. The quality of the geotechnical parameters of the tested subsoil was assessed for the constrained modulus and undrained shear strength. To determine these parameters, static penetrometers from two different manufacturers were used. The tests and the result analysis were performed in three stages. In the first stage, each penetrometer was used to investigate the homogeneity and diversification of the subsoil structure in the test sites. The subsoil structure diversification was examined by grouping statistically similar R_f coefficient values along the profile. In the second stage, the level of accuracy and precision in the assessment of the corrected cone resistance (q_t), friction on the friction sleeve (f_s), and pore pressure (u_2) were determined for individual penetrometers. In the final stage, differences between the constrained modulus and undrained shear strength were determined for both penetrometers. This analysis took into account the level of precision of the corrected cone resistance.

Keywords: CPTU quality; intermediate soils; AMU Morasko test site

1. Introduction

CPTU (Cone Penetration Test) static soundings are a widely used method for in situ determination of geotechnical parameters of soil. Their popularity stems largely from the favorable relationship between the survey cost and the results obtained, i.e., the possibility of determining the values of a wide range of geotechnical parameters. Leaving aside the issues of interpreting the direct results of static soundings [that is, cone resistance (q_c), sleeve friction (f_s), and excess pore pressure (u_2)], it is critical to ensure the appropriate quality of the tests carried out. These issues are regulated by ISO-22476-1 (2023) [1], and studies on the reliability and repeatability of CPTU measurements have been conducted by several authors.

One of the most complex and earliest studies on the repeatability of CPTU measurements was conducted by Młynarek et al. [2], who examined the results of tests performed with 9 new penetrometers from different manufacturers in an almost homogeneous soil. Conducting three tests with each penetrometer in a random square grid of the Onsøy test site ensured relatively high comparability of results. The results indicated particularly significant differences in f_s measurements, and statistical analysis allowed the penetrometers to be grouped in terms of measurement consistency. Powell and Lunne [3], on the other hand, presented the results of comparative tests performed with penetrometers with a cross-sectional area of 10 and 15 cm^2 in various fine-grained soils. In their work, they stated that while the cone resistance values (qt) were similar for both penetrometer sizes, the sleeve friction (fs) was slightly higher for the larger penetrometer. Research on the Onsøy clay test site was continued in a comprehensive study by Lunne et al. [4]. The study again involved different penetrometers with different cell capacities and pore pressure measuring systems. A total of seven penetrometers were tested, with each undergoing two to four tests. The results confirmed significant differences in measurements between different devices, particularly in the case of f_s but also q_c. Importantly, results also differed when subsequent tests were performed with the same penetrometer. However, as the authors noted, this may have been influenced by inaccuracies in zero readings and, in particular, different ambient temperatures during the zeroing of the penetrometers (as tests were performed under different atmospheric conditions). After taking this variable into account, the cone resistance values were much more consistent in individual tests. Wierzbicki et al. [5] came to similar conclusions, this time comparing two penetrometers of different sizes from different manufacturers. These authors also observed that the differences between the results were not constant but depended on the measurement depth and the type of soil being tested. Similar observations lead to the obvious conclusion that observed differences result in differences in geotechnical properties interpreted on the basis of CPTU results. A very clear example of this was presented by Paniagua and L'Heureux [6], who showed how different soil type assessments are obtained depending on the penetrometer used and the classification diagram used. Interestingly, when studying differences in various soils, the authors noticed that they depend on the type of soil and are most pronounced in silts.

The comparative studies cited above, which are valuable and undoubtedly influence the development of CPTU technology, focused mainly on examining the differences between penetrometers from different manufacturers and of different sizes. Against this background, Powell et al. [7] proposed a slightly different, yet valuable approach. They examined the effect of the ratio of the cone diameter to the sleeve part of the same device on f_s values, thus simulating the effect of the wear degree of the penetrometer's friction elements. Based on these results, it can be easily concluded that even small differences in the ratio of the two elements can significantly affect the results obtained.

Regardless of the high-quality standards currently imposed by ISO, it seems that a broader view of CPTU measurements is also necessary, including in the context of natural penetrometer wear unrelated to changes in cone and sleeve geometry. This points to a need for systematic replacement of penetrometers in their entirety (and not just their wear components) and to the probable cause of worse repeatability of friction measurements on the sleeve than of cone resistance.

The reason for undertaking the present study was the observation made by a commercial static sounding contractor regarding uncertainties in the measurement of q_c and, especially, f_s during tests conducted with an already worn-out device. Despite calibration and ongoing replacement of the penetrometer's friction elements to meet ISO standards, unexpectedly large variations in penetration parameter readings in relatively homogeneous sediments were observed. Similar differences were not noted in cones that were newer and twice as short in use. Hence, it was hypothesized that the quality of the device's measurement is affected not only by standard-controlled characteristics but also, for example, the aging of penetrometer components subject to deformation measured by the strain gauge system.

Figure 1. Two cones, with which more than 1000 m of soundings were performed. On top, a cone that suffered typical damage during sounding after one year of use.

In order to verify that hypothesis, at least in part, a program of comparative tests performed with three penetrometers from the same manufacturer and with the same technical specifications was proposed. All penetrometers had a calibration certificate and met the geometric requirements of ISO-22476-1 (2023) [1] (i.e., all three used new friction elements). However, they differed in the degree of wear of the strain gauge measuring system (this did not apply to the cone and sidewall geometry itself): one of the penetrometers was brand new, the second had approximately a year of use and 1500 m of probing, and the third had been in service for more than 2 years and had been used for more than 2500 m. It is worth noting that in the case of the aforementioned CPTU sounding contractor, the situation of using a penetrometer older than 1 or 1.5 years is extremely rare—earlier equipment simply succumbs to mechanical damage that prevents its reuse (Figure 1).

