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Correlations between geotechnical in situ investigations and geotechnical parameters of the Bucharest Loam layer

Corelații între încercările geotehnice de teren și parametrii geotehnici ai stratului Lutul de București

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Abstract. *The in situ geotechnical investigation methods are experiencing an upward trend in their use at national and international level. In the international literature there are numerous correlations between in situ tests and geotechnical parameters which have been developed mainly in Western European countries, the United States and Japan. This paper contributes to a better understanding of how to select, interpret and apply correlations between geotechnical soil parameters and in situ test results for the Bucharest Loam layer. New correlations between CPT and DMT tests and routine laboratory tests for the Bucharest Loam layer were developed.*

Key words: *Correlations, CPT, DMT, Bucharest Loam*

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1. Introduction

The recent national and European technical norms and standards – revision of Eurocode 7 and the Romanian technical norm on geotechnical documents, NP 074-2022 – are requiring, when using correlations for determining the geotechnical parameters based on in situ test results, to document them and provide information about the soils for which they have been developed and the correlation degree. In the national literature, there are certain correlations for specific Romanian soils, but their number is limited. Also, a good part of them were determined a few decades ago [1]. The limited existence of "national" correlations leads to the under- or improper use of field tests and to an excess or lack of caution in establishing characteristic and calculation values of geotechnical parameters. In order to increase the use of in situ tests in the Romanian practice and to have a proper interpretation of them, there is a need for new developed correlations for specific type of soils.

The main original contribution of the present paper is the determination of new correlations between in situ CPT and DMT tests and the usual laboratory tests for Bucharest Loam layer. On the basis of the literature review, an extensive investigation of the soil was carried out, including in situ investigations and geotechnical boreholes. Laboratory tests to determine geotechnical parameters were carried out on disturbed and undisturbed soil samples obtained from geotechnical boreholes. Parallel analysis of the geotechnical parameters obtained using the newly determined correlations and separately using laboratory tests helped to validate the proposed correlations. A total of 22 sites located in the North, South, Center, West and East of Bucharest were investigated. The table below summarizes the investigated sites and the investigations carried out for each of them.

Table 1

Investigated sites

Site nr.	Area	Address	Boreholes	CPT	DMT
1.	C-S	Splaiul Unirii 165	7	10	5
2.	N	Calea Floreasca 246	3	2	1
3.	N	Nicolae G. Caranfil 74	2	3	2
4.	S	Strada Povestei 10	3	12	3
5.	NV	Bulevardul Bucureștii Noi 25	6	7	2
6.	E	Șos. Vergului 4	2	2	2
7.	C-V	Șoseaua Orhideelor 46	4	3	-
8.	N	Str. Barbu Văcărescu 164	4	9	2
9.	N	Calea Floreasca 242-244	6	18	3
10.	C	Tudor Arghezi 1-3	5	3	1
11.	C-V	Strada Sg Constantin Ghercu 1b	4	5	5
12.	N	Bulevardul Pipera 1/8, Voluntari	13	-	4
13.	N-NV	Strada Menuetului Nr. 8	2	-	-
14.	E	Șos. Vergului 20	2	-	1
15.	C	Strada Logofăt Luca Stroici 45	2	-	-
16.	N-NE	Bulevardul Dimitrie Pompeiu 2D	1	-	-
17.	N-NV	Strada Jiului nr. 10	2	7	1
18.	C-E	Șoseaua Mihai Bravu nr. 321	2	-	-
19.	C-N	Bulevardul Mircea Eliade nr. 18	7	-	-

Site nr.	Area	Address	Boreholes	CPT	DMT
20.	C	Strada Mântuleasa nr. 10-18	2	3	-
21.	NV	Bd. Expoziției nr. 2	-	3	1
22.	V	Bd. Preciziei nr. 6	-	3	1

Reviewing the information in Table 1 a total of 79 boreholes, 88 CPT (Cone Penetration Tests) and no less than 34 DMT (Dilatometer Marchetti Tests) were analyzed to determine the new correlations.

2. Selection process of relevant high-quality samples

To achieve the objectives of this research a laborious selection process in order to select high-quality samples was necessary.

