Proceedings of the 7th International Young Geotechnical Engineers Conference – Scott (Ed.)

Correlations between the deformation modulus, the liquidity index and the void ratio for moraine and lacustrine glacial clayey soils

Corrélations entre le module de déformation, l'indice de liquidité et l'indice de vide pour les sols argileux glaciaires morainiques et lacustres

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ABSTRACT: There are a variety of soft soils with different characteristics that depend on soil origin. Moreover, the application of various types of foundations and technics for the preparation of foundation grounds causes changes in the geological environment, including physical and mechanical soil properties. One of the novel ground improvement methods, using dry concrete columns, was applied in complicated ground conditions at the construction sites in Belarus. The method showed an increase in the deformation modulus while reducing the porosity and the water content of natural soft clayey soils. Therefore, the main objective of this research is to obtain relationships between the deformation modulus, the void ratio and the liquidity index for moraine and lacustrine-glacial clayey soils as the most common quaternary deposits in the territory of Belarus to predict their deformations. This study is based on data from 100 engineering geological reports on field investigations and laboratory testing using a statistical analysis of more than 450 units of clayey soils. As the result, the correlations $E = f(e)$, $E = f(I_L)$ and $E = f(e, I_L)$ are received and can be used as a simple method to evaluate the deformation modulus of both natural soils and soils when changing the void ratio and the liquidity index during application of dry concrete columns, drains, displacement piles, etc.

RÉSUMÉ : Il existe une variété de sols mous avec des caractéristiques différentes qui dépendent de l'origine du sol. De plus, l'application de divers types de fondations et de techniques pour la préparation des sols de fondation provoque des changements dans l'environnement géologique, y compris les propriétés physiques et mécaniques du sol. L'une des nouvelles méthodes d'amélioration des sols, utilisant des colonnes en béton sec, a été appliquée dans des conditions de sol complexes sur les chantiers de construction en Biélorussie. La méthode a montré une augmentation du module de déformation tout en réduisant la porosité et la teneur en eau des sols argileux mous naturels. Par conséquent, l'objectif principal de cette recherche est d'obtenir des relations entre le module de déformation, l'indice de vide et l'indice de liquidité pour les sols argileux morainiques et lacustres-glaciaires en tant que dépôts quaternaires les plus courants sur le territoire de la Biélorussie pour prédire leurs déformations. Cette étude est basée sur les données de 100 rapports d'ingénierie géologique sur des enquêtes sur le terrain et des tests en laboratoire utilisant une analyse statistique de plus de 450 unités de sols argileux. En conséquence, les corrélations $E = f(e)$, $E = f(I_L)$ et $E = f(e, I_L)$ sont reçues et peuvent être utilisées comme une méthode simple pour évaluer le module de déformation des sols naturels et des sols lorsque changer l'indice de vide et l'indice de liquidité lors de l'application de colonnes en béton sec, drains, pieux de déplacement, etc.

KEYWORDS: correlation, deformation modulus, void ratio, liquidity index, clayey soils.

1 INTRODUCTION

The construction process causes changes in the geological environment including physical and mechanical soil properties that are needed to be predicted and controlled. Determination of soil properties by direct methods in situ and a laboratory is associated with material costs and time. Indirect ways such as correlations between geotechnical parameters allow the cost and time for performing geotechnical investigations to be reduced. The correlations can be used to predict the values of some properties for others about which the necessary information is available. That makes establishing a relationship between soil properties an important task.

Many scientific works were published on different methods to estimate soil properties in an indirect way (Dysli 2011, Ameratunga et al. 2016, Carter 2016), but a search for any relationship firstly should be carried out only within certain age and genetic types of deposits (Busel 1989). Therefore, this study is based mainly on the results of investigations carried out in the territory of Belarus.

