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The importance of the geological origin of cohesive deposits in determining their basic geotechnical parameters – liquid limit and liquidity index

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The liquidity index (I_L), as the leading parameter for cohesive deposits, determines the physical condition of the soil and shows clear and important correlations with the mechanical and hydraulic parameters of the subsoil, such as compressibility, shear strength and permeability. In the traditional approach, to calculate the I_L value, it is necessary to know the values of three parameters determined in the laboratory: natural moisture content (w_n) and the consistency limits: plastic limit (w_P) and liquid limit (w_L). Various methods of determining these parameters have developed over time. This diversity applies in particular to methods of determining the liquid limit, and to a lesser extent the plastic limit. I_L values may vary depending on the methodology used to determine its components, and making comparisons between them is an important issue in engineering geology. The literature on the subject offers proposals for universal correlation relationships between I_L or w_L values determined on the basis of various research methods. However, a question arises whether such correlations can be created as generalized for all cohesive deposits, or should they have local features and be created for individual genetic groups. As part of this article, laboratory tests were carried out on glacigenic clays of different ages, developed in different facies. Their results show that correlations between the values of the liquidity index vary depending on various laboratory methods used to calculate this parameter.

Key words: geotechnical parameters, liquid limit, liquidity index, cohesive soils, North Polish and Middle Polish Glaciations clays, basal and ablation tills, fall cone test, Casagrande cup.

INTRODUCTION

Cohesive deposits (commonly termed “soils” by engineering geologists), occurring commonly in the subsoil, may have various geological origins. They can be postglacial, lacustrine, marine, fluvial, stagnation, weathering, aeolian, volcanic or even anthropogenic deposits of various facies (Selley, 2000; Nichols, 2009; Leeder, 2012; Ford et al., 2014). Therefore, they differ from each other in terms of mineral and petrographic composition, structure and texture, and the degree of consolidation, these not always being taken into account in geological-engineering studies.

One of the basic geological-engineering parameters is the I_L. As a leading parameter for cohesive deposits, it determines the physical state of the soil and shows clear and important correlations with the mechanical and hydraulic parameters of the subsoil, such as compressibility, shear strength and permeability (Wesley, 2003; Niedzielski et al., 2006; Dragoni et al., 2008). In Polish engineering practice, its value is used to determine many geotechnical parameters using the indirect method, i.e. on the basis of the existing correlation relationships and not on the basis of the results of laboratory or field tests. This method is commonly used for less complex building structures, founded in less complicated soil-underground water conditions. With this method, it is possible to determine parameters such as bulk density ( ), internal friction angle (Φ), cohesion (c), shear strength ($_f$) at a given normal stress, primary deformation modulus (E_0) and oedometer constrained modulus of elasticity (M_0).

In the traditional approach, to calculate the I_L value, it is necessary to know the values of three parameters determined in the laboratory: w_n and the consistency limits: w_P and w_L, according to formula [1]:

$$I_L = \frac{w_n - w_P}{w_L - w_P} = \frac{w_n - w_P}{I_P} [\ ] \quad [1]$$

where: w_n – natural moisture content of the soil [%]; w_P – plastic limit [%]; w_L – liquid limit [%]; I_P – plasticity index [%].

Various methods of determining these parameters have developed over time. This diversity applies especially to methods of determining the liquid limit (Casagrande, 1932; Hansbo, 1957; Sherwood and Ryley, 1970; Leroueil and Le Bihan, 1996; Mohajerani, 1999; PN-88/B-04481; PN-EN 1997-2:

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2009) and to a lesser extent the plastic limit (Casagrande, 1932; Campbell, 1976; Wood and Wroth, 1978; Bobrowski and Griekspoor, 1992; Feng, 2004). Therefore, it can be assumed that the value of the liquidity index may vary depending on the methodology of determining its components. Comparing I_L values calculated on the basis of various research methods is an important issue in engineering geology (Wires, 1984; Belviso et al., 1985; Budhu, 1985; Wasti and Bezirci, 1986; Wasti, 1987; Christaras, 1991; Leroueil and Le Bihan, 1996; Suchnicka, 1999; Orhan et al., 2006; Dragoni et al., 2008; Fojtová et al., 2009; Özer, 2009; Grønbech et al., 2011; Di Matteo, 2012; Spagnoli, 2012; Jaśkiewicz and Wszędyrówny-Nast, 2013; Hrubesova et al., 2016; O'Kelly et al., 2018; Krawczyk et al., 2019). Research in this field is often conducted in isolation from the geological origin of the sediment being tested – on deposits of various origins (Orhan et al., 2006; Dragoni et al., 2008; Özer, 2009; Fojtová et al., 2009; Di Matteo, 2012) or on artificial mineral samples consisting of a mixture of random particles (Sridharan et al., 1999). This procedure is necessary in attempting to establish a generalized relationship between the results of various research methods. However, a question arises whether such correlations can be formed as universal for all cohesive deposits or should they have local features and be created for individual genetic groups.

In this article I seek to establish whether the origin of cohesive deposits and the related genetic features of the sediment affect the accuracy of determination of basic geotechnical parameters, such as consistency limits (in particular the w_L) and the I_L. This is based on constructing correlation relationships between I_L values calculated on the basis of various research methods, and then comparing the results (as mathematical formulae) for three different groups of cohesive deposits.

MATERIAL AND METHODS

The materials studied were natural soils occurring in northern and central Poland (Fig. 1), characterized by a similar geological origin but divided into three separate facies. These were the North Polish Glaciation tills (of ablational and basal facies) and Middle Polish Glaciation tills (of basal facies). Outcropping across a relatively large area of the European Lowlands, these deposits often constitute a building subsoil.

