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Engineering geological and geotechnical properties of till soil of the Middle Pleistocene glacial period

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Abstract. Glacial deposits make up the biggest volume of deposits of the Quaternary system in Lithuania. The deposits of the Medininkai glacial period are spread across the entire territory of Lithuania, but occur on the surface only in the southeastern area. The main purpose of this study is to explore the stiffness and deformation of till soils of the Medininkai glacial period and compare the obtained values with the glacial till soil properties presented in the literature. The triaxial cell apparatus, direct shear apparatus and oedometer test apparatus were used for soil investigation in order to achieve the aim of the study. During the in-situ tests the cone penetration test was performed and the borehole was described. Such physical properties of soil as bulk density and moisture content were evaluated, the plastic and liquid limits were established and the grain size distribution of soil was analysed. The mechanical properties of soil were investigated with several different devices; one-dimensional compression, direct shear and triaxial cell tests were performed. The results showed no significant difference between the data obtained during the triaxial cell test and the data obtained from the direct shear test. A significant difference was noticed between the values of the secant modulus E_{50} calculated during the triaxial cell test and the values of the oedometer modulus E_{oed} obtained during the oedometer test and those presented in the literature; therefore these values should be considered very carefully. No significant difference was observed between the values of E_{50} and E_{oed} obtained during the oedometer test by applying the similar loading intervals. The comparison of E_{oed} values calculated during the cone resistance test with the results obtained during the E_{50} and E_{oed} oedometer test led to similar results. A summary of the results regarding the mechanical properties of till soils of the Medininkai glacial period shows that values obtained by different laboratory methods may be correlated, but may be rarely compared with values presented in the literature.

Key words: Medininkai glacial period, one-dimensional compression test, direct shear test, triaxial cell test, cohesion, angle of internal friction, deformation modulus.

INTRODUCTION

The surface of the territory of Lithuania and surficial geological surroundings which are relevant from an engineering point of view formed during the Quaternary period. The most important feature of the Quaternary is a glacial period. Glacial ice covered Lithuania several times, and glacial deposits are distributed on the entire surface of Lithuania. The average thickness of these deposits is about 100 m, maximum thickness more than 315 m (Bičkauskas et al. 2011). Glacial deposits differ significantly, depending on the conditions of formation. The moraines cover the largest areas, being formed at the side of the ice flow and under its coverage. Layers of sand, gravel and pebbles have been formed by glacial meltwater. Clay and silt deposited in glacial lakes. Sand dunes, which cover large areas in South Lithuania, were shaped by the wind during the ice age and after it (Bičkauskas et al. 2011).

The soils found in Lithuania are classified as glacial (till (moraine)), fluvioglacial, limnoglacial and Holocene (marine, aeolian, limnic, marsh, diluvial, technogenic) deposits. According to the distribution of Quaternary surficial deposits, glacial soils are the most common on the territory of Lithuania, making up approximately 41.35% (Guobytė et al. 2001). The volumetric spread of Quaternary surficial deposits, calculated by two methods in Putys et al. (2010), also shows that glacial soils are prevalent in the entire territory of Lithuania. Glacial deposits comprise the biggest volume of deposits of the Quaternary system, about 70.30% (Putys et al. 2010). The spread of Quaternary deposits in the territory of Lithuania has been evaluated according to their area and volume in the Quaternary layer. Summarizing and evaluating the available research results, it can be said that till soils are the most common in Lithuania, comprising 41.33% by area and around 70% by volume (Guobytė et al. 2001; Putys et al. 2010).

According to the available data, glacial till soils are predominant in Lithuania, but the mechanical properties of soils during several geological periods have been poorly studied and analysed. The main focus has been on physical properties and spread of soil. The soils of this period not only cover the surface of Lithuania, but are often subject to human economic activity (as a medium for structures and their structural members, mineral resource, etc.).

Each continent or country has the most common, most popular or most investigated geological period or type of soil (sand, clay, etc.). The main focus is on London clays in Great Britain (Tsiampousi et al. 2017; Standing 2018), on quick clays in Norway (Helle et al. 2018) and on Ottawa sands in the USA (Garboczi et al. 2017). Igbokoda sands are very popular in Nigeria (Ojuri & Agbolade 2015), Jumunjin sands in Korea (Kim et al. 2016) and Fujian sands in China (Pei-Yong & Qing 2009).

