Studia Geotechnica et Mechanica, 2020; 42(2); 168–178

Research Article

Open Access

Katarzyna Goławska, Zbigniew Lechowicz*, Władysław Matusiewicz, Maria Jolanta Sulewska

Determination of The Atterberg Limits of Eemian Gyttja on Samples With Different Composition

https://doi.org/10.2478/sgem-2019-0041
received July 10, 2019; accepted February 3, 2020.

Abstract: The paper presents the results of laboratory tests of plastic limit w_P and liquid limit w_L of Eemian gyttja characterized by different organic matter content I_{om} and calcium carbonate content $CaCO_3$. Comparison of the liquid limit w_L determined with the use of the Casagrande apparatus w_{LC} and a cone penetrometer with cones having apex angles of 60° w_{L60} and 30° w_{L30} is shown. Based on statistical analysis of the test results, single- and two-factor empirical relationships for evaluating the plastic limit w_P and liquid limit w_L of Eemian gyttja depending on the organic matter content I_{om} and/or calcium carbonate content $CaCO_3$ are presented in this study.

Keywords: plastic limit; liquid limit; Eemian gyttja; Casagrande cup; cone penetrometer; statistical analysis.

1 Introduction

In engineering practice, Holocene organic soils are considered to represent difficult geotechnical conditions for structure foundation due to their high compressibility with creep effects, low undrained shear strength, significant changes in permeability with porosity changes, and nonlinear variability of material characteristics with spatial variability [22,24,44,45]. Organic soils formed during the Eemian Interglacial of the Pleistocene reveal slightly better index properties and higher stiffness and strength than Holocene organic soils [23,25]. In the past, Eemian organic soils were overloaded and subjected to long-term creeping; therefore, they have the behavior of preconsolidated soils [31]. Eemian gyttja is an example of such organic soils. However, the composition of the Eemian gyttja skeleton displays significant variability, especially regarding the organic matter content I_{om} and the calcium carbonate content $CaCO_3$, which considerably affects the physical and mechanical properties. It is, therefore, necessary to take into account the nature of the geotechnical properties in procedures and interpretation of field and laboratory testing and calculation methods for geotechnical design. Currently, the physical and mechanical properties of Eemian gyttja and its behavior under complex stress conditions are being investigated, as well as work on elaborating design methods for structure foundation on the subsoil with the Eemian gyttja is conducted [15,23].

In addition to the basic properties of organic soils determined in engineering practice, such as bulk density ρ, specific density ρ_s, water content w_n, and Atterberg consistency limits [2]: plastic limit w_P and liquid limit w_L, physical parameters that are also taken into account include the organic matter content I_{om} and the calcium carbonate content $CaCO_3$ [9,31]. Currently, the liquid limit w_L is most often determined using the Casagrande cup [4] or the cone penetrometer [10,18,21,36,47]. The test results presented in the literature show that values of the liquid limit determined by the mentioned methods differ from each other [1,17,33]. Studies show that the use of a cone penetrometer provides more reliable and repeatable measurements of soil strength at a water content within the liquid limit [17,20]. The analysis carried out by O'Kelly [26] indicates that Atterberg limits are not suitable for classification of peat material, especially more fibrous peat.

The experiments carried out by Wasti [42] on natural cohesive soils from various locations in Turkey have shown that the liquid limits determined by the Casagrande and the cone methods were in good agreement for liquid

---

***Corresponding authors: Zbigniew Lechowicz,** Institute of Civil Engineering, Warsaw University of Life Sciences – SGGW, Nowoursynowska 159, 02-776 Warsaw, Poland, E-mail: zbigniew_lechowicz@sggw.pl, ORCID: 0000-0002-1426- 5881;
Maria Jolanta Sulewska, Institute of Civil Engineering and Transport, Bialystok University of Technology, Wiejska 45E, 15-351 Bialystok, Poland, E-mail: m.sulewska@pb.edu.pl, ORCID: 0000-0002-7405-8710
Katarzyna Goławska, Władysław Matusiewicz, Institute of Civil Engineering, Warsaw University of Life Sciences – SGGW, Nowoursynowska 159, 02-776 Warsaw

Table 1: Relationships between the fall cone liquid limit and the Casagrande liquid limit for cohesive soils in the literature.

Equations (no.)	Range of liquid limit	Cone type	Soil type	References
Linear relationships				
$w_{L60} = 0.95\, w_{LC} + 9.4$ (1)	85%–200%	60°–60 g	Danish Eocene clays	Grønbech et al. 2011 [16]
$w_{L60} = 0.86\, w_{LC} + 3.75$ (2) $R^2 = 0.99$, n = 63	13%–117%	60°–60 g	Fine-grained soils	Matusiewicz et al. 2016 [28]
$w_{L60} = 0.772\, w_{LC} + 10.71$ (3) $r = 0.993$, n = 33	30%–390%	60°–60 g	Fine-grained soils, kaolin–bentonite mixtures	Mendoza and Orozco 2001 [29]
$w_{L30} = 0.832\, w_{LC} + 13.28$ (4) $r = 0.989$, n = 9	30%–350%	30°–80 g		
$w_{L(FC)} = 0.95\, w_{LC} - 0.85$ (5)	<150%	30°–80 g/100 g 60°–60 g	Fine-grained soils	Shimobe 2010 [36]
$w_{L30} = 1.0056\, w_{LC} + 4.92$ (6)	27%–110%	30°–80 g	Turkish natural soils	Wasti 1987 [42]
$w_{L30} = 0.841\, w_{LC} + 11.686$ (7)	80%–150%	30°–80 g	Soil–bentonite mixtures	Mishra et al. 2012 [30]
$w_{L30} = 0.91\, w_{LC} + 3.20$ (8) $R^2 = 0.99$, n = 63	13%–117%	30°–80 g	Fine-grained soils	Matusiewicz et al. 2016 [28]
Power relationships				
$w_{L30} = 2.56\, w_{LC}^{0.78}$ (9)	>100%	30°–80 g	Natural clays	Schmitz et al. 2004 [34]
$w_{L30} = 1.86\, (w_{LC,\, BS\ \mathrm{cup}})^{0.84}$ (10) $R^2 = 0.98$, n = 216	Up to approx. 600%	30°–80 g	Fine-grained soils	O'Kelly et al. 2018 [27]
$w_{L30} = 1.62\, (w_{LC,\, BS\ \mathrm{cup}})^{0.88}$ (11) $R^2 = 0.96$, n = 199	<120%			
$w_{L30} = 1.90\, (w_{LC,\, ASTM\ \mathrm{cup}})^{0.85}$ (12) $R^2 = 0.97$, n = 199	Up to approx. 600%			
$w_{L30} = 1.45\, (w_{LC,\, ASTM\ \mathrm{cup}})^{0.92}$ (13) $R^2 = 0.97$, n = 188	<120%			