Most of the territory of Belarus is covered with quaternary deposits the thickness of which ranges from several metres to 300 m and more, on average 80 m (Lukashev 1969). The deposits are composed of a complex of glacial, water-glacial, lacustrine, alluvial, loess, aeolian and bog formations. A feature of the quaternary deposits of the territory of Belarus is a relatively high water cut (Lukashev 1969, Kolpashnikov 2004). The deposits of the glacial complex constitute 88% of the total volume of anthropogenic rocks within Belarus and are, in most cases, the basis of the designed buildings and structures. According to the classification (Matveev 1976), the main genetic types of deposits of the glacial formation in Belarus include moraine, fluvioglacial and lacustrine-glacial. Moraines account for 52%, fluvioglacial and lacustrine-glacial deposits - 36% of the total anthropogenic cover (Busel 1989).

During the application of various types of foundations and methods for foundation grounds, the moisture regime and density of soils change, and following this, the change in plasticity and porosity of silty clayey soils mainly affects their deformation. Moreover, some methods and foundations are applied to change soil properties. For example, dry concrete columns (Tronda 2016, Sernov and Tronda 2019) are used in soft clayey soils to improve their properties due to both the reinforcing and draining effects. Knowing the potential change in water content and porosity, it is possible to predict soil deformation through correlations between these geotechnical parameters.

The correlation between the deformation modulus and different geophysical parameters of clayey soils were studied by many Belarusian scientists (Ignatova and Mikheev 1965, Zaitseva 1969, Lukinskaya 1972, Busel 1989). The study showed that participation of two physical parameters in a predictive equation for the deformation modulus, where one of the parameters characterises the density, and the second one characterises the soil moisture, ensures sufficient accuracy and reliability of the forecast. This also excludes the duplication of arguments, i.e. the set is optimal. Thus additional consideration of the properties of plasticity, such as the plastic limit and the liquidity index, clarifies the relationship between the deformation modulus and the void ratio.

Some of earlier established relations between geotechnical parameters are used in the national regularities, but actual values can exceed the values that are given in the tables (for example, the liquidity index in TKP 45-5.01-67-2007). Some Belarusian geologies point out the need to broaden the regularities as well (Lazhevich & Zaika 2017). Also, many Belarusian regularities have almost the same tables and values for characteristic soil properties with the regularities in Russia despite regional differences in genetic types of deposits (for example, TKP 45-5.01-67-2007 and SP 22.13330.2011). Moreover, equipment and technologies change with time, so it is necessary to check the existing correlations periodically, clarify them and develop new ones of necessity. Therefore, there is a need to specify existing correlations and define them in a wider range according to territorial and genetic types of deposits.

In view of the aforesaid, the main objective of this research is to obtain relationships between the deformation modulus, the void ratio and the liquidity index for moraine and lacustrine-glacial clayey soils as the most common quaternary deposits in the territory of Belarus to predict their deformations.

2 RESEARCH PROGRAMME

For the study of the relationships, 100 reports on the engineering geological investigations at construction sites were chosen. Each report contains the results of tests performed in a geotechnical laboratory and in situ. The construction sites are located in different places in Belarus but on quaternary (Q) moraine (g) and lacustrine-glacial (lg) clayey soil deposits.

In this paper the characteristic values of the deformation modulus (E), the liquidity index (I_L) and the void ratio (e) from summary tables of the reports are used to determine relationships between these parameters. The physical and mechanical soil properties were assessed via the national regularities (GOST 12248-2010, GOST 20276-2012, GOST 20522-2012, GOST 5180-2015).

The research was carried out in three stages:
1) data collection and database creation;
2) gross error detection and data exclusion;
3) correlation analysis of relations $E = f(e)$, $E = f(I_L)$ and $E = f(e, I_L)$.

3 DATABASE ANALYSED IN THIS STUDY

A total of 517 quaternary silt clayey soil units were considered to obtain the relations:
1) moraine clayey sands (gQ SC-SM) – 231 units;
2) moraine sandy clay loams (gQ CL) – 54 units;
3) lacustrine-glacial clayey sands (lgQ SC-SM) – 65 units;
4) lacustrine-glacial sandy clay loams (lgQ CL) – 137 units.

