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Determination of liquidity index of glacial tills based on the fall cone single point methods

Détermination de l'indice de liquidité de tillite glaciaire par les méthodes de pénétromètre à cône

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ABSTRACT: Liquidity index (I_L) is one of the basic geotechnical parameters of cohesive soils. It defines the consistency and physical state of soil. Since the state of the cohesive soil determines the bearing capacity of the subsoil, the value of I_L is often used for various correlations used in the design of foundations.
The cone penetrometer is a device used to determine the liquid limit (w_L) based on which the value of the liquidity index is calculated according to both Polish (PN-88/B-04481) and European (PKN-CEN ISO/TS 17892-12) standards. In this method the liquid limit is read out from the relationship between the moisture content of soil paste and the depth of cone penetration. This relationship must be determined by interpolation between at least four test points. However, several, so-called single point methods, can be found in the literature. They are to be used for a quick and efficient measurement of the liquid limit using existing empirical correlations.
This article discusses the possibility of applying some of those methods to calculate the value of the liquidity index for selected cohesive soils. The analysis was carried out on ablation and subglacial tills which occur in northern and north-western Poland. Based on the test results it is concluded that the empirical formulae used in the single point methods have a limited application and should be used with caution taking into account the type, genesis and mineral composition of examined deposits.
RÉSUMÉ: L'indice de liquidité est un des paramètres basiques des sols cohésifs. Il définit la consistance et l'état physique du sol. Comme l'état physique d'un sol cohésif détermine la portance du sol sous-jacent, la valeur de I_L est souvent utilisée pour différentes corrélations dans la conception de fondations.
Le pénétromètre statique est un outil utilisé pour déterminer la limite de liquidité (w_L) sur laquelle est calculée la valeur de l'indice de liquidité selon les deux standards polonais (PN-88/B-04481) et européen (PKN-CEN ISO/TS 17892-12). Dans cette méthode la limite liquide est déterminée à partir de la relation entre la teneur en eau du sol sous forme de pâte et la profonfeur atteinte par le pénétromètre. Cette relation doit être déterminée par interpolation entre au moins quatre points de tests. Cependant plusieurs méthodes dites du point unique sont disponibles dans la littérature. Elles sont utilisées pour des mesures rapides et efficaces de la limite liquide en suivant des corrélations empiriques existantes.
Cet article discute la possibilité d'appliquer certaines de ces méthodes pour le calcul de la valeur de l'indice de liquidité pour une sélection de sols cohésifs. L'analyse a été réalisée sur des tillites d'ablation et sous-glacière qui sont produites dans le nord et le nord-ouest de la Pologne. A partir des résultats des tests, il a été déduit que les formules empiriques utilisées dans les méthodes à point unique ont un champ d'application limité et devraient être utilisées avec précaution en prenant en compte le type, la génèse et la composition minérale des dépôts.
Key words: cone penetrometer, one-point method, glacial tills, liquid limit, liquidity index

1 INTRODUCION

Continuously increasing volume and rate of civil engineering construction in Poland demands a more frequent use of very efficient yet accurate ground investigation methods. The necessity of shortening time needed to determine geology and engineering parameters of subgrade is manifested, among others, in the rapid development of geotechnical tests carried out in situ, without any need for time-consuming soil sampling and transporting samples to laboratories. In Poland, the contribution of in-situ testing methods in geotechnical investigations is growing significantly and the in-situ methods are often considered as a competition to traditional laboratory testing, whose main disadvantage is time-consuming.

One of soil parameters, determined both in the laboratory and in situ, is the liquidity index (I_L). I_L is the fundamental geotechnical parameter used for determining the consistency and physical state of cohesive soils. In the traditional laboratory approach its value is calculated based on the liquid limit (w_L), which characterizes the degree of soil consistency. These parameters are often correlated with the strength parameters of soils, required for the design of foundations (Niedzielski et al., 2006).

