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A description of the physical properties of selected sediments of the Weichselian and Wartanian glaciations

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Abstract. Subsurface sediments in Poland were deposited mainly in the Pleistocene, and have varying origins and, consequently, differing geological and engineering parameters. Fluvioglacial deposits were formed during both the glacial and interglacial periods, which differed from each other in climatic conditions. Based on the results of laboratory analysis and fieldwork, till and fluvioglacial sands were compared in Central and North-Eastern Poland. The research included consistency limits, relative density, plasticity index, constrained modulus of initial compressibility and modulus of initial deformation. Despite the existing view that there exists a large diversity of geological, engineering and geotechnical parameters of variously-aged deposits in Poland, no major differences in their properties were determined at the study sites.

Key words:
fluvioglacial deposits,
physical properties,
Weichselian glaciation,
Wartanian glaciation

Introduction

A series of several glaciations that occurred in the Pleistocene resulted in a continental glacier which partially or completely covered the area of Poland. The ice sheet did not reach the southern regions of the country, where periglacial conditions consequently prevailed. During warmer periods, the increased rainfall (occurring instead of snowfall) triggered sediment erosion processes (Lindner et al. 2002).

The Middle-Polish (Saale) glaciations reached the Sudetes and the Central Polish Uplands in the south. Each of the colder periods of the Wartanian glaciation left behind till (boulder clay) interspersed with sandy-gravel fluvioglacial sediments or glaciolacustrine silt and clay (Harasimiuk and Terpiłowski 2004). The lake districts are strongly associated with the range of the Weichselian glaciation. In this period, a periglacial climate prevailed in the area not covered by the glacier, and was conducive to denudation processes (frost weathering). This climate caused a reduction in the geotechnical parameters of rocks and sediments.

The study area within the Łódź city limits is located within the range of the Wartanian glaciation, in the district of Pabianice, whereas the site at Bargłów Kościelny, with deposits from the Weichselian glaciation, is located in the Augustów district of the Podlasie Province (Fig. 1).

Description, analysis and comparison of the geological and engineering parameters of deposits (till and fluvioglacial sands) of the Weichselian and Wartanian glaciations refer only to these selected regions of the country.

Assessment of sediment parameters was carried out on the basis of geological-engineering conditions determined in the course of fieldwork and laboratory analysis, and of the sediments' origin.

The strength parameters of the till (boulder clay) from the Weichselian glaciation have been determined by Wierzbicki (2008). He found that there are some correlations between the strength parameters of the substrate and its origin. The impact of geological processes on deposit strength can be determined by static probing. Probing allows, among other things, assessment of deposit strength parameters at a given site (Wierzbicki et al. 2008). The strength parameters of glacial till have also been examined by Pawlak and Chudy (2013). The authors showed that, in addition to sediment origin, the index of sediment plasticity and density index, as well as geomorphology and tectonics, are important.

As evidenced by their research, assessment of strength parameters according to standard PN-86/B-03020 (based on plasticity index and density index, determined in the course of field and laboratory research) may not be explicit. The actual strength parameters might be lower than those provided by the standard (Pawlak and Chudy 2013). Unfortunately, due to the high costs of laboratory sediment strength tests, and a lack of relevant provision in the regulation, these tests are not mandatory for the design of foundations in engineering facilities.

Geological structure

The commune of Pabianice is located in the drainage basin of the Warta River and in the Szczecin-Łódź-Miechów synclinorium built of Jurassic limestone-marl sequences and Cretaceous marl, sandstone and limestone. Miocene clay, silt and sand are deposited on the Mesozoic roof surface. In the described area, the Quaternary period is represented by Pleistocene tills, sands and gravels, fluvioglacial sands and gravels, and Holocene sands, gravels and silts (Fig. 2).