For comparative penetrometer studies, the AMU-Morasko test site plot was selected, which is characterized by the presence of glacial sediments with high homogeneity over a large area and significant thickness, typical of extensive areas of the Central European lowlands [8,9]. Differences were analyzed using noise analysis and statistical significance tests for differences in data from individual static soundings.

2. Materials and methods

2.1. Test site and the study program

The research was carried out in the southern part of the AMU Morasko test site. The test site is located within the Adam Mickiewicz University campus next to the northern border of Poznań, close to Morasko Meteorite Nature Reserve [9] (Figure 2).

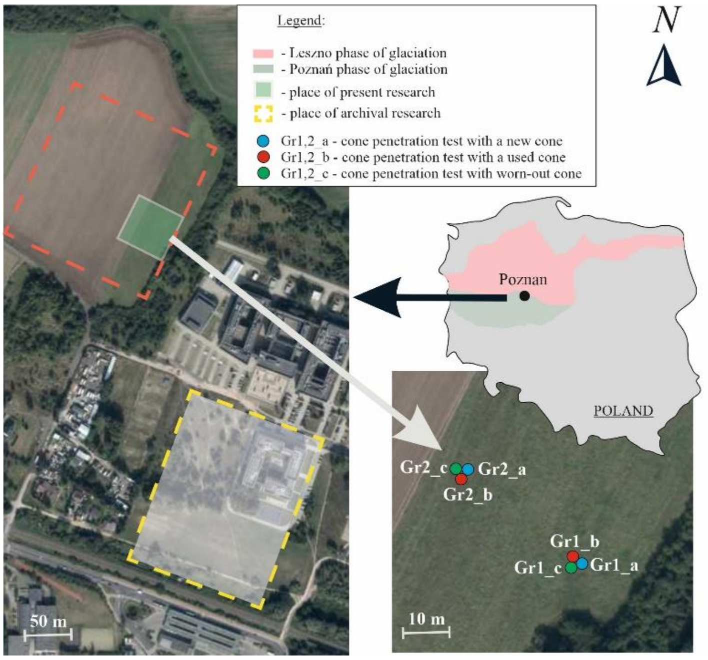

Figure 2. Location of CPTU on the AMU-Morasko test site (yellow line: southeastern part; red line: northwestern part).

The morphology of the test site was formed by glacial and fluvioglacial processes from the Vistulian glaciation [10]. The Quaternary sediment thickness in the test site area reaches c. 40 m. These deposits represent the thick glacial till of the Riss glaciation (Oder and Warta) and the glacial till of the Weichselian glaciation (Vistula). The complex of glacial sediments is covered by fine and medium sands with single grains of gravel of the so-called first sandur level from the youngest Poznan glaciation. A generalized geological profile of the test site and an example of CPTU results are presented in Figure 3.

