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Case Report

Correlational Research of Strength Parameters of Waste Soils Determined in the Laboratory and In Situ in Cracow

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Abstract: This work presents an analysis of the relationship between strength parameters determined in the laboratory and the results of a cone penetration test with pore water pressure measurement (CPTU) of waste soils in the "White Seas" area in Cracow. Anthropogenic soil is an alkaline waste formed during the production of soda ash and deposited in the area of the former Solvay Sodium Plant factory in Cracow, Poland. Due to the large area of the land and numerous investment plans and completed buildings, there was a need to identify reliable functional relationships enabling the determination of the strength parameters of these soils based on the results of the CPTU. Statistical analysis showed that the best correlation with the test results was provided by two logarithmic functions in which the dependent variables were the effective friction angle and effective cohesion. The dependent variable for both cases was the corrected cone resistance q_t. The functional relationship combined data from labour-intensive, long-lasting and costly laboratory measurements with quick and less expensive measurements, i.e., in situ CPTUs. The obtained relationships enable the determination of the strength properties of the subsoil of these anthropogenic soils.

Keywords: waste soil; strength parameters; correlation function

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1. Introduction

This article contains an analysis of the correlation of selected geotechnical parameters of waste soils determined in the laboratory and "in situ" in the "White Seas" area in Cracow. The correlations of the strength parameters obtained from laboratory tests and in situ CPTUs have been widely studied and reported by many researchers for various soils. Correlation formulas were created from scientific research for various soils in order to quickly assess their properties for construction purposes. This saves on the time and costs that are needed to perform laboratory tests. Correlation formulas usually concern natural soils. It is rare to find waste in such a large area where there are large construction investments (buildings, roads, tunnels, bridges). The novelty of this article is to obtain such a correlation for the tested waste. There is no such relationship reported so far, and it is important from the point of view of construction investments on these anthropogenic soils. There are many correlation formulas and relationships in the literature which have been established for a specific soil, but these can also be applied to soils with the same parameters and mineral composition. It may be in a different location, but the soil must be the same in terms of geotechnical parameters.

The premise for choosing the research topic of the work was due to the number of construction investments in the area of the "White Seas" in Cracow in recent years and the difficulties that have been encountered with regard to determining the geotechnical parameters of this soil [1,2]. The research was conducted on anthropogenic soil in the "White Seas" area, which is located in the southern part of Cracow, Poland (Figure 1).

Anthropogenic soil landfill is an alkaline calcareous sludge flotation waste disposal product that was formed during the production of industrial soda in the Solvay Sodium

Plant in Cracow. The soil is an alkaline waste residue and primarily consists of suspended particles such as $CaCO_3$, $CaSO_4$, and soluble chloride salts ($CaCl_2$, NaCl) [3–5]. Flotation waste is a white-coloured, fine-grained material commonly stored in landfills or settling ponds [6,7]. The unusual soil condition and lack of correlation between the geotechnical parameters and the results of the cone penetration test with pore water pressure measurement (CPTU) have been problems for engineers in the structural design process of future buildings [3].

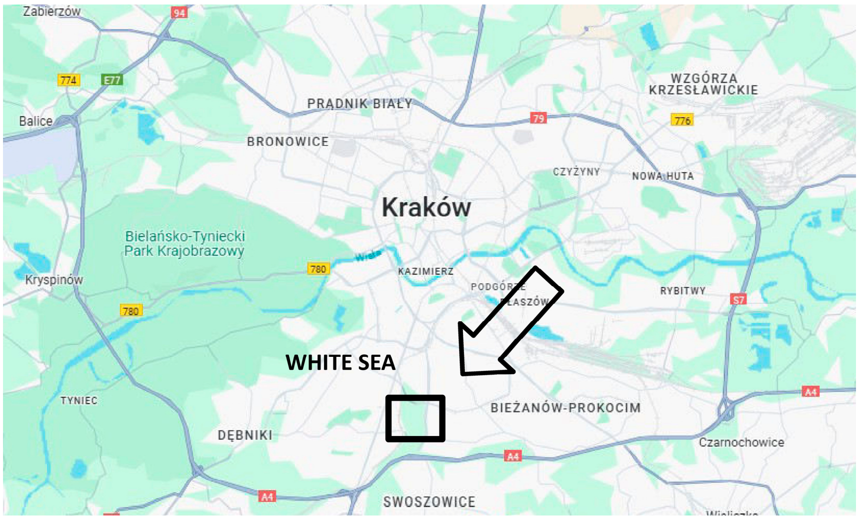


Figure 1. Location of the "White Sea" area in Cracow [google maps].

One of the most popular in situ soil testing methods is the cone penetration test with pore water pressure measurement (CPTU). Advantages such as speed, accuracy and the repeatability of test results are the reasons why the CPTU is the most widely used in geotechnical investigation. CPTUs provide information about soil condition in the tested profile of the subsoil at a relatively low cost. Soil testing and obtaining material strength parameters in the tested soil are important elements in the correct assessment of subsoil for planned investments. There are many publications in both the international and Polish literature on the possibility of using the results from the CPTU method to assess the properties of subsoil [8–11].

Using in situ soil investigations, it is possible to survey a significantly larger area in a short amount of time. All investigations are conducted on the site of the future investment in natural conditions in situ, meaning within the current state of stress, saturation level, and temperature. These probes are minimally invasive and are sometimes the only method for determining soil parameters when terrain conditions do not enable the collection of samples.

Despite their benefits, in situ investigations also have certain limitations [12]. The most significant limitations include the inability to determine parameters under different stress conditions, high rates of soil deformation during the investigation, and the inability to control drainage conditions. For these reasons, most field studies do not directly enable the measurement of basic geotechnical parameters.

The results of the CPTU are the following values in relation to the probing depth: qc—cone resistance, fs—sleeve friction, u—pore pressure. None of these parameters, however, directly determine the material parameters of the tested soil, which consequently necessitates the adoption of reliable correlations to determine soil parameters each time. Based on the aforementioned quantities of qc, fs, and u, it is possible to estimate soil parameters; yet, estimating the correlation between the results of static CPTU probing and soil parameters remains both a challenging task and an open problem [9,13–15]. This is mainly due to regional factors, i.e., specific geological conditions of the soil foundation within a given region of the country. Determining parameters based on the CPTU is possible using strength parameters estimated from reliable correlations. An example of such a correlation is the assessment of the effective internal friction angle based on parameters obtained from CPTUs [10]. The correlation function (Equation (1)) between the effective internal friction angle φ' and the normalised cone resistance Q_{tn} [10] is

$$\varphi'[deg] = 17.6 + 11\log(Q_{tn}) \quad (1)$$

Over the past few years, experimental studies have been conducted aimed at assessing the potential use of various functional relationships in Polish conditions [9,16–18]. These studies have also identified the need to modify formulas to achieve a higher value of the Pearson correlation coefficient R^2. New proprietary formulas often rely on the same leading parameters and deviate slightly from the original formulas [16]. Generally, the transformation of function forms for local soils is presented in a simpler form.

Due to the high costs and extensive time required for laboratory tests, the scientific literature often lacks information and research on the characteristics of various types of soils [19]. The current Polish standard Eurokod 7 1997 [20] provides assumptions for determining the strength parameters based on the CPTU for natural soils, without considering anthropogenic soils. Therefore, obtaining reliable functional dependencies for anthropogenic soils is only possible after conducting laboratory and field studies.

Several construction projects have already been implemented in the area where these anthropogenic soils occur, with more planned for the future. The first investment was the construction of a complex of buildings comprising the John Paul II Center, which was carried out in stages between 2010 and 2013. Another investment in the area was the construction of a footbridge between the Sanctuary of Divine Mercy and the John Paul II Center in 2016. The next investment was a road-tram tunnel section of the Łagiewnicka route, which was completed between 2019 and 2022 (Figure 2).