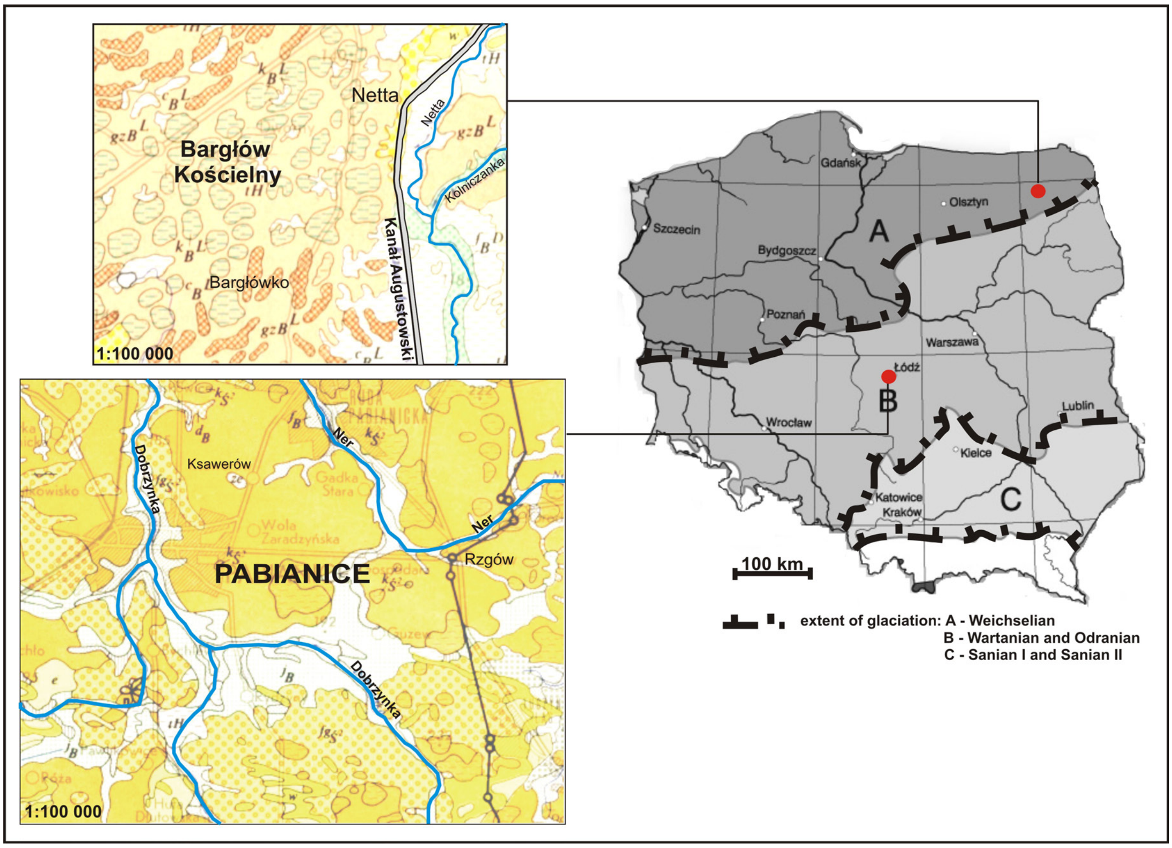

Fig. 1. Location of Pabianice and Bargłów Kościelny against glaciations in Poland

The Holocene deposits are found mainly in the Dobrzynki River valley and in the valleys of surrounding water courses (Libera 2008). The area of the Pabianice commune was covered by the Wartanian glaciation. In addition to till, kames are characteristic landforms. These landforms were washed out in the course of periglacial processes by post-Wartanian waters, or denuded by weathering processes (Różycki 1966).

The dominant deposits in Bargłów Kościelny are Pleistocene till of the Weichselian glaciation, as well as sand, silt, clay and kame gravels, and fluvioglacial sand and gravel (Fig. 3).