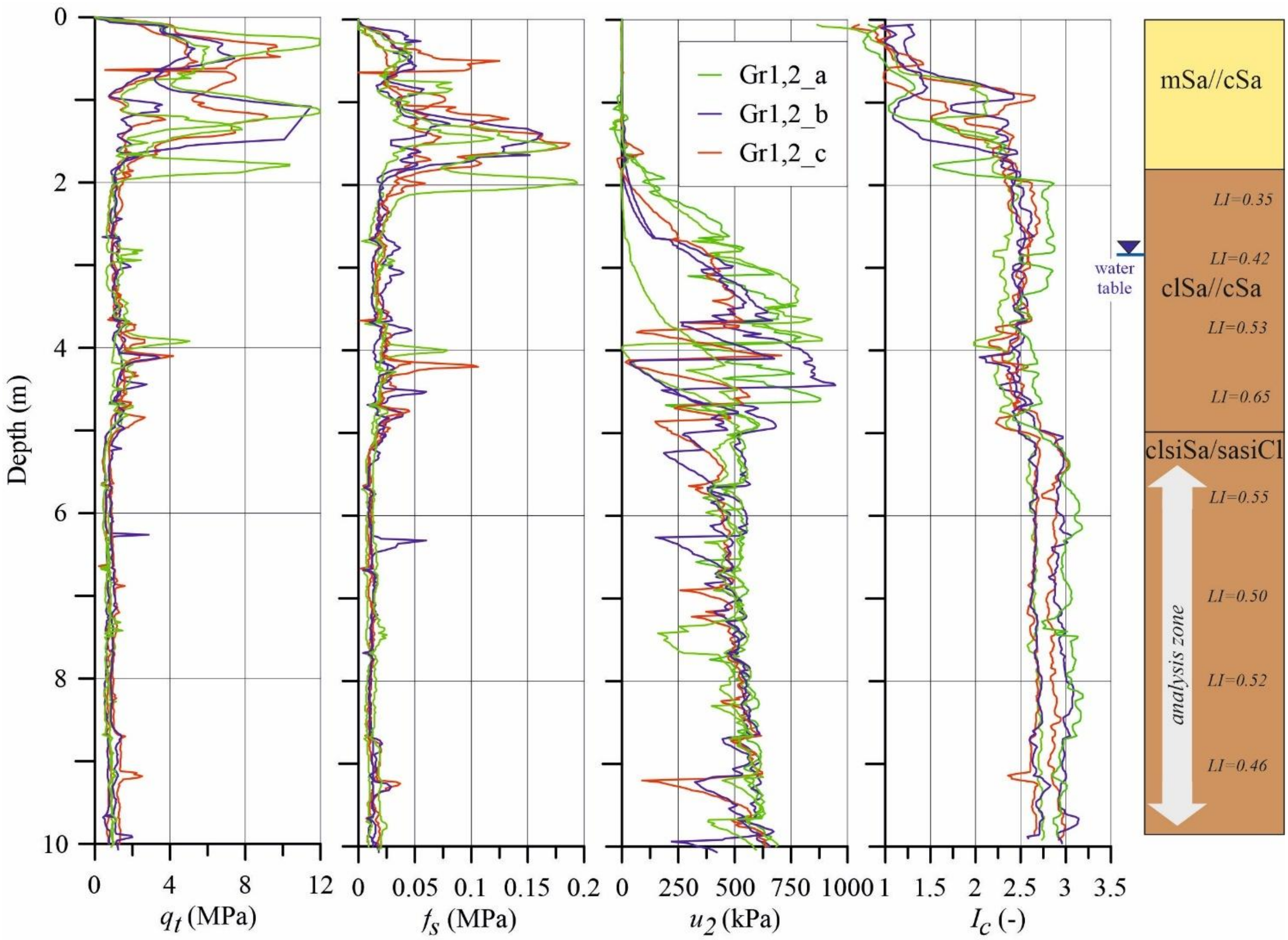

Figure 3. Generalized soil profile of the AMU Morasko test site [soil type and consistency as liquidity index (*LI*)] and results of 6 performed CPTUs.

In previous years, CPTU static soundings were performed in the southern part of the experimental field (Figure 1). The tests were conducted using two different measurement systems, and the results have been presented and discussed [6,9]. Currently, a student dormitory named Meteor has been constructed on the site where the earlier investigations took place. Consequently, the present study was conducted in the northwestern part of the AMU Morasko test site (Figure 2). For the purposes of the current analysis, tests were carried out using three cones exhibiting different levels of wear: (a) new, (b) partially worn (Figure 4), and (c) worn. The same penetrometer model with a cross-sectional area of 10 cm² and a measuring range of q_c up to 100 MPa, f_s up to 1 MPa, and u_2 up to 2 MPa was used for the tests. The resolution of the penetrometer varied depending on the device: q_c in the range of 0.865–0.901 kPa, f_s in the range of 0.0091–0.0102 kPa, and u_2 in the range of 0.0210–0.0214. The penetrometer was inserted into the ground using a GEOTECH device (Figure 5). All tests were carried out on a single day in October, at an air temperature of approximately 15 °C, at which the cone was also zeroed. The temperature range for correct operation of the penetrometer was 5–40 °C, and the maximum error due to the temperature effect did not exceed 27 kPa. The investigations were performed at two test points to a depth of approximately 9.8 m. Each test point consisted of three CPTUs placed at the corners of a triangle, 2 m apart from each other (Figure 5).

Figure 4. Used, partially worn penetrometer (b) prepared for testing.

Figure 5. Research node 1 with indicated CPTU test locations.

Based on the preliminary analysis of the sediment profile and the geological structure of the test site, the geological series occurred at a depth of 4–14 m, with sandy interlayers at a depth of approximately 10 m and a noticeable decrease in the sand fraction content below [8,9]. Detailed information on the physical properties of soil, such as granulometric composition and Atterberg limits, was presented by Radaszewski and Wierzbicki [9]. The current studies were carried out to a depth of 10 m in the potentially most homogeneous fragment of the profile. The final selection of the depth range of 5.4–9.8 m was based on the observation of the most pronounced monotonicity of penetration parameters in this fragment (Figure 3). This interval consists of a mixture of silty clayey sands and silty sandy clays, showing minor lithological variability in the form of interbedded sandy layers (Figure 3). The analyzed soils are characterized by a calcium carbonate content of approximately 4% and exhibit a plastic or soft-plastic consistency (according to ISO standard [11]). According to [8], this is a result of the high soil porosity and the shallow groundwater table (Table 1) (Figure 3). Due to the low clay fraction content, the tested soils are characterized by a low plasticity index.

Table 1. Basic physical parameters of the analyzed soils (after [6]).

	Natural moisture (%)	Plastic limit (%)	Liquid limit (%)	Plasticity index (%)	Liquidity index (-)	$CaCO_3$ (%)
Interval	13.25–17.35	9.07–12.67	15.39–23.90	4.44–10.96	0.35–0.75	3–5
Average	16.67	10.88	17.01	6.13	0.66	–

2.2. Analysis of differences

2.2.1. Model

The adopted comparative model analyzed two parameters, corrected cone resistance (q_t) and sleeve friction (f_s), and three penetrometers, Gr_a, Gr_b, and Gr_c, used at two locations (1 and 2). Data from the depth interval of 5.4–9.8 m observed every 2 cm were selected for analysis. The following model was adopted:

$$\xi_k(z) = f_k(z) + \varepsilon_k(z), \quad k = 1, \ldots, K, \tag{1}$$

where $\xi_k(z)$ is the observed value of the parameter (q_t, f_s) at depth z for location k, $f_k(z)$ is the trend [true value of the parameter (q_t, f_s)] at depth z for location k, $\varepsilon_k(z)$ is the noise (random value with zero expected value) at depth z for location k, and K is the number of locations.

The moving average method was used to estimate the trend. For the i-th observation at z_i depth, the smoothed trend value is calculated from the formula:

$$\hat{f}_k(z_i) = \frac{1}{2m+1} \sum_{l=i-m}^{i+m} \xi_k(z_l), \ i = m+1, \ldots, n-m, \tag{2}$$

where n is the number of observations.

In further calculations, we assumed $m = 3$. The value of m was chosen as a reasonable compromise between the degree of fitting between measured and predicted values. Higher m values result in smoother predicted values, greater noise reduction, but also greater deviation from the measurement data. In addition, $n = 221$.