In the Baltic Sea region and in the neighbouring countries, the study of glacial till soils is relevant. Till soils from the Medininkai glacial period are common in entire Lithuania, Poland (Wartanian), Latvia (Kurzeme), Estonia (Ugandi) and in other countries of Europe. Pre-Quaternary rocks occur in most of Estonia, but in the surface Quaternary deposits are found as well (Sibul et al. 2017). Glacial till soils are the most common among Quaternary deposits (Kasparinskis & Nikodemus 2017). In Estonia the Medininkai glacial period (Ugandi) is divided into early and late stages (Kalm et al. 2011), but is not found on the surface. Quaternary deposits cover almost the whole territory of Latvia (up to 5–60 m deep). The most common Quaternary deposits are glacial Middle Pleistocene deposits (Zelčs et al. 2011; Zelčs & Nartišs 2014; Kasparinskis & Nikodemus 2017). In Latvia, the Medininkai glacial period (Kurzeme) is not found on the surface either. In Poland, like in Lithuania, Quaternary deposits cover the whole territory. Here deposits of the Middle Pleistocene Medininkai (Wartanian) glacial period occur on the ground surface and cover a considerable part of the territory. Mainly, soils of this glacial period are found in the southern and southwestern part of the country. The main deposit of the Medininkai (Wartanian) glacial period is end moraine (Marks et al. 2016). When summarizing the spread of glacial soils in the aforementioned countries (Ehlers et al. 2011), it can be concluded that the investigations of glacial till soils are important internationally as well.

According to the Lithuanian Quaternary stratigraphic chart (Satkūnas 2009), which is based on the genesis of soils, the investigated soil is classified as a glacial deposit of the Middle Pleistocene Medininkai glacial period (gt II md). The Medininkai glacial period (195–128 thousand years) formed the coverage of an average thickness of 30–40 m. The maximum thickness of the layer is 50–100 m (Kavoliutė 2012), the prevailing thickness approximately 10–30 m (Grigelis et al. 1994).

This study focuses on the mechanical properties of the till soils of the Medininkai glacial period. The main aim is to investigate the stiffness and deformation of these soils and to compare the obtained values with the properties of glacial till soils presented in the literature. In order to achieve the aim of the study, the soil was investigated with a triaxial pressure apparatus, direct shear apparatus and oedometer testing apparatus. The physical properties were estimated as well. During the in-situ tests the cone penetration test (CPT) was conducted and the borehole was described.

STUDY AREA

The investigated soil occurs in eastern Lithuania (Fig. 1). The deposits of the Medininkai glacial period are spread across the whole country, but are exposed on the surface only in the southeastern area. These soils cover approximately 1459.6 km^2 (2.25%) of Lithuania's territory.

Deposits of the second glacial period (middle Pleistocene II) occur in southeastern Lithuania (Fig. 2). In this side of the country, the deposits of the Medininkai glacial period are found on the surface and consist practically only of glacial (g II md) and fluvioglacial (f II md) sediments.

In the study area in-situ tests were conducted: the drilling of boreholes (Fig. 3) and cone penetration (Fig. 4). During the drilling, the samples of disturbed and undisturbed soil were taken in order to analyse the physical and mechanical properties in the laboratory. The general depth of investigations was up to 20 m, extending through almost the full thickness of the Medininkai layer in the study site.

The borehole study (Fig. 3) revealed that the glacial till (g II md) deposits dominated under sediments of the Baltic stadial (f III bl). Till clay with medium sand lenses and interlayers were the most common.