Soils were assessed via a classification in accordance with the national standard (STB 943-2007). Additionally, according to the unified soil classification system (Terzaghi et al. 1996), soil units are represented by symbols given in brackets.

Some of the data were not used for the correlation analysis because the results were far different from those obtained from the rest of the data. To exclude inappropriate data, four criteria were applied: Romanovsky criterion, 3σ criterion, Smirnov criterion, Chauvenet's criterion. A summary of received data are listed in Table 1, Table 2 and Table 3.

Table 1. The void ratio (e) values obtained for the correlation analysis.

	Num. of data	Min	Max	Mean	Standard deviation
gQ SC-SM	214	0.28	0.50	0.37	0.04
gQ CL	50	0.32	0.70	0.48	0.11
lgQ SC-SM	59	0.31	0.68	0.51	0.09
lgQ CL	121	0.38	1.14	0.63	0.13

Table 2. The liquidity index (I_L) values obtained for the correlation analysis.

	Num. of data	Min	Max	Mean	Standard deviation
gQ SC-SM	230	-0.60	0.91	0.17	0.25
gQ CL	53	-0.33	0.95	0.26	0.27
lgQ SC-SM	64	-0.20	1.03	0.40	0.26
lgQ CL	134	-0.14	1.00	0.49	0.21

Table 3. The deformation modulus (E) values obtained for the correlation analysis. E is expressed in MPa in all tables.

	Num. of data	Min	Max	Mean	Standard deviation
gQ SC-SM	222	2.30	50.10	18.43	10.11
gQ CL	50	3.20	40.00	17.40	10.52
lgQ SC-SM	61	3.00	37.00	15.25	8.06
lgQ CL	128	3.00	30.00	12.14	7.00

The reports and received database show that moraine clayey sands are more common than moraine sandy clay loams, while lacustrine-glacial sandy clay loams are more common than lacustrine-glacial clayey sands on the territory of Belarus.

The data of the liquidity index and the void ratio (see Table 1 and Table 2) show the difference between the soils of the study. On average the liquidity index and the void ratio are higher for lacustrine-glacial soils than moraine clayey soils, and sandy clay loams than clayey sands, while all the soils have a wide range of values.

The data of the deformation modulus (see Table 3) show higher values for moraine clayey soils than lacustrine-glacial clayey soils, and clayey sands than sandy clay loams.

The received database is coherent with previous researches on the soil characterisation of quaternary deposits provided in Belarus by other authors (Lukashev 1969, Matveev 1976, Busel 1989, Kolpashnikov 2004, Busel 2020).

4 CORRELATION ANALYSIS

As mentioned above, due to the difficulty or impossibility of measuring soil properties directly, it is necessary to look for indirect ways to estimate the deformation modulus of soils.

In the study values of the deformation modulus (E) were compared with values of the liquidity index (I_L) and the void ratio (e).

The correlation analysis was conducted in accordance with mathematical statistics (Gmurman 1999, Tretyak 2004).

4.1 *Relationship between the deformation modulus and the void ratio*

From the comparison of the deformation modulus (E) with the void ratio (e), linear, rational, exponential and quadratic functions were separately considered for each soil unit (Figures 1-4). For each function, the correlation ratio (η), the correlation coefficient (r) and the coefficient of determination (R^2) were calculated. The results from these correlation analyses are shown in Tables 4-7.

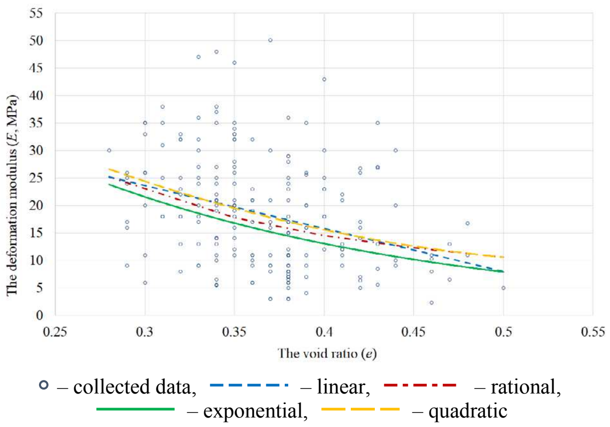

Figure 1. Correlations between the deformation modulus (E, MPa) and the void ratio (e) obtained from the database of this study for moraine clayey sands.