Laboratory methods used for determining the liquid limit can be divided into two broad groups, dynamic (e.g. Casagrande's apparatus) and static (e.g. cone penetrometer). Dynamic and static methods are based on significantly different research concepts. Consequently, w_L values obtained from each method are not always comparable. Standardisation of geotechnical investigation practice in Europe took place with the introduction of Eurocode 7 (European Standard EN 1997 - Geotechnical Design). Technical specification (PKN-CEN ISO / TS 17892-12: 2004), an integral part of Eurocode 7, identifies a cone penetrometer as the method 'recommended for determining the liquid limit'. This is consistent with the published literature, which emphasise that the correlation of soil's moisture content with the penetration depth of the metallic cone into soil's paste gives quite accurate and repeatable results (e.g. Karlsson, 1977, Feng, 2001). The liquid limit in this method is typically determined based on minimum four test points. Several, so-called one-point methods, can also be found in the literature, which allow a quick and efficient measurement of the liquid limit based on one test point and appropriate empirical correlations. Due to growing demand for conducting a large number of laboratory tests and obtaining geotechnical parameters in a short time, the use of single-point methods is highly desirable. However, the suitability of w_L values obtained from the single-point and multiple-point methods may vary depending on the type and origin of soil, in particular the mineral composition of the clay fraction.

The main aim of this article is to verify the possibility of using single-point methods for typical soils found in the Polish Lowlands. Numerous laboratory test results obtained from soils with specific granulometric and mineralogical characteristics were used to compare and identify the most suitable one-point testing methods. The extent of cone penetration, for which a given correlation method can be used successfully without any significant effect of the liquid limit on the magnitude of the liquidity index, was also defined.

2 TESTED SOILS AND TESTING METHODS

The current investigation was conducted on glacial tills located in the area of Polish Lowlands and formed during the North-Polish glaciation (the Leszno phase) and the Central-Polish glaciation (the Warta glaciation). Shallow deposits of these tills can be found in large areas of northern and north-western Poland, and thus are often involved in civil engineering construction. The tills are classified mainly as sandy-silty clays (sisaCl) (PN-EN ISO 14688-1: 2006). Their basic granulometric, physical and consistency properties are summarised in Table 1.

Table 1. Average values of granulometric and physical properties of clays from Polish Lowlands (Krawczyk, 2016)

Clay origin	Gr [%]	Sa [%]	Si [%]	Cl [%]	ρ_s [g/cm^3]	ρ [g/cm^3]	ρ_d [g/cm^3]	n [-]	w_n [%]	w_L [%]	w_P [%]	I_P [%]	I_L [-]
North-Polish Glaciation	3	70	16	13	2.68	2.10	1.82	32	15	20	12	8	0.36
Middle-Polish Glaciation	4	58	31	11	2.67	2.03	1.76	34	15	20	11	8	0.46

Typical mineral compositions of clay particles found in the majority of Quaternary deposits in Poland (especially glacial tills) include mainly montmorillonite, other minerals from the mica group (mainly illite), and small amounts of kaolinite (Kenig, 2009). The mineralogy of glacial tills reported in the literature was verified in the recent research carried out in the city of Poznan. The main minerals of clay formed in the North- and Middle-Polish glaciations are illite, kaolinite and illite/smectite layers. The presence of vermiculite in glacial tills of the Middle-Polish glaciation differentiates them from the younger deposits, as shown in Table 2.

Table 2. Mineral composition of clay fractions of glacial tills from the Polish Lowlands (Krawczyk, 2016)

The age of glacial deposits	**Clay minerals**	**Other minerals** *in clay fraction*
North-Polish Glaciation tills of the Leszno Phase	smectite/illite mixed-layer minerals, illite, kaolinite	quartz, calcite, dolomite, plagioclase – anorthite and bytownite
Middle-Polish Glaciation tills of the Warta glaciation	smectite/illite mixed-layer minerals, illite, kaolinite, vermiculite	quartz, calcite, dolomite, plagioclase – anorthite, amphibol

The liquid limits of the glacial tills were determined using a 30°/80g (apex angle/mass) cone penetrometer (PKN-CEN ISO / TS 17892-12: 2004). The tests were carried out on 40 clay samples, 20 of which were formed in the North-Polish glaciation, and another 20 in the Middle-Polish glaciation. Linear relationships between the moisture of the clay paste and the depth of cone penetration were determined for all the samples. Each of these correlations was plotted using 4 to 6 data points. In this way, 179 data points, in the range of penetration depth of 12 to about 26 mm, were obtained for further analysis.