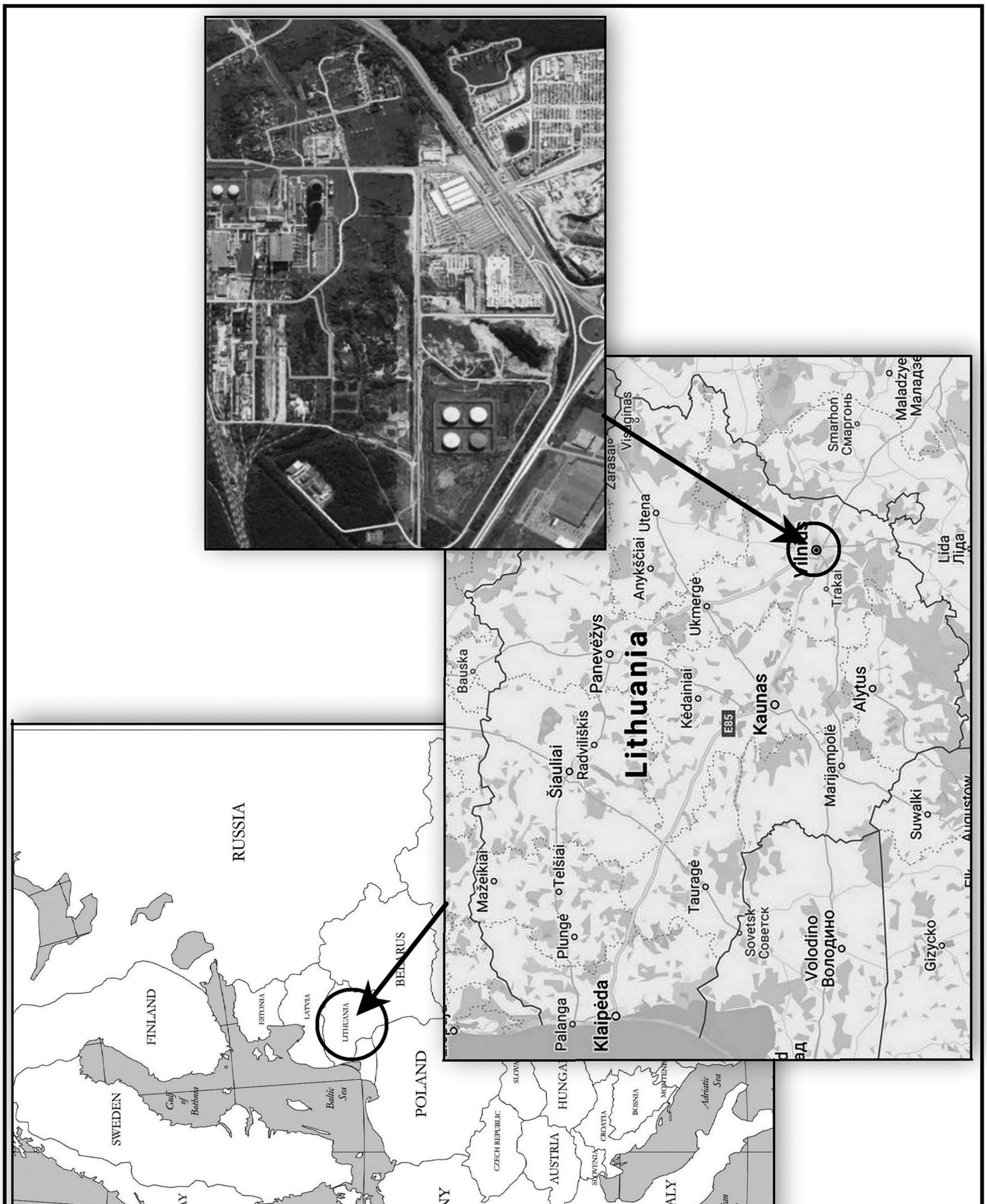


Fig. 1. The site of the investigated soil.

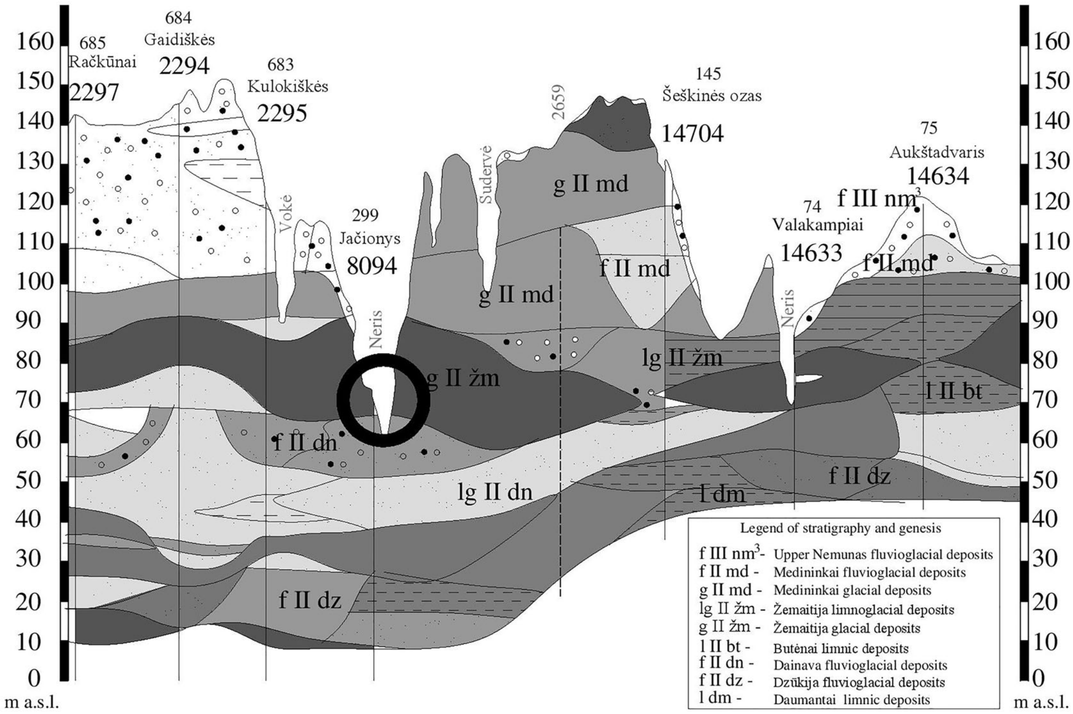


Fig. 2. Geological cross section of the study site.