Table 4. Parameters of correlations between the deformation modulus (E, MPa) and the void ratio (e) obtained from the database of this study for moraine clayey sands.

Type of function $E = f(e)$	Num. of data	η	r	R^2
Linear	206	0.488	-0.322	0.104
Rational			—	0.104
Exponential			—	0.106
Quadratic			—	0.106

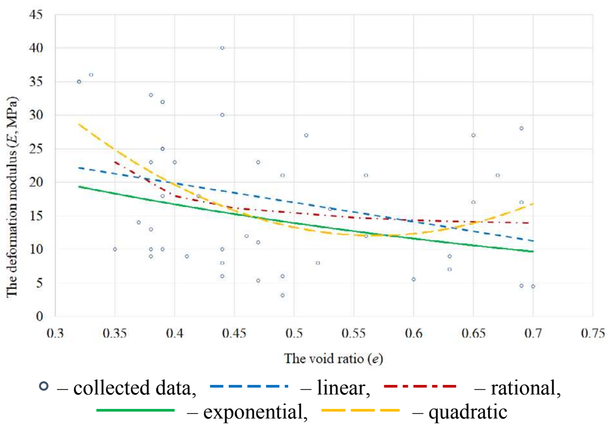

Figure 2. Correlations between the deformation modulus (E, MPa) and the void ratio (e) obtained from the database of this study for moraine sandy clay loams.

Table 5. Parameters of correlations between the deformation modulus (E, MPa) and the void ratio (e) obtained from the database of this study for moraine sandy clay loams.

Type of function $E = f(e)$	Num. of data	η	r	R^2
Linear	46	0.701	-0.312	0.098
Rational			—	0.217
Exponential			—	0.115
Quadratic			—	0.185

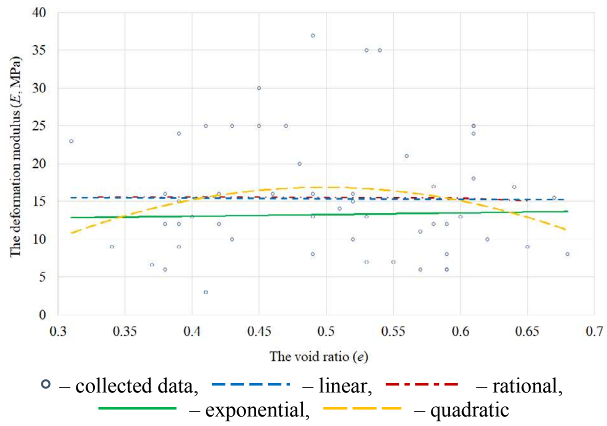

Figure 3. Correlations between the deformation modulus (E, MPa) and the void ratio (e) obtained from the database of this study for lacustrine-glacial clayey sands.

Table 6. Parameters of correlations between the deformation modulus (E, MPa) and the void ratio (e) obtained from the database of this study for lacustrine-glacial clayey sands.