The following in-situ and laboratory tests were used to determine new correlations:

- Cone Penetration Tests (CPT)
- Dilatometer Marchetti Tests (DMT)
- Geotechnical Boreholes
- Laboratory tests for identification and classification of soils
- Mechanical laboratory tests

The sample selection steps are detailed below.

Step 0 consisted of the pre-selection of sites. Before starting the actual process of selecting the different laboratory samples or in situ tests, sites with a typical stratification for the Municipality of Bucharest were selected. For example, sites that have been subject to extensive changes in the recent past were excluded. The following were considered as significant changes: the site has been subject to pollution with hydrocarbons or other liquids \ materials that may affect the geotechnical characteristics or the bearing capacity, land on which excavations and fills have been carried out.

Step 1 of the actual screening process consisted in the selection of investigation points (geotechnical borehole, CPT and DMT tests) that could fit into a circle with a radius of no more than 3 m. The 3 m criterion was chosen because, for technological reasons, it is sometimes not possible to set points closer than 1.5 m without influencing each other. The distance of 1.5 m was chosen assuming that the test/survey deviates less than 1°/m from the vertical position. This is also the rejection criterion for DMT equipment and can also be assimilated with the rejection criterion for CPT equipment, if an average survey depth of 25 m and a maximum allowable inclination of 25° are considered.

In Step 2 geotechnical profiles were created and analyzed. The geotechnical profiles included, as a minimum, the geotechnical borehole log with stratification description and field test plots, as well as tests not covered by this report. This allowed for the removal of tests that showed anomalies compared to the other 2 corresponding tests. As an example, if the laboratory tests corresponding to a geotechnical borehole in the vicinity of the CPT/DMT tests showed significantly lower or significantly higher modulus values than the other boreholes on site, while the CPT/DMT tests showed similar values, the borehole or sample was eliminated from the analysis.

Step 3 consisted of eliminating laboratory and field tests with implausible values. For example, if a laboratory compressibility test showed a modulus $E_{oed\ 0\text{-}50}$ higher than $E_{oed200\text{-}300}$, the test was eliminated. Another example of eliminated samples due to implausible values are those in which the oedometric modulus corresponding to 200-300 kPa was higher than 30-40 MPa or q_c values higher than 5 MPa for Bucharest Loam. These values are outside the range of variation of the respective parameters. On top of that, the Bucharest Loam layer is a cohesive soil with a consistency ranging from stiff to hard. Values of $E_{oed200\text{-}300}$ higher than 30-40 MPa for q_c above 5 MPa are not typical.

3. Determination of new correlations for the Bucharest Loam layer

The following linear correlations were determined:

- Between cone resistance q_c and oedometric modulus $E_{oed200\text{-}300}$
- Between cone resistance q_c and dilatometer modulus M_{DMT}
- Between dilatometer modulus M_{DMT} and oedometric modulus $E_{oed200\text{-}300}$
- Between q_c and undrained shear resistance determined from DMT $c_{u,\ DMT}$

The "Bucharest Loam" layer has, probably, the most important contribution in the design of geotechnical structures in the Bucharest area. It develops immediately below the topsoil layer and down to depths of about 6 - 10 m usually, and in some areas, it can reach depths of approx. 20 m.

In terms of particle size distribution, the Bucharest Loam consists of silty clays to clayey silts and sandy clays with a slight loess character. According to SR EN ISO 14688-1 and 2, the soil can be predominantly classified as siCL (silty clay) and Cl (clay), less frequently as clSi (clayey silt). Rarely it may contain up to 5% gravel-sized particles, which can be observed especially in the central-southern part of the municipality.

The correlations that have been developed specifically for the Bucharest Loam layer are presented below. These were developed using the geotechnical parameters obtained from laboratory tests and those obtained directly from field or in situ tests and surveys.

To determine the correlations in situ investigations were performed. They consisted of Cone Penetration Tests (CPT) and Dilatometer Marchetti Tests (DMT). Common laboratory tests were also performed. Those were classification and identification tests as sieve analysis and Atterberg limits. Mechanical laboratory tests were also performed. They consisted of Direct Shear Test and Oedometer Tests.

Figure 1 shows the correlations between the cone resistance q_c and the oedometric modulus $E_{oed200\text{-}300}$. The correlations were determined on all available samples (blue dots and line). During pre-screening a good correlation was observed for samples with a fine particle content (<0.063 mm) greater than 90%. For these samples another correlation was determined separately (red dots and line). The correlation factor r^2 was 0,75 and 0,99.

