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The value of plasticity index (I_P) and liquidity index (I_L) of North Polish ablation boulder clays and varved clays depending of the method of its determination

Key words: plasticity index, liquidity index, varved clays, postglacial ablation tills, cone penetrometer, Casagrande apparatus

Introduction

The plasticity and liquidity indexes are the basic geotechnical parameters of cohesive soils. The liquidity index (I_L) determines the consistency and physical state of soil. The plasticity index refers to the type of soil, its degree of cohesion. Both show clear and important correlations with the strength parameters of the substrate (Niedzielski, Tschuschke & Wierzbicki, 2006) and are used in the process of designing the construction foundations. In order to calculate the value of the liquidity and plasticity index, laboratory methods may be used. In that case, it is necessary to determine the liquidity limit (w_L).

There are two laboratory approaches to marking this value (Suchnicka, 1999):

- dynamic, based on the Atterberg's concept, refined and standardised by Casagrande in 1932, consisting in placing a sample of soil in a brass cup, cutting it with a grooving tool and observing the closing of the groove while hitting the cup with a rubber base (the so-called impact method);
- static, based on the cone penetrometer method proposed by the Geotechnical Commission of the Swedish State Railways (GCSSR) between 1914 and 1922 (Leroueil & Le Bihan, 1996), originally used to determine shear strength in soil (Hansbo, 1957) and adapted for determination of the liquid limit (Karlsson, 1981); in this approach, the depth of immersion of a cone-shaped weight applied to the surface of soil defines the w_L value.

Based on both these approaches, various methods for determining the liquid limit have developed and have been sanctioned by internal state standards in individual countries. The unification of regulations for geotechnical research in Europe took place with the introduction of Eurocode 7. The technical specification PKN-CEN ISO/TS 17892-12, which is the integral part of the Eurocode, defines the cone penetrometer as the method "recommended for determining the liquid limit" and the Casagrande apparatus as the 'alternative' method, giving much less reliable results. Nevertheless, in Poland, the Casagrande apparatus is a ubiquitous method strongly rooted in the engineering practice and is still widely used for determining the w_L value. The impact method is very subjective, highly dependent on the experience of the person performing the study and, by extension, it gives unsatisfactory reproducibility of results (Sherwood & Ryley, 1970; Medhat & Whyte, 1986; Leroueil & Le Bihan, 1996; Feng, 2004).

In the professional literature worldwide, there are many publications that attempt to correlate the results obtained with the Casagrande apparatus and the cone penetrometer (Wires, 1984; Budhu, 1985; Wasti, 1987; Christaras, 1991; Leroueil & Le Bihan, 1996; Suchnicka, 1999; Ozer & Isik, 2006; Prosperini & Vinti, 2008; Franeková, & Kovàr, 2009; Özer, 2009; Dragoni, Fojtová, Marschalko, Grønbech, Nielsen & Ibsen, 2011; Di Matteo, 2012; Orhan, Spagnoli, 2012; Jaśkiewicz & Wszędyrówny-Nast, 2013; Hrubesova, Lunackova & Brodzki, 2016). They focus mainly on comparing only the w_L value. Often this comparison is made for man-made clay-silt-sand mixtures or for soils with different geological origins.

In Polish literature, relationships between values of liquidity index calculated on the basis of the liquid limit determined using various laboratory methods (in accordance with Polish and European standards) can be found (Jaśkiewicz & Wszędyrówny-Nast, 2013). These correlations can be universal, since they were created on the basis of soil samples of different origin and varied content of clay fraction, e.g. $I_{L/cone} = 1.27\ I_{L/cup}$ for clayey sands and sandy-silty clays in the plastic state or $I_{L/cone} = 1.28\ I_{L/cup}$ assigned to hard-plastic clays.

The aim of this paper was to create this type of correlation but only for specific, strictly defined and geographically separate deposits – postglacial cohesive soils occurring in the area of Poznań (the North Polish ablation boulder clays and varved clays).