Type of function $E = f(e)$	Num. of data	η	r	R^2
Linear	55	0.737	-0.009	0.0001
Rational			—	0.016
Exponential			—	0.0001
Quadratic			—	0.031

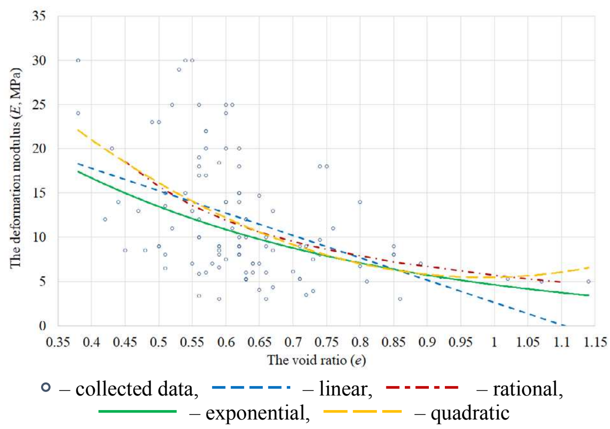

Figure 4. Correlations between the deformation modulus (E, MPa) and the void ratio (e) obtained from the database of this study for lacustrine-glacial sandy clay loams.

Table 7. Parameters of correlations between the deformation modulus (E, MPa) and the void ratio (e) obtained from the database of this study for lacustrine-glacial sandy clay loams.

Type of function $E = f(e)$	Num. of data	η	r	R^2
Linear	112	0.628	-0.468	0.219
Rational			—	0.263
Exponential			—	0.252
Quadratic			—	0.257

The correlation ratio (η) indicates variables of the deformation modulus (E) and the void ratio (e) which can be considered from moderately to highly correlated for all considered soil units.

The correlation coefficient (r) shows from moderate to strong negative linear relationship for the functions $E = f(e)$, except for lacustrine-glacial clayey sands where there is no relationship or it is interpreted as negligible.

But the functions $E = f(e)$ having the highest coefficient of determination (R^2) are rational and quadratic.

4.2 *Relationship between the deformation modulus and the liquidity index*

From the comparison of the deformation modulus (E) with the liquidity index (I_L), linear, rational, exponential and quadratic functions were separately considered for each soil unit (Figures 5-8). For each function, the correlation ratio (η), the correlation coefficient (r) and the coefficient of determination (R^2) were calculated. The results from these correlation analyses are shown in Tables 8-11.

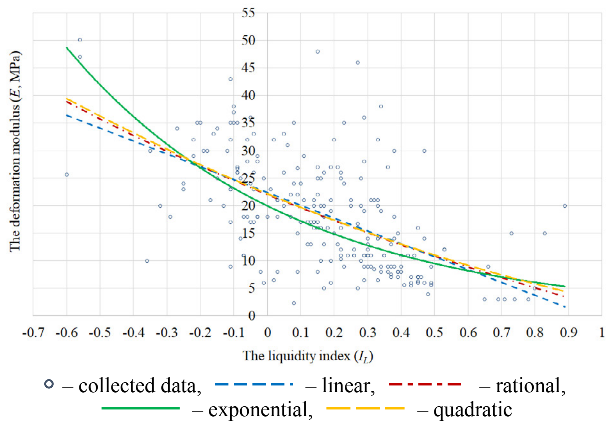

Figure 5. Correlations between the deformation modulus (E, MPa) and the liquidity index (I_L) obtained from the database of this study for moraine clayey sands.

Table 8. Parameters of correlations between the deformation modulus (E, MPa) and the liquidity index (I_L) obtained from the database of this study for moraine clayey sands.

Type of function $E = f(I_L)$	Num. of data	η	r	R^2
Linear	221	0.764	-0.582	0.339
Rational			—	0.341
Exponential			—	0.325
Quadratic			—	0.342

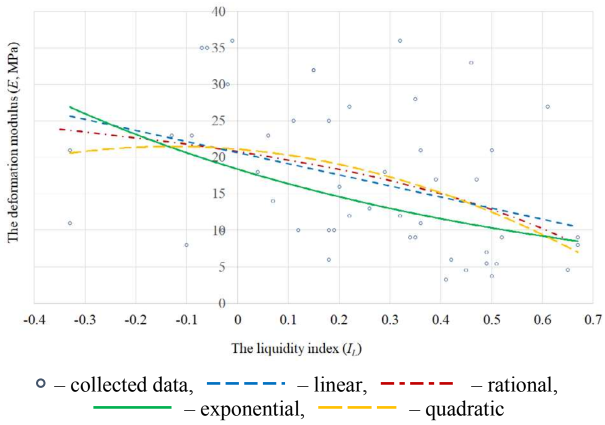

Figure 6. Correlations between the deformation modulus (E, MPa) and the liquidity index (I_L) obtained from the database of this study for moraine sandy clay loams.