According to the old Polish standard (PN-86/B-02480), these North Polish Glaciation soils are classified as sandy tills, less often clayey sands and clayey sandy tills. According to the European standardization system (PN-EN ISO 14688-2), they are classified as clays with sand and silt, clays with silt and sand and sands with clay and silt. A characteristic feature of the soils under discussion is their high sand content (sand fraction content of ~47–73%) and a small admixture of gravel in each sample (average slightly >4%). The tills in question are classified mainly as medium-cohesive soils by engineering geologists, but also as low and high cohesive soils, in which the content of the clay fraction ranges from ~8 to 21% (Fig. 2).

The parameters of the tested deposits shown on the Casagrande plasticity chart classify them in the group of low

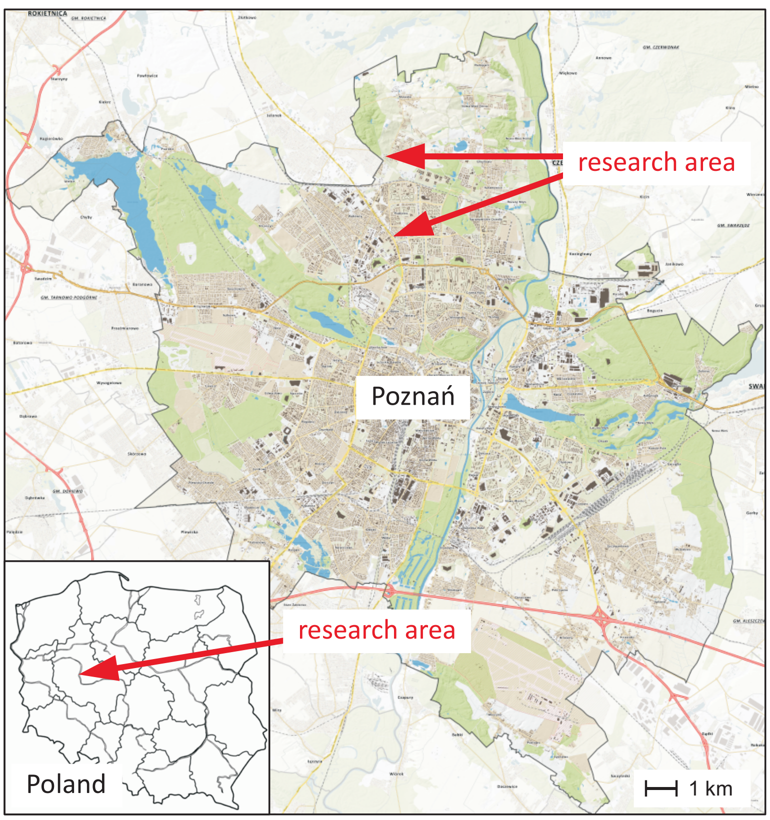

Fig. 1. Location of the study area (cohesive soil sampling sites) on a map of Poznań (Poland)