Figure 2. Excavation during the construction of the Łagiewnicka route in the "White Seas" area (photo Pilecka).

2. Laboratory and CPTU

Research was conducted on anthropogenic waste in the area known as the "White Seas" in Cracow. The "White Seas" area in Cracow is an approximately eighty-hectare site in which post-production waste from the Solvay Soda Works Plant was stored in the twentieth century. During the peak production period of the Krakow Soda Works Plant, up to 600 [Mg/day] of raw soda were produced, resulting in approximately 6000 [m^3/day] cubic metres per day of post-production sludge (approximately 9–10 m^3 per ton of product) [21]. The decision to close the Krakow Soda Plant in 1989 marked the end of waste storage. Currently, most of the surface of the four soil pounds is covered with vegetation, except for the northern pounds where the research was conducted. The locations where soil samples were taken for laboratory testing and the CPTU are shown in Figure 3 below.

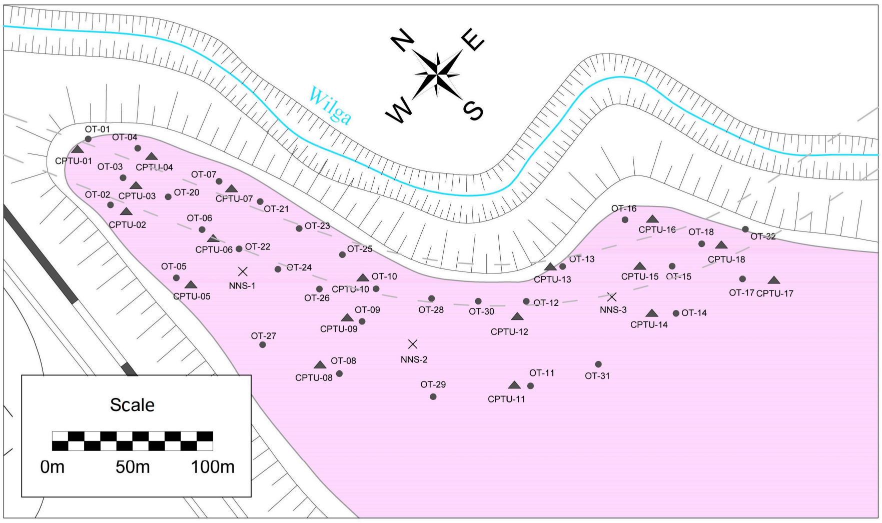


Figure 3. Location of boreholes and CPTUs [22].

Laboratory tests were conducted on samples of anthropogenic soil collected at various depths in boreholes in order to determine the effective parameters. Typically, the determination of these strength parameters is conducted using triaxial compression apparatus [23,24].

The first stage of the study involves saturating the soil sample. Saturation of the soil sample is necessary due to the measurement of pore pressure and changes in the volume of the soil sample. Only when fully saturated can the results of the study be reliably interpreted [23]. The second stage of the triaxial test is soil consolidation. This stage aims to achieve the desired level of effective stress in the test sample. The final stage of the study involves uniaxial compression of the sample in a triaxial state in the testing cell. By applying the loading scheme, it is possible to study the relationship between soil stress and strain. The tests were conducted on samples that were fully saturated, consolidated, and sheared under conditions allowing water drainage from the sample (Figure 4).

(**a**) (**b**) (**c**)

Figure 4. Soil sample tested in triaxial compression apparatus (**a**) before the test, (**b**) after the shear, and (**c**) after the test (photo Zięba).

The primary objective of the study is to determine the stress–strain characteristics. Based on the determined relationship, it is possible to determine the maximum shear stress in the tested sample (shear strength). The most commonly used criterion for shearing a sample is the criterion of the maximum value of shear stress according to the Coulomb–Mohr condition. Under effective stress conditions, this criterion is presented as follows:

$$\tau_f = \sigma' \cdot \tan \varphi' + c' \quad (2)$$

where

τ_f—shear stress [kPa].

φ', c'—shear strength parameters, respective angle of friction [deg], and cohesion [kPa].

σ'—effective stress [kPa], $\sigma' = \sigma - u$.

σ—total stress [kPa].

u—pore water pressure [kPa].

The criterion for sample failure is described by strength parameters relating to the effective internal friction angle φ′ [deg] and effective cohesion c′ [kPa]. The determination of these strength parameters is performed by fitting a tangent to the Mohr circles. Based on the tangent's inclination, the friction angle can be determined, while the intersection point with the vertical axis allows for the determination of the cohesion value (Figure 5).

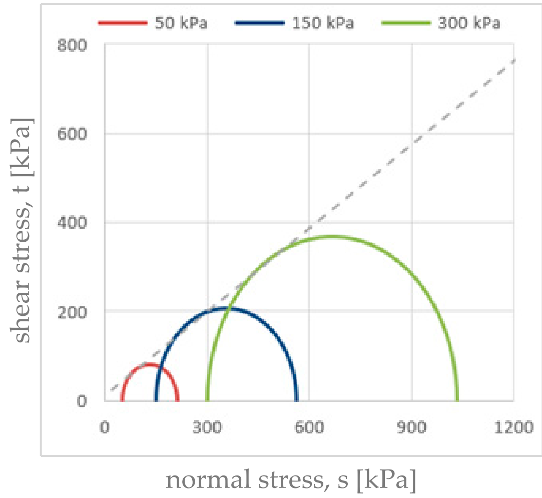


Figure 5. Selected Mohr circle research results from [22].

In engineering practice, procedures enabling the determination of soil parameters based on CPTU results are commonly used [8–10,25]. Example CPTU results from the tested anthropogenic soils are presented in Figure 6.

To determine functional relationships with the laboratory parameters of the soils, normalised parameters from CPTUs are commonly used. This means that parameters directly determined during the CPTU, qc, fs, and u_2, require normalisation because this also facilitates interpretation of the emerging classes by reference to Soil Behaviour Type charts (SBT) [11,26]. Based on the measured sounding parameters, derivative parameters are determined [8], which will ultimately be considered when searching for functional relationships.

Cone penetration, especially in cohesive soils, causes an increase in pore water pressure. To eliminate the influence of this pressure increase, the corrected cone resistance is determined according to the formula expressed by Equation (2) [8].

$$q_t = q_c + (1 - a) \cdot u_2 \quad (3)$$

where

q_t—corrected cone resistance.

q_c—cone resistance [MPa].

a—the net area ratio determined from laboratory calibration (the value is provided by the manufacturer as a standard and approximates the ratio of the cross-sectional area of the cone tip shank to the total cross-sectional area of the cone tip for the cone used a = 0.8).

u_2 –pore water pressure obtained in CPTU [kPa].

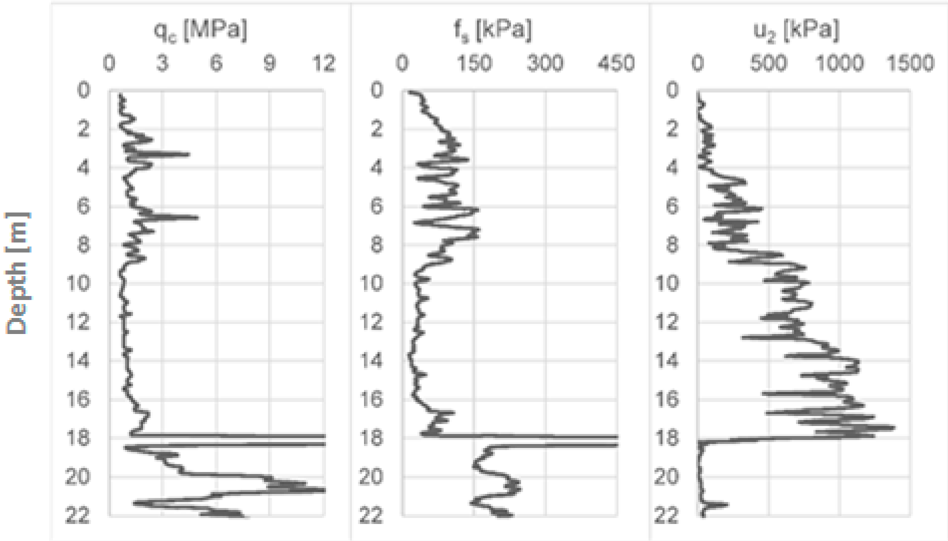


Figure 6. Selected profile with the piezocone test results [22].