Table 9. Parameters of correlations between the deformation modulus (E, MPa) and the liquidity index (I_L) obtained from the database of this study for moraine sandy clay loams.

Type of function $E = f(I_L)$	Num. of data	η	r	R^2
Linear	49	0.888	-0.373	0.139
Rational			—	0.217
Exponential			—	0.113
Quadratic			—	0.166

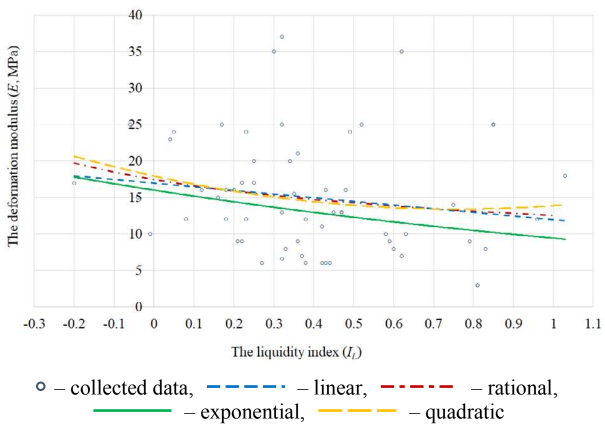

Figure 7. Correlations between the deformation modulus (E, MPa) and the liquidity index (I_L) obtained from the database of this study for lacustrine-glacial clayey sands.

Table 10. Parameters of correlations between the deformation modulus (E, MPa) and the liquidity index (I_L) obtained from the database of this study for lacustrine-glacial clayey sands.

Type of function $E = f(I_L)$	Num. of data	η	r	R^2
Linear	60	0.820	-0.168	0.028
Rational			—	0.032
Exponential			—	0.031
Quadratic			—	0.037

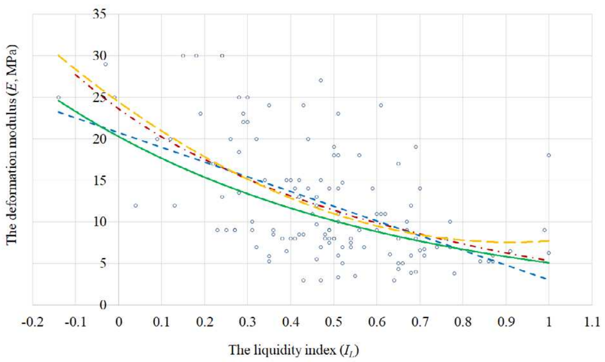

Figure 8. Correlations between the deformation modulus (E, MPa) and the liquidity index (I_L) obtained from the database of this study for lacustrine-glacial sandy clay loams.

Table 11. Parameters of correlations between the deformation modulus (E, MPa) and the liquidity index (I_L) obtained from the database of this study for lacustrine-glacial sandy clay loams.

Type of function $E = f(I_L)$	Num. of data	η	r	R^2
Linear	126	0.797	-0.533	0.285
Rational			—	0.311
Exponential			—	0.314
Quadratic			—	0.323

The correlation ratio (η) indicates variables of the deformation modulus (E) and the liquidity index (I_L) which can be considered highly correlated for all considered soil units.

The correlation coefficient (r) shows from moderate to strong negative linear relationship for the functions $E = f(I_L)$, except for lacustrine-glacial clayey sands where the relationship is interpreted as negligible.

But the functions $E = f(I_L)$ having the highest coefficient of determination (R^2) are rational and quadratic.