Note: $w_{L(FC)}$, fall cone liquid limit; w_{L30}, liquid limit using 30°–80 g fall cone; w_{L60}, liquid limit using 60°–60 g fall cone; w_{LC}, Casagrande liquid limit; $w_{L,\, BS\ \mathrm{cup}}$, BS Casagrande cup liquid limit; $w_{L,\, ASTM\ \mathrm{cup}}$, ASTM Casagrande cup liquid limit; R^2, determination coefficient; r, correlation coefficient; n, number of data points.

limit values up to about 100%. Research conducted by Di Matteo [6] on natural cohesive soils characterized by a liquid limit w_L in the range of 20%–50% showed that w_L determined in the cone penetrometer was 2.2% higher compared to that obtained in the Casagrande apparatus. In the case of testing soil mixture with bentonite at various concentrations of NaCl and $CaCl_2$ solutions, Mishra et al. [30] received comparable liquid limit values for values of w_L at less than 100% by two methods, while above this value, higher values of the liquid limit were obtained using the Casagrande method than the cone penetrometer. The experiments show that the values of the liquid limit obtained with the Casagrande procedure and with the Swedish or British cones for liquid limits below 100% could be correlated linearly [16,29,36]; however, when the liquid limits exceed 100%, the relationship is nonlinear [27,34].

Existing reports supply empirical relationships between the liquid limit w_L determined by the Casagrande method and the cone penetrometer for cohesive soils [6,16,19,20,28]. Linear and power relationships between the fall cone liquid limit and the Casagrande liquid limit selected from literature are shown in Table 1. Relationships between the consistency limits and other properties of fine-grained soils are also present in the literature [3,35,40,41,43,46,48]. The relationships between the

Table 2: Relationships between the Atterberg limits and the clay and organic matter contents in the literature.

Equations (no.)		Soil type	References
$LL = 13.75 + 0.637 \cdot \text{clay} + 2.937 \cdot \text{organic C}$ $R^2 = 0.86$, n = 276	(14)	Fine-grained soils with organic content below 6%	De Jong et al. 1990 [5]
$PL = 10.95 + 0.239 \cdot \text{clay} + 1.156 \cdot \text{organic C}$ $R^2 = 0.35$, n = 256	(15)		
$PI = 3.11 + 0.394 \cdot \text{clay} + 1.726 \cdot \text{organic C}$ $R^2 = 0.55$, n = 259	(16)		
$w_P = 3.45 + 13.05\, I_{om}^{0.69}$ $r = 0.98$, n = 43	(17)	Holocene gyttja $I_{om} = 0.6\%–73.1\%$ $CaCO_3 = 2.0\%–88.4\%$	Długaszek 1991 [8]
$w_{LC} = 59.6 + 4.08\, I_{om}^{1.325}$ $r = 0.96$, n = 43	(18)		

Note: LL or w_{LC}, Casagrande liquid limit in %; PL or w_P, plastic limit in %; PI, plasticity index in %; clay, clay content in %; organic C or I_{om}, organic matter content in %; R^2, determination coefficient; r, correlation coefficient; n, number of data points.

Atterberg limits and the clay and organic matter contents selected from the literature are presented in Table 2.

In Poland, as in other European Union countries, geotechnical design according to EN 1997-1 [12] has been in force since 2010. According to EN 1997-2 [13], the cone penetrometer method is preferred for determination of the liquid limit w_L. In practice, determination of the limit w_L by the Casagrande method is still carried out in many cases. A rich set of data containing the liquid limit w_L determined by the Casagrande method for different types of organic soils is available in local practice [8,15,25,28,31]. Change of the method and the need to use archival research results in the future requires analysis of the results of comparative tests carried out using the two methods.

The aim of this work was to analyze the results of comparative studies of the plastic limit w_P and the liquid limit w_L of Eemian gyttja characterized by different organic matter content I_{om} and calcium carbonate content $CaCO_3$. A comparison of the liquid limit w_L determined with the use of the Casagrande apparatus w_{LC} and by means of a cone penetrometer with cones having apex angles of 60° w_{L60} and 30° w_{L30} is presented. In addition, analysis of the test results allowed to develop single- and two-factor relationships of the plastic limit w_P and the liquid limit w_L with the organic matter content I_{om} and/or the calcium carbonate content $CaCO_3$.

2 Laboratory Tests

The studied organic soil was gyttja from the Eemian Interglacial of the Pleistocene, collected from the Żoliborz channel – one of the parts of Warsaw with very complex geotechnical conditions. The Żoliborz channel is located in the western part of Warsaw and currently extensively developed (metro station and tunnels, residential and office buildings with two- or three-floor basements). The channel is about 12 km long and nearly 800 m wide in its central part. In the Żoliborz channel, organic soils, that is, organic mud and gyttja, reach thicknesses up to 10 m. The first subsurface layer in the tested subsoil is formed by fills with thicknesses varying between 0.5 and 4.0 m. The fills are underlain by sand and mud deposits of the Vistulian glaciation to a depth of approximately 4–6 m below the ground level. Sand and mud layers cover a continuous layer of gyttja and organic mud from the Eemian Interglacial. The top of this layer was found to be at a depth of approximately 6 m with the bottom reaching down to 16 m below the ground level. Organic soils of the Eemian Interglacial are overconsolidated, with an overconsolidation ratio (OCR) varying in the range of 2.0 and 3.5. The grain size composition of the mineral part of gyttja points to silts without both the fine silt and clay fractions. The bottom of the channel is filled with moraine deposits from the Odranian Glaciation, represented mainly by sandy clays, followed by sand deposits of the Mazovian Interglacial, represented by dense fine, medium, and silty sands. Free ground water occurs in the sand layer from the Vistulian Glaciation at a depth of about 3 m. In the sand layer from the Mazovian Interglacial at a depth of 20–21 m, the water pressure is artesian, reaching up to 5 m below the ground level.