The normalisation of sleeve friction resistance is based on the results of the friction values measured in the fs test and the cone resistance. The formula used for normalisation conforms to Equation (3) [8].

$$F_r = \frac{f_s}{q_t - \sigma_{vo}} \cdot 100\% \quad (4)$$

where

f_s—sleeve friction [kPa].

σ_{vo}—total overburden stress [kPa].

The undisturbed soil samples were collected from a depth between 0.5 and 18.0 mbgs (metres below ground surface). The natural water content of the tested soil samples varied from 35% to 200%. Bulk density (ρ) ranged from 1.15 to 1.70 g/cm^3. The pycnometric method indicated that the density of the soil skeleton ranged from 2.58 to 2.62 (on average 2.60).

The soil grain size analysis was performed in accordance with the applicable standard [27]. A total of 17 analyses were performed. The results showed that the number of particles smaller than 0.063 mm in the soil was between 94 and 98%. Therefore, an areometric analysis was performed. The results of the analyses, due to the high homogeneity of the tested soil, are presented in the form of a range in Figure 7.

In order to determine the chemical composition of the analysed soil samples, the X-ray powder diffraction method (XRD) was used. The tests were carried out for selected representative samples at the Faculty of Chemical Engineering and Technology of the Krakow University of Technology. The SmartLab SE diffractometer from Rigaku was used for the above analysis.

Based on the XRD analysis, and in particular the diffraction images of the analysed samples, it was found that one component, calcite ($CaCO_3$), was present in the analysed sample (Figure 8).

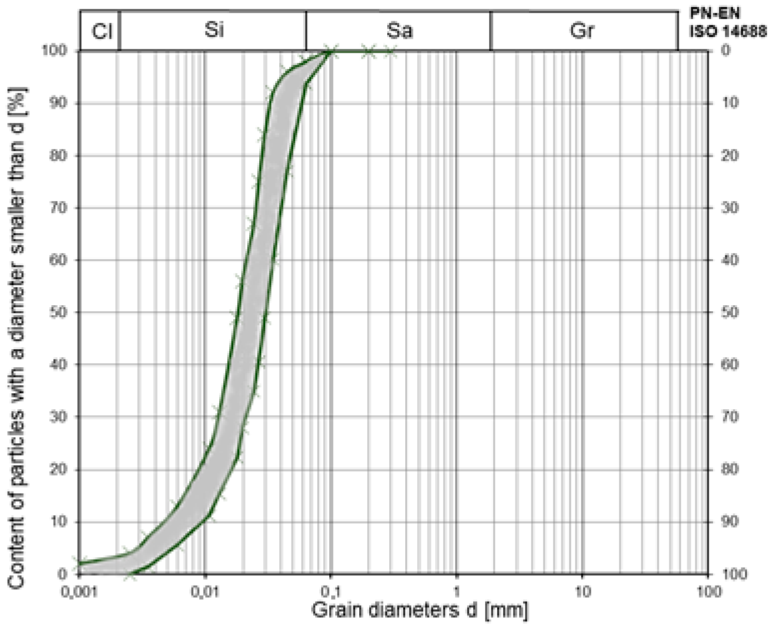


Figure 7. Grain size range for limestone waste [22].

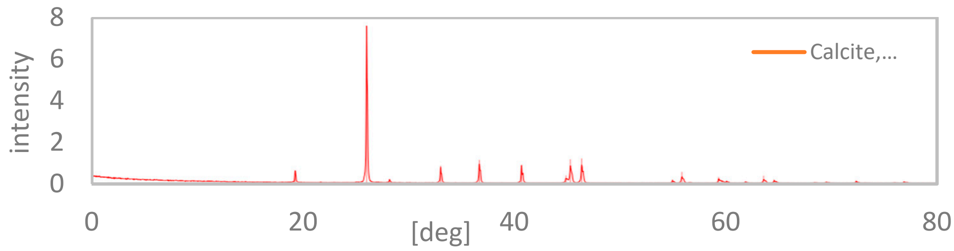
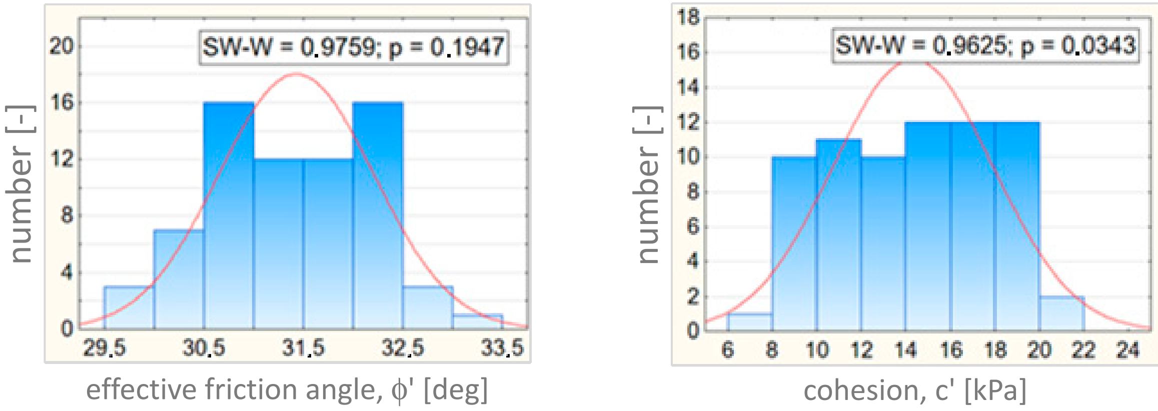


Figure 8. Diffraction image of the analysed soil sample [22].

To examine the relationships between the field CPTU results and the laboratory test results, statistical analysis methods using the Statistica ver 13.3 programme were applied. The analysis started with examining the distribution of variables, namely the results of the field and laboratory tests. The results of the distribution analysis allowed for the determination of the appropriate correlation method, based on which the degree of correlation dependence and the correlation coefficient (using Pearson's or Spearman's method) were estimated. The normality of the distribution of the analysed variable was assessed using the Shapiro–Wilk test. The analysis was conducted on a sample of seventy soils. When the value of the W statistic in the test is less than the critical value equal to 0.957, it means that the null hypothesis H_0 should be rejected, which is equivalent to accepting the alternative hypothesis H_1, where the variable distribution is different from normal. In all statistical analyses conducted in the study, a significance level of 0.05 was adopted.

