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The physical-mechanical and structural properties of boulder clays of the Vistula Glaciation in the area of Poland

In the light of the investigations, it has been found that the boulder clays of Pomeranian and Leszno phases have not generally reached the full consolidation. In most cases, illite is the main clay mineral, and in few cases it is montmorillonite. The physical properties (specific density, volume density, natural water content, liquid limit, plastic limit, soaking and swelling) and the mechanical properties (angle of the internal friction, cohesion) of both types of boulder clays are very much alike, and at the same time these parameters are lower than in the boulder clays of the older glaciations.

INTRODUCTION

The published papers on the physical-mechanical and structural properties of boulder clays of Vistula Glaciation are not numerous. Practically, these soils may be considered the gap in the knowledge of the geotechnical characteristics of soils in Poland. Some papers contain some fragmentary data which are connected with some local objects and geotechnical solutions.

The paper given below, because of the number of investigations made and the enormous area of occurrence of these sediments, does not pretend to the full, regional or monographic grasp of their geotechnical parameters; it may nevertheless form the guide for the properties of boulder clays of Vistula Glaciation and may serve in the future for preparing of the catalogue of the properties of soils in Poland.

The samples for the laboratory investigations were cut (by shearing) from the monoliths or cylinders taken at the depth between 1.5 and 5 m below terrain level. The

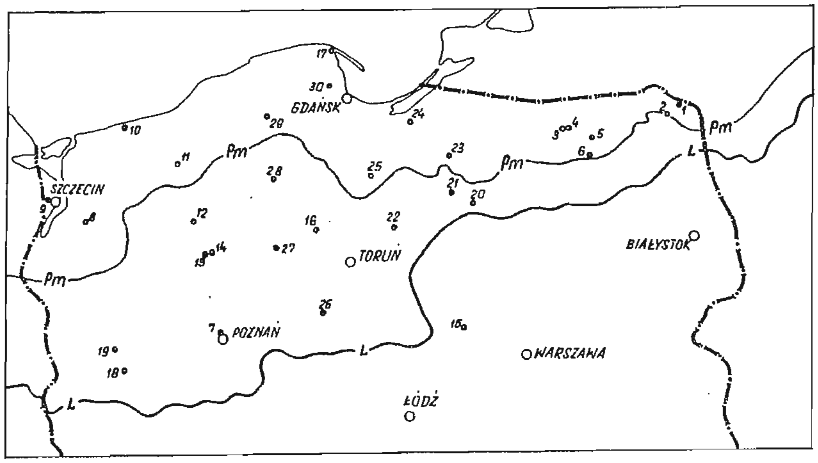

Fig. 1. The localization of the observation points at the area of Vistula Glaciation in which the samples of boulder clays were taken for the loboratory investigations

1 — Puńsk, 2 — Żubryń near Suwałki, 3 — Giżycko I, 4 — Giżycko II, 5 — Panty, 6 — Orzysz, 7 — Poznań, 8 — Stargard Szczeciński, 9 — Szczecin, 10 — Włodarka near Trzebiatów, 11 — Jelonki near Połczyn Zdrój, 12 — Wałcz, 13 — Ujście I near Piła, 14 — Ujście II near Piła, 15 — Kobierniki near Płock, 16 — Trzeciewiec near Bydgoszcz, 17 — Władysławowo, 18 — Brzezie near Sulechów, 19 — Świebodzin, 20 — Wielka Turza near Działdowo, 21 — Lubawa, 22 — Tiwoli near Brodnica, 23 — Wólka Majdańska near Ostróda, 24 — Elbląg, 25 — Kwidzyn, 26 — Strzelno, 27 — Nakło, 28 — Chojnice, 29 — Bytów, 30 — Przodkowo near Kartuzy; Pm — Pomeranian Phase, L — Leszno Phase

Lokalizacja punktów obserwacyjnych na obszarze zlodowacenia Wisły, w których pobrano próbki glin zwałowych do badań laboratoryjnych

1 — Puńsk, 2 — Żubryń k. Suwałk, 3 — Giżycko I, 4 — Giżycko II, 5 — Panty, 6 — Orzysz, 7 — Poznań, 8 — Stargard Szczeciński, 9 — Szczecin, 10 — Włodarka k. Trzebiatowa, 11 — Jelonki k. Połczyna Zdroju, 12 — Wałcz, 13 — Ujście I k. Piły, 14 — Ujście II k. Piły, 15 — Kobierniki k. Płocka, 16 — Trzeciewiec k. Bydgoszczy, 17 — Władysławowo, 18 — Brzezie k. Sulechowa, 19 — Świebodzin, 20 — Wielka Turza k. Działdowa, 21 — Lubawa, 22 — Tiwoli k. Brodnicy, 23 — Wólka Majdańska k. Ostródy, 24 — Elbląg, 25 — Kwidzyn, 26 — Strzelno, 27 — Nakło, 28 — Chojnice, 29 — Bytów, 30 — Przodkowo k. Kartuz; Pm — faza pomorska, L — faza leszczyńska

sites of taking of the soil samples were chosen carefully in the fresh foundation pits, canalization pits and so on, and in the open cuts near the factories of building ceramics. The samples were taken from 30 investigation points in the years 1988–1989. Especial care was taken of proper sampling and preparing of suitable laboratory samples. It ought to be pointed out, that all samples prepared for the given series of determinations were tested using oedometers, consolidometers, box shear apparatus and compression triaxial apparatus.