Samples of Eemian gyttja for laboratory tests were taken as block samples during deep excavations made for the construction of Płocka station of the II metro line and residential buildings along the Skierniewicka Str. in Warsaw. The collected samples were used to study deformation, creep, and strength characteristics and

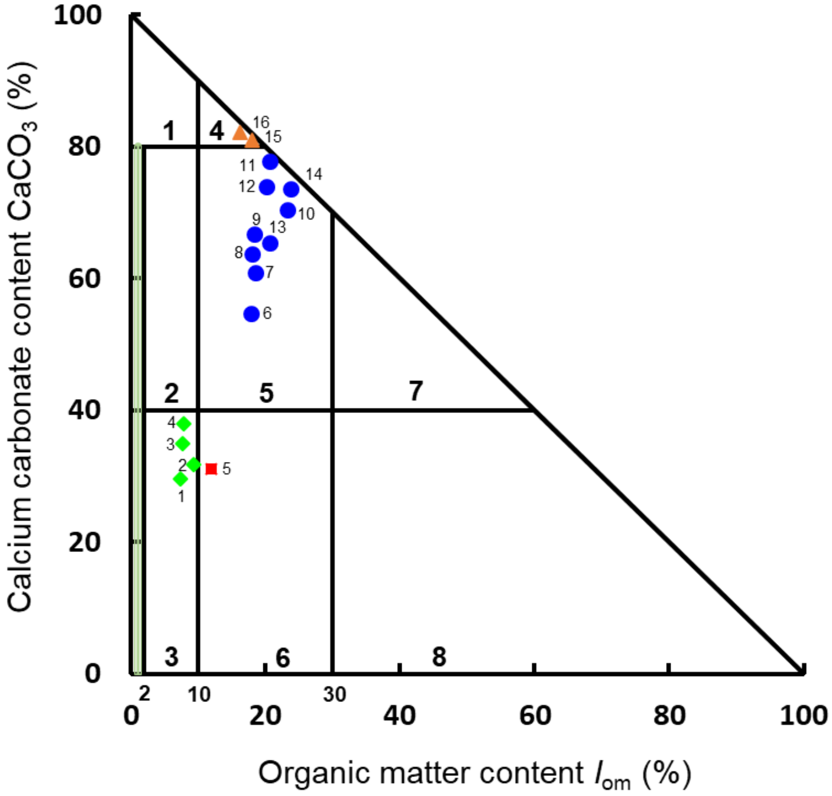

Figure 1: Tested samples of Eemian gyttja according to the classification of Długaszek [7]: I_{om} = 0%–2% mineral soils.
Note: **1**, low organic lacustrine marl; **2**, high calcareous mineral gyttja; **3**, low calcareous mineral gyttja; **4**, high organic lacustrine marl; **5**, high calcareous mineral-organic gyttja; **6**, low calcareous mineral-organic gyttja; **7**, high calcareous organic gyttja; **8**, low calcareous organic gyttja; ◆■●▲ 1–16, test number

parameters of Eemian gyttja. Laboratory tests included oedometer tests, triaxial tests, and torsional shear hollow cylinder tests [15,25]. The following physical properties were determined in the tested samples: bulk density ρ, water content w_n, plastic limit w_P, liquid limit w_L, organic matter content I_{om}, calcium carbonate content $CaCO_3$, specific density ρ_s, and void ratio e [15]. The paper presents the test results of selected physical properties carried out for four basic types of Eemian gyttja, determined according to the classification of Długaszek [7] as: 3, low calcareous mineral gyttja; 4, high organic lacustrine marl; 5, high calcareous mineral-organic gyttja; and 6, low calcareous mineral-organic gyttja. The study involved 16 soil samples (Figure 1).

The liquid limit w_L was determined using the Casagrande method according to PN-B-04481 [32] and the cone penetrometer method according to EN ISO/TS 17892-12 [14]. The plastic limit was determined by the roll-forming method according to PN-B-04481 [32] and EN ISO/TS 17892-12 [14]. Determination of the liquid limit w_L was carried out in the Casagrande apparatus with a hard base percussion cup and 25 blows. A Swedish cone penetrometer with an apex angle of 60°, mass of 60 g, and penetration value of 10 mm and a British cone penetrometer with an apex angle of 30°, mass of 80 g, and penetration value of 20 mm were used.

The organic matter content I_{om} was determined by combustion at a temperature of +440°C. The calcium carbonate content $CaCO_3$ was determined by the gasometer method [44]. The results of index properties of the 16 tested samples of Eemian gyttja are shown in Table 3. The tested gyttja had an organic matter content I_{om} at 7%-24% and calcium carbonate content $CaCO_3$ at 30%-82%. The liquid limit w_{LC} determined using the Casagrande method varied between 81% and 165%. The plastic limit w_P varied between 51% and 131%. The samples of the tested gyttja are shown on Casagrande's plasticity chart (Figure 2). It can be seen that low calcareous mineral gyttja is only in the range of very high plasticity soils (V), whereas the rest of the tested samples are in the range of extremely high plasticity soils (E).

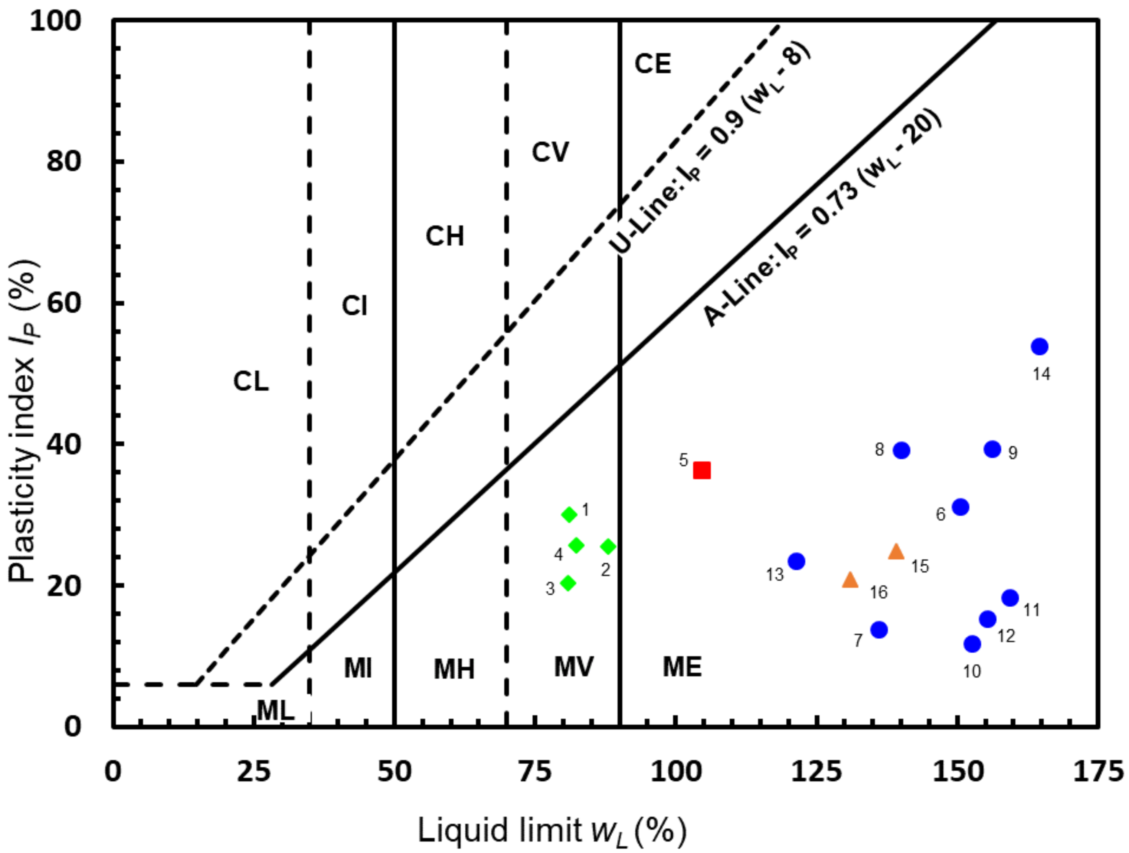

Figure 2: Tested samples shown on Casagrande's plasticity chart.
Note: ◆■●▲ 1–16, test number.