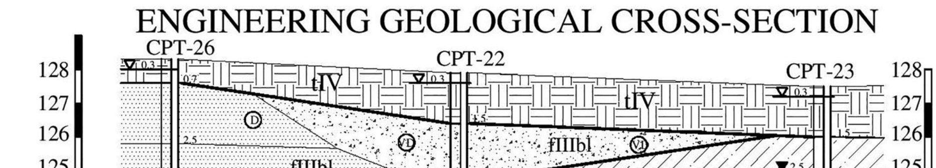


Fig. 3. One of engineering geological cross sections from the study site (Geotestus 2017). D, dense; VD, very dense; ST, stiff; VST, very stiff. For the description of deposits see Fig. 4.

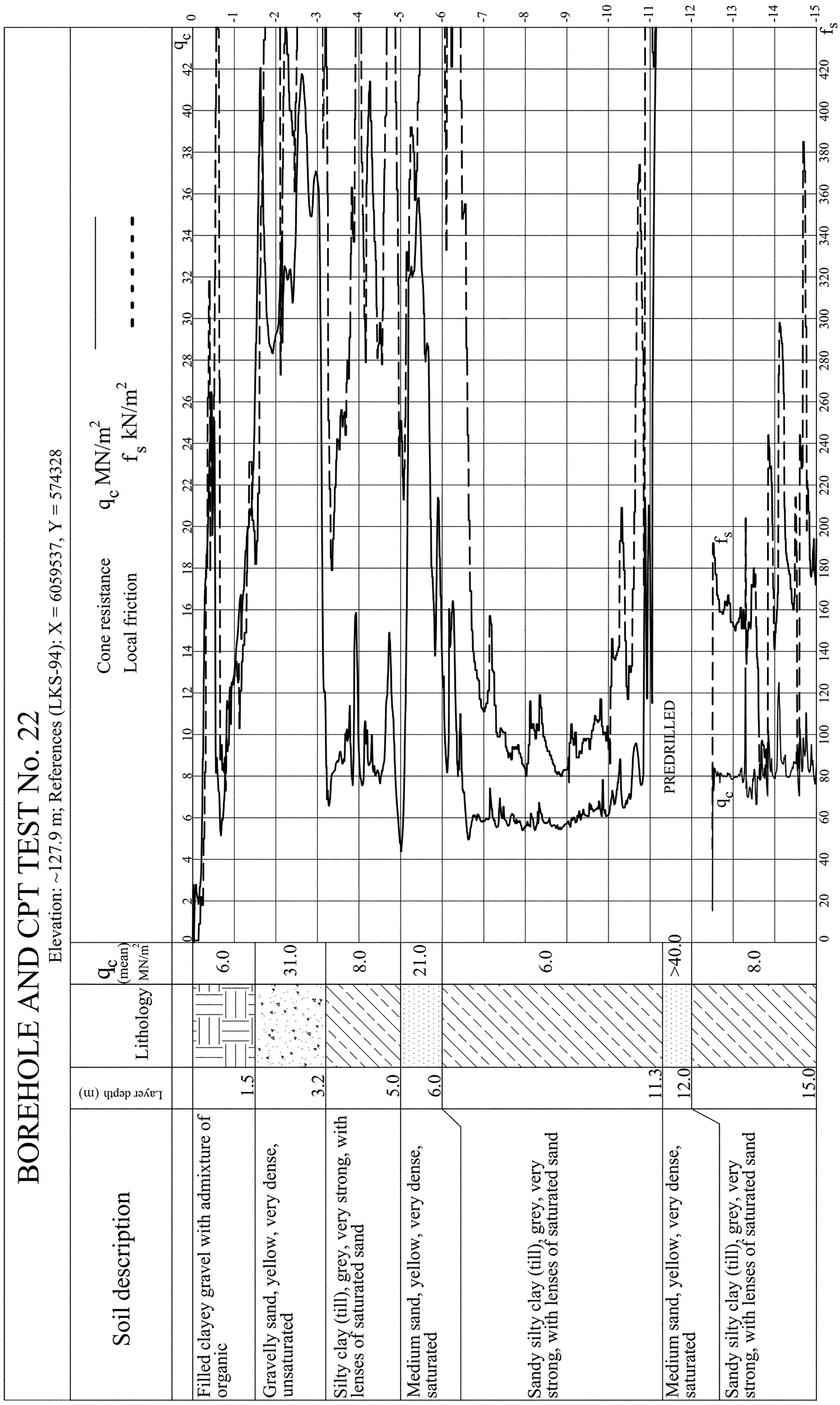


Fig. 4. Borehole and the CPT test of the sampling site (Geotestus 2017).