All the investigations of properties of the boulder clays were made in the laboratory of Instytut Hydrogeologii i Geologii Inżynierskiej, Uniwersytet Warszawski (Institute of Hydrogeology and Engineering Geology, Warsaw University) by the same group of workers. The work was finished in 1990.

This paper was prepared using as a basis the unpublished paper: "The physical-mechanical properties of boulder clays in the area of Vistula Glaciation", worked-out in Zakład Prac Geologicznych, Uniwersytet Warszawski (Department of Geological

Works, Warsaw University), which was commissioned by Instytut Techniki Budowlanej (Institute of Building Technics).

The authors thank Prof. J. Pinińska for the consultations and discussion of the results of investigations, and all collegues from Instytut Hydrogeologii i Geologii Inżynierskiej for help and for taking part in the investigations, especially Dr P. Dobak, J. Wróblewski, M. S., H. Górka, M. S., and the technicians: J. Wiewiór, A. Kasprzak and W. Ćwierzyńska.

THE GEOLOGICAL CONDITIONS OF OCCURRENCE OF THE BOULDER CLAYS

Figure 1 shows the extends of the continental glacier during Leszno Phase (L) and Pomeranian Phase (Pm), and at this background the localities were shown, in which the samples for the laboratory investigations were taken. They can be divided as follows: samples from 16 localities (observation points) were taken in the area of Pomeranian Phase and younger phases, and samples from 14 localities were taken in the area of the phase older than Pomeranian Phase.

The characteristic features of the glacial environment are: low temperature and lack or small amount of the vegetative cover. The elements of transport and sedimentation are: ice, water from thawing of the glacier, sometimes wind. The typical, characteristic product of the glacier sedimentation of broad extension is the boulder clay, existing in the form of the glacier moraines.

The boulder clays consist of the heterogeneous material. Their composition depends on the rocks transported by the continental glacier from the farther and nearer distances and on the rocks taken immediately from the basement. The boulder clays are formed as a result of thawing of the lower part of the continental glacier (ground moraine), its surficial part (ground ablation moraine), and its frontal part (frontal moraine).

The boulder clays belonging to the individual moraines often possess different colours. Generally, older boulder clays are grey, younger are brown or red-brown. The difference of colour has its reason in the different petrographic composition of the moraines and probably in the different redox potential of the environment.

THE LITHOGENETIC FEATURES OF THE BOULDER CLAYS

The lithogenetic features of soils are connected with the defined processes, which formed their actual condition. During the forming of the boulder clay the grains, cobbles, boulders and the particles of the mineral substance must have been transported in the body of the continental glacier and thawed out of it. Because of this, the percent content of several fractions, that is gravelly, sandy, silty and clayey fractions, show the dynamics of the processes of thawing, transport and sedimentation, which are the first stages of the sedimentogenesis (W. C. Kowalski, A. Kowalski, 1975; N. Lipińska, 1975).

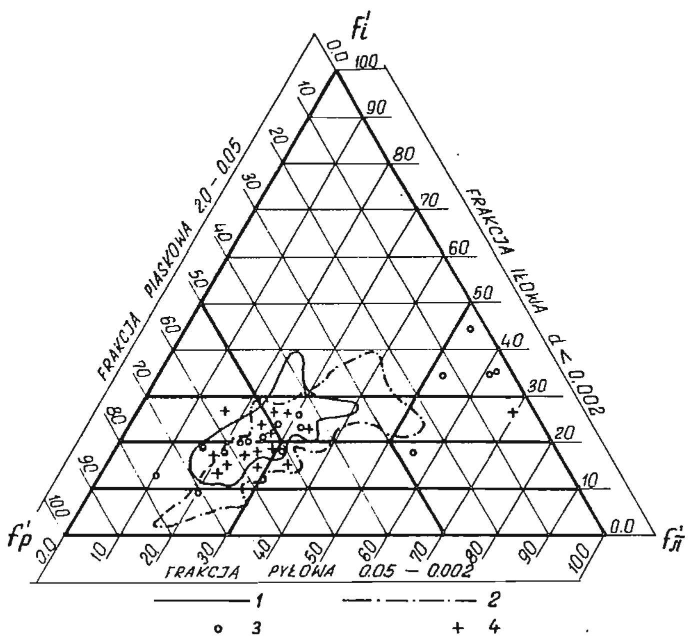

Fig. 2. The grain-size distribution in the horizons of boulder clays of Vistula Glaciation

1 — brown boulder clays of the Vistula Glaciation from Płock (after L. Wysokiński, 1967); 2 — grey boulder clay of the Odra Glaciation from Płock (after L. Wysokiński, 1967); 3 — Pomeranian Phase (16 samples investigated); 4 — Leszno Phase (14 samples investigated)