3. Results of Statistical Analyses and Discussion

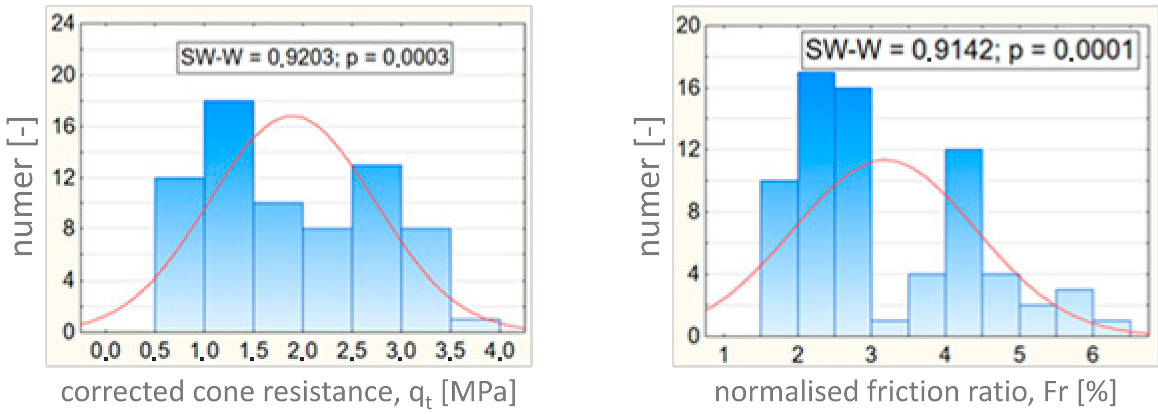
The total number of triaxial compression tests used in the analysis is 70. For all selected soil parameters, a Shapiro–Wilk analysis of distribution was conducted. The dependent variables, namely the internal friction angle (ϕ') and cohesion (c'), obtained a "W statistic value" for the Shapiro–Wilk test greater than the critical value of 0.957 (for 70 samples). This indicates that the data distribution is normal (Figure 9).



(**a**) (**b**)

Figure 9. Histogram of the analysed data: (**a**) effective friction angle and (**b**) effective cohesion [22].

The histograms of the CPTU parameter, i.e., the corrected cone resistance q_t [MPa] and normalised friction ratio Fr [%], results are presented in Figure 10. The 70 CPTU sounding results obtained correspond to the average value from the depth at which the sample was taken for analysis.



(**a**) (**b**)

Figure 10. Histogram of the analysed data: (**a**) corrected cone resistance q_t and (**b**) normalised friction ratio Fr [22].

As indicated by the Shapiro–Wilk test, the independent variables, namely the corrected cone resistance (q_t) and the normalised friction coefficient (Fr), do not follow a normal distribution (Figure 8).

To determine if the variables are dependent, the Spearman correlation coefficient was calculated for two sets of data separately: the corrected cone resistance (q_t) and the laboratory-determined internal friction angle (ϕ') (Table 1). Table 2 shows the Spearman correlation coefficient values for the normalised friction coefficient (Fr)—a variable derived from field studies—and the laboratory-determined internal friction angle (ϕ'). The significance level was set at 0.05, indicating a 95% probability of dependence between the variables. The calculations reveal that, at the specified significance level of 0.05, both q_t and Fr are dependent on the variable ϕ'. The significance of the correlation coefficient was tested using hypothesis testing, yielding positive results. However, the Spearman correlation coefficient for q_t and ϕ' is higher, at 0.91, indicating that the internal friction angle ϕ' is more dependent on q_t than on Fr.

Table 1. Correlation results for corrected cone resistance (q_t) and the friction angle (ϕ').

Variable	φ'	q_t
φ'	1	0.91
q_t	0.91	1

Table 2. Correlation results for normalised friction coefficient (Fr) and the friction angle (ϕ').

Variable	φ'	Fr
φ'	1	−0.45
Fr	−0.45	1

The next stage in the statistical analysis was to determine the functional relationship between the variables using regression analysis. The dependent variable was set as the friction angle φ'. Various functional relationships were considered: linear, polynomial, logarithmic, and exponential. The best fit to the data was shown by the logarithmic function. Below are the results of the functional relationships, which demonstrated a coefficient of determination R^2 in the regression analysis, as shown in Figures 11–14.

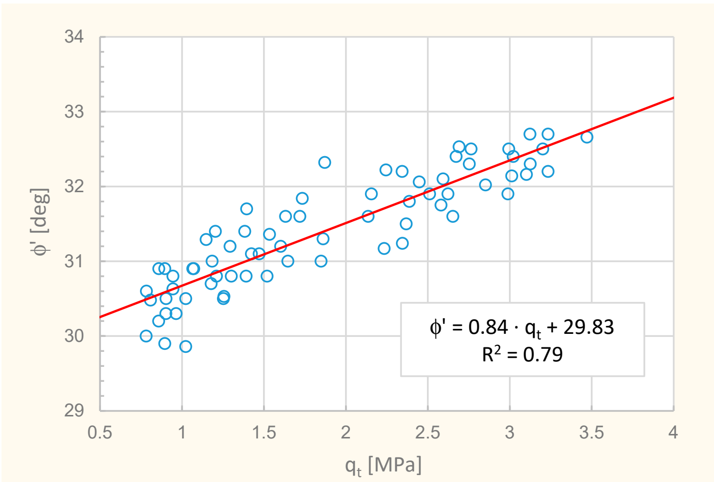


Figure 11. The linear relationship between the effective friction angle (ϕ') and corrected cone resistance (q_t).

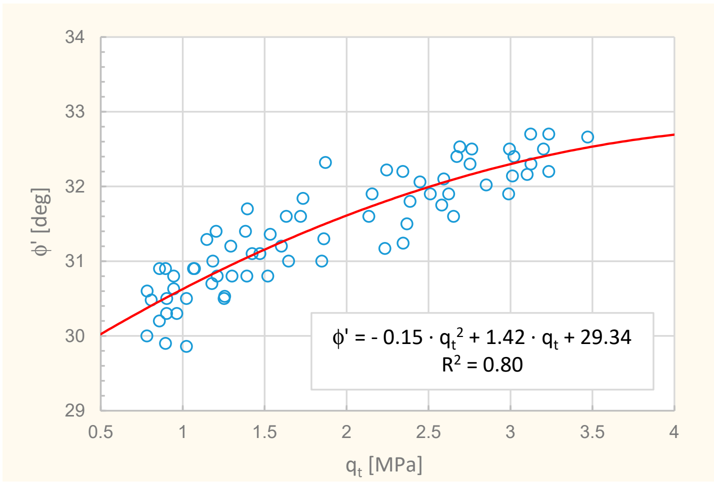


Figure 12. The polynomial relationship between the effective friction angle (ϕ') and corrected cone resistance (q_t).

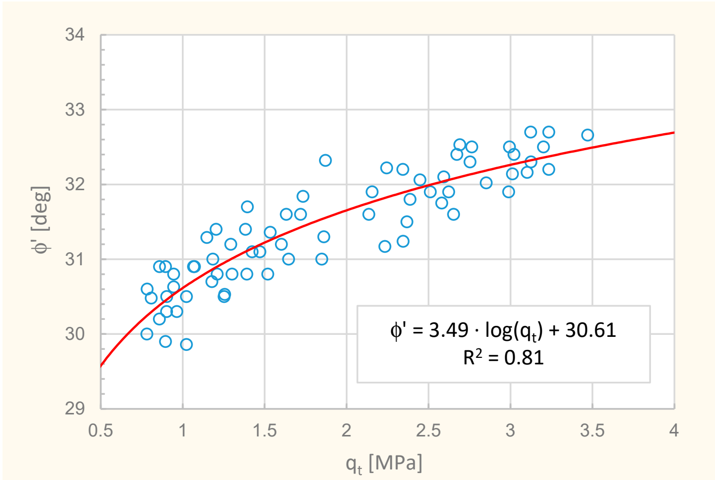


Figure 13. The logarithmic relationship between the effective friction angle (ϕ') and corrected cone resistance (q_t).