The data points were used to analyse two of the correlations published in the literature, proposed based on one-point cone penetrometer tests

(Sherwood and Ryley 1970, Leroueil and Le Bihan 1996).

The first correlation investigated in the current research was proposed by Leroueil and Le Bihan (1996):

$$w_{L(1/30)} = \frac{40(w-15)}{P_{30}+20} + 15 \quad (1)$$

where

$w_{L(1/30)}$ (%) is the liquid limit determined by the one-point method using the 30°/80g cone and Eq. (1)

P_{30} (mm) is the penetration of the standard (30°/80g) cone

w (%) is the moisture content of the soil paste corresponding to the measured cone penetration.

The applicability of Eq. (1) is limited to the relatively narrow penetration range of 16-22 mm (Leroueil and Le Bihan 1996).

The second relationship was proposed by Sherwood and Ryley (1970) and Nagraj and Jayadev (1981)

$$w_{L(2/30)} = \frac{w}{0{,}65+0{,}0175P_{30}} \quad (2)$$

where

$w_{L(2/30)}$ (%) is the liquid limit determined by the one-point method using the 30°/80g cone and Eq. (2)

P_{30} (mm) is the penetration of the standard (30°/80g) cone

w (%) is the moisture content of the soil paste corresponding to the measured cone penetration.

In this paper, the analysis was carried out in order to verify the applicability of these relationships to the glacial tills from the Polish Lowlands and to determine whether these correlations can be used to shorten time needed for determining the liquid limit and liquidity index in the laboratory.

3 RESULTS AND THEIR INTERPRETATION

The comparison of the liquid limit values determined by the standard multi-point method (according to PKN-CEN ISO / TS 17892-12: 2004) and the one-point method according to Eq. (1) shows that the convergence of results is not very high (Fig. 1). Although the trend line is close to the $w_{L(ISO/30)} = w_{L(1/30)}$ function, the scatter of results is relatively large with the coeeficient of determination R_2 of 0.71. The largest difference between the liquid limits determined by the two methods was equal to 2.91% and was calculated for the penetration depth of 12.32mm. The observed scatter of the experimental results may be caused by conducting tests in a greater range of the cone penetration depth than that recommended by Leroueil and Le Bihan (1996). Therefore, the test results were also analysed with a detailed breakdown into the individual ranges of the cone penetration depth, as shown in Tab. 1 and Fig. 2.

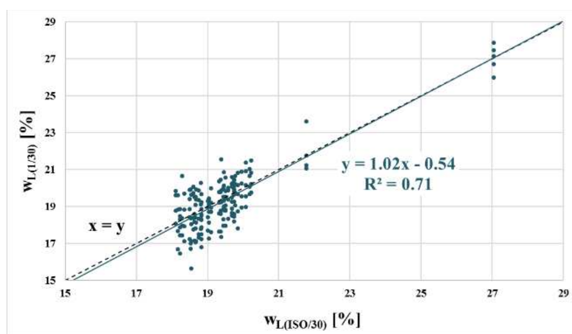

Figure 1. Correlations between the liquid limit values determined by the 30°/80g cone penetrometer according to PKN-CEN ISO/TS 17892-12 ($w_{L(ISO/30)}$) and the one-point method proposed by Leroueil and Le Bihan (1996) ($w_{L(1/30)}$) for the wide penetration range (approximately 12 - 26 mm)

The correlations presented in Tab. 1 and Fig. 2 prove that the results of the one-point method proposed by Leroueil and Le Bihan (1996) are strictly dependent on the cone penetration depth used for the calculations. It was observed that the results of this one-point method are more accurate (i.e. $w_{L(1/30)}$ gets closer to $w_{L(ISO/30)}$ when penetration depths are close to 20mm, that is to the value corresponding to the liquid limit, according to the standard definition.