Rozkład uziarnienia w poziomach glin zwałowych zlodowacenia Wisły

1 — gliny brązowe zlodowacenia wisły z Płocka (według L. Wysokińskiego, 1967); 2 — gliny szare zlodowacenia odry z Płocka (według L. Wysokińskiego, 1967); 3 — faza pomorska (16 badań); 4 — faza leszczyńska (14 badań)

The boulder clays are characterized by the mutability of the grain size, genetically reasonable, existing in the vertical and horizontal profile. These sediments in the ground moraine do not show the sorting of the fragments and are marked by the evident compaction, sometimes by the horizontal parting and distinct orientation of the constituents. In the ground ablation moraine, the clays are without fine fraction because of the washing-out, and show smaller degree of compaction and lack of distinct orientation of the fragments. The frontal moraines contain much sandy-gravelly material.

In the boulder clays of Vistula Glaciation the sandy fraction forms the main constituent. The sediments investigated by granulometrical method (samples were taken at random) — Fig. 2 — form sandy loams (G_p, ML [1]) — 40%, clay loams (G_z,

[1] Symbols according to ASTM classification D-2487.

Table 1

The results of the investigations of the grain size distribution of the boulder clays of the Vistula Glaciation

Fraction		Pomeranian Phase Pm	Leszno Phase L	Vistula Glaciation Pm+L
Clay <0.002 mm [%]	R	8.0–45.0	13.0–28.0	8.0–45.0
	$\bar{x}$	22.8	19.1	21.1
	σ	9.369	4.470	7.713
	V	41.1	23.4	36.6
Silty 0.002–0.05 mm [%]	R	10.0–61.0	16.0–70.0	10.0–70.0
	$\bar{x}$	33.9	28.7	31.5
	σ	16.211	12.337	14.764
	V	47.8	43.0	46.9
Sandy 0.05–2.0 mm [%]	R	2.0–78.0	2.0–62.0	2.0–78.0
	$\bar{x}$	41.0	49.6	45.0
	σ	22.572	14.286	19.636
	V	55.1	28.8	43.6
Gravelly >2.0 mm [%]	R	0.0–10.0	0.0–4.0	0.0–10.0
	$\bar{x}$	2.2	2.5	2.4
	σ	3.112	1.239	2.429
	V	141.5	49.6	101.2
Coloidal activity, A	R	0.29–0.72	0.33–0.78	0.29–0.78
	$\bar{x}$	0.58	0.56	0.57
	σ	0.135	0.151	0.143
	V	23.3	27.0	25.1
Sorption capacity, MBC [g/100 g]	R	0.9–3.3	1.0–3.0	0.9–3.3
	$\bar{x}$	2.3	2.1	2.2
	σ	0.730	0.527	0.650
	V	31.7	25.1	29.5
Density surface, S_t [m^2/g]	R	19.1–66.6	25.4–63.7	19.1–66.6
	$\bar{x}$	48.1	43.2	45.8
	σ	15.212	11.267	13.742
	V	31.6	26.1	30.0

R — variation area, x_{min} — x_{max}; $\bar{x}$ — arithmetic mean ; σ — standard deviation; V — variation coefficient, $V = (\sigma : \bar{x})\,100\%$

ML) — 17%, sandy clay loams (G_{pz}, ML) — 13.5%, silty clays (Iπ, CL) — 13.5%. The rest consists of argillaceous sands (PG, SC), loams (G, ML) and silty loams (Gπ, ML).

The average contents of separate fractions, according to the results of investigations of 30 samples, is following: clay fraction — 8–45%, average 21.1%; silty fraction — 10–70%, average 31.5%; sandy fraction — 2–78%, average 45.0%; gravelly fraction — 0–10%, average 2.4%, while the coefficient of variation does not exceed 50% (Tab. 1).