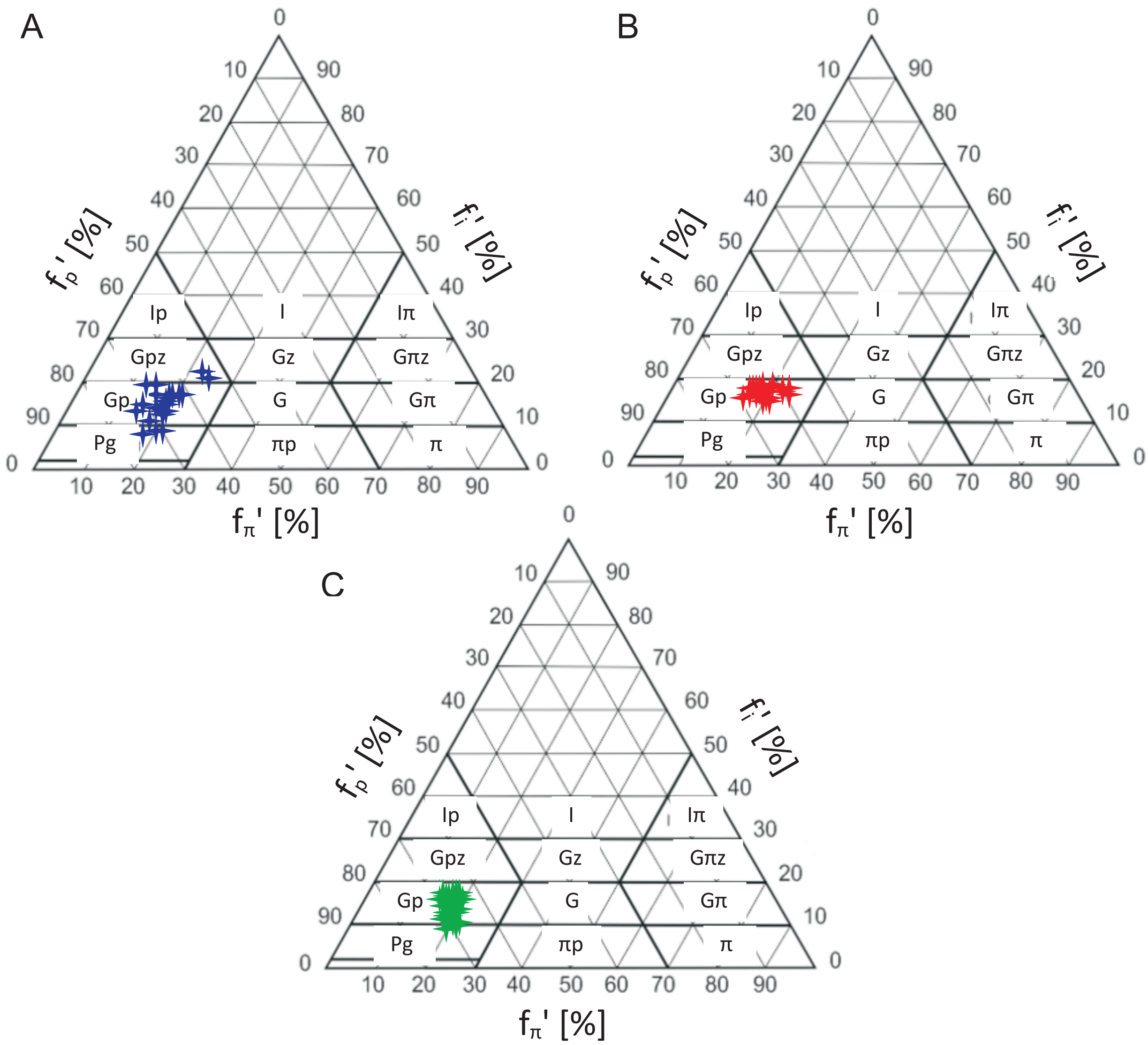

Fig. 2. The granulometric composition of the cohesive deposits used for the tests shown by means of triangular diagrams according to the Polish standard PN-86/B-02480: A – samples of the North Polish Glaciation tills, ablational facies; B – samples of the North Polish Glaciation tills, basal facies; C – samples of the Middle Polish Glaciation tills

f_p' – sand fraction, *f* ' – silt fraction, f_i' – clay fraction (the content of individual fractions is given as a value discounting fractions >2 mm); Pg – clayey sand, p – sandy silt, – silt, Gp – sandy till, G – till, G – silty till, Gpz – clayey sandy till, Gz – clayey till, G z – clayey silty till, Ip – sandy clay, I – clay, I – silty clay

plasticity clays. The points representing all the samples tested are arranged exactly on the U-line, which means that these soils show very low values of the liquid limit (Fig. 3).

The main clay components of tills of the youngest glaciation are illite, smectite, kaolinite and mixed-layer minerals of the smectite/illite type (Table 1 and Fig. 4).

The natural moisture content of the clays tested is in the range of 12–15% (Fig. 5).

They occur mainly in the plastic state, rarely in the stiff-plastic state (the average value of the liquidity index ranges from 0.26–0.35, depending on the methodology of the determination; Fig. 6).

In the study area, tills of the youngest glaciation form a clearly bipartite succession. Deposits located from the ground surface to ~4–5 m b.g.l. are yellow-brown (Fig. 7), with a pseudo-layered structure (the layering appears as lenses and grey sandy and silty interbeds) whereas at deeper levels, down to ~7–9 m b.g.l., they are replaced by brown tills (Fig. 7) characterized by a massive, homogeneous structure. These have been classified as ablational and basal tills, respectively.

One criterion for the facies classification of the tills examined is the petrographic composition of the gravel fraction. In the ablational tills, the material originating from long-distance transport, i.e. mainly fragments of Scandinavian rocks, dominates. Basal tills contain more rocks of local origin, which can be explained by the mode of transport of the subglacial material (Figs. 8 and 9).

According to the Polish standard (PN-86/B-02480), Middle Polish Glaciation tills (so-called “grey tills”) are sandy tills and less often clayey sands. However, according to the European standardization system (PN-EN ISO 14688-2:2018-05P), they are classified as clays with sand and silt (), and sometimes as

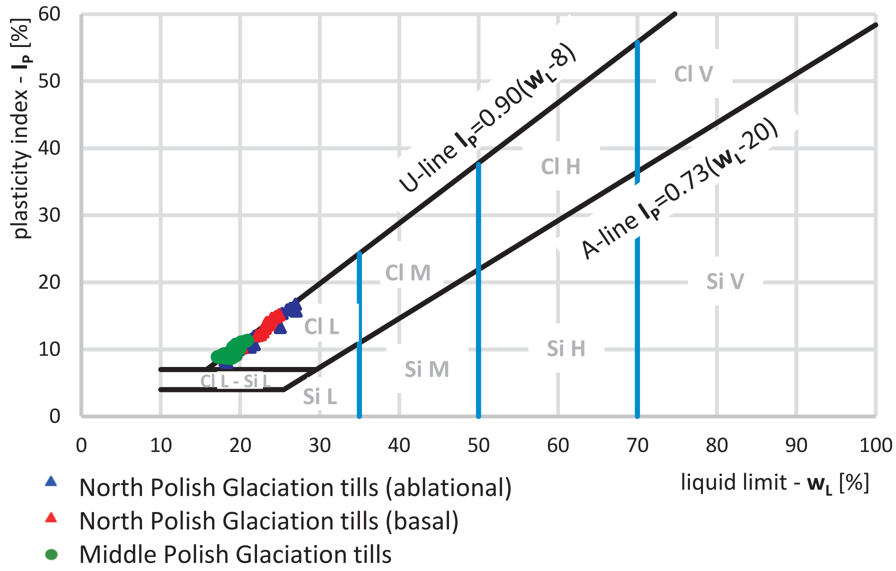

Fig. 3. The characteristics of the cohesive deposits tested, shown on a Casagrande plasticity chart according to the Polish standard PN-EN ISO 14688-2:2018-05P

Cl – clay, Si – silt, L – low, M – medium, H – high, V – very high plasticity

Table 1

Mineral composition of the clay fraction of glacial tills in Poznań (Krawczyk, 2016)

Age of glacigenic deposits	Clay minerals	Other minerals in clay fraction
Tills of the Leszno Phase of the North Polish Glaciation (both ablational and basal)	mixed-layer minerals smectite/illite, illite, smectite, kaolinite	calcite, dolomite, plagioclase – anorthite and bytownite
Tills of the Warta Glaciation of the Middle Polish Glaciations	illite, kaolinite, vermiculite, swelling chlorite	quartz, calcite, plagioclase – anorthite, amphibole

sands with clay and silt (). Similarly to younger deposits, the Middle Polish Glaciation tills are characterized by a small admixture of the gravel fraction in all samples (average slightly >4%) and the quantitative dominance of the sand fraction (~58–67%). However, these deposits are more homogeneous in terms of the content of the clay fraction (9–16%) (Fig. 2). The main components comprising the finest fraction are illite, kaolinite, vermiculite and swelling chlorite (Table 1 and Fig. 4). The natural moisture content of Middle Polish Glaciation tills is statistically slightly higher than the moisture content of clays of the younger glaciation and averages ~14.5% (Fig. 5). On the other hand, the values of the liquidity index are much higher (on average from 0.38 to 0.49, depending on the determination methodology) (Fig. 6), which means that the grey tills in question are in a plastic and soft-plastic state, less often in a stiff-plastic state (PN-86/B-02480). Middle Polish Glaciation tills occurring in the study area are dark grey in colour (Fig. 7), homogeneous, massive and without any interlayers or lenses.