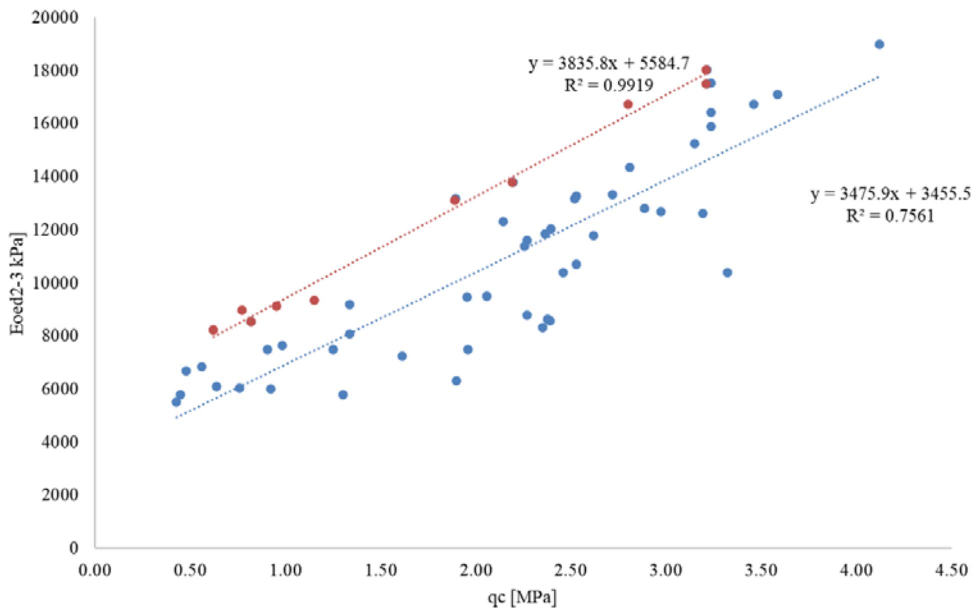

Fig. 1. Correlations between cone resistance qc and oedometric modulus $E_{oed200\text{-}300}$

In Figure 2 is presented the newly determined correlation between cone pressure q_c and M_{DMT} dilatometric modulus. The correlation was determined for 40 high quality samples. In this case a correlation coefficient of approx.. 0,85 was obtained.

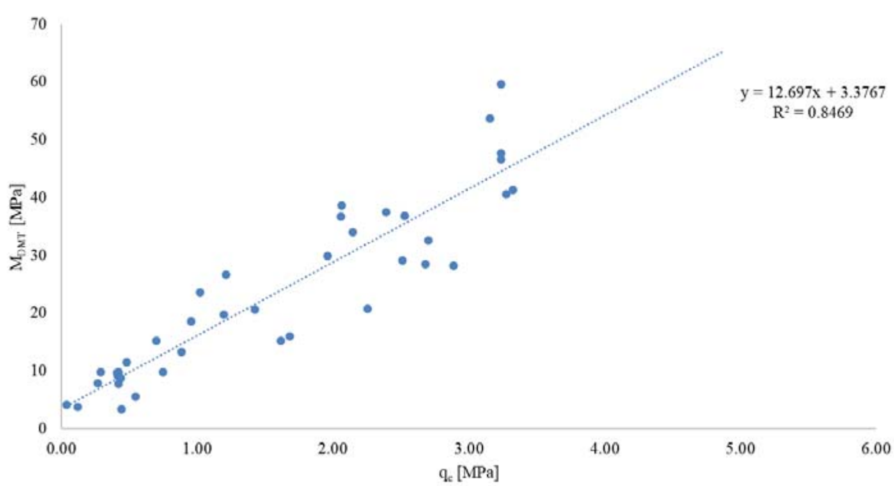

Fig. 2. Correlations between cone resistance q_c and dilatometer modulus M_{DMT}

Cone pressure q_c and undrained shear strength determined using DMT were correlated using a approximately 40 samples. As shown in Figure 3 a correlation coefficient of approx.. 0,70 was obtained.