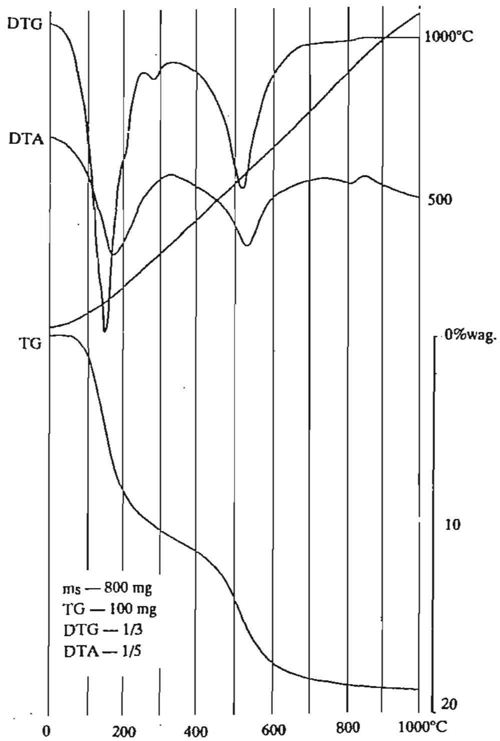

Fig. 3

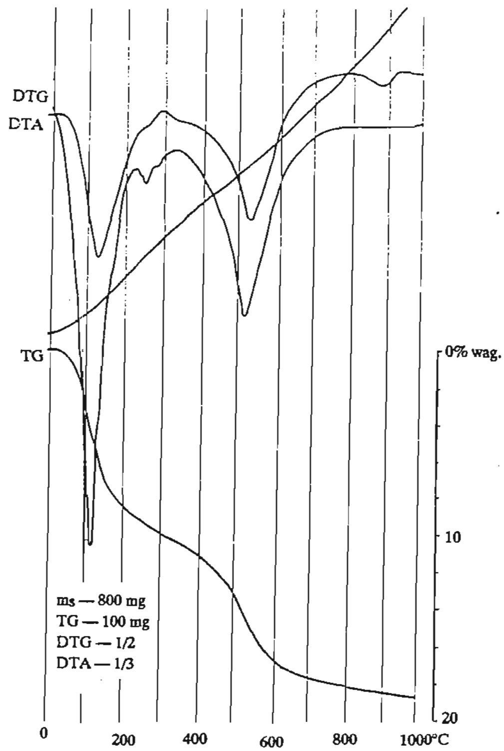

Fig. 4

Fig. 3. DTA curves of the clay fraction of the boulder clay (documentation point No. 11)
Derywatogram frakcji iłowej gliny zwałowej (punkt dokumentacyjny nr 11)
Fig. 4. DTA curves of the clay fraction of the boulder clay (documentation point No. 6)
Derywatogram frakcji iłowej gliny zwałowej (punkt dokumentacyjny nr 6)

Supplementary to the granulometric investigations are the microstructural investigations. In the boulder clays investigated, according to the photograms taken using the scanning electron microscope (SEM), following microstructures can be discerned (B. Grabowska-Olszewska et al., 1984): skeletal microstructure, skeletal-matrix (mixed) microstructure and matrix microstructure.

In the boulder clays with skeletal microstructures (Pl. I), the argillaceous material is unevenly distributed and does not form the homogeneous, continual matrix. It concentrates mostly at the surface of big sandy grains. This microstructure consists mainly of silty grains which together with clay particles form the contacts through "clay bridges". The orientation of the structural elements does not exist. The void spaces consist of the isometrical pores, uniformly spaced. The clay particles amount to 12–21%, mostly of the mixed-packet group — illite with small amount of montmorillonite. The porosity oscillates between 32 and 35%.

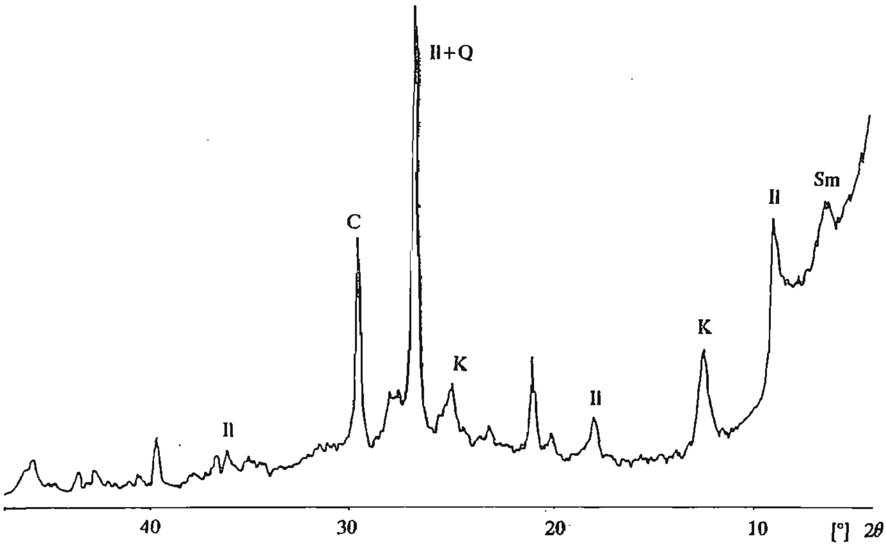

Fig. 5. The X-ray photograph of the clay fraction of the boulder clay (documentation point No. 19)
2θ — the angle of deflection; Il — illite; K — kaolinite; Q — quartz; C — carbon; S — smectite
Rentgenogram frakcji iłowej gliny zwałowej (punkt dokumentacyjny nr 19)
2θ — kąt ugięcia; Il — illit; K — kaolinit; Q — kwarc; C — węgiel; Sm — smektyt

The intermediate microstructure is represented by the boulder clays with skeletal--matrix microstructure (Pl. II). It is formed in the boulder clays containing 22 to 28% of the clay fraction and consists mainly of fragments covered with clay envelopes. The clay material does not form the typical matrix, but its presence can be observed at the contacts of the clay and silty grains. The void space consists of the isometric pores unevenly distributed. The distinct orientation is lacking; porosity amounts to 36–44%.