Based on this geological recognition, the research was carried separately for North Polish Glaciation tills (ablational and basal) and Middle Polish Glaciation tills. During the multifaceted study of the liquidity index, the results obtained from these tills constituted three separate datasets.

During the laboratory tests of these glacial tills, the following parameters were determined: the values of w_n using the oven-drying method (PN-88/B-04481), the values of plastic limit (w_P) using the rolling method (PN-88/B-04481) and the values of w_L using four different methods:
- Casagrande apparatus – w_{Lcup} (PN-88/B-04481);
- cone penetrometer using the “Polish” method – $w_{LconePN}$ (Table 2);
- cone penetrometer using the “British” method – $w_{Lcone80}$ (Table 2);
- cone penetrometer using the “Swedish” method – $w_{Lcone60}$ (Table 2).

The Casagrande apparatus with a so-called “hard” rubber base (70 ±2 shore degrees) and a mechanical drive, and a semi-automatic cone penetrometer with two interchangeable cone tips (Fig. 10) were used to determine the value of the liquid limit.

All these studies were carried out on 80 glacial till samples (47 samples from tills of the North Polish Glaciation, Leszno Phase, including 23 of ablational facies and 24 of basal facies, and 33 samples from tills of the Middle Polish Glaciations, Warta Glaciation).

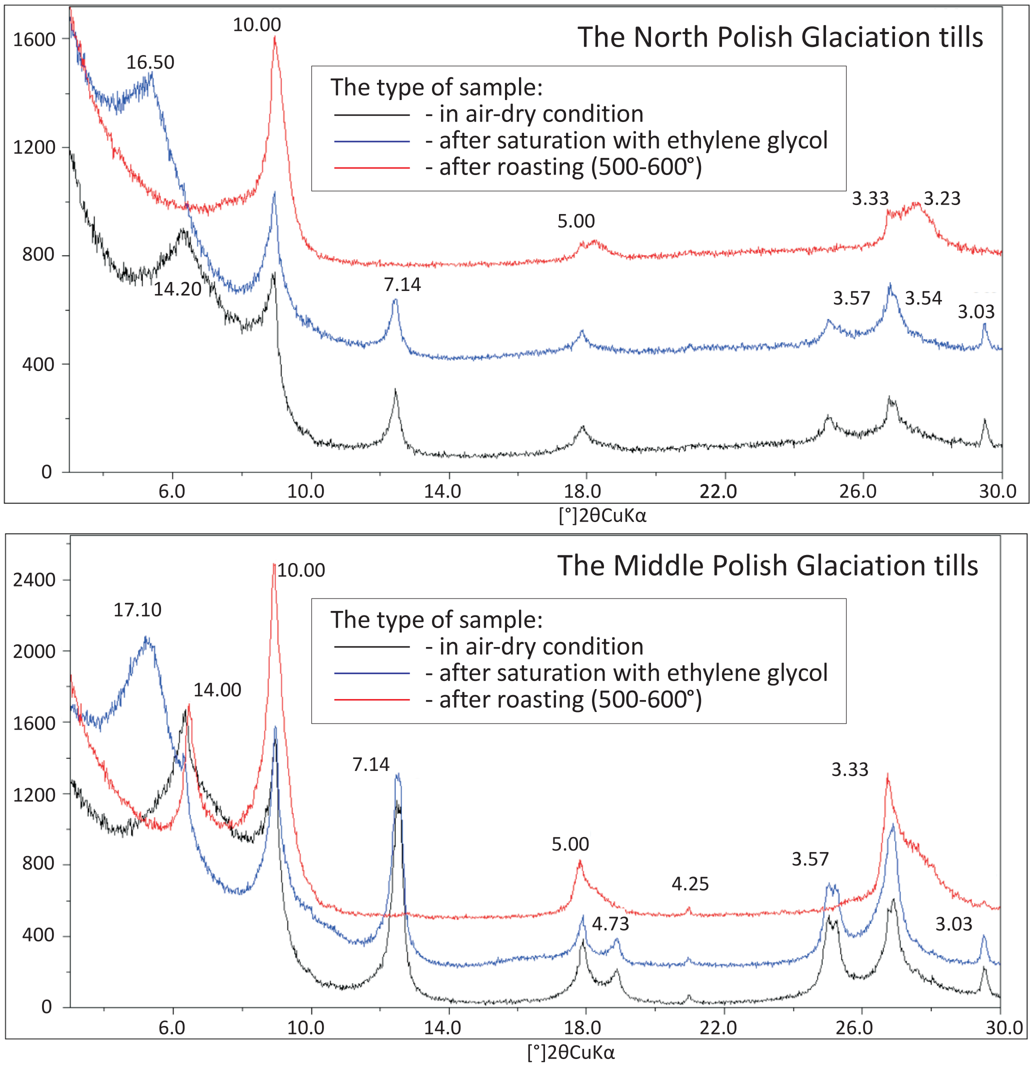

Fig. 4. X-ray diffractograms of the glacial tills studied

In order to determine the consistency and physical states of the tills, the values of the I_L were calculated according to formula [1]. Calculations were made based on the values of w_n, w_P and w_{Lcup}, $w_{Lcone80}$, $w_{Lcone60}$, $w_{LconePN}$. For each sample tested, four values of the liquidity index were so obtained: I_{Lcup}, $I_{Lcone80}$, $I_{Lcone60}$, $I_{LconePN}$.