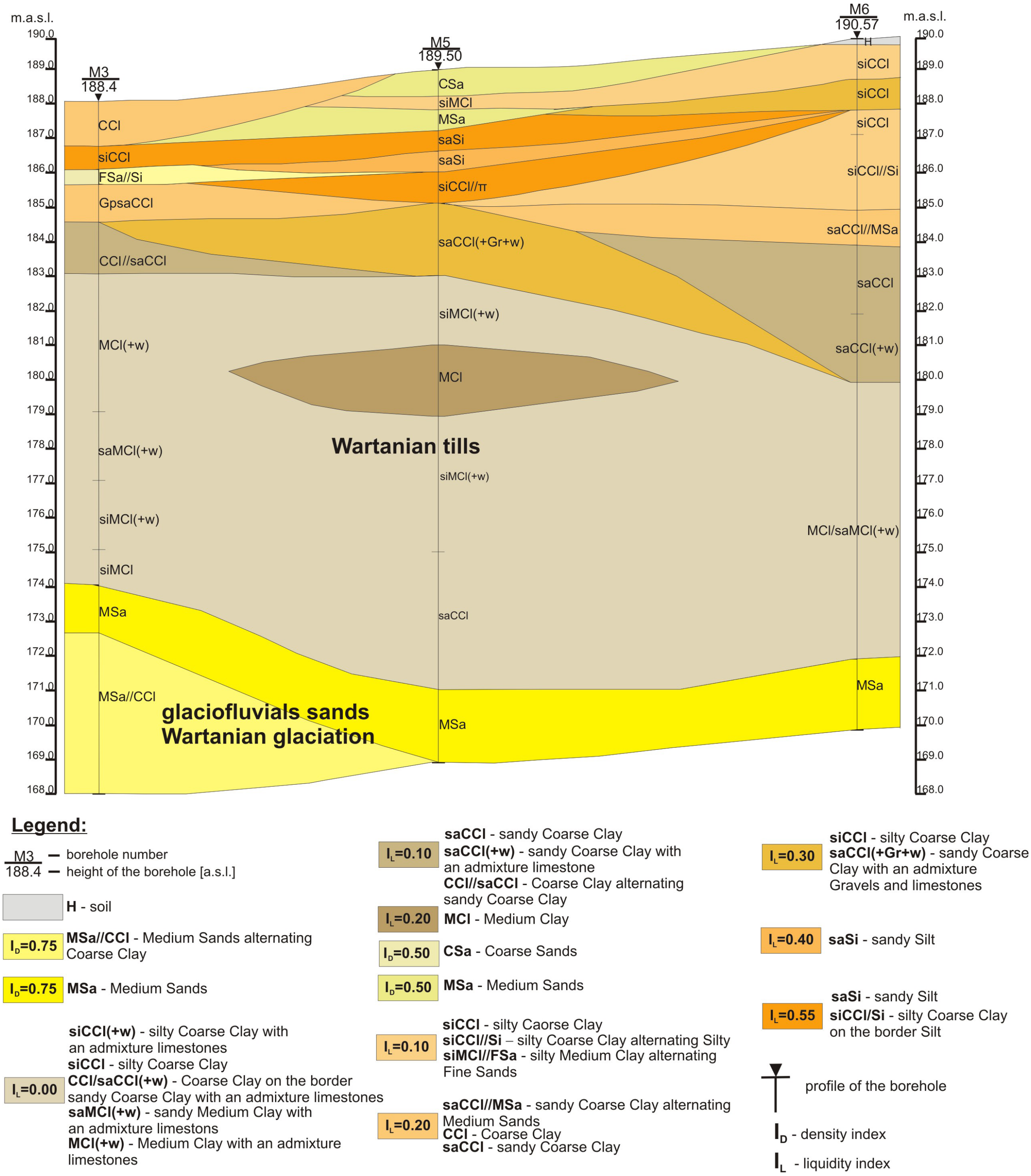

Fig. 2. Synthetic geological cross-section in Pabianice (based on the card of boreholes according to Libera et al. 2008)