The boulder clays having the features of the matrix microstructure are shown in Pl. III. The clay material is evenly spaced in the whole mass, without distinct orientation, with silty and sandy grains plunged in it. The void space consists mostly of the isometric pores; the porosity is in the range of 45%.

In the boulder clays of Leszno Phase, the matrix microstructure was not found and the skeletal microstructure prevails over the skeletal-matrix microstructure. However, for the boulder clays of Pomeranian Phase characteristic is the skeletal microstructure. The two others types of microstructure exist in equilibrium.

The mineral composition of the clay fraction was established as a result of the thermal and X-ray analysis. Figs. 3 and 4 show the typical differential thermal analysis photographs for illite and montmorillonite; their interpretations were made using as a basis the paper of R. Wyrwicki (1988). In most of the samples of boulder clays investigated illite and the minerals of the mixed-packet group were found. Only in small number of cases montmorillonite prevails with association with illite. In some cases chlorite is observed as the admixture. Small amounts of kaolinite can be observed at the diffractograms (Fig. 5). The results shown above for the mineral composition

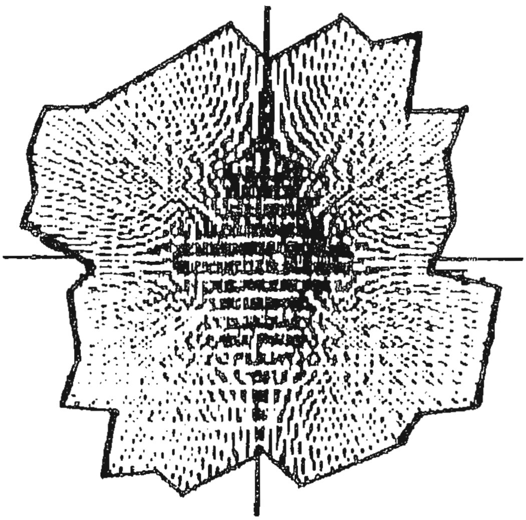

Fig. 6. The quantitative distribution of particle configuration
Ilościowy rozkład orientacji cząstek

Angle	Quantity
0–9	4.3
9–18	4.5
18–27	4.5
27–36	5.4
36–45	4.5
45–54	6.0 max1
54–63	5.2
63–72	5.5 max2
72–81	4.7
81–90	4.3
90–81	5.1
81–72	4.9
72–63	4.8
63–54	5.0
54–45	4.8
45–36	5.7
36–27	5.7
27–18	5.2
18–9	5.3
9–0	3.7

confirm generally the already known facts for the types of clay minerals encountered in these boulder clays (A. Stankowska, 1979).

The pictures obtained using the scanning electron microscope, when elaborated in the computer [2] allow to evaluate quantitatively the structure of the soils. This modern technique allows to obtain the data about the distribution of voids, particles and their orientation (structural anisotropy) — W. I. Osipow et al. (1989), V. N. Sokolov (1990).

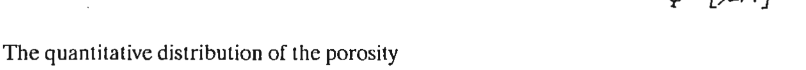

Fig. 7. The quantitative distribution of the porosity
n — porosity; ϕ — the pore diameter
Ilościowy rozkład porowatości
n — porowatość; ϕ — średnica porów

[2] The quantitative structural investigations using the scanning electron microscope — SEM — were made in the Department of Geology of Moscow University.

As an example, for the boulder clay from the documentation point No. 26, Fig. 6 shows the diagram of orientation of particles. Its shape is rounded and shows small anisotropy, about 10%. The diagram at Fig. 7 shows the distribution (in percent) of pore diameters.

The quantitative structural investigations of this type have great futurity in the prognosis of physical parameters of soils and rocks.

THE CHARACTERISTICS OF THE PHYSICAL PROPERTIES

The characteristics of basic properties of boulder clays of Vistula Glaciation was elaborated using the authors' own investigations made in one laboratory. The number of determinations for one parameter amounted to even 20. For these parameters the average values were computed together with the coefficient of variation. The authors possessed the results of investigations for 30 sites of sampling of the soils. For each documentation point about 100 numerical parameters were determined.

The specific density of the boulder clays investigated (Tab. 2) is changing between 2.63 and 2.75 g/cm^3, average 2.69 g/cm^3, with the coefficient of variation not exceeding 1.2%. The average specific density of the boulder clays of Pomeranian Phase amounts to 2.70 g/cm^3; of Leszno Phase, 2.69 g/cm^3. These values are characteristic for the boulder clays. The changes of the specific density reflect in the small degree the course of the postsedimentary processes.

The volume density. The mineral substances thawed out of the continental glacier and deposited as a sediment do not fill the whole space. The volume density in the natural state changes in the broad limits of 1.78–2.08 g/cm^3. The average volume density equals 1.91 g/cm^3, while for the boulder clays of Leszno Phase it is higher by 0.05 g/cm^3 than for Pomeranian Phase. The volume density of the soil skeleton (with the average volume density of 1.91 g/cm^3 and average natural water content of 15.6%) equals 1.65 g/cm^3.