2.2.2. Noise

For the i-th observation at depth z_i, we determined the noise value $\varepsilon_k(z_i)$ as the difference between the observed value of the analyzed parameter $\xi_k(z_i)$ and the smoothed value of the trend $\hat{f}_k(z_i)$, $i = m+1, \ldots, n-m$.

Deviations from the trend are characterized by the standard deviation of the noise σ and by a spatial correlation, which can be analyzed by examining the coefficient of autocorrelation ρ. The noise level is determined according to formula 3:

$$noise = \sqrt{1-\hat{\rho}^2} \cdot \hat{\sigma}, \quad (3)$$

where $\hat{\sigma} = \sqrt{\frac{1}{n-2m}\sum_{l=m+1}^{n-m}(\varepsilon_k(z_l) - \bar{\varepsilon}_k)^2}$ and $\hat{\rho} = \frac{1}{(n-2m-1)\hat{\sigma}}\sum_{l=m+1}^{n-m-1}\big((\varepsilon_k(z_l) - \bar{\varepsilon}_k)(\varepsilon_k(z_{l+1}) - \bar{\varepsilon}_k)\big)$ are the estimators of standard deviation and coefficient of autocorrelation, respectively.

2.2.3. Statistical tests

Let $\xi_{sk}(z)$ be a value of a parameter (q_t, f_s) for the s-th penetrometer (s = 1, 2) on depth z for location k. The index s identifies the compared penetrometers; for example, s = 1 denotes penetrometer Gr_a, and s = 2 denotes penetrometers Gr_b. We verify the null hypothesis that there are no significant differences in the parameter values for both penetrometers, while under the alternative hypothesis that significant differences exist. For this purpose, we use the test statistic, which is a measure of dissimilarity between the series corresponding to the values of parameters $\xi_{1k}(z)$ and $\xi_{2k}(z)$. In the case of small values of this dissimilarity measure, we will not reject the null hypothesis, and when its values are large, we will reject the null hypothesis in favor of the alternative hypothesis. We have chosen Dynamic Time Warping (DTW) as a measure of dissimilarity between series. Its description was taken from the paper by Górecki and Łuczak [12].

DTW is a method for comparing two series by aligning them in a way that minimizes the distance between corresponding points, even if the depth axes are not perfectly synchronized. The calculation of DTW is as follows:
Let $x = (x_1, \ldots, x_n)$ and $y = (y_1, \ldots, y_m)$ be two series. First, we construct a matrix with the (i, j)th element corresponding to $d(x_i, y_j) = (x_i - y_j)^2$, $i = 1, \ldots, n$, and $j = 1, \ldots, m$. Second, we find a path through this matrix with minimal cumulative distance between series. DTW corresponds to the path with minimal warping cost:

$$DTW(x,y) = \min_{W} \sqrt{\sum_{l=1}^{L} w_l}, \quad (4)$$

where w_l is the matrix element that also belongs to the lth element of a warping path W.

The warping path is subject to three constraints:

- boundary conditions: $w_l = (1, 1)$ and $w_L = (n, m)$,
- continuity: for $w_l = (a, b)$ and $w_{l-1} = (a', b')$, $a - a' \leq 1$ and $b - b' \leq 1$,
- monotonicity: for $w_l = (a, b)$ and $w_{l-1} = (a', b')$, $a - a' \geq 0$ and $b - b' \geq 0$.

To find this warping path, one can use dynamic programming by applying the following recurrence:

$$\gamma(i, j) = d(x_i, y_j) + min\{\gamma(i-1, j-1), \gamma(i-1, j), \gamma(i, j-1)\}. \quad (5)$$

Here, $\gamma(i, j)$ is the cumulative distance of $d(x_i, y_j)$ and the minimum cumulative distances from the three adjacent cells.

To approximate the null distribution of the test statistic (i.e., DTW) and calculate the p-value, the nonparametric bootstrap was used. These are well-known nonparametric methods that allow for efficient testing of statistical hypotheses, even with small samples. Example papers on this topic are [13] and [14].

In the considered problem, the bootstrap test proceeds according to the following steps for a fixed location k:

1. Compute DTW for original data $\xi_{sk}(z_i)$, $s = 1, 2$, where z_i denotes the i-th depth, and $i = 1, \ldots, 221$.

2. Create a bootstrap sample from the given data in the following way: From all observations $\xi_{1k}(z_1), \ldots, \xi_{1k}(z_{221}), \xi_{2k}(z_1), \ldots, \xi_{2k}(z_{221})$, select randomly with replacement 221 observations for the first new sample, and from the remaining ones, create the second new sample.

3. Repeat step 2 a large number of times, e.g., B = 1,000, and obtain B-independent bootstrap samples $\xi_{sk}^{boot,b}\left(z_i\right)$, $s = 1, 2$, $i = 1, \ldots, 221$, and $b = 1, \ldots, B$.

4. For each bootstrap sample, compute the value of the test statistic DTW. Denote them by $DTW^{boot,b}$, $b = 1, \ldots, B$.

5. The final p-value of the bootstrap test is defined by $\frac{1}{B}\sum_{b=1}^{B} I\ (DTW^{boot,b}\ >\ DTW)$,

where I $(DTW^{boot,b} > DTW) = 1$ if $DTW^{boot,b} > DTW$, and I $(DTW^{boot,b} > DTW) = 0$ if $DTW^{boot,b} \leq DTW$.