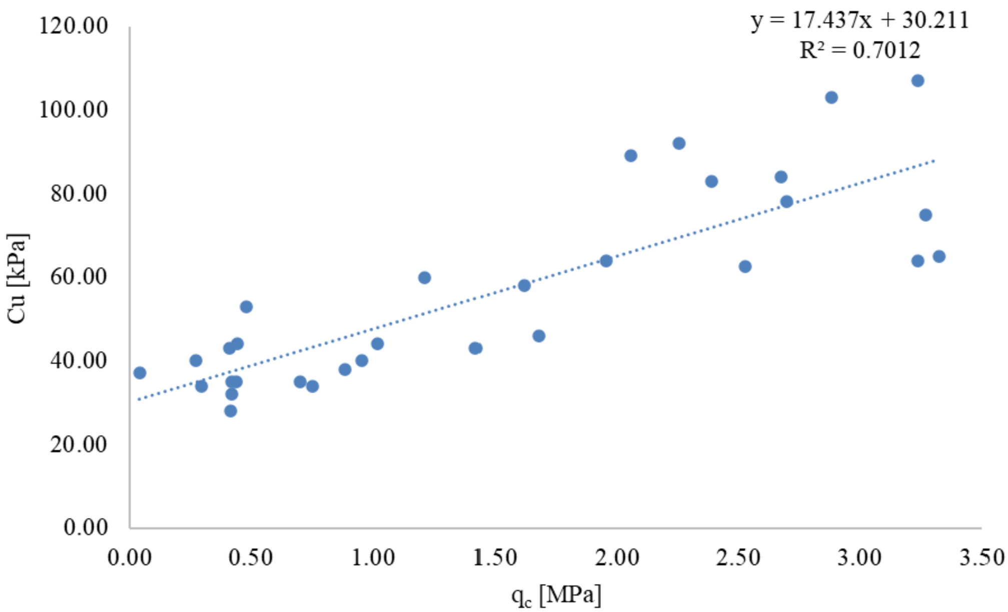

Fig. 3. Correlations between cone resistance q_c and undrained shear strength $c_{u\ DMT}$

The dilatometric modulus and the $E_{oed200-300}$ oedometric modulus were correlated using 38 common points. As shown in Figure 4, a correlation coefficient of $r^2 = 0,58$ was obtained, which corresponds to a correlation coefficient r of approximately 0,70.

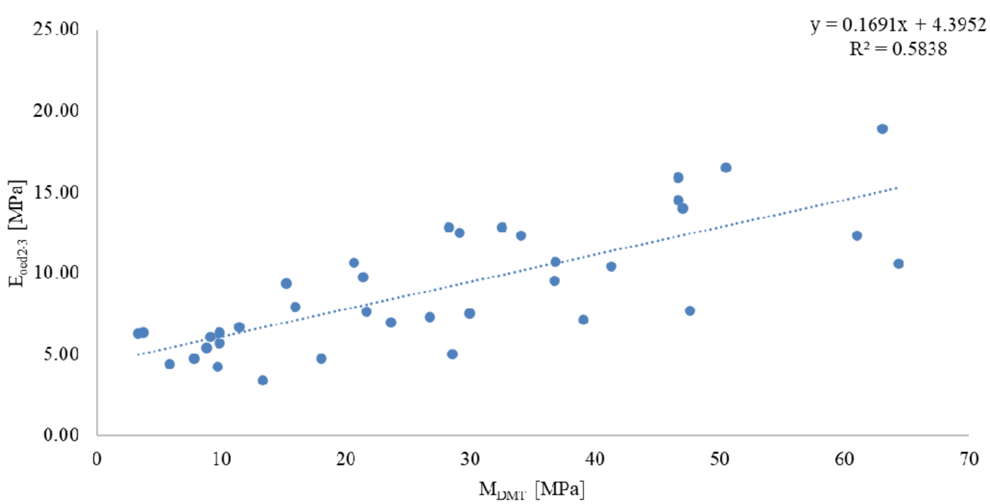

Fig. 4. Correlations between the dilatometer modulus M_{DMT} and the oedometric modulus $E_{oed200-300}$

Figure 5 shows the correlation between the cone pressure q_c and the tangent of the internal friction angle φ, determined using 20 points . The correlation coefficient r^2 is of about 0.70.