The test results were used to compare the liquidity index values determined on the basis of various laboratory methods and to form correlation relationships between them. These relationships were created for each genetic type of till separately and then compared with each other.

RESULTS AND THEIR INTERPRETATION

Comparison of the liquid limit value determined by various laboratory methods in all samples tested is shown in Figure 11.

The Casagrande test (PN-88/B-04481) was adopted as the reference method for determining the w_L value due to the widespread use of this method in Poland and Europe. The test results obtained with other standard methods were compared to the value of the liquid limit determined by the reference method. The correlation relationships shown are clear and demonstrate the good quality of the model fit; the value of the coefficient of determination R^2 ranges from 0.84 to 0.89 (Fig. 11).

However, after separating the results obtained in different till facies groups, it turns out that the correlation relationships discussed gain in accuracy, and the values of the R^2 coefficient increase by an average of 0.06, ranging from 0.89 to 0.96 (Fig. 12). Other studies conducted for Polish deposits also show that differences in w_L values determined by various laboratory methods depend on lithology (Kowalska et al., 2017). According to these studies, the greatest differences between $w_{Lcone80}$ and w_{Lcup} are noted where there is a high content of sand fraction (in Quaternary sandy tills), i.e. deposits similar to those of this study.

Figure 12 shows that the w_{Lcup}/w_{Lcone} correlations, determined in the range of ~17–30% of the w_L value, show a different pattern for tills of different ages (North and Middle Polish Glaciations) and a closer one for tills of the same age, but of differ-

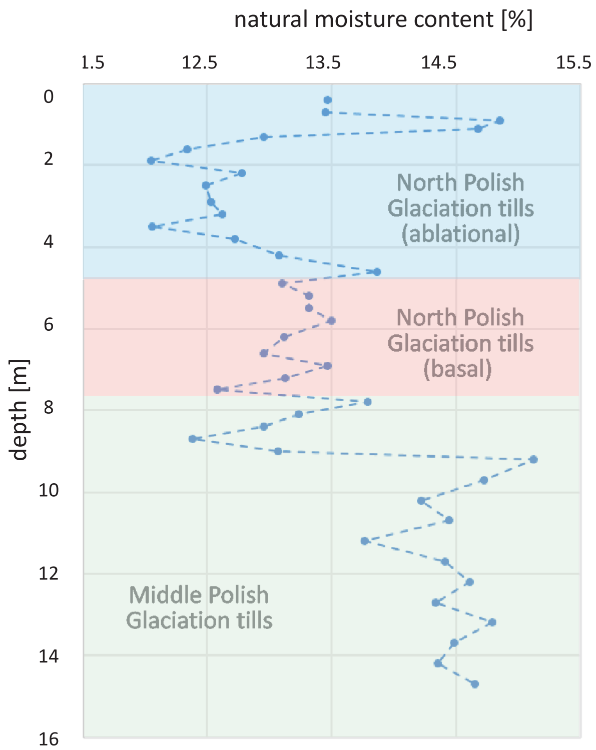

Fig. 5. Distribution of moisture content with depth

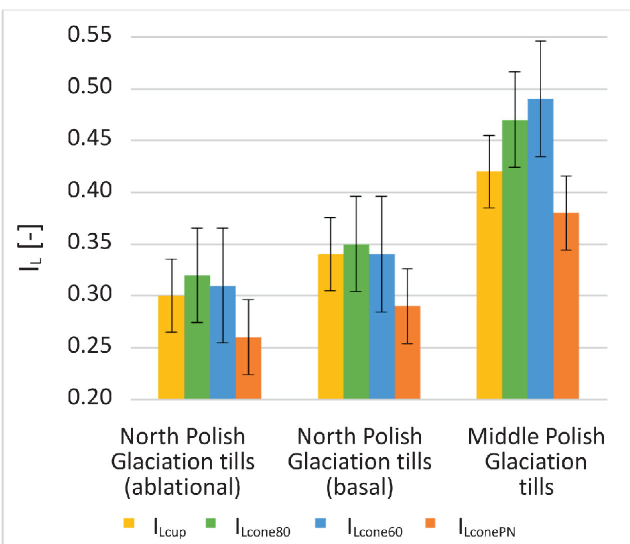

Fig. 6. Average values of the liquidity index determined by four methods for tills of different facies

I_L – value of the liquidity index calculated on the basis of the value of the liquid limit determined in: I_{Lcup} – Casagrande apparatus; $I_{Lcone80}$ – cone penetrometer using the "British" method (Table 2); $I_{Lcone60}$ – cone penetrometer using the "Swedish" method (Table 2); $I_{LconePN}$ – cone penetrometer using the "Polish" method (Table 2)

Fig. 7 Till samples during macroscopic examination, from the left: yellow-brown layered North Polish Glaciation tills (ablational), brown North Polish Glaciation tills (basal), Middle Polish Glaciation grey till

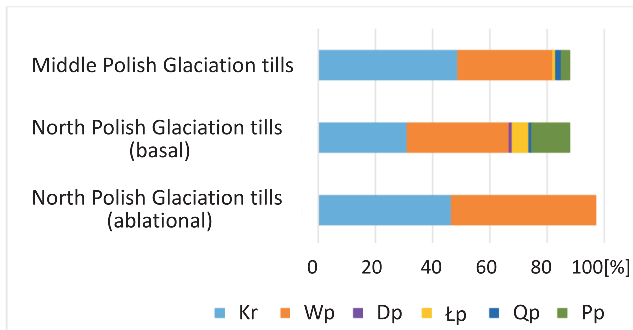

Fig. 8. The share of Scandinavian components in the petrographic composition of the medium gravel fraction (5–10 mm) from the North and Middle Polish Glaciation tills