We have chosen DTW in our analysis as it is known as an efficient similarity measure for time series. One of the most significant advantages of DTW over traditional dissimilarity measures, such as cross-correlation, is its ability to handle nonlinear distortions along the time axis. While cross-correlation is an excellent tool for identifying a fixed, linear time lag between two signals, it fails when the same patterns occur at different speeds or with varying durations. DTW excels in these scenarios by finding the optimal, nonlinear alignment between two time series. Instead of looking for a single, static shift, it calculates a path that allows for "warping" of the time axis to match similar points, providing a more robust and accurate measure of similarity for signals that vary in pace. This flexibility makes DTW a superior choice for a wide range of applications where patterns are shape-based rather than time-locked. For example, Ding et al. [15] demonstrated that the DTW distance is one of the most effective time series classification techniques. Moreover, in Tsinaslanidis et al. [16], it is demonstrated that DTW, as a similarity measure, shows better properties than Pearson's and Spearman's correlations, indicating its unique capability to analyze time series, especially during varying volatility periods and across different months. On the other hand, Imamura and Nakamura [17] showed that DTW is superior to other similarity measures, like Euclidean distance, for time series analysis, particularly in motif discovery, due to its ability to handle warping and manage lags between dimensions effectively in two-dimensional time series.

3. Results

As noted in Section 2, soundings were performed in a system of two triangular test nodes (1 and 2). At each corner of the node, CPTU soundings were performed with a new (a), used (b), and worn (c) cone (Figures 3 and 6).

The results of the soundings are shown in Figure 3. Measured q_c values were corrected to q_t according to formula 6. In order to avoid removing disturbances, all measurements were filtered using a moving median from a 14 cm range. Additionally, the f_s values were correlated with the penetration depth corresponding to the middle of the sleeve part.

$$q_t = q_c + (1 - a)u_2 \tag{6}$$

where u_2 is the excess pore pressure measured behind the tip, and a is the cone area factor.

Soil Behavior Type Index (I_c) values were determined according to formula 7 using the soil bulk density values determined by Radaszewski and Wierzbicki [9].

$$I_c = [(3{,}47 - log\, Q_{tn})^2 + (1{,}22 + log\, F_r)^2]^{0{,}5} \tag{7}$$

where Q_{tn} is the normalized cone resistance, and F_r is the normalized friction ratio.

Following the observations on the homogeneity of the subsoil [8], only its fragment between 5.4 and 9.8 m depth was used for further analysis (Figure 6). The results of the preliminary work made it possible to classify the results of the CPTU soundings on the Soil Behavior Type Chart [18] (Figure 7).

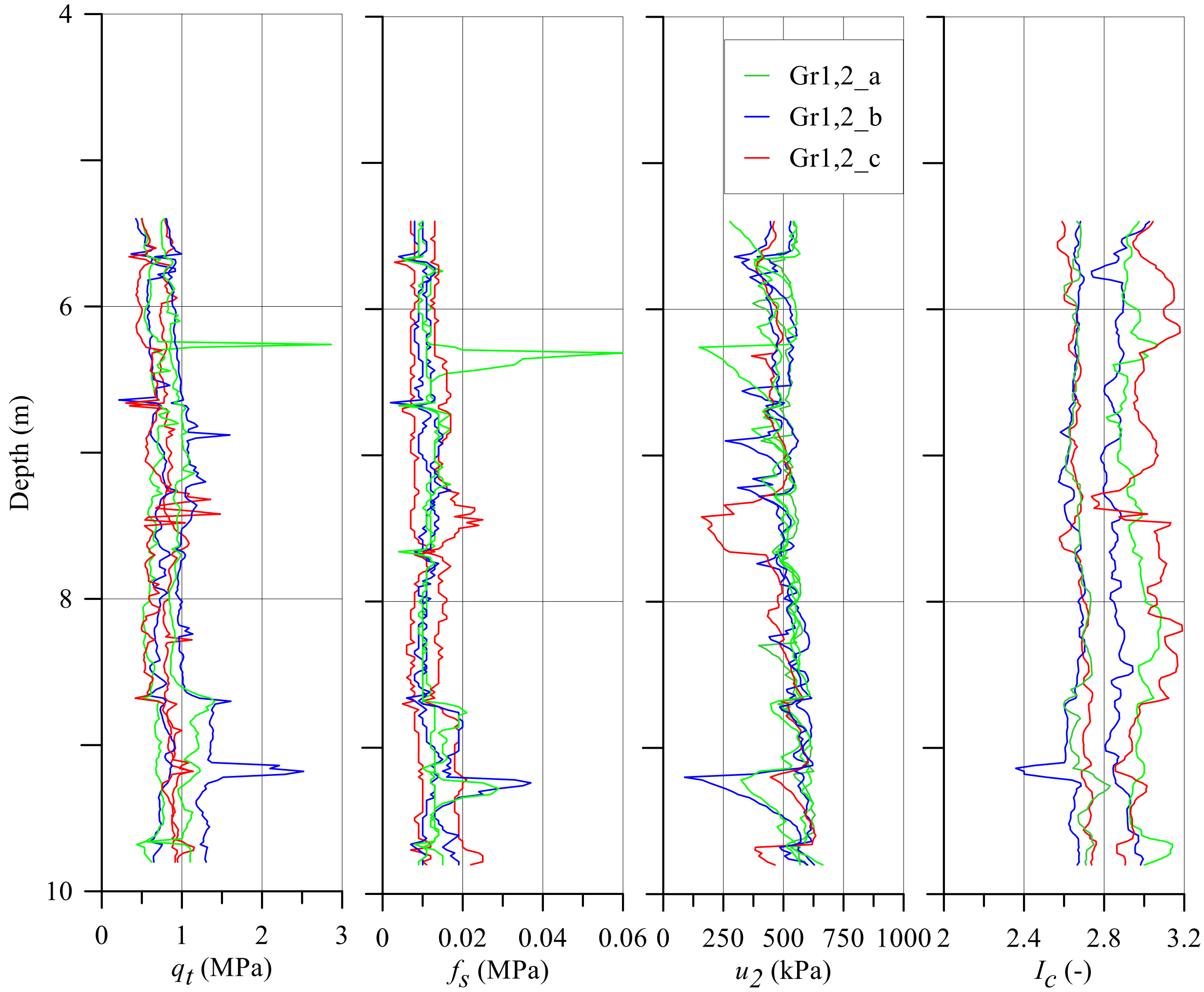

Figure 6. CPTU results for the analyzed part of the test site profile.