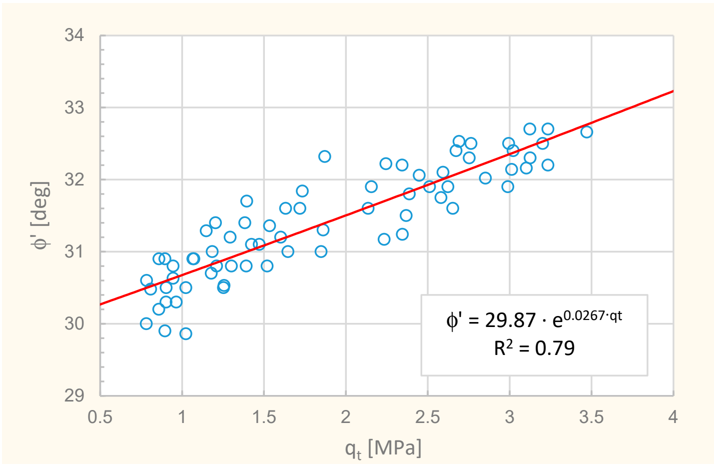


Figure 14. The exponential relationship between the effective friction angle (ϕ') and corrected cone resistance (q_t).

Utilising the corrected q_t parameter from the CPTUs, which incorporates the pore water pressure value, enabled the establishment of a relationship as depicted in Figure 13 with a high degree of agreement and a coefficient of determination $R^2 = 0.81$.

Finally, based on linear regression analysis, the functional relationship result can be represented by Equation (5):

$$\varphi' = 3.49 \cdot \log_{10}(q_t) + 30.61 \quad \left(R^2 = 0.81\right) \tag{5}$$

Furthermore, the calculation of the effective friction angle, due to small differences in the R^2 parameter, can be determined for simplicity using the linear formula shown in Figure 11 (Equation (6)).

$$\varphi\prime = 0.84\ (qt) + 29.83 \quad \left(R^2 = 0.79\right) \tag{6}$$

Prediction of the effective friction angle (ϕ') based on the normalised friction coefficient Fr will be inaccurate due to the low degree of agreement with the data. Below are the functional relationship results, which demonstrated the coefficient of determination R^2 in the regression analysis, as shown in Figures 15–18.

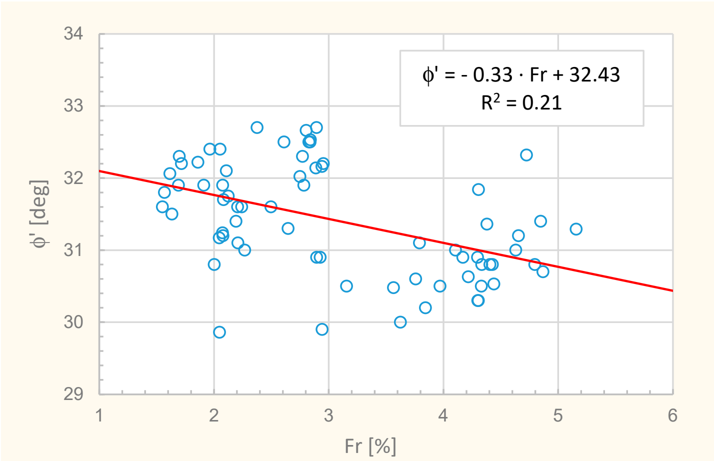


Figure 15. The linear relationship between the effective friction angle (ϕ′) and the normalised friction coefficient Fr.

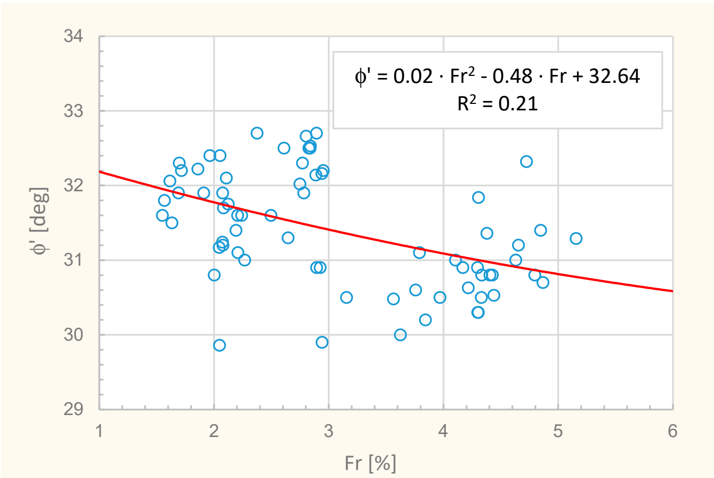


Figure 16. The polynomial relationship between the effective friction angle (ϕ′) and the normalised friction coefficient Fr.

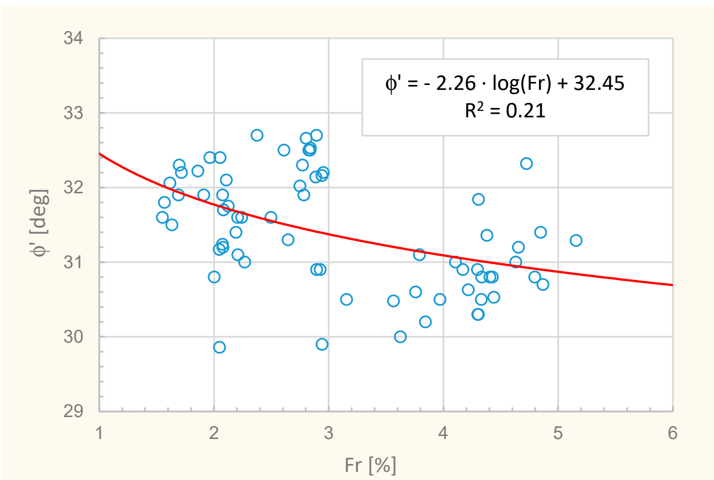


Figure 17. The logarithmic relationship between the effective friction angle (ϕ′) and the normalised friction coefficient Fr.

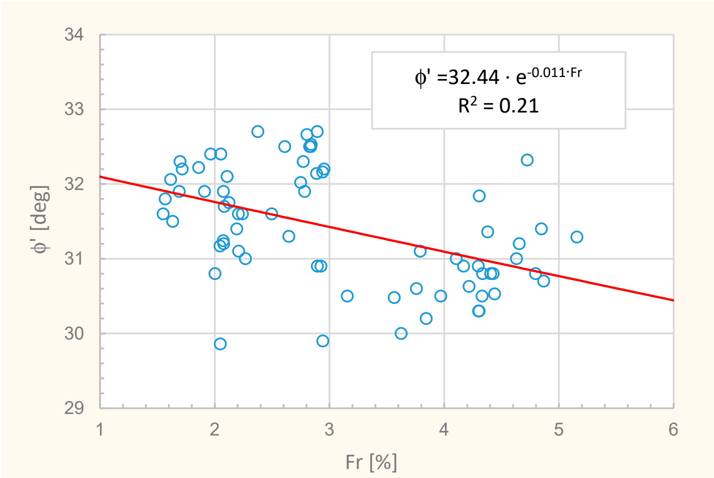


Figure 18. The exponential relationship between the effective friction angle (ϕ′) and the normalised friction coefficient Fr.

In the case of the relationship utilising the normalised friction coefficient Fr, it takes the form:

$$\varphi' = -2.26 \cdot \log_{10}(F_r) + 32.45 \quad \left(R^2 = 0.21\right) \tag{7}$$

In this case, the coefficient of determination, compared to results based on the corrected cone resistance qt, is lower and statistically unacceptable, with $R^2 = 0.21$ [27]. The remaining analysed functions have the same coefficient of determination. The authors do not recommend using these relationships. A better relationship was applied to determine the effective friction angle, where the independent variable was the corrected cone resistance qt (Equations (5) or (6)).