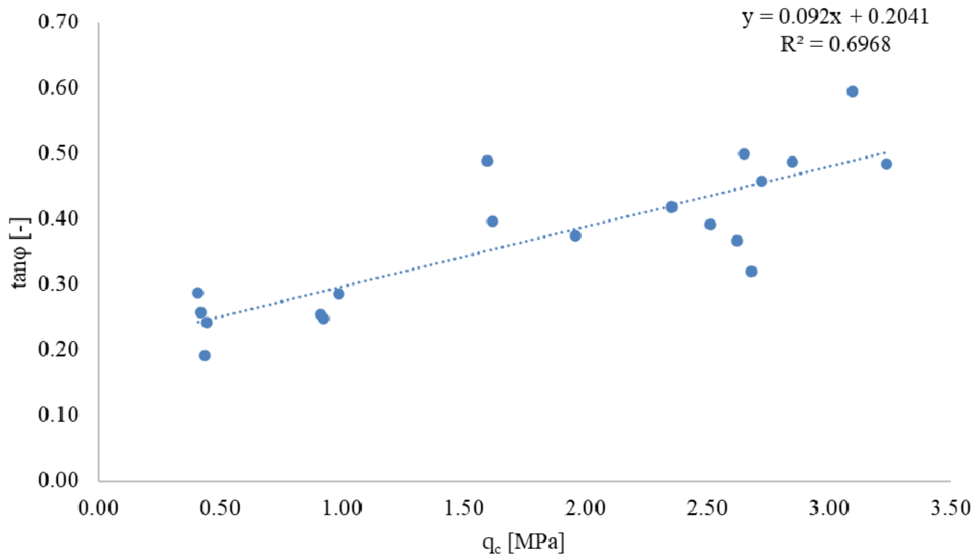

Fig. 5. Correlations between cone resistance q_c and the internal friction angle φ

Figure 6 shows the correlation of the cone pressure q_c and the cohesion c obtained from the shear box tests under natural moisture content and undrained conditions (CUn). 20 points were used in determining the correlation. The correlation coefficient is about $r^2 = 0{,}67$, respectively $r = 0{,}85$.

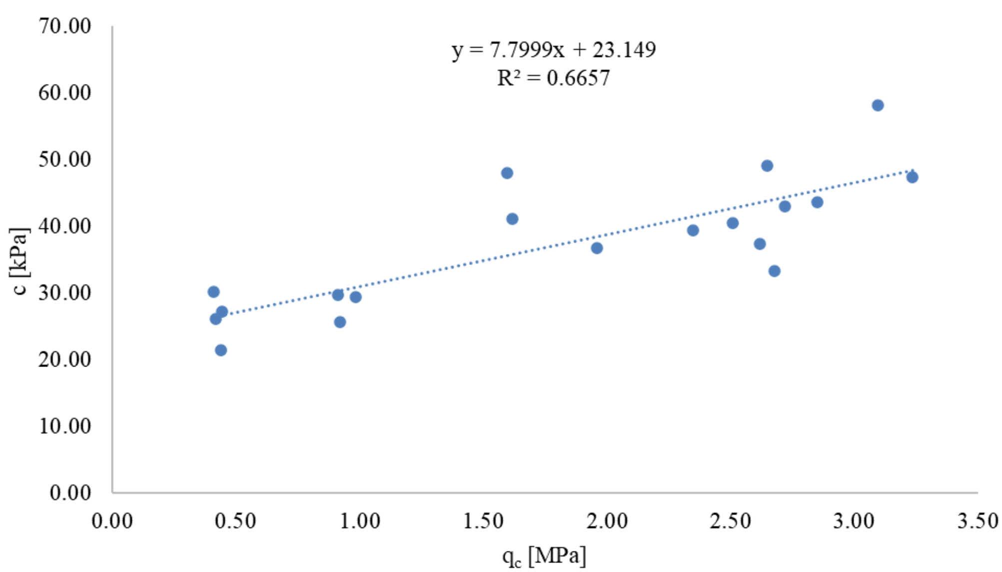

Fig. 6. Correlations between cone resistance q_c and the cohesion c

The correlations between the different parameters presented in Fig. 1 to Fig. 6 are summarized in the following table. The safe correlation gives an assured value and involves translating the correlation slope by the value of the standard deviation.