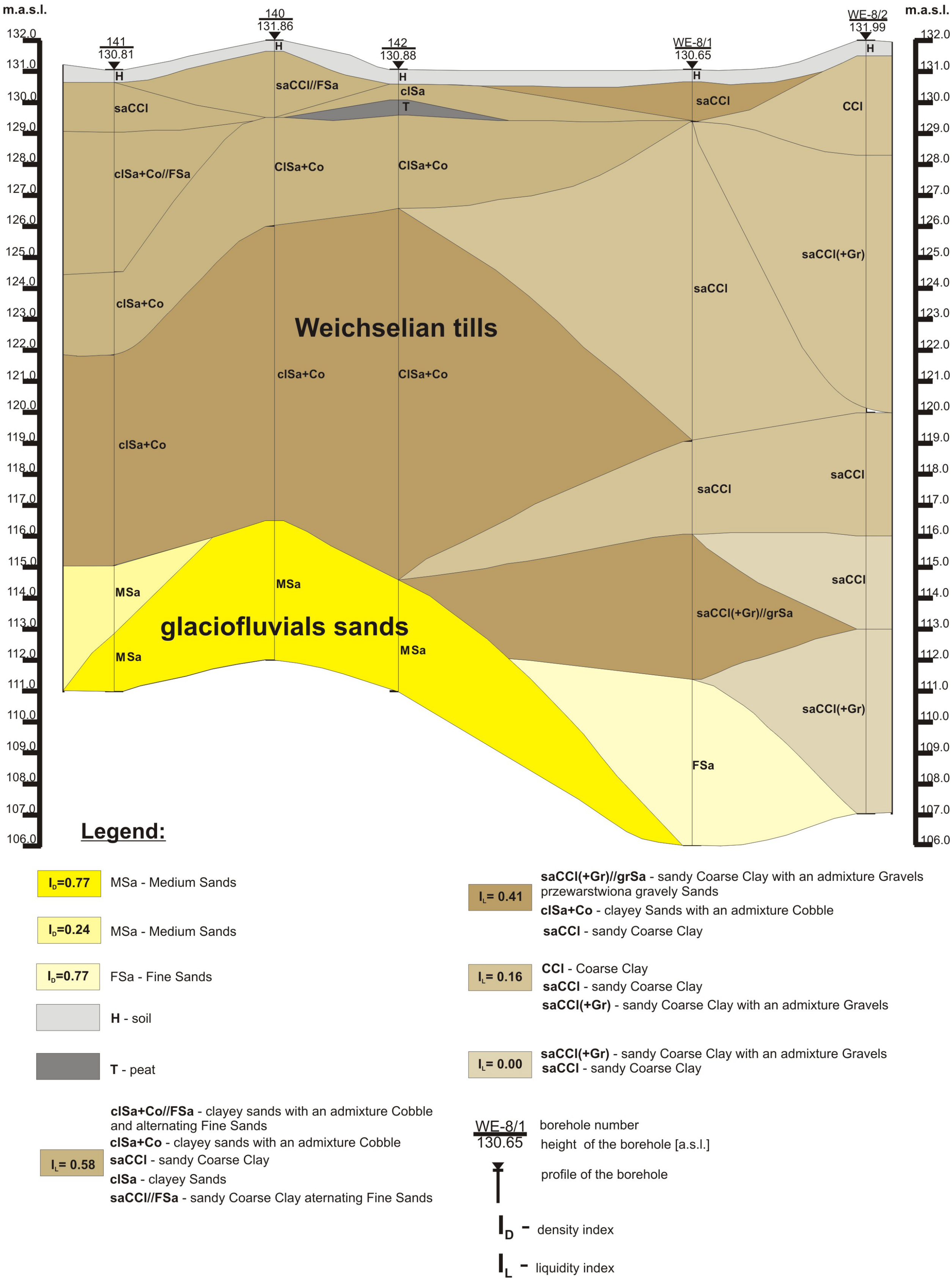

Fig. 3. Synthetic geological cross-section in Bargłów Kościelny (based on the card of boreholes according to Ciesielski et al. 2011)

The deposits in Bargłów Kościelny come from the Weichselian glaciation. They are ca. 0.01 million years younger than the sediments in Pabianice. Despite the presence of lithologically similar deposits in the study areas (till and fluvioglacial sands), their mineralogical and petrographic composition are significantly different. In the region of Pabianice, limestone is frequently encountered in the till layer. This is caused by stronger glacial exaration of the substrate during the Wartanian glaciation. In the sediments occurring in Bargłów Kościelny at a depth of up to 20 m, no admixture or interbeddings of older Mesozoic and Paleozoic rocks occurs. Because the age of the sediments varies, the values of their geological and engineering parameters should also vary.

Hydrological conditions

In the area of Pabianice, groundwater is found in Quaternary sediments: in sands of varying granularity, between till and sands characterised by varying grain-size structure, and deposited beneath the till. The depth of the aquifer below the till is ca. 5 m. This layer is of no practical importance. According to an MhP (Hydrological Map of Poland) sheet on a scale of 1:50,000 (Poradowska 1997), an Upper Cretaceous aquifer occurs in carbonate (limestone) deposits where weathering fissures dominate. This is the most exploited aquifer in the study area.