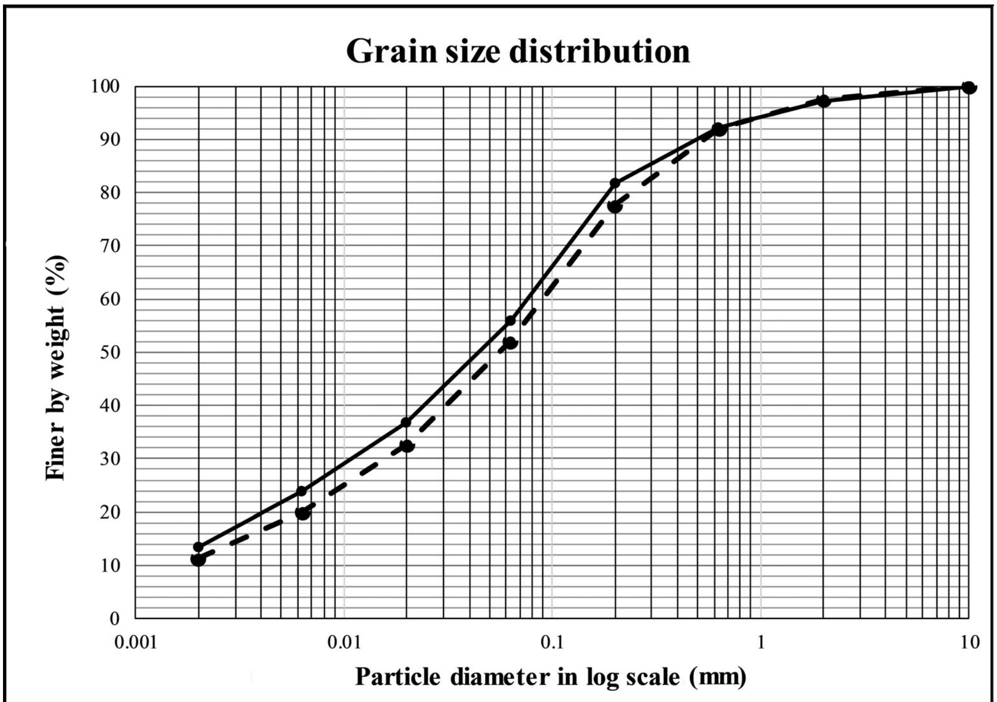
PHYSICAL AND MECHANICAL PROPERTIES OF THE INVESTIGATED SOIL

According to the borehole description (Fig. 4), the analysed till soil of the Medininkai glacial period lies at a depth of 6 m and deeper. The samples for laboratory tests were taken from 8.4–8.6, 9.3–10.1 and 13.1–13.9 m depth intervals. Based on the cone penetration data (using cone resistance (q_c) values), the analysed soil is classified as very stiff soil, when $q_c > 4$ MPa (standard EN 1997-2:2007; CEN 2007). Cone resistance of the samples taken at depths of 8.4–8.6 and 9.3–10.1 m, was 6.0 MPa. The sample from 8.4–8.6 m was analysed by the direct shear and oedometer tests, the sample from 9.3–10.1 m by the saturated consolidated drained triaxial test method (SCD). Cone resistance of the sample from 13.1–13.9 m, which was analysed by the unsaturated consolidated undrained test method (UCU), was 8.0 MPa. The testing conditions with a triaxial cell device represent the engineering geological and geotechnical conditions of the investigated site (Fig. 3).

Physical properties

Physical properties of the soil were estimated, i.e., bulk density, moisture content and plastic and liquid limits were established and grain size distribution analysis of soil was carried out (Fig. 5, Table 1). Laboratory tests were conducted according to standards CEN ISO/TS 17892-4:2004 and CEN ISO/TS 17892-12:2004 (CEN 2004a, 2004b).

Based on the grain size distribution of the soils, according to the standard CEN ISO/TS 17892-4:2004 (CEN 2004a), the analysed soil samples are sandy silty clay till (sasiCl). There are practically no differences in the results of the obtained physical properties between the samples taken at various dephts.



Sample depth, triaxial test methodology	Clay	Silt			Sand			Gravel
		Fine	Medium	Coarse	Fine	Medium	Coarse	
	<0.002	0.002-0.0063	0.0063-0.02	0.02-0.063	0.063-0.2	0.2-0.63	0.63-2.0	>2.0
9.3 - 10.0 (m) SCD	11.32	8.61	12.76	19.29	25.61	14.44	5.44	2.53
13.1 - 13.9 (m) UCU	13.4	10.56	12.75	19.27	25.69	10.63	4.82	2.88
Soil name according to LST EN ISO 14688-2					**Sandy silty clay (sasiCl)**			

Fig. 5. Grain size distribution graph.