3 Statistical Analysis

Statistical analysis of the test results was carried out using Statistica software version 12 [37,38,39]. Comparison of the liquid limits of the studied Eemian gyttja determined by the Casagrande method w_{LC} and the cone penetrometer with an apex angle of 60° w_{L60} and 30° w_{L30} was carried out using the significance of average differences nonparametric Kruskal–Wallis test (as a nonparametric equivalent of variance analysis) [38]. The null hypothesis that the differences between the average liquid limit w_L obtained by each of the three methods is not statistically significant at the significance level of $p = 0.05$ was tested. The test results allowed to determine whether the applied test method had an impact on the obtained w_L value.

Regression analysis was performed and single-factor models of linear or nonlinear regression equations were obtained, expressed by the formulas [11,38]:

$$y = a + bx, \tag{19}$$

where a and b are the empirical coefficients of linear function, a is the intercept of line, and b is the slope of line and

$$y = cx^d, \tag{20}$$

where c and d are the empirical coefficients of nonlinear – power function.

A multiple linear regression analysis was carried out, with I_{om} and $CaCO_3$ taken as independent variables, and two-factor linear regression models were obtained, expressed by the formula [11, 39]:

$$y = a_0 + a_1 x_1 + a_2 x_2, \tag{21}$$

where a_0, a_1, and a_2 are the empirical coefficients.

One of the assumptions of regression analysis is the absence of collinearity of two explanatory variables (weak correlations with each other). The most common collinearity is estimated by two parameters: tolerance and

Table 3: Laboratory test results of the index properties of Eemian gyttja.

Test no.	Soil type	Water content w_n (%)	Plastic Limit w_P (%)	Liquid limit w_L (%)			Calcium carbonate content $CaCO_3$ (%)	Organic matter content I_{om} (%)
				Casagrande w_{LC}	Cone 60° w_{L60}	Cone 30° w_{L30}		
1	Gyttja (**3**)	62.3	50.9	81.0	76.7	81.5	29.6	7.44
2		67.8	62.4	88.0	86.4	87.2	31.7	9.41
3		61.3	60.7	80.9	75.1	78.1	34.9	7.69
4		58.5	56.6	82.3	81.5	85.5	37.9	7.92
5	Gyttja (**6**)	74.4	68.0	104.5	101.5	105.5	31.1	12.0
6	Gyttja (**5**)	102.1	119.2	150.4	148.5	163.6	54.7	17.8
7		98.7	122.2	136.1	135.5	137.5	60.9	18.6
8		98.9	100.8	140.0	137.1	143.6	63.8	18.1
9		110.1	116.8	156.2	156.8	159.0	66.7	18.4
10		115.6	130.7	152.5	154.8	160.1	70.4	23.3
11		87.1	130.9	159.2	166.1	171.0	77.7	20.6
12		100.3	125.9	155.2	159.5	162.0	74.0	20.2
13		97.7	97.7	121.3	125.4	130.6	65.4	20.7
14		118.5	110.5	164.5	171.6	173.8	73.6	23.8
15	Marl (**4**)	90.6	114.3	139.1	131.6	140.1	81.0	18.1
16		79.9	110.1	131.0	130.8	133.4	82.1	16.2

Note: **3**, low calcareous mineral gyttja; **4**, high organic lacustrine marl; **5**, high calcareous mineral-organic gyttja; **6**, low calcareous mineral-organic gyttja.

variance inflation factor (VIF). The smaller the tolerance for an explanatory variable, the more redundant is its contribution to the regression equation. The variable is unnecessary when the tolerance is less than 0.1. In the case when VIF = 1, there is no collinearity of variables, and when VIF > 10, collinearity has a disturbing effect on the parameters of the regression model [39].

In order to assess the quality of prediction by means of regression equations, the determination coefficient (R^2), relative error (RE) of the cases, and standard error of estimation (SEE), expressed by the following formulas, were used:

$$R^2 = \frac{\sum_{i=1}^{n}(\hat{y}_i-\bar{y})^2}{\sum_{i=1}^{n}(y_i-\bar{y})^2} \tag{22}$$

$$RE = \left|\frac{y_i-\hat{y}_i}{y_i}\right| \cdot 100\ \% \tag{23}$$

$$SEE = \sqrt{\frac{\sum_{i=1}^{n}(y_i-\hat{y}_i)^2}{n-2}}, \tag{24}$$

where y_i is the measured value of dependent variable, $\hat{y}_i$ the predicted value of dependent variable (based on regression model), $\bar{y}$ the mean value of measured value of dependent variable, and n is the number of cases.

3.1 Comparison of the testing methods of the liquid limit

Comparison of the liquid limits of the studied Eemian gyttja determined by the Casagrande method w_{LC} and the cone penetrometer with an apex angle of 60° w_{L60} and 30° w_{L30} is shown in Figure 3.

Figure 3 shows that in the tested range, the average values and standard deviations of the liquid limit determined by individual methods are similar to each other. The calculated values are: w_{LC} = 127.64 ± 30.54, w_{L60} = 127.43 ± 33.17, w_{L30} = 132.03 ± 33.91, where the average value of w_{L30} is slightly higher than the average values of w_{LC} and w_{L60} (by about 3%) and the standard deviation of

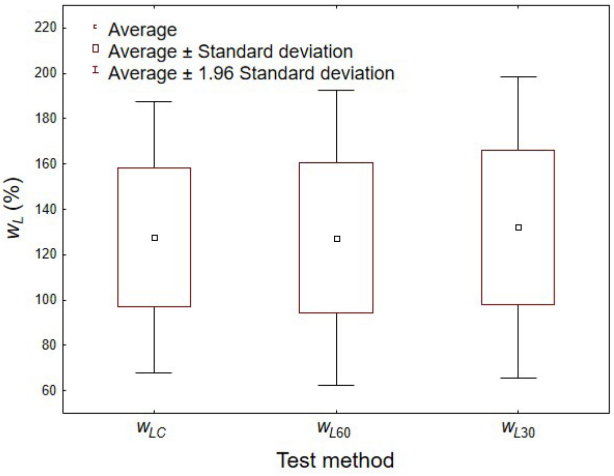

Figure 3: Average values of the liquid limit w_L depending on the test method.