For the characterization of the state of compaction — consolidation, W. A. Prikłoński in 1947 (1955) proposed the use of the degree of natural consolidation (K_d), taking into consideration two characteristic conditions of the sediment:

$$K_d = \frac{e_{wl} - e}{e_{wl} - e_{wp}}$$

where: e — void ratio in the natural state; e_{wl}, e_{wp} — void ratio at the liquid limit and plastic limit, respectively.

The degree of natural consolidation (K_d) according to W. A. Prikłoński is identical with the degree of consistency (I_k), introduced by the Polish standard PN-88/B-04481:

$$I_k = 1 - I_L$$

where: I_L — liquidity index.

Table 2

The collection of physical parameters of the boulder clays of Vistula Glaciation

Parameter		Pomeranian Phase Pm	Leszno Phase L	Vistula Glaciation Pm+L
1		2	3	4
Specific density, ρ_s [g/cm^3]	R $\bar{x}$ σ V	2.63–2.75 2.70 0.033 1.2	2.64–2.74 2.69 0.026 1.0	2.63–2.75 2.69 0.031 1.2
Volume density, ρ_o [g/cm^3]	R $\bar{x}$ σ V	1.78–1.98 1.88 0.069 3.7	1.80–2.08 1.93 0.078 4.0	1.78–2.08 1.90 0.079 4.2
Porosity, n [%]	R $\bar{x}$ σ V	32.8–44.6 40.7 3.430 8.4	31.4–41.4 36.6 3.011 8.2	31.4–44.6 38.8 3.825 9.9
Void ratio, e	R $\bar{x}$ σ V	0.49–0.84 0.69 0.106 15.4	0.46–0.71 0.58 0.075 12.9	0.46–0.84 0.64 0.107 16.7
Natural water content, w_n [%]	R $\bar{x}$ σ V	11.6–25.9 17.2 4.158 24.2	11.0–15.9 13.8 1.487 10.8	11.0–25.9 15.6 3.636 23.3
Plastic limit, w_P [%]	R $\bar{x}$ σ V	11.9–20.7 15.4 3.149 20.4	10.2–14.2 12.4 1.343 10.8	10.2–20.7 14.0 2.901 20.7
Liquid limit, w_L [%]	R $\bar{x}$ σ V	14.2–47.1 28.9 8.726 30.2	15.9–29.0 23.0 4.496 19.6	14.2–47.1 26.1 7.657 29.3
Plasticity index, I_P [%]	R $\bar{x}$ σ V	2.3–19.2 13.4 6.203 46.3	4.9–16.4 10.6 3.423 32.3	2.3–19.2 12.1 5.280 43.6
Liquidity index, I_L	R $\bar{x}$ σ V	–0.13–0.49 0.15 0.193 128.7	–0.08–0.51 0.16 0.153 95.6	–0.13–0.51 0.16 0.175 109.4

Tab. 2 continued

1	2		3	4
Saturation degree, S_r	R $\bar{x}$ σ V	0.49–0.89 0.68 0.115 16.9	0.50–0.77 0.64 0.083 13.0	0.49–0.89 0.66 0.102 15.5
Water content during full saturation, w_r [%]	R $\bar{x}$ σ V	19.9–30.9 26.1 3.384 13.0	17.3–25.5 21.6 2.780 12.9	17.3–30.9 24.0 3.818 15.9

Explanations as in Tab. 1

The values K_d and I_k for the boulder clays of Vistula Glaciation change in the interval 0.49–1.15, average 0.84. It means, that in most cases the inequality: $e_{wp} < e < e_{wl}$ is accomplished. It responds to the plastic and hard plastic consistence and indicates the nonconsolidated state ($K_d < 1$) of the boulder clays investigated (Fig. 8).

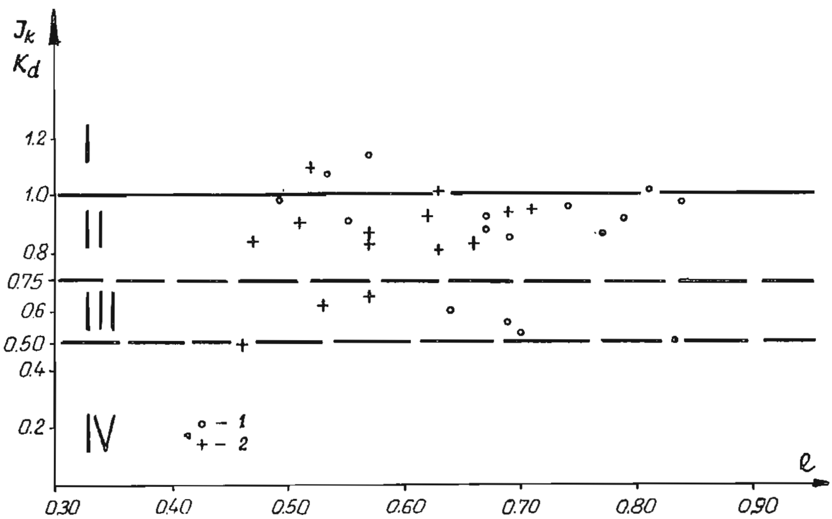

Fig. 8. The dependence degree of consistency (I_k) and the degree of natural consolidation (K_d) on the void ratio (e)