Table 2

New correlations between different soil parameters specific to Bucharest Loam

Parameters	New correlations	Correlation coef.	Nr. of Samples	Standard deviations	Safe correlation
q_c vs. E_{oed}2-3	3476 q_c + 3456 kPa	0,870	50	300 kPa	3476 q_c + 3156 kPa
q_c vs. E_{oed}2-3*	3836 q_c + 5584 kPa	0.996	10	122 kPa	3836 q_c + 5462 kPa
q_c vs. tanφ	0,092 qc + 0,204	0,834	20	0,015	0,092 qc + 0,189
q_c vs. c	7,8 qc + 23 kPa	0,816	20	1,35 kPa	7,8 qc + 21 kPa
q_c vs. M_{DMT}	12,7 q_c + 3,4 MPa	0,920	40	0,88 MPa	12,7 q_c + 2,5 MPa
q_c vs. $c_{u,DMT}$	14,4 q_c + 30 kPa	0,837	32	2,11 kPa	14,4 q_c + 28 kPa
M_{DMT} vs $E_{oed200-300}$	0,17 M_{DMT} + 4,4 MPa	0,764	38	1,7 MPa	0,17 M_{DMT} + 2,7 MPa

*Samples with over 90% fine particles (<0,063 mm)

4. Validation of the new correlations

This chapter aims to validate the new correlations proposed in chapter 3. To this end, in order to be able to analyze the validity of the new correlations, they were compared with some well-established correlations available in the literature. The main aim of the present paper is to obtain new correlations specific to the Bucharest area. Since the field and laboratory tests carried out, as well as the processing methods, are similar to those from which the existing correlations were obtained, the new correlations are practically a calibration of the existing correlations for the specific soils of the Bucharest area.

Table 3

New and literature correlations for the deformation modulus for the Bucharest Loam layer

Parameter	Deformation modulus E		
	Correlation	Soil type	Observations
New correlation	$E_{oed200-300}$ = 3,48 q_c + 3,45	Cohesive soil	Oedometric modulus between 200 and 300 kPa vertical stress
New safe correlation	$E_{oed200-300}$ = 3,48 q_c + 3,15	Cohesive soil	Oedometric modulus between 200 and 300 kPa vertical stress
Marcu, 1983 [1]	E = 4,8 q_c	Cohesive soil	In this case E can be approx. with $E_{oed200-300}$

Figure 7 shows the theoretical values (linear variation) of the deformation modulus E for the Bucharest loam layer that can be assigned to a value of q_c ranging from 0.5 to 4 MPa using the new proposed correlations and the literature ones [1]. The area shaded in green represents the range of values corresponding to a 95% confidence level of the deformation modulus determined for the Bucharest Loam soil [2]. By analyzing the graph, a good fit between the new proposed correlation and the one known from the literature can be observed [1]. Considering the information presented in [1], the correlation available in the literature is affected by a safety coefficient, which leads to more conservative values. It should be noted, however, that literature correlations [1] better covers the range of values of the deformation moduli [2]. This may be due to the determination of the correlation in [1] between q_c and the deformation modulus determined with the static loading plate and not the one determined in the laboratory, as is the case for the current correlation.