Table 4: Linear and power regression models of relationships between the liquid limit w_L determined by Casagrande method and fall cone methods for Eemian gyttja.

Equations (no.)	R^2 (–)	n (–)	SEE	Max. RE (%)
$w_{L60} = -10.39 + 1.08\ w_{LC}$ (25) or $w_{L60} = 3.07\ w_{LC}^{1.08}$ (25a)	0.989	16	3.62	±5
$w_{L30} = -8.93 + 1.10\ w_{LC}$ (26) or $w_{L30} = 1.32\ w_{LC}^{1.10}$ (26a)	0.990	16	3.58	±7
$w_{L60} = 1.07 + 0.97\ w_{L30}$ (27)	0.990	16	3.41	±5

Note: RE, relative error; SEE, standard error of estimation.

the w_{LC} results is smaller than the results obtained with cones by around 11%. The Kruskal–Wallis test allowed the authors to draw a conclusion (at the significance level of $p = 0.74 > 0.05$) that the test method has no significant statistical effect on the liquidity limit test result.

Table 4 shows single-factor regression relationships of the liquidity limit w_L of Eemian gyttja tested by three methods (w_{LC}, w_{L60}, w_{L30}), with the Casagrande method being considered as the reference one. Reliable conversion formulas (25)–(27) shown in Table 4 were obtained. Their high accuracy of about max RE = 5%–7% indicates that these methods can be used interchangeably, and the results can be calculated using the proposed formulas.

Single-factor regression relationships (25) and (26) are shown in Figure 4. The dispersion of the points of both studied relationships is clearly arranged along straight lines. The relationship (25) does not differ much from the line of equality, which indicates that the cone 60° method is almost equivalent to the Casagrande method. The relationship (26) coincides with the line of equality in the w_{LC} range within 60%-100%; for $w_{LC} > 100\%$, the 30° cone method gives higher values than the Casagrande method up to a maximum of 7%.

A comparison of the relationships $w_{L60} = f(w_{LC})$ and $w_{L30} = f(w_{LC})$ for Eemian gyttja obtained by the authors (presented in Table 4) with selected relationships taken from the literature for cohesive soils (presented in Table 1) is shown in Figure 5.

Figure 5 shows that for the relationships $w_{L60} = f(w_{LC})$ taken from the literature for cohesive soils, the best agreement with test results for Eemian gyttja was obtained from the relationship (1) proposed by Grønbech et al. [16]. However, for the relationships $w_{L30} = f(w_{LC})$ taken from the literature for cohesive soils, the best agreement with test results of Eemian gyttja was obtained from the relationship (12) proposed by O'Kelly et al. [27].

3.2 Relationships between w_P and w_{LC} versus I_{om} and $CaCO_3$

Based on the calculated matrix of linear correlation coefficients according to Stanisz [38], it was found that the liquid limit w_L and the plastic limit w_P depend on the organic matter content I_{om} and the calcium carbonate content $CaCO_3$. Higher I_{om} or $CaCO_3$ values result in higher liquid limit w_L values, regardless of the liquid limit test method. Regression analysis was performed and models of linear or power equations were obtained, expressed by the formulae (19) and (20). A multiple linear regression analysis was carried out, with I_{om} and $CaCO_3$ taken as independent variables, and two-factor linear regression models were obtained, expressed by the formula (21).

The simple and multiple linear regression relationships of w_P and w_{LC} developed together with the values of determination coefficients R^2, SEE, and maximum RE are given in Table 5.

For two-factor models, statistical indicators were checked to detect the redundancy of the explanatory variables introduced in the models: the tolerance of $CaCO_3$ is 0.267 and the VIF = 3.74, which allows to conclude that the collinearity of I_{om} and $CaCO_3$ variables is not disturbing and both independent variables can enter the model.

Based on Equations (28)–(33) in Table 5, it can be stated that in the case of the studied Eemian gyttja, there are positive correlations of the Atterberg limits w_P and w_L with the contents of I_{om} and $CaCO_3$ (positive equation coefficients for the variables I_{om} and $CaCO_3$), which means

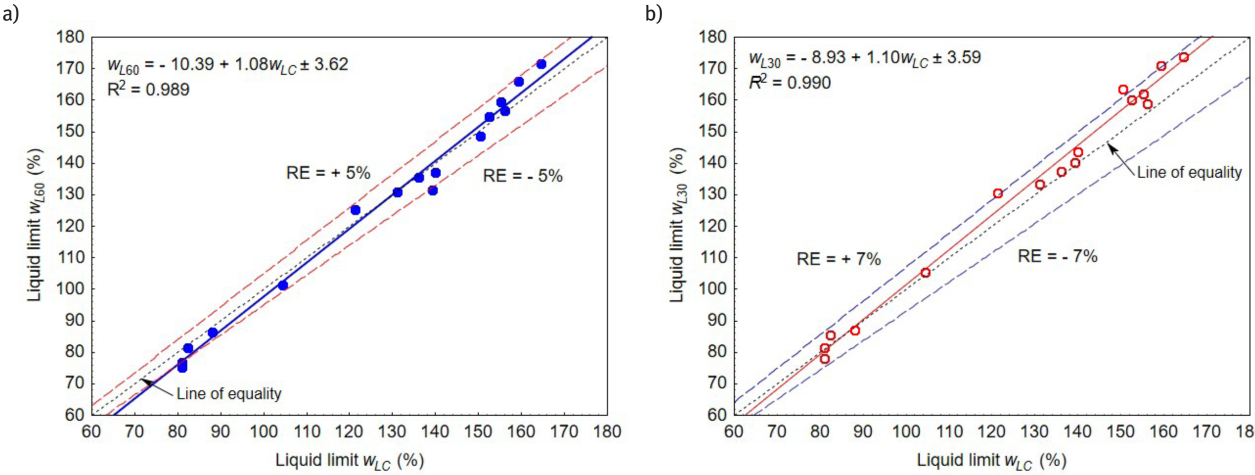

Figure 4: Regression models of relationships between the liquid limits: a) $w_{L60} = f(w_{LC})$, b) $w_{L30} = f(w_{LC})$.
Note: RE, relative error.