Data and testing methods

Samples of North Polish glaciation soils occurring in the vicinity of Poznań and the surrounding area were examined. These were the ablational morainic tills of the Leszno phase and the varved clays that were deposited in the postglacial channel between the two stages of the Baltic glaciation – Leszno and Poznań phase.

In the area of Poznań, varved clays occurring in the central part of the catchment area of the Junikowski Stream reach the maximum thickness of 10–15 m. In their vertical profile, they are considerably heterogeneous sediments in granulometric terms. These clays are characterised by a specific structure with the alternating occurrence of light layers (sandy-silty or silty) and dark layers (silty-clay or clay) (Flieger-Szymańska & Machowiak, 2010).

Therefore, studies on clay samples were conducted separately for light and dark layers. Engineering properties of varved clays, among others, the value of the liquid limit may also depend on the mineral composition, mainly, the clay fraction in the light and dark layers (Florkiewicz, Flieger-Szymańska, Machowiak & Wanatowski, 2015). The main clay minerals in the both light and dark layers are hydromicas (illites), and in smaller amounts kaolinite and smectite/chlorite. On the other hand, there is a clear difference in the content of quartz. In the light layers there is much more quartz than in the dark ones.

Glacial tills of Leszno phase exhibit a significant content of sand fraction (68–74%) according to PN-86/B-02480 and 65–71% according to PN-EN-ISO 14688-1. They are formed as sandy tills (Gp) or clayey sands (clSa) of yellow colour. Their thickness is usually 3–5 m, and in some cases it reaches up to 12 m. The main clay minerals of the studied tills are illite, kaolinite and smectite/illite mixed-layer minerals. In addition, the finest fraction contains quartz, calcite, dolomite and plagioclase.

Fifty samples of tills and clays were tested. Their value of the liquid limit was in the range of 18–89% and the clay fraction content was 14–84%. Macroscopic analysis of soil samples, determination of natural moisture content, grain size analysis using a combined areometric and sieve method, determination of plastic limit and the liquid limit in the cone penetrometer with a 30°/80 g cone and in the Casagrande apparatus with the so-called hard case have been conducted.

On the basis of the results of laboratory tests, the value of plasticity index was calculated (I_L). It is the ratio of the difference of natural moisture content (w_n) of a given soil and the plastic limit (w_P) to the difference between the liquid limit (w_L) and the plastic limit (w_P):

$$I_L = \frac{w_n - w_P}{w_L - w_P} \qquad (1)$$

Since the value of the liquid limit determined by two different methods (using the Casagrande apparatus and the cone penetrometer method) was used for the calculations, two values of the plasticity index were also obtained for each soil sample. They were marked respectively $I_{L/cup}$ and $I_{L/cone}$.

Next, the value of plasticity index (I_P) was calculated. It is the difference between the liquid limit and the plastic limit:

$$I_P = w_L - w_P \qquad (1)$$

The plasticity index indicates the amount of water, in relation to the mass of the soil skeleton, that is absorbed when a given soil changes from the semi-solid to the liquid state.

Results and their interpretation

The studies carried out on glacigenic soils of the North Polish Glaciation occurring in Poland, near Poznań, allow to formulate the following correlational relationship between the value of the liquidity index determined on the basis of tests carried out in the Casagrande apparatus ($I_{L/cup}$) and in the cone penetrometer ($I_{L/cone}$) taking into account standard error of estimation (ε):

$$I_L/_{cone} = 0.970\ I_L/_{cup} + 0.015 \pm \varepsilon \qquad (3)$$

It is a dependence confirmed experimentally for a relatively wide range of w_L values (18–89%) for natural soils of a similar genesis and occurrence.

The determination coefficient (R^2), being one of the basic measures of the goodness of fit and indicating what percentage of one variable explains the variance of the second variable, for equation (3) is 0.960 (Fig. 1), so it falls in the so-called very good fit (Sobczyk, 1995).