In Bargłów Kościelny, the Quaternary aquifer is isolated from the ground surface by a layer of till or clay. At a depth ranging from 0 to 10 m, only a local (unusable) aquifer occurs. On the other hand, the usable aquifer occurs in Quaternary sands and gravels at a depth ranging from 10 to 40 m. In the Neogene and Paleogene deposits, the usable aquifer occurs in silt and clay deposits. In the Upper Cretaceous deposits, the aquifer occurs in the strata of marl and chalk. The aquifer level may change due to fluctuations in the groundwater recharge resulting from differences in levels of precipitation infiltration during wet and dry hydrological years. With a significant increase in the groundwater level or inundation of lands with rainwater, deterioration of geotechnical sediments parameters has been observed.

Analysis of geological and engineering parameters

Understanding the mechanical behaviour of sediments is the main part of engineering geology and sediment mechanics (Chandler 2000). The mechanical properties of sediments were described in terms of their response to forces acting on a sediment fragment. According to the Coulomb-Mohr strength theory, the lithological characteristics of sediments, as well as the cohesion (resistance of sediments to external forces, triggered by bonding between particles) and the angle of internal friction (the critical angle at which the material is in transition between a state of rest and a state of motion. It is one of the parameters describing sediments' shear strength), and the state of stress which occurs in the substrate, all affect the soil shear strength (Wierzbicki et al. 2008).

Sediment strength parameters, including angle of internal friction and deformation parameters (such as the constrained modulus of primary compressibility and the constrained modulus of initial deformation), depend on the sediments' mineral composition, density index and saturation with water (Wiłun 2010). If the pores in the sediments (especially in cohesive sediments) are filled with water and run-off is not possible, the applied load will cause an increase in the pore water pressure without any increase in the effective stress (σ'). Sedimentary particles will not be displaced and the sediments will not be consolidated, and consequently the volume of sediments under the applied load will not be reduced (Szymański 2007). Experiments conducted by Terzaghi, with sediments saturated with water and subjected to the pressure of a water column, showed that this pressure was provided only to the water contained in the pores, without affecting in any way the mechanical properties or density of the sediments (Pisarczyk 2005). But the most important geotechnical variables influencing strength parameters and deformation parameters are the stress history and stress itself.

Analysis of geological, engineering and strength sediment parameters was carried out on sediments with a similar grain-size composition. In both cases, till is represented by sandy Coarse Clay (saCCl) and sandy Coarse Clay with clayey Sands (saCCl+clSa), whereas fluvioglacial deposits are represented by Medium-grained Sands and Coarse-grained Sands (MSa+CSa). Among other methods, static and dynamic probing were applied to analyse the deposits, as a result of which, the plasticity index (I_L) and relative density (I_D) were determined. On this basis, it is possible to determine the strength parameters of sediments in accordance with the applicable standards, if the parameters of the study have not been established in the field or in the laboratory. These kinds of studies allow the identification of sediment properties, including strength parameters. The relative density index (I_D) is a parameter that helps to determine the state of sediments (very loose, loose, medium loose, etc.). This parameter also determines sediment bearing capacity, and depends on the dominant particle size in the sediments' basement and is independent of the overconsolidation ratio OCR (Khan et al. 2011).

Till is poorly sorted and may include all grain size fractions, as well as lenses of other material, such as sand or gravel. Such variability of petrographic composition causes changes in the physical and mechanical properties of the sediment. Till is usually consolidated and, hence, relatively resistant to shear stress (the maximum shear force or the maximum resistance of the sediments to this force, the exceeding of which results in a considerable deformation of the sediments).

The bearing capacity of ground built of till is often reduced through alternate, irregular distribution of interbeddings or lenses of, e.g., sand, gravel and clay, often saturated with water. Heterogeneity of the till is additionally increased by the presence of numerous cobbles and boulders, as well cracks and crevices. The behaviour of glacial till is significantly affected by its age and history of stress, i.e. their strength and deformation properties are affected by glacier loading (Kaczyński 2011). According to Boulton and Paul (1976) the mechanical properties of tills are connected to the phase of transport of debris by the glacier, deposition and post-deposition. Grain-size distribution, state of consolidation and presence of joints affect a wide range of geotechnical parameters.