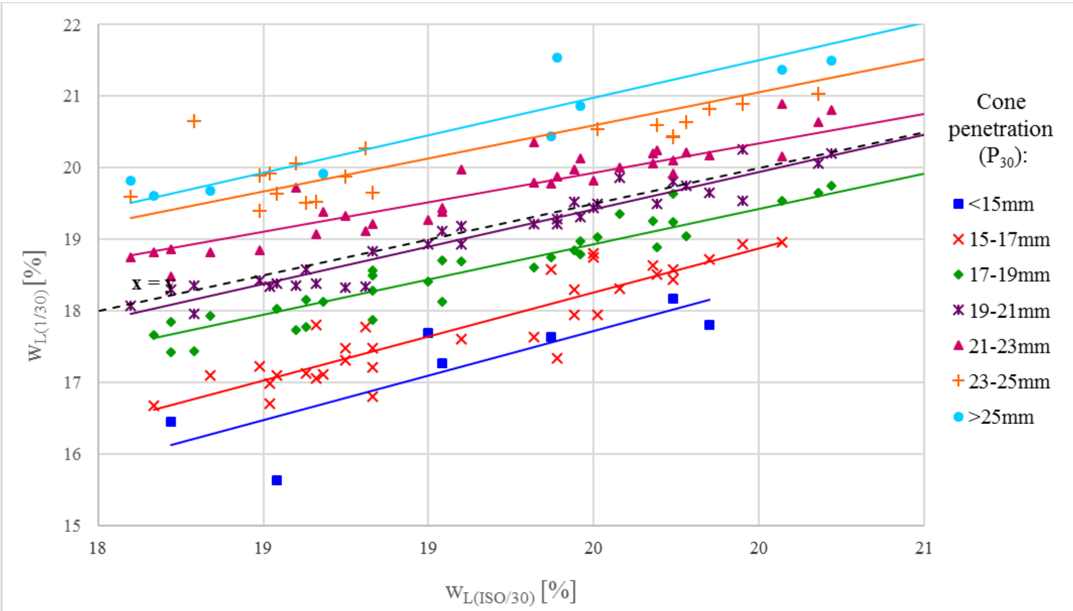

Figure 2. Correlations between the liquid limit values determined by the 30°/80g cone penetrometer according to PKN-CEN ISO/TS 17892-12 ($w_{L(ISO/30)}$) and the one-point method proposed by Leroueil and Le Bihan (1996) ($w_{L(1/30)}$) for the specific penetration ranges

In the penetration range of 19-21mm, the liquid limit determined by Eq. (1) differed from that determined by the standard method (PKN-CEN ISO/TS 17892-12:2004) by 0.12 % (see Tab. 1). Such a difference results in a very small change of the liquidity index (approximately 0.01).

Considering the determination coefficients (R^2) of correlations presented in Tab. 2, it can be concluded that the one-point method proposed by Leroueil and Le Bihan (1996) can be used successfully for the tested clays is the range of penetration depth 17 - 21mm.