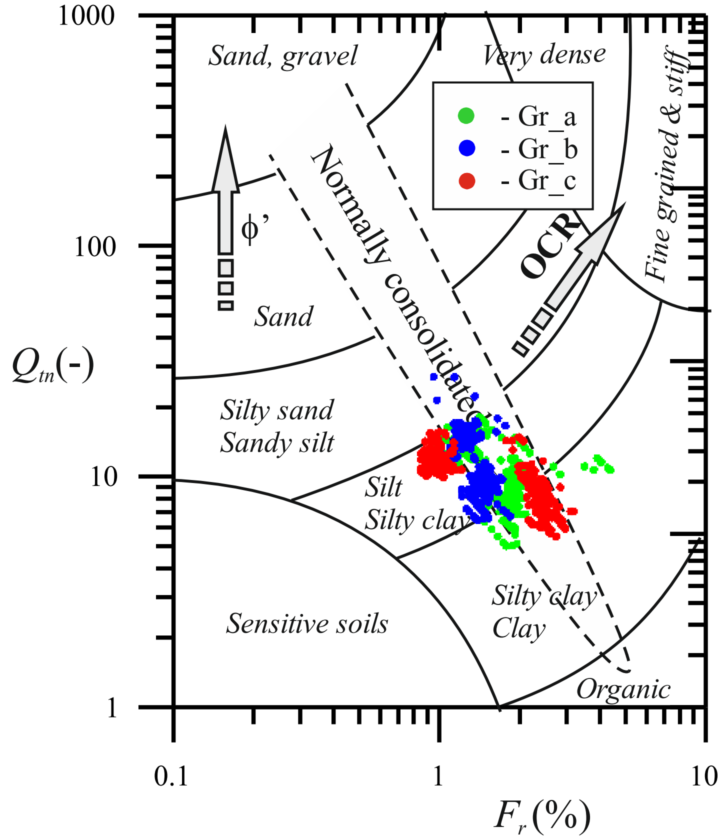

Figure 7. CPTU results on the SBT chart.

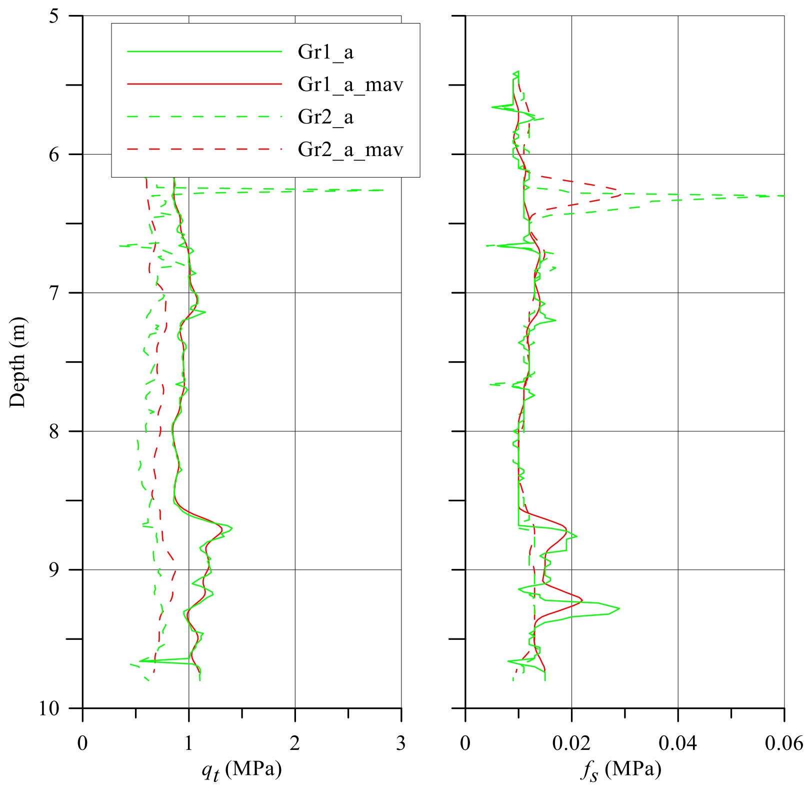

Figure 8. Comparison between direct CPTU results and the smoothed (mav) on the example of Gr_a penetrometer.

The values of cone resistance and sleeve friction from this interval were then smoothed using a moving average in accordance with the adopted methodology. The effect of the applied smoothing procedure can be seen in the example of the results obtained with the brand-new penetrometer (Figure 8).

Based on the adopted analysis methodology, the measurement noise of the two basic parameters (cone resistance and sleeve friction) was determined through the strain gauge system (Table 2).

Table 2. Results of noise calculation of q_t and f_s.

Penetrometer	Location	Noise of q_t (MPa)	Noise of f_s (MPa)
Gr_a	1	0.02341	0.00022
	2	0.00746	0.00015
Gr_b	1	0.00930	0.00044
	2	0.00973	0.00048
Gr_c	1	0.04151	0.00038
	2	0.01700	0.00017

Analysis of the sounding data treated as a series allowed us to determine the statistical significance of the differences between the different penetrometers in each location (Tables 3 and 4). The significance of differences is established for a p-value < 0.05.