The main parameter describing the shear resistance of clay is undrained shear strength. The value of this parameter corresponds to the tangential stress, caused by the destruction of sedimentary structures in the course of shearing (Wierzbicki 2008). Analysis of the above-mentioned parameter can be performed only during static probing CPT or CPTU, because this allows direct assessment of the stress state in the sediment, e.g. the overconsolidation ratio OCR.

In the area of Bargłów Kościelny, till occurs in the form of sandy silt, silty sands and silty clay. These are compact deposits which contain admixture and interbeddings of fine sand, cobbles, silty sands, gravel, medium-grained sand, clay, organic sediments, silt and sandy silt. These sands are of soft to hard plasticity, and solid and semi-solid consistency.

Till in Pabianice developed as moraine, cohesive sandy silt, compact sandy silt, compact clays and silty clays. These deposits might be locally interbedded with medium-grained sand, gravel and limestone debris. The plastic consistency of these sediments is of low plasticity and semi-compacted.

Table 1 presents the results of laboratory analysis on till and meltwater deposits at the Pabianice and Bargłów Kościelny sites. The comparison of geological and engineering parameters such as: moisture content, yield point, liquid limit, degree and plasticity index, were conducted on the following sediments: sandy Coarse Clay (saCCl) and sandy Coarse Clay interbedded with clayey Sands (saCCl+clSa).

After analysing the values of individual parameters, it appears that tills both in Pabianice and in Bargłów Kościelny have similar properties, even though they come from different glaciations. The deposits are of moderate plasticity, and soft consistency. This means that the sediments deform under external forces and maintain their new form after the applied forces cease to act. The plasticity of the sediments increase with the value of the plasticity index. The sediment conditions are determined by the amount and properties of the water contained in the sediments, as well as by the composition and properties of the solid particles (Table 2).

Admixtures of sand fractions in sediments cause a reduction in values of sediment consistency limits and plasticity. Only sandy silt in Pabianice is in the hard-plastic state. As it appears from the analysis of geological and engineering parameters collated in Table 1, the sediments of the Wartanian glaciation are distinguished by slightly lower values compared

Table 1. Results of laboratory analysis on tills and meltwater deposits from Pabianice and Bargłów Kościelny (Libera 2008; Ciesielski 2011)

	Bargłów Kościelny						
	saCCl	saCCl+clSa	clSa	clSa+saCCl	clSa+saCCl+Co	clSa+saCCl//MSa	clSa+Co
Water content w [%]	**17.22**	**17.09**	13.5	14.02	15	27.7	11.3
Plastic limit w_p [%]	**11.39**	**12.34**	10.10	10.92	9.70	14.60	8.7
Liquid limit w_L [%]	**29.12**	**28.84**	21.50	20.54	19.60	31.50	14.4
Liquidity index I_L [-]	**0.30**	**0.28**	0.30	0.32	0.53	0.78	0.45
Plasticity index I_p [%]	**17.74**	**16.51**	11.50	9.64	9.90	16.90	5.7
	Pabianice						
	saCCl	saCCl+Gr	saCCl+clSa	saCC //MSa	saCCl//MSa(+Gr)	saMCl	saCCl //CCl
Water content w [%]	**13.42**	13.60	**13.7**	13.55	11.35	14.4	12.9
Plastic limit w_p [%]	**10.76**	10.98	**9.60**	9.80	10.20	13.20	11.2
Liqiud limit w_L [%]	**24.52**	23.88	**21.00**	21.17	22.85	35.70	26.4
liqiudity index I_L [-]	**0.19**	0.23	**0.36**	0.32	0.09	0.05	0.11
Plasticity index I_p [%]	**14.88**	12.90	**11.40**	11.37	12.65	22.50	15.2

Key to abbreviations: saCCl – sandy Coarse Clay, clSa – clayey Sand, Co – Cobble, MSa – medium Sand, CCl – Coarse Clay, saMCl – sandy Medium Clay, Gr – Gravels, water content – mass of water which can be removed from the sediments, usually by drying, expressed as a percentage of the dry mass, plastic limit – water content at which a fine sediment becomes too dry to be in a plastic condition, as determined by the plastic limit test, liquid limit – water content at which a fine sediment passes from a liquid to a plastic condition, as determined by the liquid limit test, liquidity index – numerical difference between the natural water content and the plastic limit, expressed as a percentage ratio of the plasticity index, plasticity index – numerical difference between the liquid limit and plastic limit of a fine sediment

to sediments of the Weichselian glaciation. This may be related to the periglacial climate prevailing during the Weichselian glaciation when these sediments were deposited (formed). The sediments in Central and Southern Poland were then exposed to processes of severe physical (mechanical) weathering, which may have lead to reduced values of sediment parameters in this area. This, however, has no significance for the overall classification.