1 — boulder clays of Pomeranian Phase; 2 — boulder clays of Leszno Phase; I — $I_L < 0$, II — $I_L = 0.0$–0.25, III — $I_L = 0.25$–0.50, IV — $I_L = 0.50$–1.00

Zależność stopnia konsystencji (I_k) i stopnia naturalnego skonsolidowania (K_d) od wskaźnika porowatości (e)

1 — gliny zwałowe fazy pomorskiej; 2 — gliny zwałowe fazy leszczyńskiej; I — stan półzwarty i zwarty, II — stan twardoplastyczny, III — stan plastyczny, IV — stan miękkoplastyczny

N a t u r a l w a t e r c o n t e n t consists of water remaining from the saturation of the thawed-out sediments (boulder clays), much greater then, which during at least 20 thousands years were undergoing the dehydration, attaining the actual state of saturation. The samples of boulder clays were taken in the zone of aeration and their degree of saturation is changing in the limits: 0.49–0.89, average 0.66. However, the natural water content of boulder clays oscillates in the intervall: 11.0–25.9%, average 15.1% (the coefficient of variation equals 23.3%). The boulder clays of Pomeranian Phase have higher natural water contents and higher degree of saturation of the pores with water than the boulder clays of Leszno Phase. It can be connected with their younger age and with greater amount of the clay fraction in the boulder clays of Pomeranian Phase. The water content during full saturation of voids with water is changing in the limits 17.3–30.9% (average 24.0%) and the coefficient of variation is 15.9% (Tab. 2).

L i q u i d l i m i t — may indicate the processes which took part in the earliest stages of sedimentogenesis, when the liquid and semiliquid mass of the sediment started to become the boulder clay. The liquid limit of boulder clays is contained in the limits 14.2–47.1%, average 26.1%, with the coefficient of variation equaling 29.3%.

P l a s t i c l i m i t, which points to the processes which took part in the later stage of the sedimentogenesis, is changing in the limits 10.2–20.7%, average 14.0%, and the coefficient of variation equals 20.7%.

P l a s t i c i t y i n d e x is contained in the interval 2.3–19.2%, average value is 12.1%.

L i q u i d i t y i n d e x as the end effect of the whole set of processes taking part at the surface of clay particles (during several stages of sedimentogenesis and in part diagenesis) is changing in the broad limits from –0.13 to 0.51, average 0.16 (with the coefficient of variation 95–130%).

T h e c o n s i s t e n c e of boulder clays of both phases (Pomeranian and Leszno) is very much alike (liquidity index 0.0–0.50).

S o a k i n g, s w e l l i n g a n d s h r i n k i n g play the important role in the development of the weathering processes. As a result of soaking and cyclical swelling and shrinking the structural bonds are weakened, leading to their destroying and forming of the surface of discontinuity, that is, the disintegration of the primary structure of the soil.

The samples of boulder clays with the structure intact and the diameter and height of 3 cm were subjected to the investigations of soaking. The quantitative evaluation of soaking as a change of the mass of sample was shown by the indications of the areometer, to which the network container with the sample was connected. The soaking is determined by the index:

$$Z = \frac{a-c}{a-b} \cdot 100 \ [\%]$$

where: *a, b, c* — the areometer readings at the beginning, at the end and after the time *t*.

The value of soaking depends mainly on the mineral composition, the amount of the clay fraction, carbonates and the water content at the beginning.

The time of full desintegration of air dried clays (Z = 100%) is contained in the interval between 1 min to over 24 h, the average amounts to several (3–5) minutes. For the clays having the natural water content it takes from 3 min (Z = 100%) to 24 h (Z = 1.5%); the average value is 1–5 h (Z = 50–100%). The boulder clays with the granulometric composition corresponding to clays and the natural water content are soaking in small degree. In the course of soaking some textural and microstructural features of boulder clays are revealed, especially the network of cracks.

The investigation of swelling of the boulder clays were made in the traditional way in the oedometric ring; the change in height of the sample of soil is measured. For the samples of boulder clays having the natural water content and the structure intact, linear bulling index is in the limits 0.0–12.7%, and in most cases does not exceed 5%, and the water content after swelling is in the interval 17.3–36.5%; in this case these values are higher than the natural water content and the water content with full saturation of voids with water.

THE CHARACTERISTICS OF THE MECHANICAL PROPERTIES

Deformability. The parameters of deformation allow to determine the ultimate equilibrium of the soil medium. Uniaxial state of deformation plays an important role in the soil mechanics because of the analogy to the conditions encountered in the practice. During the sedimentation of sediments, in the course of the operation of perpendicular pressure with great extent in the plane, stresses and deformations appear, which are similar to the state happening when the lateral expansion is not possible.