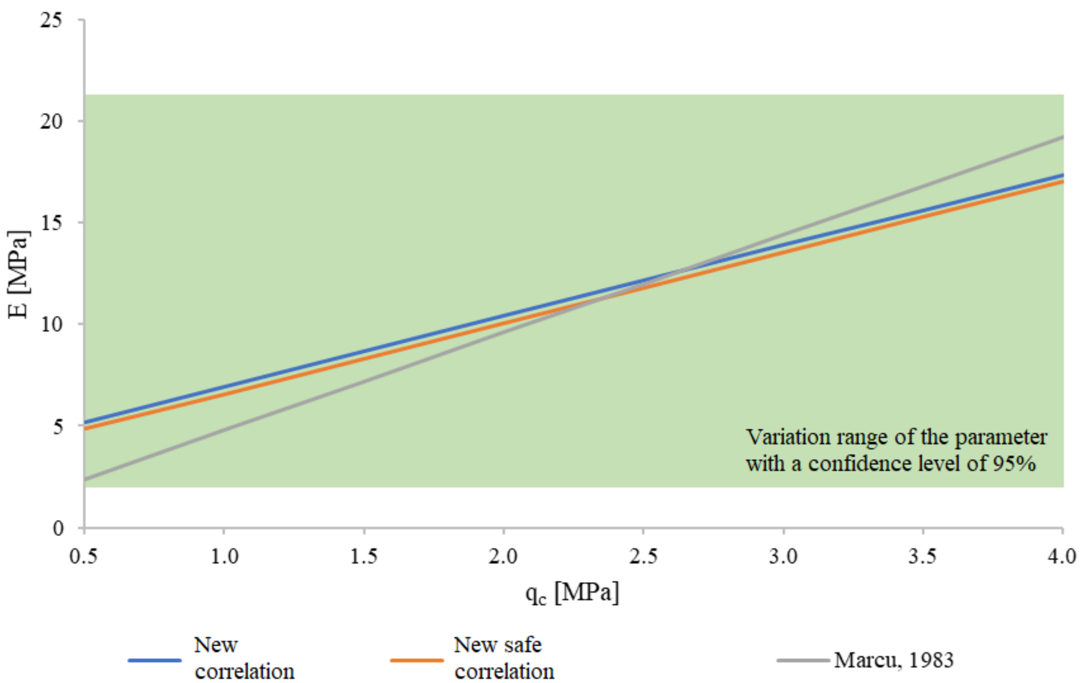

Fig. 7. Bucharest Loam layer, comparison of results for the proposed correlation and those in the literature for deformation modulus E

Table 4 presents the new correlations determined as described above. The shear parameters from Table 4 and Table 5 correspond to those determined by shear box tests on samples with natural moisture content and sheared in undrained conditions.

Table 4

New and literature correlations for the friction angle φ for the Bucharest Loam layer

Parameter	Friction angle		
	Correlation	Soil type	Observations
New correlation	$\tan\varphi = 0{,}092\ q_c + 0{,}204$	Cohesive soils	tanφ determined using direct shear test CUn
New safe correlation	$\tan\varphi = 0{,}092\ q_c + 0{,}189$	Cohesive soils	tanφ determined using direct shear CUn
Trofimenkov & Vorobkov, 1974 [3]	$\tan\varphi = 0{,}045\ q_c + 0{,}260$	Cohesive soils	-

Figure 8 shows the theoretical values (linear variation) of the tangent of the internal friction angle for the Bucharest Loam layer that can be assigned to a cone pressure q_c ranging from 0.5 to 4 MPa, using the new proposed correlations and those available in the literature [3]. The analyzed q_c values represent typical values for the Bucharest Loam layer. The area hatched in green represents the range corresponding to a 95% confidence level of the tangent of the angle of internal friction determined in [2]. By analyzing the graph, a similarity can be observed between the new correlation and the one known from the literature [3].

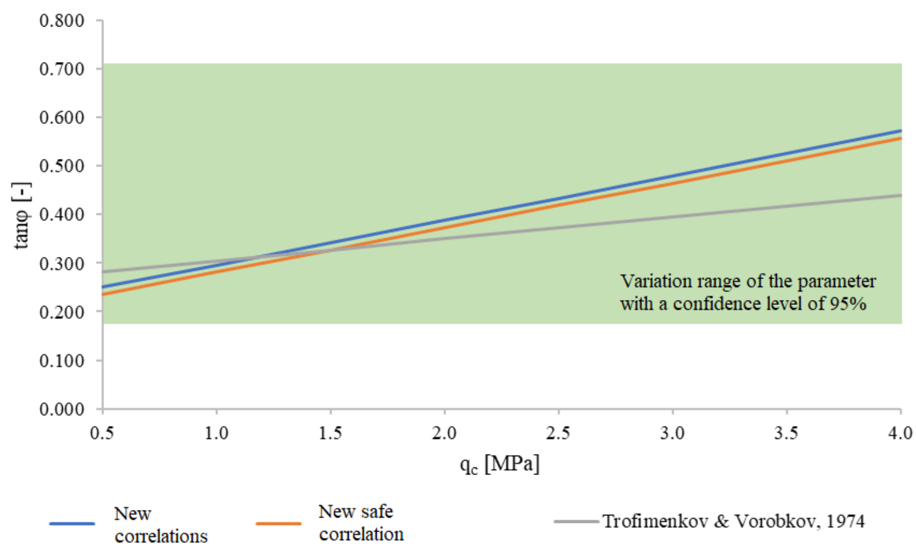

Fig. 8. Bucharest Loam, comparison of results for new correlations and literature correlations for internal friction angle φ