Table 1. Physical properties of the investigated samples

Sample depth (m), triaxial test method	Bulk density	Particle density	Void ratio	Moisture content	Plasticity index			
	ρ (g/cm^3)	ρ_s (g/cm^3)	e (part.u.)	w (part.u.)	w_L (part.u.)	w_P (part.u.)	I_P (part.u.)	I_L (part.u.)
9.3–10.1, SCD	2.27	2.72	0.33	0.11	0.222	0.125	0.111	–0.185
13.1–13.9, UCU	2.29	2.72	0.33	0.119	0.245	0.139	0.1	–0.215

Mechanical properties

Mechanical properties of soil were investigated with several different devices (Skels & Bondars 2017; Bajestani et al. 2018; Youwei et al. 2018): one-dimensional compression, direct shear and triaxial cell tests. Soil deformation properties were estimated in the laboratory during the oedometer test, which was gradually overloaded (standard ISO 17892-5:2017; CEN 2017). The test was carried out for a sample of undisturbed structure with the height $H = 20$ mm and diameter $D = 70$ mm. The loads used in tests were 50, 160, 360, 780 and 1610 kPa. A new grade of load was applied every 24 h. Physical properties of the investigated sample (sampling depth 8.6–8.9 m) are given in Table 2.

Table 2. Physical properties of the sample investigated with the oedometer and direct shear tests

Initial void coefficient e_o	0.35
Particle density ρ_s (Mg/m^3)	2.69
Average of moisture content w (part.u.)	0.119
Saturation S_r	0.88
Average of soil bulk density ρ (Mg/m^3)	2.21

The soil was tested by a direct shear test according to the standard CEN ISO 17892-10:2018 (CEN 2018). The height of the rings (H) ranged from 34.5 to 34.9 mm, and the diameter (D) from 71.3 to 71.5 mm. The soil sample was taken from a depth interval of 8.4–8.6 m. Its physical properties are presented in Table 2. The vertical loads used in tests were 100, 200 and 300 kPa.

With the height (H) to diameter (D) ratio of the triaxial cell test apparatus $H/D = 2$ ($H = 100$ mm, $D = 50$ mm), two test series were carried out according to two different test methods (Fig. 6) (Rahman et al. 2018; Youwei et al. 2018). The first series of tests was conducted by applying the UCU triaxial cell test (Ding et al. 2018; Wu et al. 2018), which is called a fast test (Lee et al. 2016). The following loads were created in this test: 160, 260 and 360 kPa. The second series of tests was run by applying the SCD triaxial cell test (Favero et al. 2018), which is called a slow test. Here the consolidation stress was, respectively, 200, 300 and 400 kPa. Test loads were selected according to the conditions in which undisturbed and natural soil occurs, taking into account that the soil may be loaded or unloaded with 100 kPa. During both tests, the velocity

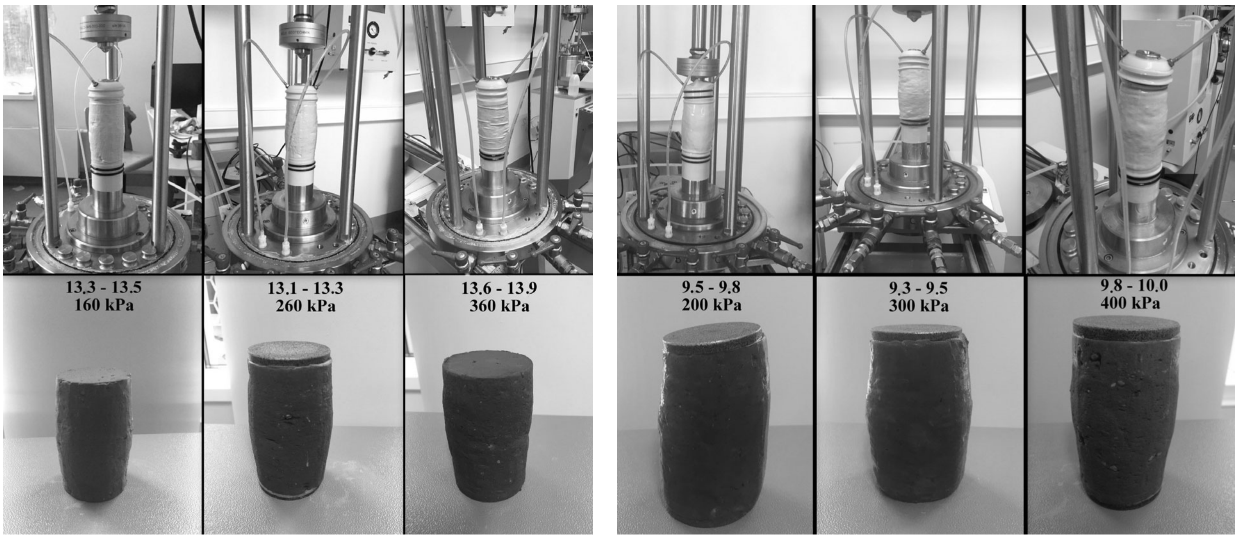


Fig. 6. Right, samples after SCD tests; left, samples after UCU tests.

of vertical deformations was 0.002%/min (to the biggest 15% vertical deformation) (Lekstutytė et al. 2018).