To determine if the variables are dependent, the Spearman correlation coefficient was calculated for two sets of field data. The first was the correlation between the corrected cone resistance q_t and the laboratory-determined cohesion c′ (Table 3). Table 4 shows the Spearman correlation coefficient values for the normalised friction coefficient Fr—a variable derived from field studies—and the laboratory-determined effective cohesion c′. The significance level was set at 0.05, indicating a 95% probability of dependence between the variables. The calculations reveal that, at the specified significance level of 0.05, both q_t and Fr are dependent on the variable c′. The significance of the correlation coefficient was tested using hypothesis testing, yielding positive results. However, the Spearman correlation coefficient for q_t and c′ is better, at −0.89, indicating that the friction angle ϕ′ is more dependent on q_t than on Fr.

Table 3. Correlation results of corrected cone resistance q_t and cohesion c′.

Variable	c′	q_t
c′	1	−0.89
q_t	−0.89	1

Table 4. Correlation results of normalised friction coefficient Fr and cohesion c′.

Variable	c′	Fr
c′	1	0.54
Fr	0.54	1

In the case of regression analysis for the effective cohesion c′ [kPa] and corrected cone resistance q_t [MPa], a relationship was obtained, as shown in Figures 19–22.

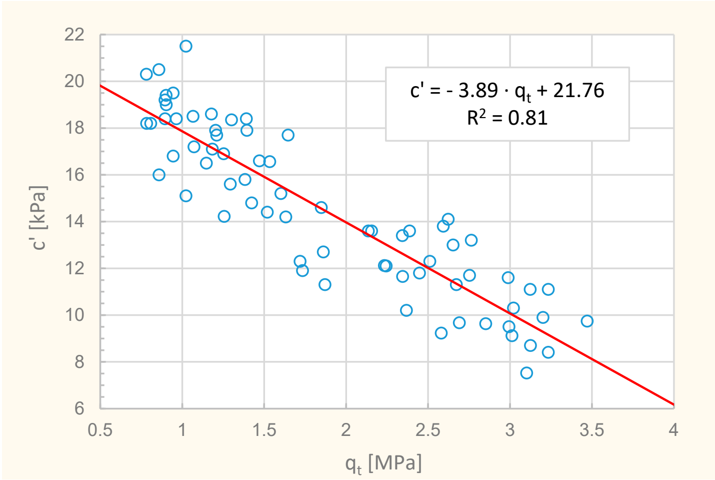


Figure 19. The linear relationship between the effective cohesion c′ and corrected cone resistance (q_t).

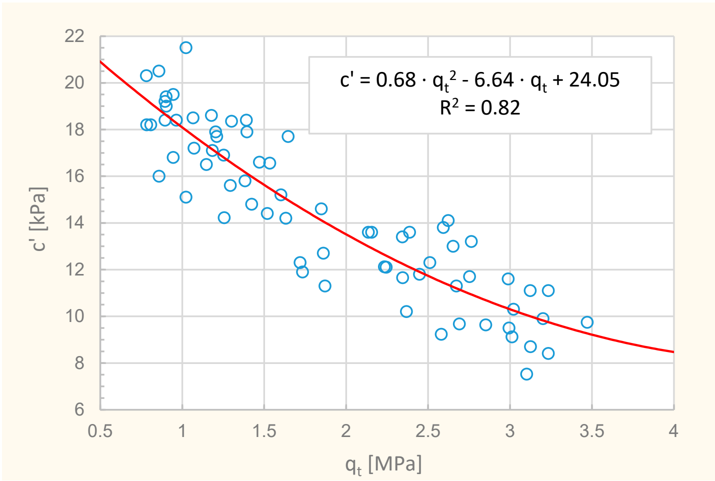


Figure 20. The polynomial relationship between the effective cohesion c′ and corrected cone resistance (q_t).

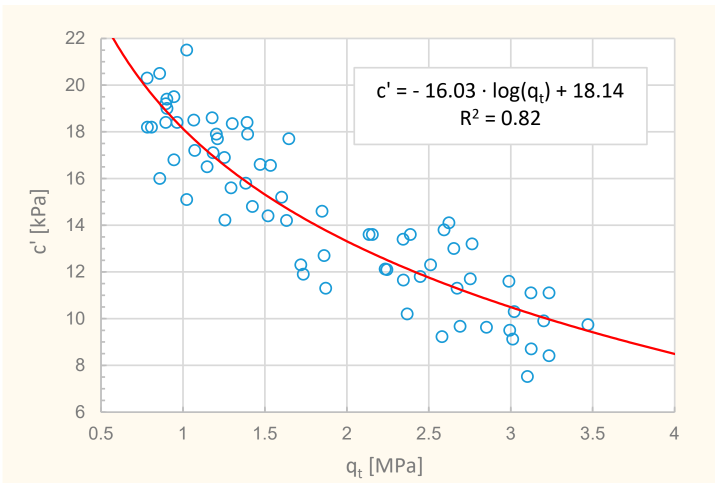


Figure 21. The logarithmic relationship between the effective cohesion c′ and corrected cone resistance (q_t).

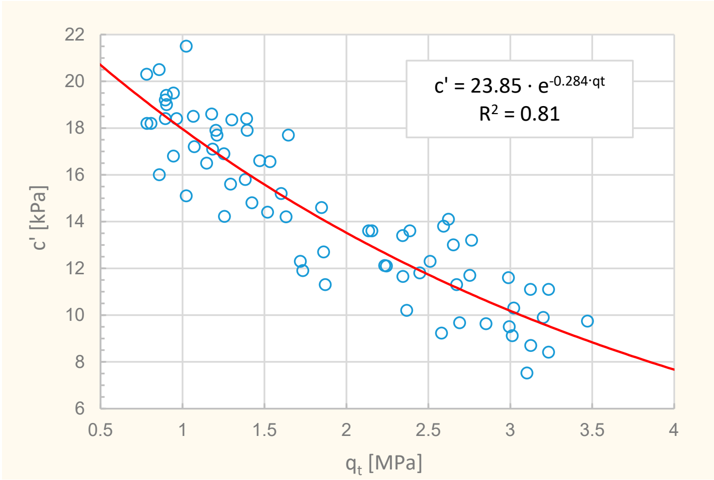


Figure 22. The exponential relationship between the effective cohesion c′ and corrected cone resistance (q_t).

The logarithmic relationship between the effective cohesion c′ [kPa] and the corrected cone resistance q_t [MPa] is shown in Figure 21. The regression analysis result, based on seventy cases [22], achieved a high coefficient of determination R^2 = 0.82, for which the functional relationship can be represented by Equation (7).

$$c' = -16.03 \cdot \log_{10}(q_t) + 18.14 \ \left(R^2 = 0.82\right) \tag{8}$$

Furthermore, the calculation of the effective friction angle, due to small differences in the R^2 parameter, can be determined for simplicity using the linear formula shown in Figure 19 (Equation (9)).

$$c' = -3.89\ (q_t) + 21.76\ (R^2 = 0.81) \tag{9}$$

The functional relationship between the effective cohesion c′ [kPa] and the normalised friction coefficient Fr [%] is presented in Figures 23–26.

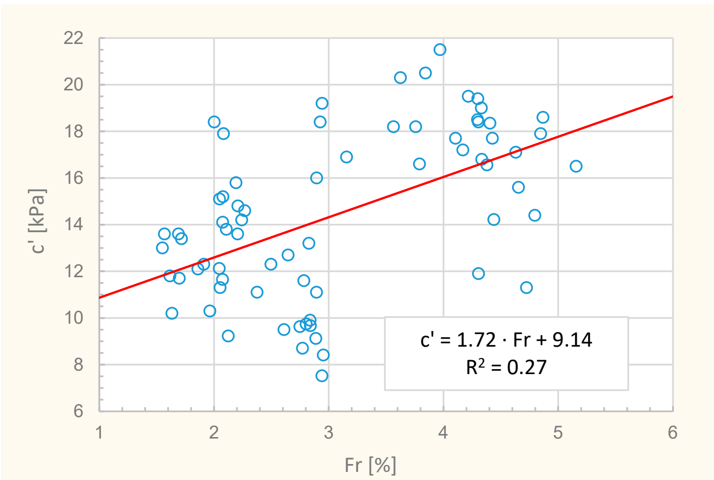


Figure 23. The linear relationship between the effective cohesion c′ and the normalised friction coefficient Fr.