The new proposed correlation tends to underestimate the values of the tangent of the internal friction angle for q_c values below 1.25 MPa and to overestimate the same value for q_c higher than 1.25 MPa, in comparison with the correlation proposed by [3]. Given the information presented in [1], the correlation in the literature [3] is affected by a certain safety coefficient, which is however not known, leading to more conservative values. Even in comparison with the new safe correlation, when using correlation [3] more conservative parameters are obtained. However, the proposed correlation better covers the range of usual values of the Bucharest Loam layer. The differences between the new and existing correlations can be explained by the fact that the new correlations are optimized for the Bucharest Loam layer.

Table 5 shows the new proposed correlations and the correlations from the literature [3] for the indirect determination of cohesion. In the case of the present paper the new proposed correlation corresponds to the cohesion obtained from the shear box test on sample at natural water content in CU conditions (CUn).

Table 5

New and literature correlations for the cohesion for the Bucharest Loam layer

Parameter	Cohesion c (kPa)		
	Correlation	Soil type	Observations
New correlation	$c = 0,078\ q_c + 0,023$	Cohesive soils	c determined using direct shear CUn
New safe correlation	$c = 0,078\ q_c + 0,021$	Cohesive soils	c determined using direct shear CUn
Trofimenkov & Vorobkov, 1974 [3]	$c = 0,0116\ q_c + 0,0125$	Cohesive soils	-

Fig. 9 shows the typical cohesion range values for the Bucharest Loam layer that can be assigned to cone pressure values q_c ranging from 0.5 to 4 MPa using the new proposed and the literature correlations. It should be noted that all correlations underestimate the cohesion value which leads to conservative results.

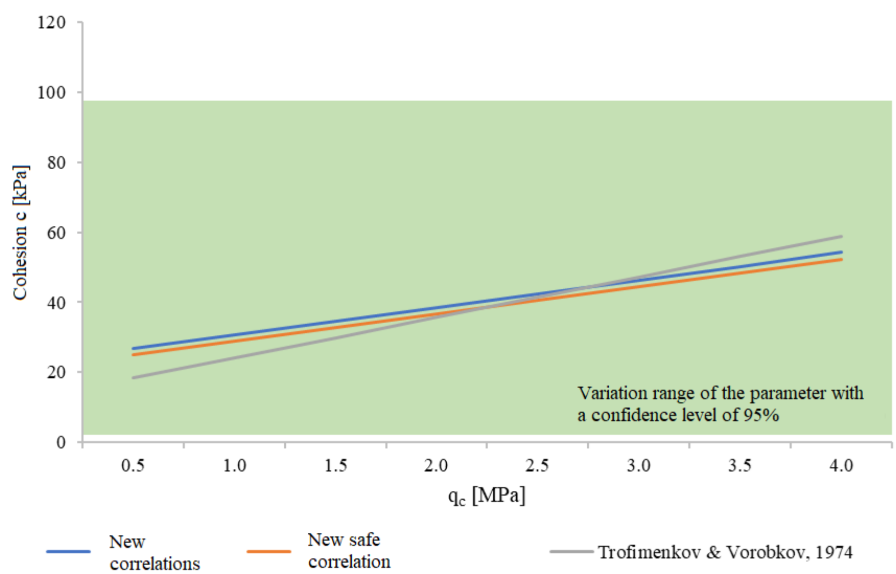

Fig. 9. Bucharest Loam, comparison of results for new correlations and literature correlations for cohesion c

For q_c values lower than 1 MPa the correlations tend to overestimate the cohesion value.

6. Conclusions

In the present paper new correlations between the geotechnical parameters of the Bucharest Loam layer and the in situ geotechnical investigations have been proposed. Correlations were obtained by comparing the results of the in-situ investigations with the geotechnical laboratory results. The newly proposed correlations were validated by comparing their results with those obtained using correlations available in the literature and currently used [1],[3]. Thus, it can be concluded that the newly proposed correlations better cover the range of variation of the studied parameters compared to the parameters obtained using correlations from the literature [1],[3]. Using the newly proposed correlations in the current geotechnical design can lead to an optimized design of the foundations and deep excavation support systems in Bucharest area.

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