4.3 *Relationship between the deformation modulus, the void ratio and the liquidity index*

From the comparison of the deformation modulus (E) with the void ratio (e) and the liquidity index (I_L), linear, rational, exponential and quadratic functions were separately considered for each variable and each soil unit. Since the application of any type of function $E = f(e, I_L)$ other than linear did not improve the condition, it was decided to consider only linear ones to simplify expressions. The exception is quadratic relations. For each function, the coefficient of determination (R^2) was calculated. The results from these correlation analyses are shown in Tables 12-15.

Table 12. Parameters of correlations between the deformation modulus (E, MPa), the liquidity index (I_L) and the void ratio (e) obtained from the database of this study for moraine clayey sands.

Type of function $E = f(e, I_L)$	Num. of data	R^2
Linear, linear	205	0.406
Rational, linear		0.407
Exponential, linear		0.407
Quadratic, quadratic		0.409

Table 13. Parameters of correlations between the deformation modulus (E, MPa), the liquidity index (I_L) and the void ratio (e) obtained from the database of this study for moraine sandy clay loams.

Type of function $E = f(e, I_L)$	Num. of data	R^2
Linear, linear	45	0.190
Rational, linear		0.190
Exponential, linear		0.190
Quadratic, quadratic		0.325

Table 14. Parameters of correlations between the deformation modulus (E, MPa), the liquidity index (I_L) and the void ratio (e) obtained from the database of this study for lacustrine-glacial clayey sands.

Type of function $E = f(e, I_L)$	Num. of data	R^2
Linear, linear	54	0.022
Rational, linear		0.024
Exponential, linear		0.024
Quadratic, quadratic		0.114

Table 15. Parameters of correlations between the deformation modulus (E, MPa), the liquidity index (I_L) and the void ratio (e) obtained from the database of this study for lacustrine-glacial sandy clay loams.

Type of function $E = f(e, I_L)$	Num. of data	R^2
Linear, linear	110	0.370
Rational, linear		0.398
Exponential, linear		0.402
Quadratic, quadratic		0.418

The coefficient of determination (R^2) indicates variables of the deformation modulus (E), the void ratio (e) and the liquidity index (I_L) which can be considered moderately correlated for all considered soil units, except lacustrine-glacial clayey sands where the relationship is interpreted as low correlated.

The function $E = f(e, I_L)$ having the highest coefficient of determination (R^2) is quadratic.

Note that the coefficient of determination (R^2) for a function of one variable (Tables 4-11) should not be compared with the coefficient of determination (R^2) for a function of two variables (Tables 12-15).

5 CONCLUSIONS

A total of 517 quaternary silt clayey soil units from 100 reports on the engineering geological investigations at construction sites in Belarus were considered during the study. Values of the deformation modulus (E) were compared with values of the void ratio (e) and the liquidity index (I_L) for moraine and lacustrine-glacial clayey soil deposits.

The relationships between the deformation modulus (E), the void ratio (e) and the liquidity index (I_L) were analysed. The relations $E = f(e)$, $E = f(I_L)$ and $E = f(e, I_L)$ were obtained for moraine and lacustrine-glacial clayey soils during correlation analysis. All relations can be considered from moderately to highly correlated for all soil units. The best functions describing the relations $E = f(e)$ and $E = f(I_L)$ are rational and quadratic, while $E = f(e, I_L)$ are quadratic.

The study results can be used in practice to predict the deformability of clayey soils and settlements when changing their porosity and moisture content.

First of all, the study was carried out to predict the deformation of clayey soils preliminary after the application of dry concrete columns. However, the relations can also be used in other cases that cause changes in the porosity and moisture of soils, for example, when using displacement piles, stone columns, different drains etc.

Due to the research was carried out only for moraine and lacustrine-glacial clayey soil deposits in the territory of Belarus, then, to predict the deformation of other genetic type soils, there is a need for additional research.

6 ACKNOWLEDGEMENTS

The author would like to express gratitude to UE Geoservice for providing data for the analysis.

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