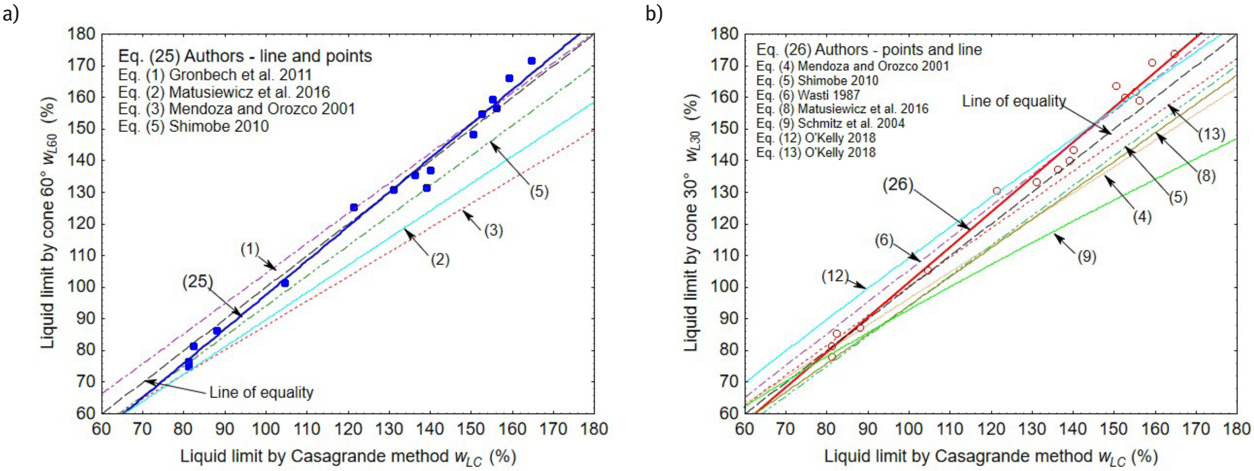

Figure 5: Comparison of relationships obtained by the authors for Eemian gyttja with relationships for cohesive soils taken from the literature: a) $w_{L60} = f(w_{LC})$, b) $w_{L30} = f(w_{LC})$.

Table 5: Single- and two-factor linear regression models of the plastic limit (w_P) and liquid limit (w_{LC}) relationship versus the organic matter content (I_{om}) and/or calcium carbonate content ($CaCO_3$) relationship for Eemian gyttja.

Equations (no.)		R^2 (–)	SEE	Max. RE (%)
$w_P = 22{,}12 + 4.70\ I_{om}$	(28)	0.833	12.15	±17
$w_P = 20{,}75 + 1.33\ CaCO_3$	(29)	0.786	13.75	±20
$w_P = 15.79 + 2.96\ I_{om} + 0.59\ CaCO_3$	**(30)**	**0.874**	**10.93**	**±16**
$w_{LC} = 44.25 + 5.12\ I_{om}$	(31)	0.876	11.13	±20
$w_{LC} = 47.80 + 1.37\ CaCO_3$	(32)	0.731	16.39	±20
$w_{LC} = 40.81 + 4.18\ I_{om} + 0.32\ CaCO_3$	**(33)**	**0.887**	**11.04**	**±15**

Note: RE, relative error; SEE, standard error of estimation.

that w_P and w_L increase with the increase of I_{om} and $CaCO_3$. The w_P and w_L values are more influenced by the I_{om} content than $CaCO_3$.

Using single-factor linear regression models, w_P can be determined on the basis of I_{om} or $CaCO_3$ contents with a lower accuracy of around 17% and 20%, respectively (Table 5), than with the two-factor linear regression model with an accuracy of around 16% (Figure 6a).

Using single-factor linear regression models, w_{LC} can be determined on the basis of I_{om} or $CaCO_3$ with a lower accuracy of about 20% (Table 5) than using the two-factor linear regression model with an accuracy of around 15% (Figure 6b).

A comparison of the relationships $w_P = f(I_{om})$ and $w_{LC} = f(I_{om})$ for Eemian gyttja obtained by the authors (presented in Table 5) with Długaszek relationships taken

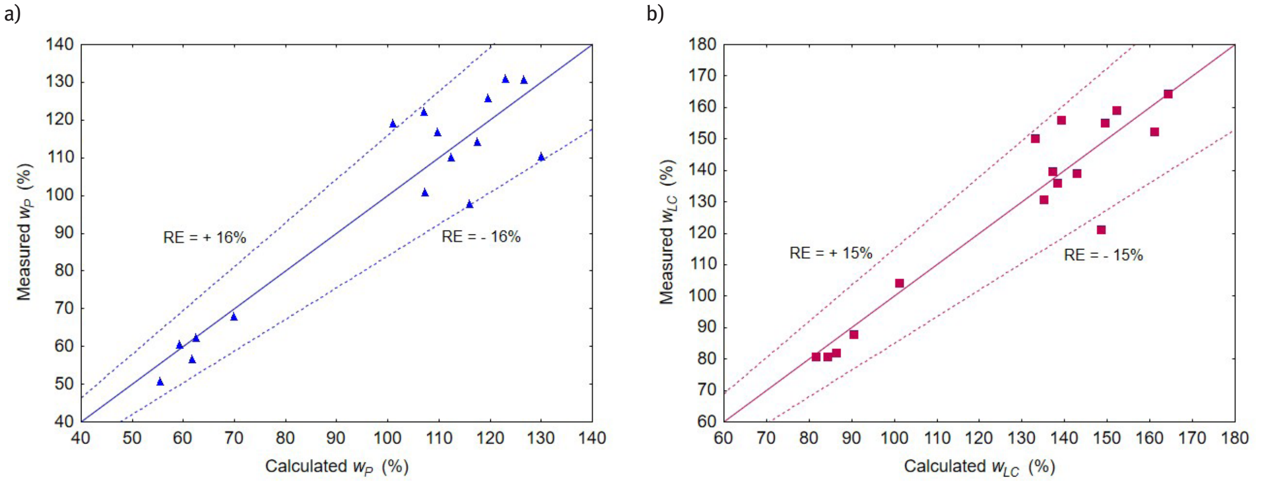

Figure 6: Comparison between the measured and calculated values: a) w_P and w_P from Equation (30) in Table 5, b) w_{LC} and w_{LC} from Equation (33) in Table 5 of Eemian gyttja, with zones of maximum RE for regression models.
Note: RE, relative error.