Fluvioglacial deposits develop from material carried by glacial water. Sedimentation of the drifted material takes place when the force of waters flowing from under the glacier is reduced. Both in Pabianice and Bargłów Kościelny, the deposits developed as sands of varying particle-size distribution containing gravel, or as gravel. These sediments are loose, semi-compacted and compacted (Table 3).

Tables 4 and 5 present the strength parameters of moraine deposits (tills and fluvioglacial sands) from the described study areas.

The values of strength parameters (the moduli of initial deformation and primary compressibility) from Bargłów Kościelny were compiled based on the nomograms from Polish Standard PN-81/B-03020. Due to lack of other data, it was not possible to analyse the results of the secondary deformation modulus and the edometric compressibility modulus.

Fluvioglacial deposits in the compacted state were characterised by high values of physical and mechanical parameters; they are therefore classified as sediments with the highest bearing capacity. They

Table 2. State and consistency of cohesive sediments (according to Wiłun 2010 and PN-EN ISO 14688-2)

The value of I_L and w_n	State of the soil	symbol	Consistency	PN-EN ISO 14688-2
$I_L < 0$ and wn $\leqq$ ws	Very stiff	pz	Very stiff	$I_c > 1.0$
$I_L < 0$ and $w_s < w_n \leqq w_p$	Semi-stiff	pzw		
$0 < I_L \leqq 0.25$	Stiff	tpl	Plastic	$0.75 \leqq I_c < 1.0$
$0.25 < I_L \leqq 0.50$	Firm	pl		$0.50 \leqq I_c < 0{,}75$
$0.50 < I_L \leqq 1.00$	Soft	mpl		$0 \leqq I_c < 0.50$
$I_L > 1.00$ or $w_n > w_L$	Very soft	pł	Viscous	$I_c < 0$

Key to abbreviations: I_L – liquidity index [-], w_L – liquid limit [%], w_n – natural water content [%], w_p – plastic limit [%], w_s – shrinkage limit [%], I_c – consistency index [-]

Table 3. Corelations to classify density terms (according to PN-B-02480 and PN-EN ISO 14688-2)

I_D [-] according to PN-B-02480	State of soil	symbol	I_D [-] according to PN-EN ISO 14688-2
	very loose	bln	0.00 – 0.15
$0.00 < I_D \leqq 0.33$	loose	ln	0.15 – 0.35
$0.33 < I_D \leqq 0.67$	medium dense	szg	0.35 – 0.65
$0.67 < I_D \leqq 0.80$	dense	zg	0.65 – 0.85
$0.80 < I_D \leqq 1.00$	very dense	bzg	0.85 – 1.00

Key to abbreviations: ID – density index (coarse sediments – sands and gravels) index dependent upon the void ratio, and the void ratios corresponding to the minimum density and the maximum density, as measured in the laboratory

Table 4. Research results concerning the physical-mechanical parameters of moraine deposits in Pabianice (A) and Bargłów Kościelny (B) (Kowalewski and Pogorzelska 1985; Libera 2008; PN-EN ISO 14688:2006). A - Research conducted in the field and in the laboratory. B - I_L and I_D tests performed in the field (based on probing). The values of strength parameters read from the existing nomograms

Bargłów Kościelny					
	I_L [-]	Cu [kPa]	$\varphi[^0]$	Mo [MPa]	Eo [MPa]
saCCl	**0.30**	**27**	**16.4**	**29.0**	**22.5**
saCCl+clSa	0.28	29	16.5	31.5	23.5
clSa	0.30	27	16.4	29.5	22.5
clSa+saCCl	0.32	26	16	27.5	21.5
clSa+saCCl/Co	0.53	21	15	21.0	18.5
clSa+saCCl//MSa	0.78	15	7	11.5	8.0
clSa+Co	0.45	23	13.8	22.5	17.5