In the range of I_L = 0.00–0.25, the value of this parameter calculated on the basis of the results of tests carried out in the cone penetrometer is overstated in relation to the value obtained on the basis of the results from the Casagrande apparatus. In addition, it can be clearly seen that for the soil samples in the hard-plastic state, the degree of matching of $I_{L/cup}$ and $I_{L/cone}$ is more significant (Fig. 2) than for the soil samples with an $I_L > 0.25$. The correlation [equation (3)] for $I_L = 0.00–0.25$ takes the form:

$$I_L/_{cone} = 1.052\ I_L/_{cup} + 0.005 \pm \varepsilon \qquad (4)$$

The determination coefficient in this range of liquidity index values is slightly higher and amounts to 0.983.

For the samples of cohesive soils in the plastic state, the $I_{L/cone} = f\,(I_{L/cup})$ interdependence is definitely less explicit (Fig. 3). The correlation (3) for I_L = = 0.25–0.50 takes the form of:

$$I_{L/cone} = 0.781\ I_{L/cup} + 0.079 \pm \varepsilon \qquad (5)$$

The determination coefficient in this range of liquidity index values is much lower and amounts to 0.576.

The relationship between the plasticity index calculated on the basis of the liquid limit value determined in the Casagrande apparatus ($I_{P/cup}$) and in the cone penetrometer ($I_{P/cone}$) shows a high degree of correlation (Fig. 4). It can be presented in the following way:

$$I_{P/cone} = 0.854\ I_{P/cup} + 1.458 \pm \varepsilon \qquad (6)$$

Based on the average values of the analysed geotechnical parameters, it can be stated that the value of the plastic-

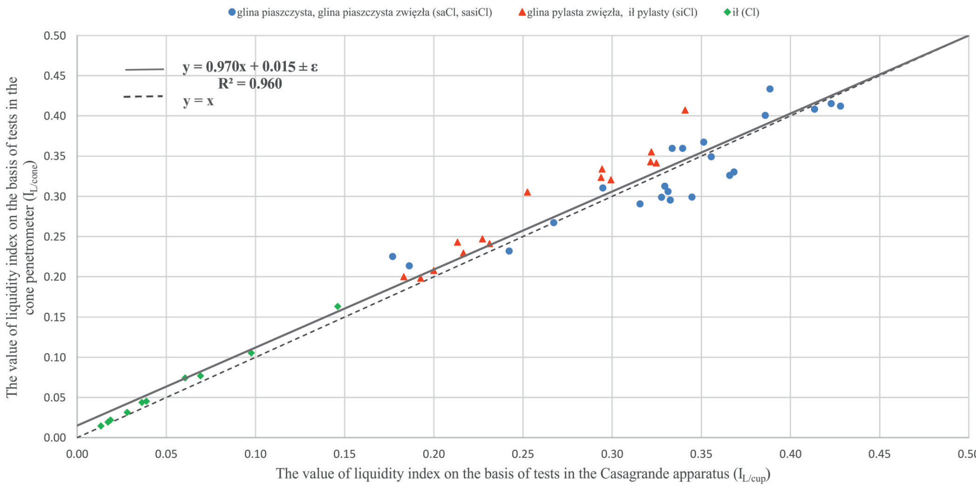

FIGURE 1. Relationship between the values of the liquidity index (I_L) calculated on the basis of two laboratory methods