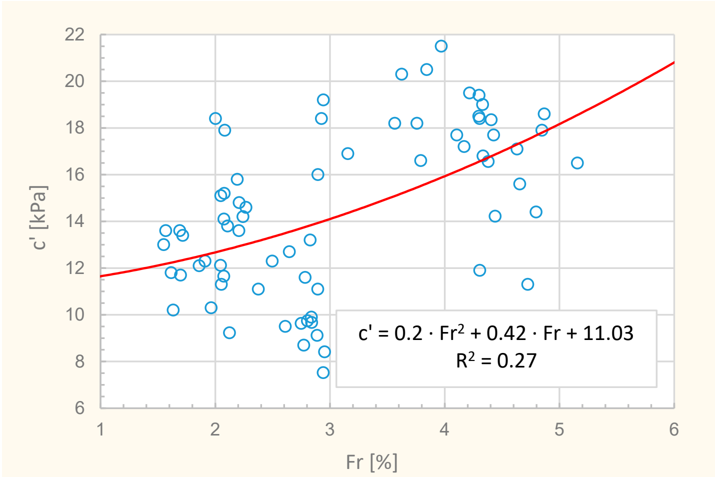


Figure 24. The polynomial relationship between the effective cohesion c′ and the normalised friction coefficient Fr.

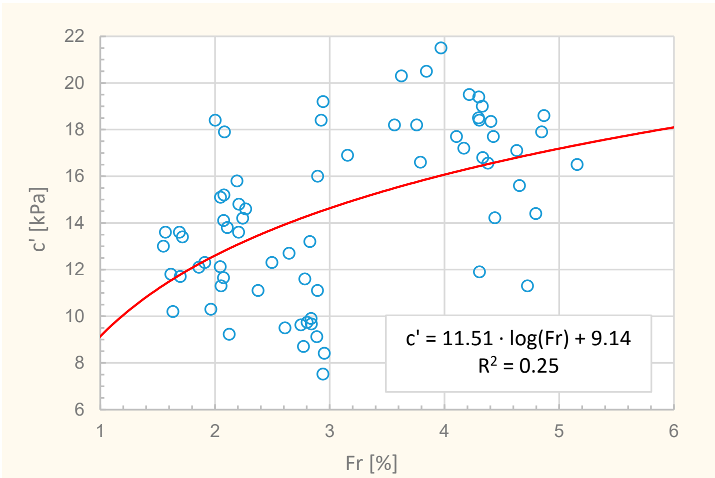


Figure 25. The logarithmic relationship between the effective cohesion c′ and the normalised friction coefficient Fr.

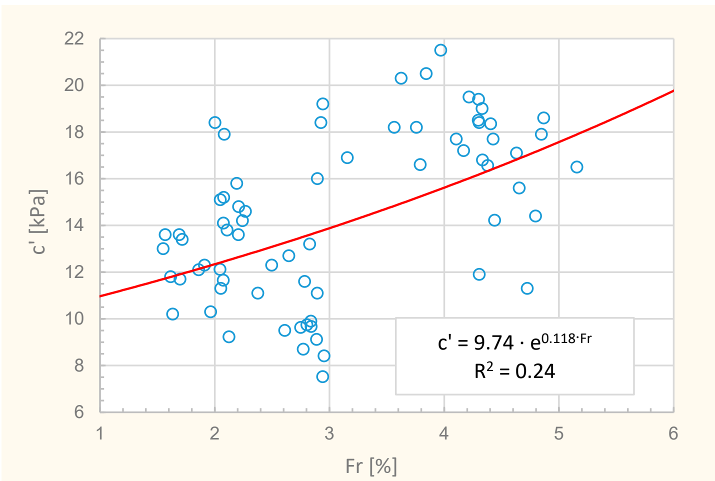


Figure 26. The exponential relationship between the effective cohesion c′ and the normalised friction coefficient Fr.

The graph depicting the logarithmic relationship between the effective cohesion c′ [kPa] and the normalised friction coefficient Fr [%] is shown in Figure 25. In this case, the coefficient of determination, compared to results based on the corrected cone resistance q_t [MPa], is lower and statistically unacceptable R^2 = 0.25 [28].

$$c' = 11.51 \cdot \log_{10}(F_r) + 9.14 \quad \left(R^2 = 0.25\right) \tag{10}$$

In this case, the coefficient of determination, compared to results based on the corrected cone resistance qt, is lower and statistically unacceptable, with R^2 = 0.25 [27]. The remaining analysed functions have small different values of coefficient of determination. The authors do not recommend using these relationships.

The result of predicting effective cohesion based on the normalised friction ratio is a less precise method which should not be used in calculations for the discussed waste soil. The recommended method for predicting effective cohesion c′ [kPa] is to utilise the corrected cone resistance q_t [MPa] from the CPTU along with Equations (8) or (9).

4. Conclusions

Despite many proposals for determining the shear strength parameters of soils based on the results of static CPTU probing, this problem has not been sufficiently solved. There exists extensive literature on this subject [9,29–31], but all of the proposed methods seem to not be sufficiently tested by authors on anthropogenic soil from Cracow (Poland).

The failure envelope in non-cohesive soils with a small amount of fine fractions (silt or clay) generally passes through the origin in the τ-σ′ plane for most normally consolidated soils, suggesting c′ = 0 [kPa]. In the authors' opinion, the high cohesion value obtained in the tests indicates a case of cemented soil. A cementation process occurred in the tested soil, because the soil consisted of suspended particles of carbonate calcium $CaCO_3$. Moreover, the shear strength parameters were significantly better correlated with the corrected cone resistance q_t than with the normalised friction ratio Fr tested soil (Tables 1 and 3). This has also been confirmed by numerous studies, presenting relationships more frequently utilising the cone resistance value [9].

Correlation for effective friction angle φ' [deg] (Equation (5))

$$\varphi' = 3.49 \cdot \log_{10}(q_t) + 30.61 \quad \left(R^2 = 0.81\right) \tag{11}$$

Correlation for effective cohesion c' [kPa] (Equation (8))

$$c' = -15.98 \cdot \log_{10}(q_t) + 18.01 \quad \left(R^2 = 0.82\right) \tag{12}$$

Due to small differences in the value of the determination coefficient R^2, the authors do not exclude the possibility of using the simplest linear dependence correlation for effective friction angle φ' [deg] (Equation (6))

$$\varphi\prime = 0.84\ (qt) + 29.83 \quad \left(R^2 = 0.79\right) \tag{13}$$

and linear dependence correlation for effective cohesion c' [kPa] (Equation (9))

$$c' = -3.89\ (q_t) + 21.76 \quad (R^2 = 0.81) \tag{14}$$

The presented equations are original functions depicting the relationship between the results of static CPTU probing and the geotechnical parameters of anthropogenic ground substrates deposited in the "White Seas" settling tanks in Krakow.

The statistical relationships presented in the article may serve as a basis for estimating, based on established equations, the strength parameters for the examined anthropogenic subsoil. The obtained functional relationships will enhance the process of subsoil recognition on these waste soils. They can be utilised in conceptual and design work for future construction investments on the approximately eighty hectares of the "White Sea" area in Cracow. They may also allow for the specification of more detailed criteria regarding the protection of existing structures during the exploitation phase.