Table 3. Significance of differences (calculated as a distance in the DTW method) between penetrometers due to q_t and the location of the test.

Penetrometer	Location 1 – q_t		Location 2 – q_t	
	Difference	p-value Bootstrap method	Difference	p-value Bootstrap method
Gr_a – Gr_b	38.005	0.008	41.666	0.000
Gr_b – Gr_c	65.560	0.000	25.709	0.000
Gr_a – Gr_c	20.134	1.000	9.797	1.000

Table 4. Significance of differences (calculated as a distance in the DTW method) between penetrometers due to f_s and the location of the test.

Penetrometer	Location 1 – f_s		Location 2 – f_s	
	Difference	p-value Bootstrap method	Difference	p-value Bootstrap method
Gr_a – Gr_b	0.672	0.000	0.775	0.000
Gr_b – Gr_c	0.398	1.000	0.187	1.000
Gr_a – Gr_c	0.163	1.000	0.301	0.880

4. Discussion

The noise value, as described in Section 2.2.2, can be interpreted as a fluctuation in the value of the parameter, resulting from the natural variability of the characteristics of the soil in the analyzed depth range. In the case of cone resistance, this fluctuation ranged from 1% to 4% of the average value of the measured cone resistance (Table 5). The brand-new cone, which can be considered a reference, had a noise under 1.5%. It can be noted that higher degrees of penetrometer wear (still within ISO criteria) increased the noise up to 3.8%. Among the used penetrometers, a markedly higher variation in noise values was also observed (e.g., from 0.9% to 3.5%), while the measurement noise of a new penetrometer almost did not change depending on the location.

Table 5. Noise as a percentage of q_t mean value.

Penetrometer	Location	Noise (MPa)	Mean (MPa)	% of mean
Gr_a	1	0.00930	0.963	1.0%
	2	0.00973	0.641	1.5%
Gr_b	1	0.04151	1.089	3.8%
	2	0.01700	0.695	2.0%
Gr_c	1	0.02341	0.673	3.5%
	2	0.00746	0.838	0.9%

Slightly different conclusions can be drawn from the analysis of the noise around the sleeve friction measurement. In this case, it was the new penetrometer that showed the greatest variation in the center, and the noise value decreased with wear (Table 6). At the same time, the noise level for a new penetrometer was the most stable relative to the location.

Table 6. Noise as a percentage of f_s mean value.

Penetrometer	Location	Noise (MPa)	Mean (MPa)	% of mean
Gr_a	1	0.00044	0.0124	3.6%
	2	0.00048	0.0125	3.9%
Gr_b	1	0.00038	0.0134	2.8%
	2	0.00017	0.0102	1.7%
Gr_c	1	0.00022	0.0159	1.4%
	2	0.00015	0.0082	1.8%

Such results may suggest that the investigated soil was relatively homogeneous considering the measurement through an element of about 3.5 cm in length (i.e., almost two readings of the parameter are taken over the distance of the cone's passage through a given point in the soil), while the measurement through an element of about 13.5 cm in length (almost 7 readings of the parameter are taken over this distance) showed greater variability of the medium. This interpretation, nevertheless, seems illegitimate (a reading at 13.5 cm is a more averaged reading than at 3.5 cm). However, in a medium with relatively constant strength characteristics, such as the tested sediments, the f_s measurement will indicate changes in the lithology of the sediment, which is somewhat confirmed by the geological description of the AMU test site soils and the results of the u_2 measurement. Making such an assumption indicates that the sleeve friction measurement loses its ability to identify changes in soil properties with the degree of penetrometer wear. This conclusion is confirmed by the observation of differences in f_s values recorded with different penetrometers (Figure 6). The sleeve friction measured by the worn cone (c) showed by far the greatest variation between locations. This indicates a lower precision in the measurement of this parameter than with the other devices. These differences can be seen very clearly in the SBT chart (Figure 7), where the results of penetrometer “c” are located in two distinct areas depending on the location. The results of the other penetrometers clearly form more uniform clusters.

For both the first and second test nodes, statistically significant differences in q_t measurement were found between the most worn penetrometer and the other two (Table 3). This means that excessive penetrometer wear can affect the cone resistance measurement significantly enough to generate statistically noticeable differences. This occurs despite the current calibration of the device and the comparable precision of the different devices. Significantly, the significant differences apply only to a heavily used penetrometer, in which doubts regarding measured values had already been reported by the device operator based on the mere observation of the results during earlier tests. The low level of use of the penetrometer does not lead to statistically significant differences when compared with a brand-new one.

In the case of sleeve friction, statistically significant differences were found only between new and heavily worn penetrometers (c) (Table 4). Comparison of new and used cones (b) and used and worn cones did not indicate significant differences in the measurements of this parameter. When evaluating the distances obtained from the bootstrap method, a more uniform increase in differences was noted as a result of the degree of wear of the penetrometer than when measuring the resistance of the cone. Such observation and the lack of statistically significant differences between the worn and partially used cones may mean that the f_s measurement system is subject to faster and more uniform wear than the q_t. As a result, there were no statistically significant differences between the new and used penetrometer, and the used penetrometer was also non-significantly different from the worn one.