Kr – crystalline rocks, Wp – limestones, Dp – dolomites, Łp – shales, Qp – quartz, Pp – sandstones and quartzites

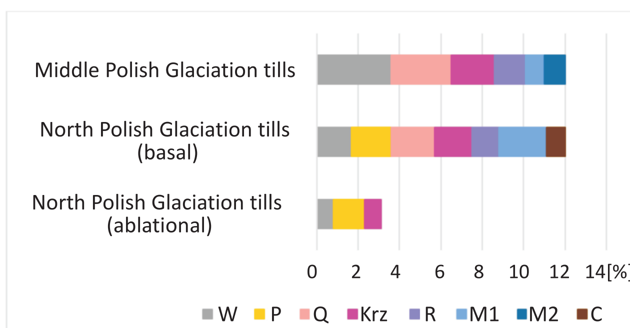

Fig. 9. The share of local components in the petrographic composition of the medium gravel fraction (5–10 mm) from the North and Middle Polish Glaciation tills

W – limestones, P – sandstones, Q – quartz, Krz – flints, R – hornstones, M1 and M2 – mudstones, C – coal

ent facies. This phenomenon may be caused by the similarity of the mineral composition of the clay fraction in clays of the same age (Table 1).

There are many published attempts to correlate w_L values determined by different methods (Krawczyk et al., 2019). Most are based on the results of studies of strictly defined groups of deposits (e.g., Matusiewicz et al., 2016), and some are of a re-

Table 2

Parameters of cones used in a fall-cone penetrometer and data on their usage

Common name of the method	Cone mass [g]	Top angle of the cone [°]	Depth of penetration corresponding to w_L [mm]	Cone penetration range [mm]	Standard/technical specification
"British"	80	30	20	15–25	PKN-CEN ISO/TS 17892-12:2009
"Swedish"	60	60	10	7–15	PKN-CEN ISO/TS 17892-12:2009
"Polish"	80	30	18 $w_L = 0.043w_{18}^2+0.8873w_{18}+3$ 62	12–20	PN-88/B-04481

w_{18} – moisture content of the soil paste which the penetrometer cone penetrates to a depth of 18 mm

Fig. 10. Tools used to determine the liquid limit value: a mechanically driven Casagrande apparatus (left) and a semi-automatic cone penetrometer (right)

view nature – they attempt to create one universal correlation based on the wide-ranging data available in the literature (O'Kelly et al., 2018). Figure 13 illustrates 3 equations illustrating the $w_{Lcone80}/w_{Lcup}$ relationship. One of them is the result of this research (Fig. 11), the second is a universal correlation (O'Kelly et al., 2018), and the third is a relationship created for Polish cohesive deposits (Matusiewicz et al., 2016). As can be seen in the range of low liquid limit values (~17–30%), in which the studies were conducted, these correlations are distant from each other (they lie on the opposite side of the line of equality). For this reason, for certain lithological groups with a precisely defined geological genesis it is justified to create this type of correlation at the local level.

Regardless of the method of laboratory determination of the liquid limit, its value is used to calculate the liquidity index. Therefore, it affects the final value of the leading parameter for cohesive deposits. The glacial tills examined in this article were in all three states of plastic consistency, so the results were obtained in a wide range of liquidity index – from 0.18 to 0.63 (according to the tests using the Casagrande apparatus) (Table 3). A comparison of the average I_L values obtained for different genetic types of clay shows that the cone penetrometer method performed according to the Eurocode rules (PKN-CEN ISO/TS 17892-12:2009) usually gives slightly higher results than the Casagrande method and definitely higher than the cone penetrometer method performed according to the rules of the Polish standard (PN-88/B-04481; Fig. 6). Other studies conducted for Polish deposits also show differentiation of the $I_{Lcone80}/I_{Lcup}$ correlation depending on the deposit type. They show that the change in the I_L value is most significant in the group with low plasticity, i.e. characterized by the plasticity index value I_P = 10–20% (in sandy tills). Similarly, the most sensitive to the change in the I_L value are deposits in a plastic state, i.e. showing I_L values = 0.25–0.50 [-] (Jaśkiewicz and Wszędyrówny-Nast, 2013).

The results of calculations of the liquidity index carried out on the basis of various laboratory methods for determination of w_L prove that the correlation relationships between them are different in different genetic types of tills. Despite this, these relationships for North Polish Glaciation tills formed in two different facies are quite convergent – presented together in the form of regression lines for samples of ablational and basal clays of the