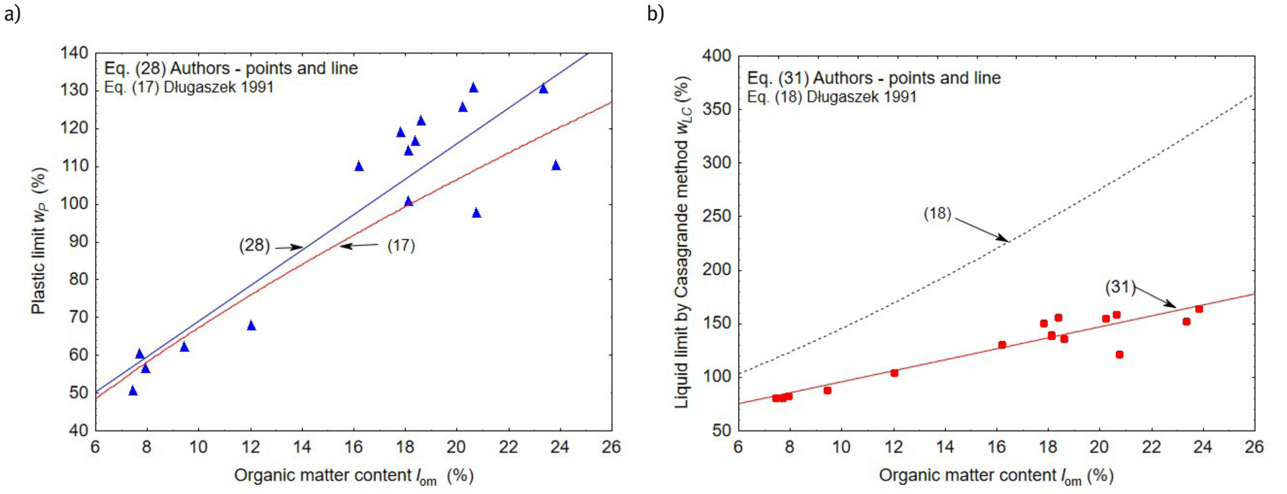

Figure 7: Comparison of relationships obtained by the authors for Eemian gyttja with the relationships for Holocene gyttja obtained by Długaszek: a) $w_P = f(I_{om})$, b) $w_{LC} = f(I_{om})$.

from the literature for Holocene gyttja (presented in Table 2) is shown in Figure 7. Figure 7 shows a significant difference between the test results obtained for Eemian gyttja and the relationships obtained by Długaszek for Holocene gyttja.

4 Conclusions

The following conclusions can be drawn based on the statistical analysis of test results of Eemian gyttja with the organic matter content I_{om} = 7.44%–23.8% and the calcium carbonate content $CaCO_3$ = 29.6%–82.1%:

- The results of the determination of the liquid limit w_L using the Casagrande apparatus w_{LC}, the cone penetrometer with an apex angle of 60° w_{L60}, and the cone penetrometer with an apex angle of 30° w_{L30} were compared. It is concluded that in the examined range of results, the three analyzed liquid limit testing methods can be used interchangeably for the material studied because the differences among the results are very small. Formulas allowing for conversion of the liquid limit w_{LC} for individual methods with a maximum RE at ±5% and 7% have been developed.
- For liquid limit w_{LC} <100%, the relationships $w_{L60} = f(w_{LC})$ and $w_{L30} = f(w_{LC})$ do not differ much for the

material studied from the line of equality and indicate that the cone 60° method is almost equivalent to the Casagrande method. For w_{LC} >100%, the cone 30° method gives higher values than the Casagrande method up to a maximum of 7%.

- The plastic limit w_P depends on the organic matter content I_{om} and the calcium carbonate content $CaCO_3$. The developed two-factor linear regression model allows for assessing the plastic limit w_P on the basis of I_{om} and $CaCO_3$ with a maximum RE of ±16% for the material studied.
- The liquid limit w_L depends on the organic matter content and the calcium carbonate content; the developed two-factor linear regression model allows for assessing the liquid limit w_{LC} on the basis of I_{om} and $CaCO_3$ with a maximum RE of ±15% for the material studied.

Acknowledgments: This work was carried out in cooperation with partners from the Warsaw University of Life Sciences (No. Q00477-99) and Bialystok University of Technology (No. S/WBiIŚ/2/2018). It was supported by the Polish Ministry of Science and Higher Education.

References

[1] ANDRADE F.A., AL-QURESHI H.A., HOTZA D. 2011. Measuring the plasticity of clays: A review. *App. Clay Sci.,* 51, 1–7.

[2] ATTERBERG S.K. 1911. Über die physikalische Bodenuntersuchung und über die Plastizität der Tone. *Internationale Mitteilungen für Bodenkunde* (in German), 1, 10-43.

[3] BUDHU M. 1985. The effect of clay content on the liquid limit from a fall cone and British cup device. *Geotech. Testing J.,* 8(2), 91–95.

[4] CASAGRANDE A. 1932. Research on the Atterberg limits of soils. *Public Roads,* 13(8), 121-136.

[5] DE JONG E., ACTON D.F., STONEHOUSE H.B. 1990. Estimating the Atterberg limits of southern Saskatchewan soils from texture and carbon contents. *Can. J. Soil Sci.,* 70, 543-554.

[6] DI MATTEO L. 2012. Liquid limit of low- to medium-plasticity soils: comparison between Casagrande cup and cone penetrometer test. *Bulletin of Engineering Geology and the Environment*, 71, 79-85.

[7] DŁUGASZEK M. 1988. *Ocena właściwości fizyczno-mechanicznych gytii Pojezierza Olsztyńskiego dla potrzeb inżyniersko-geologicznych*. (Assessment of physico-mechanical properties of the gyttja of the Olsztyn Lakeland for engineering-geological purposes), PhD Thesis. Geology Faculty, Warsaw University (manuscript, in Polish), Warsaw.

[8] DŁUGASZEK M. 1991. Charakterystyka konsystencji gytii badanej aparatem Casagrande'a i stożkiem Wasiliewa (Characteristics of gyttja consistency tested with both the Casagrande's apparatus and the Vasiliev's cone methods). *Acta Academiae Agriculturae AC Technicae Olstenensis* (Zeszyty Naukowe Akademii Rolniczo-Technicznej w Olsztynie), *Aedificatio et Mechanica*, 22, 253-263 (in Polish).

[9] DŁUGASZEK M. 1991. Wpływ zawartości substancji organicznej na gęstość właściwą i gęstość objętościową gytii (The effect of organic content on the specific density and bulk density of gyttja). *Acta Academiae Agriculturae AC Technicae Olstenensis (Zeszyty Naukowe Akademii Rolniczo-Technicznej w Olsztynie), Aedificatio et Mechanica,* 22, 265-276 (in Polish).

[10] DOLINAR B., TRAUNER L. 2005. Impact of soil compression on fall cone test results. *J. Geotech. Geoenviron. Eng.*, 131(1), 126-130.

[11] DRAPER N.R., SMITH H. 1998. Applied regression analysis. Third Edition, Wiley: New York.

[12] EN 1997-1:2008. Eurocode 7. Geotechnical design. Part 1: General rules.

[13] EN 1997-2:2009. Eurocode 7. Geotechnical design. Part 2: Ground investigation and testing.

[14] EN ISO/TS 17892-12:2004. Geotechnical investigation and testing. Laboratory testing of soil. Part 12: Determination of Atterberg limits.

[15] GOŁAWSKA K. 2020. *Analiza pełzania gytii eemskiej w złożonych stanach naprężenia. (Creep behaviour of Eemian gyttja under complex stress states)*. PhD Thesis. Warsaw University of Life Sciences – SGGW (manuscript, in Polish).

[16] GRØNBECH G.L., NIELSEN B.N., IBSEN L.B. 2011. Comparison of liquid limit of highly plastic clay by means of Casagrande and fall cone apparatus. 14th Pan-American Conference on Soil Mechanics and Geotechnical Engineering, Toronto, Canada, ON, 7 pp.