5. Conclusions

The conducted research allowed for the identification of statistically significant differences between the measurements in cone resistance and friction on the sleeve, conducted using different penetrometers from the same manufacturer. The differences between the penetrometers used were solely related to the degree of wear, excluding variations in the geometry of the cone and the sleeve. It can therefore be assumed that these differences resulted from the number of tests conducted with each penetrometer, which, to some extent, affects the repeatability and reliability of the measurements. The preliminary observation of the commercial CPTU contractor was confirmed by the statistical test of the significance of the differences. It indicated that a device with over 2500 m of use and more than two years of operation, despite having current calibration certificates and geometric compliance with the ISO standard, produces results that differ from those of less frequently used penetrometers.

A more detailed analysis also points to an increase in differences compared to a brand-new device as the penetrometer is used. In everyday practice, this effect may often go unnoticed due to the earlier degradation of the penetrometer; however, in certain cases, using worn-out equipment for CPTU testing may lead to erroneous results. As observed during the present study, this increasing error mainly concerns the measurement of friction on the sleeve, which may indirectly explain the problematic reliability of this parameter raised by many researchers.

Although this research was not comprehensive enough to definitively determine the causes of the observed differences, it seems that, regardless of monitoring the wear of the penetrometer’s friction elements, other factors may also affect the results of static sounding, such as the aging of deformable components in the measurement system.

Author contributions

Jędrzej Wierzbicki: Conceptualization, Investigation, Methodology, Writing–original draft, Writing–review & editing; Katarzyna Stefaniak: Data curation, Methodology, Validation, Visualization, Writing–original draft, Writing–review & editing; Waldemar Wołyński: Formal analysis, Methodology, Validation, Writing–original draft; Łukasz Smaga: Formal analysis, Methodology, Software, Visualization, Writing–original draft, Writing–review & editing; Dawid Matusiak: Funding acquisition, Investigation.

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

All authors declare no conflicts of interest in this paper.

References

1. ISO 22476-1, Geotechnical investigation and testing—Field testing—Part 1: Electrical cone and piezocone penetration test, Library of Faculty of Geographical and Geological Sciences Adam Mickiewicz University in Poznań, 2023.
2. Młynarek Z, Wołyński W, Kroll M (2002) Statistical evaluation of differences between the CPTU parameters obtained from tests with various penetrometers. Report for Norwegian Geotechnical Institute. Library of Faculty of Geographical and Geological Sciences Adam Mickiewicz University in Poznań. 24.
3. Powell JJM, Lunne T (2005) A comparison of different sized piezocones in UK clays. *Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering*, Osaka, 2: 729–734. https://doi.org/10.3233/978-1-61499-656-9-729
4. Lunne T, Strandvik S, Kåsin K, et al. (2018) Effect of cone penetrometer type on CPTU results at a soft clay site in Norway. *Cone Penetration Testing 2018*, CRC Press, 417–422.
5. Wierzbicki J, Młynarek Z, Wołyński W (2020) On the precision of static probing based on tests of transitional soils at the AMU Morasko test site. Przegląd Geologiczny. Available from: https://www.pgi.gov.pl/oferta-inst/wydawnictwa/czasopisma/przeglad-geologiczny.html.
6. Paniagua P, L'Heureux JS (2022) Effect of the scatter between CPTU measured parameters in soil classification, *Cone Penetration Testing 2022*, CRC Press, 630–635.
7. Powell JJM, Dhimitri L, Ward D (2021) The fric tion sleeve measurement in CPTU—Does size matter?—A new study. *6th International Conference on Geotechnical and Geophysical Site Characterization (ISC2020)*. Budapest.
8. Wierzbicki J, Radaszewski R, Waliński M (2018) The variability of CPTU results on the AMU-Morasko soft clay test site. Peuchen W, Pisanò F, Hicks A, Eds., *Cone Penetration Testing 2018*, CRC Press, 703–708.

9. Radaszewski R, Wierzbicki J (2019) Characterization and engineering properties of AMU Morasko soft clay. *AIMS Geosci* 5: 235–264. https://doi.org/10.3934/geosci.2019.2.235
10. Stankowski W (2010) Morasko Meteorite. A curiosity of the Poznań region. *Seria Geologia* 19: 94.
11. PN-EN ISO 14688–2, Geotechnical investigation and testing—Determination and classification of soils—Part 2: Classification principles, 2018. In Polish.
12. Górecki T, Łuczak M (2014) Non-isometric transforms in time series classification using DTW. *Knowl Based Syst* 61: 98–108. https://doi.org/10.1016/j.knosys.2014.02.011
13. Ditzhaus M, Smaga Ł (2025) Inference for all variants of the multivariate coefficient of variation in factorial designs. *Scand J Stat* 52: 270–294. https://doi.org/10.1111/sjos.12740
14. Konietschke F, Bathke AC, Harrar SW, et al. (2015) Parametric and nonparametric bootstrap methods for general MANOVA. *J Multivar Anal* 140: 291–301. https://doi.org/10.1016/j.jmva.2015.06.003
15. Ding H, Trajcevski G, Scheuermann P, et al. (2008) Querying and mining of time series data: experimental comparison of representations and distance measures, *Proc VLDB Endow* 1: 1542–1552. https://doi.org/10.14778/1454159.1454226
16. Tsinaslanidis P, Antonis A, Achilleas Z, et al. (2014) Dynamic Time Warping as a Similarity Measure: Applications in Finance. Hellenic Finance and Accounting Association, Volos, Greece, 12–13.
17. Imamura M, Nakamura T (2023) A Symbolic Representation of Two-Dimensional Time Series for Arbitrary Length DTW Motif, *2023 IEEE International Conference on Data Mining (ICDM)*, Shanghai, China, 1067–1072. https://doi.org/10.1109/ICDM58522.2023.00125.
18. Robertson PK, Cabal KL (2012) Guide to Cone Penetration Testing. Signal Hill: Greg Drilling & Testing, Inc.