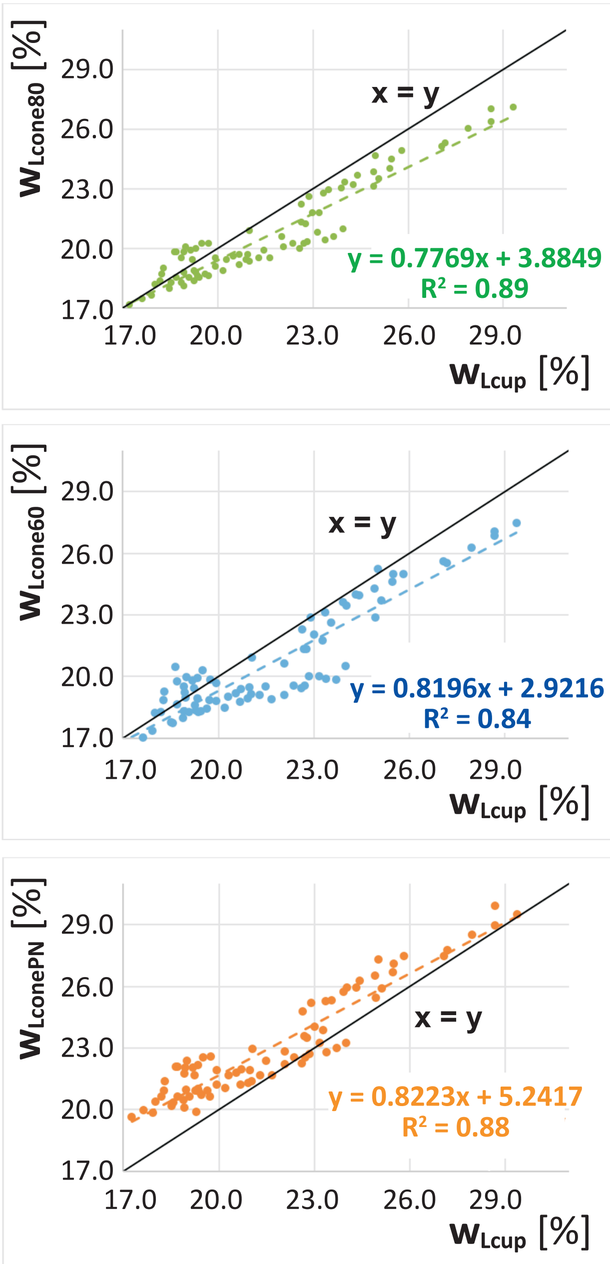

Fig. 11. Relationship between the value of the liquid limit determined in the Casagrande apparatus (w_{Lcup}) and in the cone penetrometer using the "British" ($w_{Lcone80}$), "Swedish" ($w_{Lcone60}$) and "Polish" ($w_{LconePN}$) methods

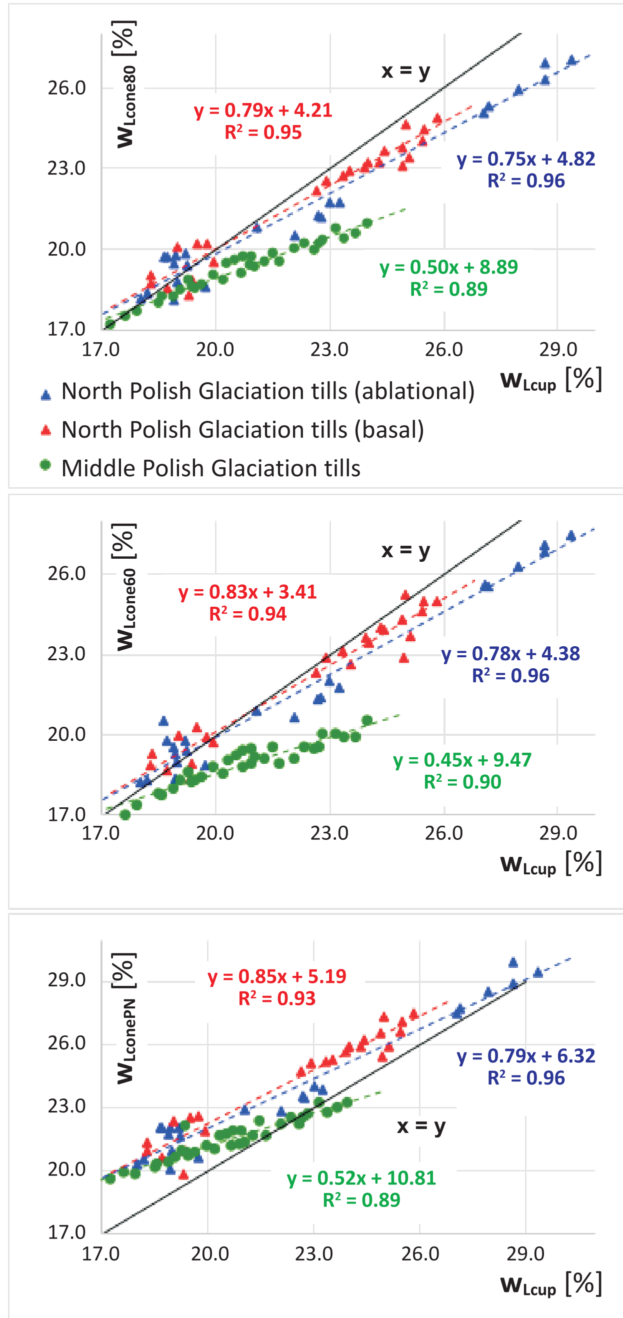

Fig. 12. Relationship between the value of the liquid limit determined in the Casagrande apparatus (w_{Lcup}) and in the cone penetrometer using the "British" ($w_{Lcone80}$), "Swedish" ($w_{Lcone60}$) and "Polish" ($w_{LconePN}$) methods in the division into genetic groups of glacial tills

youngest glaciation, they still show a high value of the coefficient of determination (R^2 >0.85), which indicates good or very good quality of model fit (Sobczyk, 1995). Therefore, the relationships discussed are presented separately for the North Polish Glaciation tills (for the ablational and basal facies together) and the Middle Polish Glaciation tills (Fig. 14).

Studies conducted on glacigenic clays occurring in the vicinity of Poznań allow the formulation of the following correlation relationships between the value of the liquidity index determined on the basis of tests in the Casagrande apparatus (I_{Lcup}) and in the cone penetrometer (I_{Lcone}) with various standard methods (Fig. 14):