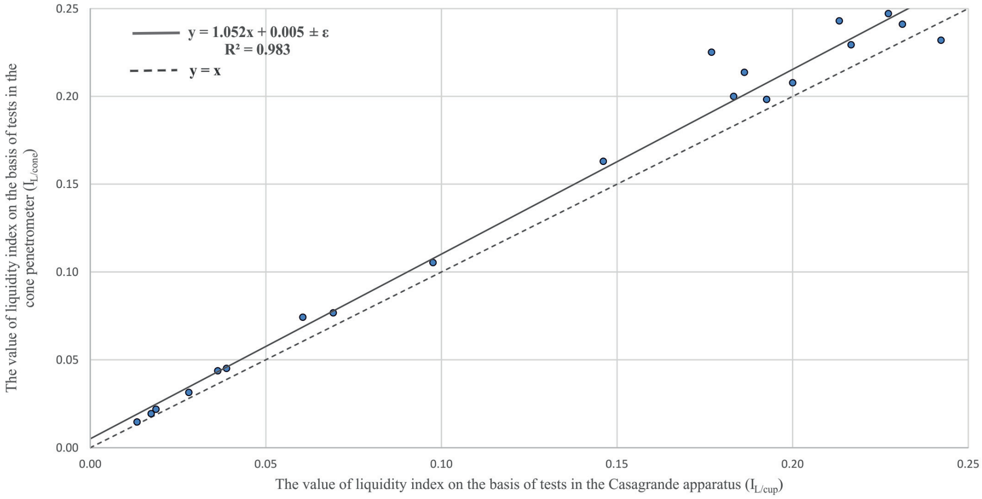

FIGURE 2. Relationship between the values of the liquidity index (I_L) calculated on the basis of two laboratory methods in the I_L range of 0.0–0.25

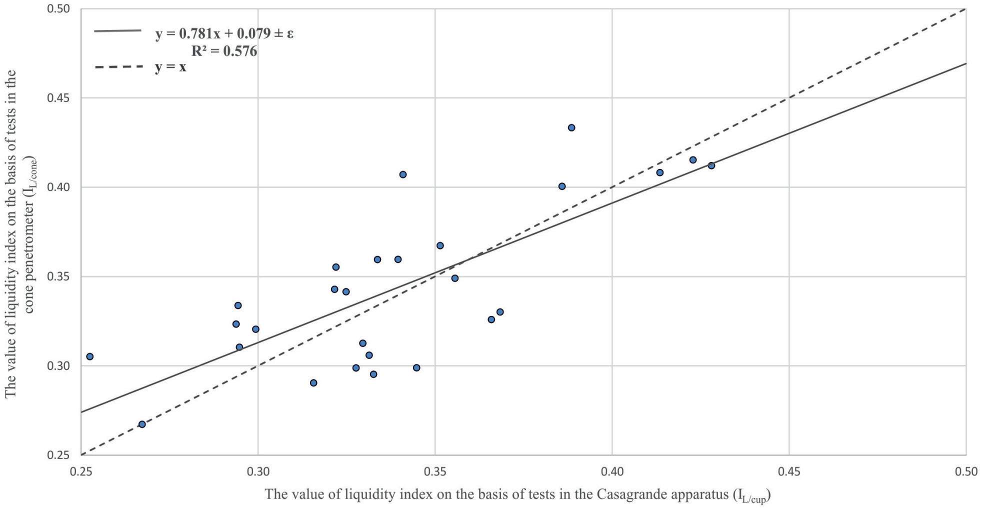

FIGURE 3. Relationship between the values of the liquidity index (I_L) calculated on the basis of two laboratory methods in the I_L range of 0.25–0.50

ity index determined on the basis of the test results from the cone penetrometer is usually higher than calculated on the basis of the w_L value determined in the Casagrande apparatus (the table). This may cause a change in the description of the soil state towards a more plastic one. This trend is confirmed in the Polish literature (Jaśkiewicz & Wszędyrówny--Nast, 2013). However, the value of the plasticity index is underestimated when the results of the penetrometer test are