Table 3. Details of correlations plotted in Fig. 2

Penetration of 30°/80g cone (**P_{30}**) [mm]	Correlation equation	Coefficient of determination (**R^2**) [-]	Liquid limit $w_{L(2/30)}$ corresponding to $w_{L(ISO/30)}$ = **20.0%**	Liquidity index $I_{L(2/30)}$ corresponding to $I_{L(ISO/30)}$ = **0.5**
< 15	$w_{L(1/30)}$=1.25$w_{L(ISO/30)}$-6.61	**0.70**	18.39 %	0.59
15 ÷ 17	$w_{L(1/30)}$=1.23$w_{L(ISO/30)}$-5.82	**0.82**	18.78 %	0.56
17 ÷ 19	$w_{L(1/30)}$=0.99$w_{L(ISO/30)}$-0.31	**0.99**	19.49 %	0.53
19 ÷ 21	$w_{L(1/30)}$=1.04$w_{L(ISO/30)}$-0.92	**0.99**	19.88 %	0.51
21 ÷ 23	$w_{L(1/30)}$=0.82$w_{L(ISO/30)}$+3.89	**0.86**	20.29 %	0.49
23 ÷ 25	$w_{L(1/30)}$=0.93$w_{L(ISO/30)}$+2.54	**0.96**	21.14 %	0.45
< 25	$w_{L(1/30)}$=1.05$w_{L(ISO/30)}$+0.52	**0.93**	21.52 %	0.43

The second method analysed in this paper (Sherwood and Ryley 1970; Nagraj and Jayadev 1981) yielded much better results despite the fact that the analysis was carried out in the same range of the penetration depths (Fig. 3). It can be observed from Fig. 3 that the results obtained from Eq. (2) correlate very well with those obtained from the standard multi-point tests. The coefficient of determination R^2 is equal to 0.96. The largest difference (1.47%) between the liquid limits determined by two methods was obtained for the penetration depth of 24.38mm.

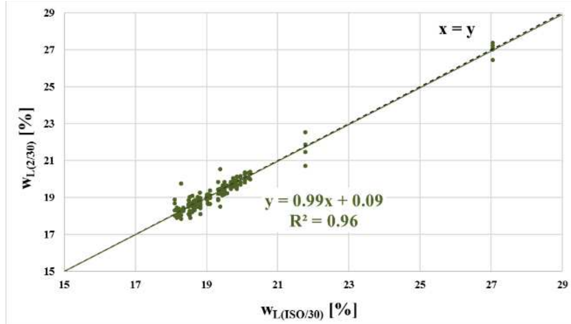

Figure 3. Correlations between the liquid limit values determined by the 30°/80g cone penetrometer according to PKN-CEN ISO/TS 17892-12 ($w_{L(ISO/30)}$) and the one-point method proposed by Sherwood and Riley (1996) ($w_{L(2/30)}$) for the wide penetration range (approximately 14 to 26 mm)