Pabianice								
	I_L [-]	ρ [t/m3]	Cu [kPa]	φ [0]	Mo [MPa]	M [MPa]	Eo [MPa]	E [MPa]
saCCl, saMCl, CCl, MCl, siMCl	0.00	1.96	36	19.8	65	87	50	67
saCCl, saMCl, CCl, MCl, siMCl	0.10	1.93	32.4	18	47	63	36	48
saCCl, saMCl, MCl, siMCl, CCl	0.20	1.90	27.9	16.2	36	48	27	36
saCCl	**0.30**	1.92	**24.3**	**14.4**	**29**	39	**22**	29

Table 5. Research results concerning the physical-mechanical parameters of meltwater deposits in Pabianice and Bargłów Kościelny (Kowalewski and Pogorzelska 1985; Libera 2008; PN-81/B-03020)

Bargłów Kościelny					
	I_D [-]	Cu [kPa]	$\varphi[^0]$	Mo [MPa]	Eo [MPa]
MSa +CSa//clSa	0.24	---	31.5	58.00	50.00
MSa+CSa//rubble	0.53	---	33.0	100.00	83.00
MSa+CSa	**0.77**	**---**	**34.5**	**140.00**	**115.00**
grSa+Gr(+saCCl)	0.27	---	31.7	110.00	98.00
grSa+Gr(CSa+CCl)	0.53	---	33.0	100.00	83.00
grSa+Gr(+saCCl)	0.69	---	34.1	197.00	177.00

Pabianice								
	I_D [-]	ρ [t/m3]	Cu [kPa]	φ [0]	Mo [MPa]	M [MPa]	Eo [MPa]	E [MPa]
FSa//MSa, FSa, MSa//CCl*	0.75	1.77	---	28.3	90	112.5	70	87.5
MSa, CSa*	**0.75**	**1.84**	**---**	**31**	**140**	**155**	**115**	128

Key to abbreviations 4 and 5: I_L – liquidity index [-], I_D – density index [-], Cu – undrained shear strength [kPa], φ - angle of internal friction [^{0}], E0 – initial deformation modulus [MPa], E – secondary deformation modulus [MPa], M0 – modulus of primary compressibility [MPa], M – modulus of secondary compressibility [MPa], ρ - bulk density of soil [t/m^3], CSa – Coarse Sands, MSa – Medium Sands, FSa – Fine Sands, grSa – gravelly Sands, Gr- Gravel, CCl – Coarse Clay, MCl – Medium Clay, saCCl – sandy Coarse Clay, saMCl – sandy Medium Clay, siMCl – silty Medium Clay, clSa – clayey Sands, *– watered sludge

are followed (in terms of strength parameter values) by compact sandy silt, compact silt and sandy silt, which are characterised by high bearing capacity, and medium or low compressibility.

Conclusions

The described area of Łódź Province (Pabianice) was located within the range of the Wartanian glaciation, whereas the region of Podlasie Province (Bargłów Kościelny) was located within the range of the Weichselian glaciation. In both cases, the substrate contains tills and fluvioglacial deposits, developed in the form of sand of varying grain-size composition, and gravel with interbeddings of silty sands and silt.

In order to properly analyse the strength and deformation parameters of sediments, they should be reliably assessed and their values correctly interpreted. Without accurate identification of the substrate, which includes, for example, field tests, it is worthwhile conducting additional laboratory analysis, which will form basis of calibration of results from the fieldwork.

Despite their varying age, the analysed sediments (saCCl, saCCl+clSa, MSa+CSa) at the study sites (Pabianice and Bargłów Kościelny) have similar values of geological and engineering parameters. This may be related to the fact that the ice sheet of the Weichselian glaciation did not reach Central Poland (Łódź Province). Between the Wartanian glaciation and the Weichselian glaciation there was a gap of several thousand years. The similar values of sediment strength parameters may also indicate that the weight of the ice-sheet during the above glaciations was the same (or similar), i.e. the ice-sheet exerted a similar pressure on the substrate. The fluvioglacial deposits with the better strength parameters are gravelly sand, gravel, coarse and medium sands of the Weichselian glaciation (Bargłów

Kościelny). These deposits could not be consolidated because the ice sheet of the Weichselian glaciation did not reach Central Poland.

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