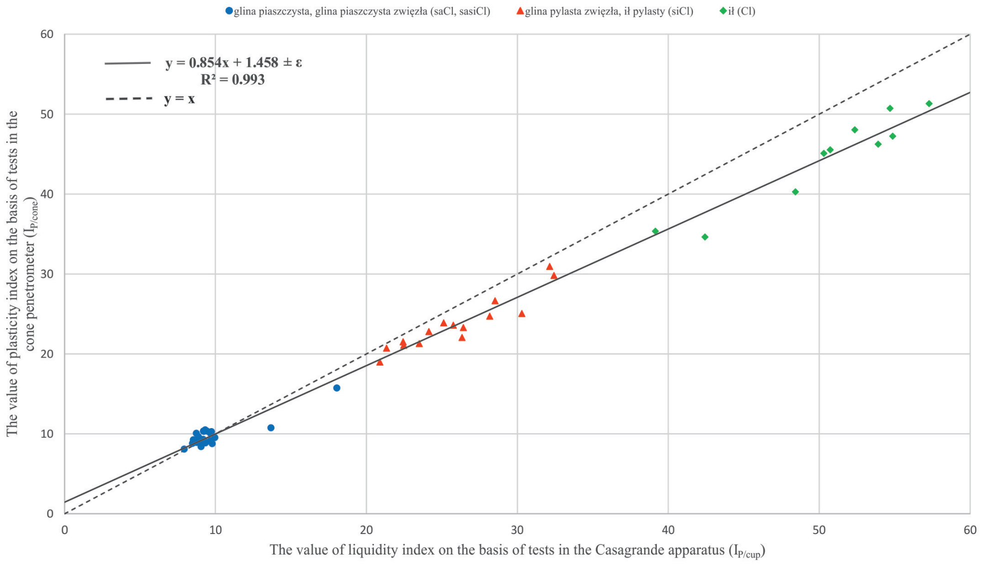

FIGURE 4. Relationship between the values of plasticity index (I_P) calculated on the basis of two laboratory methods

TABLE. The average values of the analyzed geotechnical parameters

Soil type	Soil symbol PN/ISO	w_n average value [%]	w_P average value [%]	f_i/Cl average content [%]	$I_{P/cup}$ average value [%]	$I_{P/cone}$ average value [%]	$I_{L/cup}$ average value [-]	$I_{L/cone}$ average value [-]
Ablation boulder clays	Gp/saCl	14.07	11.18	19.50	15.86	13.24	0.18	0.22
	Gpz/sasiCl	12.90	9.72	14.68	9.17	9.44	0.35	0.34
Varved clays – light layer	Gπz, Iπ/siCl	28.69	21.95	35.20	26.00	23.77	0.26	0.29
Varved clays – dark layer	I/Cl	34.86	32.25	77.10	52.42	44.45	0.05	0.06

used for calculations (the table). This can change the soil type to less cohesive.

Conclusions

For cohesive soils of the North Polish glaciation occurring in the vicinity of Poznań, the value of leading parameter (I_L) is usually overstated (related to referential Casagrande method) when determining the liquid limit (w_L) in a cone penetrometer in accordance with the recommendations of Eurocode 7. Determining the w_L value by means of the Casagrande apparatus, considered the classical method in Poland and strongly rooted in the engineering practice, leads to obtaining liquidity index values lower than from cone penetrometer. An unfavourable phenomenon from the point of view of the process of designing the foundations of construction works, it reduces the safety margin of the adopted geological-engineering parameters.

Based on the examined soils, it was found that $I_{L/cup}$ and $I_{L/cone}$ values show a much higher degree of correlation in hard plastic soils than in plastic ones (Figs. 2 and 3).

The relationship [equation (5)] found in this article for plastic soils (mainly sandy tills) does not coincide with the correlations published so far, e.g. $I_{L/cone} = 1.27\ I_{L/cup}$ for clayey sands and sandy-silty clays in the plastic state (Jaśkiewicz & Wszędyrówny-Nast, 2013). Similarly, the correlation shown in equation (4) for soils in the hard-plastic state (mainly clays) does not correspond to the literature correlation $I_{L/cone} = 1.28\ I_{L/cup}$ assigned to hard-plastic clays (Jaśkiewicz & Wszędyrówny-Nast, 2013).

The results of the study clearly show that creating a generalized dependence between plasticity index and liquidity index values determined by various methods, universal for all types of soils, is not possible. Such correlations may be created for geographically separate soils of a similar genesis and mineral composition, e.g. sediments of the youngest glaciation in the northern hemisphere.

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Summary

The value of plasticity index (I_p) and liquidity index (I_L) of North Polish ablation boulder clays and varved clays depending of the method of its determination. Article determins a correlation between the values of the plasticity and liquidity index (I_P, I_L) of cohesive soils achieved by various laboratory methods (on the basis of Casagrande apparatus and cone penetrometer method) and consists research results on natural clayey soils of known origin and strictly defined genetic features, described in detail in terms of particle size and mineralogy (the North Polish ablation boulder clays and varved clays).

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