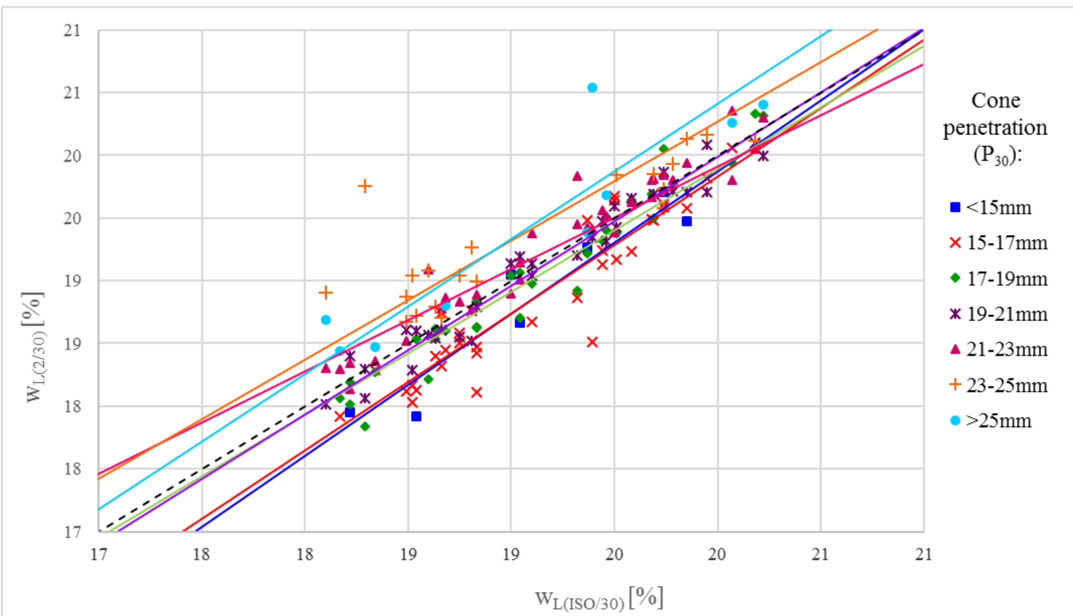

Figure 4. Correlation between the liquid limit values determined by the 30°/80g cone penetrometer according to PKN-CEN ISO/TS 17892-12 ($w_{L(ISO/30)}$) and the one-point method proposed by Sherwood and Ryley (1970) ($w_{L(2/30)}$) for the specific penetration ranges

The effectiveness of methods proposed by Sherwood and Ryley (1970) and Nagraj and Jayadev (1981) is practically independent of the penetration depth, as shown in Fig. 4. The best results were obtained in the range of 21 to 23 mm, in which the $w_{L(2/30)}$ differed from the $w_{L(ISO/30)}$ by 0.03%. Such a small difference has practically no effect on the value of I_L. In the other ranges of the penetration depth, the value of I_L changed only by 0.01 or 0.02, as shown in Tab. 2. The R^2 values, presented in Table 2, indicate the possibility of using Eq. (2) regardless of the penetration depth used in the calculations.

Table 4. *Details of correlations plotted in Fig. 4*

Penetration of 30°/80g cone (**P_{30}**) [mm]	Correlation equation	Coefficient of determination (**R^2**) [-]	Liquid limit $w_{L(2/30)}$ (%) corresponding to $w_{L(ISO/30)}$ = **20.0%**	Liquidity index $I_{L(2/30)}$ corresponding to $I_{L(ISO/30)}$ = **0.5**
< 15	$w_{L(2/30)}=1.13w_{L(ISO/30)}-2.80$	**0.91**	19.80 %	0.51
15 ÷ 17	$w_{L(2/30)}=1.09w_{L(ISO/30)}-2.00$	**0.87**	19.80 %	0.51
17 ÷ 19	$w_{L(2/30)}=0.98w_{L(ISO/30)}+0.27$	**0.99**	19.87 %	0.51
19 ÷ 21	$w_{L(2/30)}=1.03w_{L(ISO/30)}-0.57$	**1.00**	19.88 %	0.51
21 ÷ 23	$w_{L(2/30)}=0.82w_{L(ISO/30)}+3.57$	**0.90**	20.03 %	0.50
23 ÷ 25	$w_{L(2/30)}=0.95w_{L(ISO/30)}+1.28$	**0.97**	20.28 %	0.49
< 25	$w_{L(2/30)}=1.08w_{L(ISO/30)}-1.15$	**0.93**	20.45 %	0.48

4 CONCLUSIONS

Natural cohesive soils from the Polish Lowlands were analysed in this article. The possibility of using one-point methods for laboratory determination of the liquid limit was investigated. Correlation relationships between the liquid limit values determined for North- and Middle-Polish glaciation clays in the standard multi-point cone penetration test (according to PKN-CEN ISO / TS 17892-12: 2004) and selected one-point tests were proposed. The analysis of experiential results obtained in this research leads to the following conclusions:

- The accuracy of the Leroueil and Le Bihan (1996) one-point method depends to a large extent on the penetration depth of the cone, which will be used for w_L calculation. For the glacial tills analysed in this paper, the acceptable range of the cone penetration is in between 17 and 21mm, which is slightly smaller than that reported by the authors. This means that the consistency of the soil paste prepared for determining w_L using the one-point method would have to guarantee the penetration of cone in this range. However, satisfying this condition may present some difficulties and, in practice, lead to undesirably long testing times.
- The methods proposed by Sherwood and Ryley (1970) and Nagraj and Jayadeva (1981) appears to be more precise and independent of the penetration of cone used for calculations. For tested clays found in the Polish Lowlands, it can be successfully used in a wide penetration range of approximately 15 to 25mm, which should not change the I_L value by more than 0.01.

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