The derived correlation relationships are based on local data. These are waste soils. The scope of application of correlation relationships is limited to anthropogenic soils of the same chemical composition.

As shown in Figures 7 and 8, the tested soil consists of only one mineral calcite ($CaCO_3$) and has a specific grain size range. The correlation formulas that were obtained can only be applied to such soils. They will not give positive results for other soils.

The proposed correlations give cautious values of the drained strength parameters, which can be used as a first approximation for use in preliminary design of geotechnical structures. Furthermore, the proposed correlations should only be used in cases where time and cost constraints do not allow for actual effective strength tests to be carried out. In most other cases, the use of effective strength tests will provide a much more reliable and cost-effective estimate of the strength properties of the soil in question.

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References

1. Gliniak, M.; Sobczyk, W. Proposal of brownfield land development on the example of the landfills of former Krakow Soda Works „Solvay". *J. Ecol. Eng.* **2016**, *17*, 96. [CrossRef] [PubMed]
2. Zong, Y.; Gong, J.; Zhang, J.; Su, Y.; Hu, C.; Li, T.; Wu, Y.; Jiang, M. Research status of soda residue in the field of environmental pollution control. *RSC Adv.* **2023**, *13*, 28975–28983. [CrossRef] [PubMed]
3. Zięba, J.; Rzepka, P.; Olek, B.S. Strength and Compressibility of Ammonia-Soda Residue from the Solvay Sodium Plant. *Appl. Sci.* **2021**, *11*, 11305. [CrossRef]
4. Zhao, X.; Yang, T.; Yu, Z.; Zong, Z.; Li, J. Study on the Unconfined Compressive Strength Property. *Geotech. Geol. Eng.* **2024**, *42*, 5085–5106. [CrossRef]
5. Zhao, X.; Yang, T.; Yu, Z.; Zong, Z.; Li, J. Mechanical Properties and Dry–Wet Stability of Soda Residue Soil. *Buildings* **2023**, *13*, 2407. [CrossRef]
6. Likus-Cieślik, J.; Pietrzykowski, M. The Influence of Sedimentation Ponds of the Former Soda "Solvay" Plant in Krakow on the Chemistry of the Wilga River. *Sustainability* **2021**, *13*, 993. [CrossRef]
7. Gołub, A.; Piekutin, J. Pollution of Sedimentary Ponds at an Industrial Plant in Janikowo (Poland). *Water* **2020**, *12*, 536. [CrossRef]
8. Lunne, T.; Powell, J.J.; Robertson, P.K. *Cone Penetration Testing in Geotechnical Practice*, 1st ed.; CRC Press: London, UK, 1997; p. 352.
9. Sikora, Z. *Static Probing, Methods and Application in Geoengineering*; Scientific and Technical Publisher: Warszawa, Poland, 2006. (In Polish)
10. Monnet, J. *Situ Tests in Geotechnical Engineering*; John Wiley & Sons: Hoboken, NJ, USA, 2015.
11. Robertson, P.K.; Cabal, K.L. *Guide to Cone Penetration Testing for Geo-Environmental Engineering*, 5th ed.; Gregg Drilling & Testing: Signal Hill, CA, USA, 2012.
12. Jaros, M.; Majer, K.; Pietrzykowski, P. Influence of PN-EN ISO 14688 standard on the interpretation of engineering-geological cross-sections. *Geologos* **2007**, *11*, 211–218.
13. Młynarek, Z.; Gogolik, S. Directions of development and use of in-situ techniques in geotechnics—Part 1. *Acta Sci. Polonorum. Archit.* **2013**, *12*, 41–59.
14. Godlewski, T.; Szczepański, T. *Methods of Soil Stiffness Determination*; ITB: Warszawa, Poland, 2015. (In Polish)
15. Robertson, P.K. Interpretation of cone penetration tests—A unified approach. *Can. Geotech. J.* **2009**, *46*, 1337–1355. [CrossRef]

16. Pietrzykowski, P. *Engineering and Geological Assessment of Eemian Gyttja and Lacustrine Chalk from Warsaw*; University of Warsaw: Warsaw, Poland, 2014. (In Polish)
17. Młynarek, Z.; Wierzbicki, J.; Mańka, M. Constrained deformation and shear moduli of loesses from CPTU and SDMT tests. *Inżynieria Morska Geotech.* **2015**, *579*, 193–199. (In Polish)
18. Młynarek, Z.; Wierzbicki, J.; Stefaniak, K. Use of CPTU method for the evaluation of soil unit weight. *Inżynieria Morska Geotech.* **2019**, *40*, 294–302. (In Polish)
19. Jastrzębska, M.; Kalinowska-Pasieka, M. *Selected Testing Methods in Contemporary Geotechnical Laboratory: From the Subsoil to the Soil Parameters*, 1st ed.; Gliwice: Silesian University of Technology: Gliwice, Poland, 2015. (In Polish)
20. *PN-EN 1997-1:2008*; Eurokod 7—Geotechnical Design—Part 1: General Principles. Committee for Standardization: Warsaw, Poland, 2008. (In Polish)
21. Sroczyński, W.; Skrzypczak, R.; Syposz-Łuczak, B.; Wota, A. Krakow "Biale Morza"-chosen problems of management and revitalization. *Zesz. Nauk. Inst. Gospod. Surowcami Miner. Energią Pol. Akad. Nauk.* **2009**, *76*, 31–43.
22. Zięba, J. Correlational Research of Selected Geotechnical Parameters of Anthropogenic Soils Determined in the Laboratory and "In Situ" on the "White Seas" Area in Krakow. Ph.D. Thesis, Cracow University of Technology, Cracow, Poland, 2023.
23. Allam, M.M.; Sridharan, A. Influance of the back pressure technique on the shear strenght of soils. *Geotech. Test. J.* **1980**, *3*, 35–40. [CrossRef]
24. *BS 1377-8: 1990*; Methods of Test for: Soils for Civil Engineering Purposes. Part 8: Shear Strength Tests (Effective Stress). BSI: London, UK, 1990.
25. Tschuschke, W.; Młynarek, Z. Limitations to application of empirical relationship from in situ tests. *Sci. Pap. Silesian Univ. Technol.* **2007**, *111*, 315–329.
26. Schneider, J.A.; Randolph, M.F.; Mayne, P.W.; Ramsey, N.R. Analysis of factors influencing soil classification using normalized piezocone tip resistance and pore pressure parameters. *J. Geotech. Geoenvironmental Eng.* **2008**, *134*, 1569–1586. [CrossRef]
27. *ISO 17892-4:2016*; Geotechnical Investigation and Testing—Laboratory Testing of Soil—Part 4: Determination of Particle Size Distribution. ISO: Geneva, Switzerland, 2016.
28. Jusoh, H.; Osman, S.B.S. The Correlation between Resistivity and Soil Properties as an Alternative to Soil Investigation. *Indian J. Sci. Technol.* **2017**, *10*, 1–16. [CrossRef]
29. Lan, H.; Song, Z.; Bao, H.; Ma, Y.; Yan, C.; Liu, S.; Wang, J. Shear strength parameters identificatio of loess interface based on borehole micro static cone penetration system. *Geoenvironmental Disasters* **2024**, *11*, 1–16. [CrossRef]
30. Suzuki, Y.; Goto, S.; Hatanaka, M.; Tokimatsu, K. Correlation between strengths and penetration resistances for gravelly soils. *Soils Found.* **1993**, *33*, 92–101. [CrossRef]
31. Mayne, P.W. Evaluating effective stress parameters and undrained shear strengths of soft-firm clays from CPTu and DMT. In Proceedings of the 5th International Conference on Site Characterization (ISC-5), Gold Coast, Australia, 5–10 September 2016; Volume 1.