The secant modulus E_{50} (Xia et al. 2018; Soltani et al. 2019) decreased as the strain level increased because the stress–strain curve had a downward curvature. There are three means of obtaining this parameter (Zhang et al. 2019):

- laboratory triaxial tests (from calculation based on the tangent modulus of soil);
- pile–load test;
- empirical correlations based on previous experience.

In this case, the secant modulus was calculated from triaxial test results.

DISCUSSION

According to borehole description (Fig. 2), glacial till soil from the Medininkai glacial period lies at 6 m and deeper. The samples for laboratory tests were taken from 8.4–8.6, 9.3–10.1 and 13.1–13.9 m depth intervals. Based on the cone penetration data, the analysed soil is classified as very stiff soil, when $q_c > 4$ MPa (EN 1997-2:2007; CEN 2007).

Cone resistance $q_c = 6.0$ MPa for the samples taken from the depths of 8.4–8.6 and 9.3–10.1 m. The sample from 8.4–8.6 m was tested with a direct shear apparatus and an oedometer, the sample from 9.3–10.1 m by the SCD method. Cone resistance $q_c = 8.0$ MPa for the sample taken from a depth of 13.1–13.9 m, which was analysed by the UCU method. Mechanical properties of soil estimated experimentally were compared with the results found in the literature. Values of the internal friction angle and cohesion were compared separately (Table 3).

The results obtained from the triaxial test by the SCD and UCU methods display slight differences (Table 3). Minor differences are observed between various methods used to evaluate the stiffness of the till soil of the Medininkai glacial period (Lekstutytė et al. 2018). Here only the minimum and maximum values of the internal friction angle and cohesion evaluated by different methods are presented (Table 3). Comparison of the values of the triaxial cell test with those presented in the literature (Table 3, row 1) reveals significant differences (Šimkus et al. 1973; Sližytė et al. 2012). The internal friction angle found in the literature is bigger by approximately 3–5°, compared to the SCD test and by 2–6°, compared to the UCU test. Analysis of cohesion values given in the literature shows that they are bigger by approximately 54–61 kPa, compared to the SCD test and by 52–55 kPa, compared to the UCU test. The proposed shear strength parameters are much more overestimated than the internal friction angle (Lekstutytė et al. 2018).

No significant differences were observed between the minimum and maximum values of the triaxial cell test and the average values presented in the literature (Table 3, row 2). The average cohesion value found in the literature is within the average range of results obtained with the SCD test method, and only approximately 2–5 kPa bigger in the UCU test. The internal friction angle is bigger by about 9–13°, compared to the SCD and the UCU tests. Here the internal friction angle is slightly more different than in the aforementioned literature, but the differences of cohesion values are substantially lower.

The evaluation of the values of the internal friction angle and cohesion obtained during the direct shear test and comparison with those found in the literature (Šimkus et al. 1973; Sližytė et al. 2012) (Table 3, row 1) revealed insignificant difference in the values of the internal friction angle (approximately by 3–4°). However, the evaluation of the cohesion values established in laboratory showed that they were significantly lower, with the difference equalling approximately 24–40 kPa. The values of the internal friction angle also differed by only ~4° from the data from literature sources (Bucevičienė et al. 1997) (Table 3, row 2), and the cohesion value obtained during the direct shear test was bigger by 16 kPa. Compared to the presented values (Table 3, row 1), the differences of results found in the literature are lower.

Comparison of the data obtained during the triaxial cell test with data obtained during the direct shear test

Table 3. Values of the internal friction angle (ϕ) and cohesion (c)

Literature review			Triaxial test				Direct shear test	
			SCD		UCU			
	ϕ (°)	c (kPa)	ϕ (°)	c (kPa)	ϕ (°)	c (kPa)	ϕ (°)	c (kPa)
1	27.00–28.00**	66.00–82.00**	23.58–25.88*	20.55–28.03*	21.75–25.79*	27.56–30.59*	31.00	42.00
2	35.00***	26.00***						

* Minimum and maximum values (Lekstutytė et al. 2018).
** Minimum and maximum values (Šimkus et al. 1973; Sližytė et al. 2012).
*** Average value (Bucevičienė et al. 1997).

(Table 3) shows relatively minor differences. The value of the internal friction angle obtained during the direct shear test is higher by about 5–9°, compared to the SCD and the UCU tests. The cohesion value is higher than the values obtained during the triaxial cell test by approximately 14–21 kPa, compared to the SCD test and by 11–14 kPa, compared to the UCU test. In order to reach the goal of this investigation, soil deformation properties were compared additionally (Table 4).

Summing up the E_{50} values calculated during the triaxial cell test by different SCD and UCU methods (Table 4) and their evaluation at intervals of similar loads revealed no significant differences between them. However, comparison with the values presented in the literature (Bucevičienė et al. 1997) showed that the values which were calculated according to the data obtained during the triaxial cell test were lower by 32–38 MPa. It should be emphasized that the aforementioned literature sources do not mention which method was used to obtain or calculate the oedometer modulus E_{oed} value and under what conditions this was done.