– for North Polish Glaciation tills:

$$I_{Lcone80} = 0.90 I_{Lcup} + 0.041;\ [R^2 = 0.86;\ n = 47] \quad [2]$$

$$I_{Lcone60} = 0.88 I_{Lcup} + 0.045;\ [R^2 = 0.86;\ n = 47] \quad [3]$$

$$I_{LconePN} = 0.70 I_{Lcup} + 0.051;\ [R^2 = 0.86;\ n = 47] \quad [4]$$

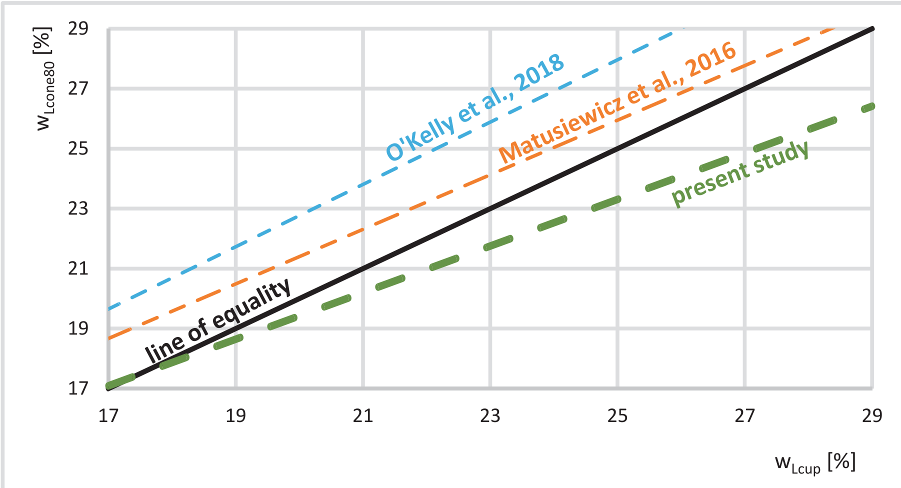

Fig. 13. Relationship between the value of the liquid limit determined in the Casagrande apparatus (w_{Lcup}) and in the cone penetrometer using the "British" ($w_{Lcone80}$) method according to different authors

Table 3

List of minimum, maximum and average values of the liquidity index determined by four different standard methods

The type of tested soils		Value of the liquidity index [-] – range; **arithmetic average**			
		I_{Lcup}	$I_{Lcone80}$	$I_{Lcone60}$	$I_{LconePN}$
North Polish Glaciation tills	ablational	0.18–0.42 **0.30**	0.21–0.45 **0.31**	0.21–0.44 **0.31**	0.18–0.39 **0.26**
	basal	0.24–0.43 0.34	0.27–0.43 **0.35**	0.26–0.43 **0.34**	0.23–0.37 **0.29**
Middle Polish Glaciation tills		0.24–0.63 **0.42**	0.29–0.64 **0.47**	0.31–0.65 **0.49**	0.24–0.50 **0.38**

– for Middle Polish Glaciation tills:

$$I_{Lcone80} = 0.87 I_{Lcup} + 0.106; [R^2 = 0.91; n = 33] \quad [5]$$

$$I_{Lcone60} = 0.88 I_{Lcup} + 0.120; [R^2 = 0.87; n = 33] \quad [6]$$

$$I_{LconePN} = 0.67 I_{Lcup} + 0.100; [R^2 = 0.86; n = 33] \quad [7]$$

After correction based on the above equations, the I_L values obtained in the penetrometer according to the Eurocode rules (PKN-CEN ISO/TS 17892-12:2009) are close to the I_{Lcup} values. The difference between them is usually –0.01 in North Polish Glaciation tills and 0.05 in Middle Polish Glaciation tills. The lowest correspondence was obtained for the penetrometer method with the "Polish" cone and the reference method. The difference between I_{Lcup} and the corrected $I_{LconePN}$ ranges from –0.02 to 0.11.

SUMMARY AND CONCLUSIONS

Laboratory tests were conducted on glacial tills of various ages and developed in different facies. Three groups of deposits were characterized based on genetic indicators such as the mineral composition of the clay fraction, the petrographic composition of the gravel fraction, and the granulometric distribution. Subsequently, the natural moisture content, plastic limit, and liquid limit (using four different laboratory methods) were determined. Based on these results, I_L values were calculated for each sample tested. The I_L values were then compared, and correlation relationships were established. These relationships were analysed both collectively for all deposits and separately within each genetic group. The results indicate that even among deposits of similar origin, but developed in different facies, the correlation patterns between I_L values obtained using different laboratory methods may vary significantly. Establishing generalized, universal correlations between results derived from dif-

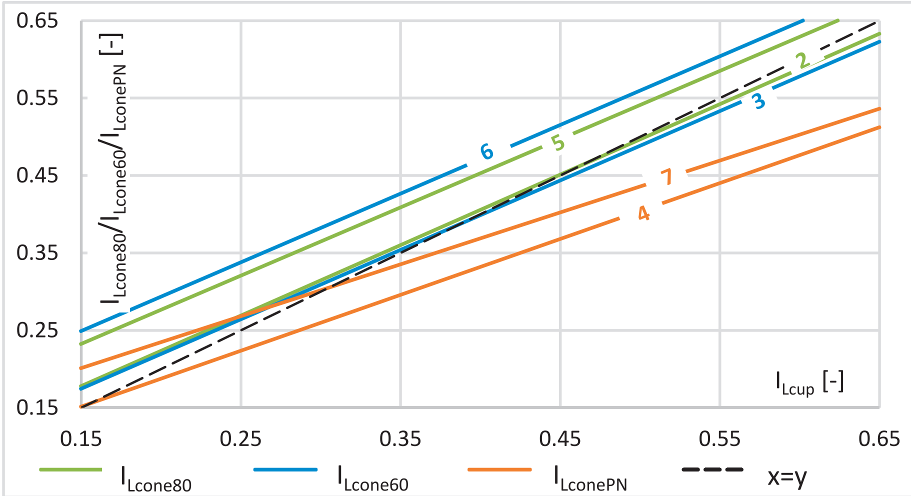

Fig. 14. Summary of the correlation relationships between the values of the liquidity index determined by four different standard methods on the basis of: 2–4 – North Polish Glaciation tills (including ablational and basal tills); 5–7 – Middle Polish Glaciation tills

ferent testing standards remains a relevant issue in engineering geology (O'Kelly et al., 2018). However, it is argued that developing localized correlations for genetically similar lithological groups is equally important. Such correlations can aid in the accurate identification of region-specific deposits and serve as a basis for calibrating and correcting test results obtained with different methods, particularly in the context of various geological-engineering studies conducted within the same area.

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