[17] HAIGH S.K. 2012. Mechanics of the Casagrande liquid limit test. *Can. Geotech. J.,* 49, 1015-1023.

[18] HANSBO, S. 1957. A new approach to the determination of the shear strength of clay by the fall cone test. Swedish Geotechnical Institute Proceedings, 14, 5–47.

[19] KARLSSON R. 1977. Consistency limits: A manual for the performance and interpretation of laboratory investigations. Swed Counc Bldg Res, Part 6, Document D6, 40 pp.

[20] KOLLAROS G. 2016. Liquid limit values obtained by different testing methods. *Bulletin of the Geological Society of Greece,* 1, 2, 778-787.

[21] KOUMOTO T., HOULSBY G.T. 2001. Theory and practice of the fall cone test. *Géotechnique,* 8, 701-712.

[22] LARSSON R. 1990. Behaviour of organic clay and gyttja. Swedish Geotechnical Institute. Report No. 38.

[23] LECHOWICZ Z., BAJDA M., RABARIJOELY S., SKUTNIK Z. 2012. Determination of mechanical parameters in organic soils for design of retaining walls. 12th Baltic Sea Geotechnical Conference "Infrastructure in the Baltic Sea Region", Rostock, Germany, (CD 133-139).

[24] LECHOWICZ Z., BAJDA M., RABARIJOELY S., WRZESIŃSKI G. 2014. Use of SDMT for the evaluation of the geotechnical parameters of organic soils. Monograph eds by Z. Młynarek & J. Wierzbicki, Poznań, Wydawnictwo Exemplum, 107-118.

[25] LECHOWICZ Z., GOŁAWSKA K., WRZESIŃSKI G., SULEWSKA M. 2019. Evaluation of creep behaviour of organic soils in a torsional shear hollow cylinder test. Proc. XVII European Conference on Soil Mechanics and Geotechnical Engineering, Reykjavik, Iceland, doi: 10.32075/17ECSMGE-2019-0338.

[26] O'KELLY B.C. 2015. Atterberg limits are not appropriate for peat soils. *Geotechnical Research,* 2(3), 123-134.

[27] O'KELLY B.C., VARDANEGA P.J., HAIGH S.K. 2018. Use of fall cones to determine Atterberg limits: a review. *Géotechnique,* 68, 10, 843-856.

[28] MATUSIEWICZ W., LECHOWICZ Z., WRZESIŃSKI W. 2016. Wyznaczanie granicy płynności w_L metodą Casagrandego i penetrometrem stożkowym (Determination of liquid limit by Casagrande method and cone penetrometer). *Przegląd Naukowy Inżynieria i Kształtowanie Środowiska,* 25(3), 290–300 (in Polish).

[29] MENDOZA M.J., OROZCO M. 2001. Quick and reliable procedure for liquid limit determination of fine-grained soils. *Geotech. Testing J., 24*, 1, 103-108.

[30] MISHRA A.K., OHTSUBO M., LI L.Y., HIGASHI T. 2012. Influence of various factors on the difference in the liquid limit values determined by Casagrande's and fall cone method. *Environmental Earth Sciences,* 65, 21-27.

[31] PIETRZYKOWSKI P. 2014. *Charakterystyka geologiczno-inżynierska eemskich gytii i kredy jeziornej z terenu Warszawy (Engineering-geological characteristics of Eemian gyttja and lacustrine marl from Warsaw site)*. PhD Thesis. Geology Faculty, Warsaw University (manuscript, in Polish), Warsaw, Poland.

[32] PN-B-04481:1988. Grunty budowlane. Badania próbek gruntu (Building soils. Laboratory tests).

[33] PRAKASH K., SRIDHARAN A. 2006. Critical appraisal of the cone penetration method of determining soil plasticity. *Can. Geotech. J.,* 43, 884-888.

[34] SCHMITZ R.M., SCHROEDER C., CHARLIER R. 2004. Chemo-mechanical interactions in clay: a correlation between clay mineralogy and Atterberg limits. *App. Clay Sci.,* 26, 351-358.

[35] SEYBOLD C.A., ELRASHIDI M.A., ENGEL R.J. 2008. Linear regression models to estimate soil liquid limit and plasticity index from basic soil properties. *Soil Science,* 173, 1, 25-34.

[36] SHIMOBE S. 2010. Determination of index properties and undrained shear strength of soils using the fall cone test. Proc. 7th International Symposium on Lowland Technology, Saga, Japan, 51-59.

[37] STATISTICA - package documentation. Polish Edition 2002 by StatSoft Polska Ltd. (in Polish).

[38] STANISZ A., Accessible statistics course using STATISTICA PL on the examples of medicine. Vol. 1, StatSoft Polska Ltd. Cracow 2006, Poland (in Polish).

[39] STANISZ A., Accessible statistics course using STATISTICA PL on the examples of medicine. Vol. 2, StatSoft Polska Ltd. Cracow 2007, Poland (in Polish).

[40] VARDANEGA P.J., HAIGH S.K. 2014. The undrained strength – liquidity index relationship. *Can. Geotech. J., 5*1, 1073-1086.

[41] VARDANEGA P.J., O'KELLY B.C., HAIGH S.K., SHIMOBE S. 2018. Classifying and characterizing fine-grained soils using fall cones. Proc. XVI Danube-European Conference on Geotechnical Engineering, Skopje, Macedonia, 2, 821-826.

[42] WASTI Y. 1987. Liquid and plastic limits as determined from the fall cone and the Casagrande methods. *Geotech. Testing J., 10*, 1, 26-30.

[43] WASTI Y., BEZIRCI M.H. 1986. Determination of the consistency limits of soils by the fall cone test. *Can. Geotech. J*., 23, 241-246.

[44] WOLSKI W., HARTLEN J. (Eds) 1996. Embankments on organic soils. Elsevier, vol. 80.

[45] WOLSKI W., SZYMAŃSKI A., MIRECKI J., LECHOWICZ Z., LARSSON R., HARTLEN J., GARBULEWSKI K., BERGDAHL U. 1988. Two stage constructed embankments on organic soils. Swedish Geotechnical Institute. Report No. 32, Linköping, Sweden.

[46] WROTH C.P., WOOD D.M. 1978. The correlation of index properties with some basic engineering properties of soils. *Can. Geotech. J.,* 15(2), 137–145.

[47] ZENTAR R., ABRIAK N.-E., DUBOIS V. 2009. Fall cone test to characterize shear strength of organic sediments. *J. Geotech. Geoenviron. Eng.,* 135, 1, 153-157.

[48] ZENTAR R., ABRIAK N.-N., DUBOIS V. 2009. Effect of salts and organic matter on Atterberg limits of dredged marine sediments. *App. Clay Sci.,* 42, 3-4, 391-397.