The values obtained during the oedometer test and the results calculated from the data received during the triaxial cell test are presented at different pressure by which the soil was loaded during the tests (Table 4). There are no significant differences in E_{50} and E_{oed} results in similar intervals of loading. At 160 kPa, the load value of E_{oed} is lower by approximately 6 MPa and at the 360 kPa load by approximately 3–4 MPa. When comparing the values obtained during the oedometer test with those presented in the literature, differences similar to the previous ones are seen. Comparison of the estimated values with those indicated in the literature (Bucevičienė et al. 1997) shows that they are lower by 26–41 MPa. These differences are significant and should be evaluated very carefully.

For the last comparison, E_{oed} values were calculated on the basis of (EN 1997-2:2007; CEN 2007) cone resistance, geostatic stress and plasticity index (Table 4). Comparing these values with the results obtained for E_{50} and E_{oed} during the oedometer test, quite similar differences can be noticed. The E_{oed} value (EN 1997-2:2007) is higher than E_{50} at the SCD test method by about 11–17 MPa, and UCU by 23–25 MPa. The average value of E_{oed} (EN 1997-2:2007) taken from both methods (SCD and UCU) is higher than E_{oed} by 10–25 MPa. However, comparison of these E_{oed} values with those found in the literature (Bucevičienė et al. 1997) shows minor differences between the estimated and literature values. The calculated average value of E_{oed} is lower than that mentioned in the literature (Bucevičienė et al. 1997) by ~16 MPa.

CONCLUSIONS

1. Comparison of the values of the soils of the Medininkai glacial period obtained during the triaxial cell and the direct shear tests with values found in Šimkus et al. (1973) and Sližytė et al. (2012) (Table 3, row 1) suggests that shear strength parameters for the glacial soil of the Medininkai glacial period proposed by these authors are overestimated. The estimated values show only minor differences from the results presented by Bucevičienė et al. (1997) (Table 3, row 2).
2. If one chooses to use the parameters presented in the literature, it is extremely important to analyse carefully for what type or genesis of soil the values were given.
3. No significant differences were observed between data obtained during the triaxial cell test and data from the direct shear test. The value of the internal friction angle obtained during the direct shear test was higher by about 5–9°, and cohesion was higher by 11–21 kPa. These values are close enough to be correlated.
4. Comparison of the E_{50} values calculated during the triaxial cell test and the E_{oed} values obtained during the oedometer test with those presented in the literature (Table 4) revealed significant differences, therefore they should be evaluated very carefully. The calculated E_{oed} values showed only slight differences from those presented in the literature.

Table 4. Soil deformation properties

Literature review		Triaxial test		Oedometer test	From CPT test	
SCD	UCU	SCD	UCU		SCD	UCU
E_{oed} (MPa)		E_{50} (MPa)		E_{oed} (MPa)	E_{oed} (MPa)	
49.00**		–	13.08^{160*}	7.33^{160*}	27.80^{200*}	39.03^{260*}
		10.67^{300*}	13.89^{260*}	12.22^{360*}		
		16.32^{400*}	15.53^{360*}	22.77^{780*}		

* Pressure loaded on the soil during the test.
** Average value (Bucevičienė et al. 1997).

5. Evaluation of E_{50} and E_{oed} results obtained during the oedometer test in similar loading intervals produced no significant differences. The E_{oed} value is lower by approximately 3–6 MPa.
6. Comparison of the calculated E_{oed} values with the results obtained during E_{50} and E_{oed} oedometer test showed quite similar differences. When the calculated value E_{oed} is higher than that of E_{50} by 11–25 MPa, the average value of the calculated E_{oed} compared to E_{oed} obtained in laboratory tests is also higher by approximately 10–25 MPa.
7. Summarizing the mechanical properties of the till soils of the Medininkai glacial period obtained by all methods, it can be concluded that the values estimated by different laboratory methods may be correlated, but they may be rarely compared with the values presented in the literature.

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Ehitusgeoloogilised ja geotehnilised omadused Kesk-Pleistotseensetes moreenpinnastes

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Uurimuse eesmärgiks on Medininkai (Leedu) jääajal moodustunud moreeni kokkusurutavust iseloomustavate parameetrite, Youngi mooduli ja deformatsioonimooduli määramine ning määrangute võrdlemine avaldatud määrangutega analoogsete moreenide kohta. Katsed viidi läbi kolmeteljelises surveaparaadis, nihkeaparaadis ja ödomeetris. Väliuuringutel kasutati surupenetratsiooniseadet, pinnase kirjeldamiseks puuriti puuraugud ja pinnaste füüsikalist seisundit iseloomustati mahukaalu, veesisalduse, lõimise ning Atterbergi piiride määramisega laboris.