In the laboratory, the testing of the boulder clays in the uniaxial state of deformation was made using the oedometer and the consolidometer, taking into account the indications given in the directions of Instytut Techniki Budowlanej No. 288 and 289 (A. Piaskowski, 1989*a*, *b*). The consolidometric method of testing allows to determine the parameters of consolidation, similar to these, which can be obtained in time-consuming oedometric tests with the traditional system of doubled pressure and the stabilization of deformations.

In the oedometric investigations made, the compressibility modulus of oedometer and the compressibility modulus was determined for the analogous interval of pressure: 50–100; 100–200; 200–400 kPa. However, in the consolidometric tests the modulus, the coefficient of consolidation and the over-consolidational pressure were determined.

The parameters determined, characterizing the deformational ability of boulder clays, are very differentiated. The coefficient of variation attains often 75–100%, and in the case of the coefficient of consolidation it exceeds 100%. The individual parameters are as follows:

— the compressibility modulus of oedometer (M_o) for the range of pressures 100–200 kPa is in the limits 1.2–28.0 MPa;

— the compressibility modulus (M_i) for the range of pressures 200–100 kPa is in the limits 16–647 MPa;

— the compressibility modulus determined in the consolidometer (M_k) for the range of pressures 100–200 kPa is in the limits 0.05–10.4 MPa;

— the coefficient of consolidation (C_v) is in the limits 0.01–2.0 x 10^{-5} cm/s^2.

The parameters computed for the compressibility of the boulder clays of Vistula Glaciation are decidedly lower than the values given in the nomograph in Polish standard.

It results from the investigations made, that the moduli of compressibility determined in the consolidometer are lower than the moduli evaluated in the oedometer, and the ratio of the oedometric modulus of compressibility to that determined using the consolidometer (M_o:M_k) depends on the range of pressures (50–100; 100–200 and 200–400) and equals (for the average values) correspondingly 2.38; 1.83; 1.16. However, the ratio of the oedometric modulus of compressibility with the correction for the modulus, without the correction of the oedometer itself, amounts to 1.22; 1.14; 1.10.

The coefficient of variation for the determinations of the parameters of deformation is of similar order, independently of the phase of glaciation from which the analysed samples of boulder clays were taken.

It ought to be pointed out, that in some papers published (A. Falkiewicz, 1962; J. Krajewska-Pinińska, 1969; L. Wysokiński, 1980) it was stated that the boulder clays, in spite of their random texture, may show the changeability and anisotropy: it touches especially the moduli of compressibility.

S h e a r s t r e n g t h . The fundamental characteristics of the resistance of soils is their shear strength. The main parameters of the shear strenght, that is the angle of internal friction and cohesion, are modelling in the first approximation the beginning of the process of shifting of one part of the soil against the other. It especially concerns the movements, which took part many times in the ground moraines. The angle of internal friction was increasing, beginning from the moment of forming of the sediment, starting from the minimal values (in the ground ablation moraine nearing to zero) till achieving the values of the actual state. The cohesion indicates the physical and physical-chemical processes of forming the bonds between the particlas of the boulder clays.

The investigations of shear strength (A. Piaskowski, 1979) were made: 1 — in the box shear apparatus (determination of S_k, Φ_{sk}, C_{sk}); 2 — in the compression triaxial apparatus by the method of repeated shearing (determination of Q_r, Φ_{Qr}, C_{Qr}); and 3 — in the compression triaxial apparatus by the method without consolidation without outlet with the measurement of water pressure in the pores of the soil (determination of *UU*, in the total normal stresses Φ_{uu}, C_{uu}, in the effective normal stresses Φ'_{uu}, C'_{uu}).

The investigations of the shearing repeated several times were made according to the directions of Z. Wiłun (1976).

All investigations were made using the samples of boulder clays with the intact structure and the natural water content; by the method 1 — 30 x 5 = 150 samples, by the method 2 — 30 x 1 = 30 samples, by the method 3 — 30 x 6 = 180 samples were investigated.

Because of the character of deformation of the boulder clays, two types of behaviour can be distinguished:

Table 3

The collection of the shear strength parameters of the boulder clays of Vistula Glaciation

Method			Parameter		Pomeranian Phase Pm	Leszno Phase L	Vistula Glaciation Pm+L
Box shear apparatus			angle of internal friction, Φ_{sk} [°]	R	15.5–32.0	13.0–27.5	13.0–32.0
				$\bar{x}$	21.7	21.3	21.5
				σ	4.579	3.499	4.116
				V	21.1	16.4	19.1
			cohesion, C_{sk} [kPa]	R	13.5–50.5	18.0–43.0	13.5–50.5
				$\bar{x}$	34.2	31.2	32.8
				σ	9.103	6.700	8.200
				V	26.6	21.5	25.0
Compression triaxial apparatus	method Q_r		angle of internal friction, Φ_{Qr} [°]	R	6.0–26.0	7.5–15.5	6.0–26.0
				$\bar{x}$	12.4	11.6	12.1
				σ	5.205	2.642	4.226
				V	42.0	22.8	34.9
			cohesion, C_{Qr} [kPa]	R	14.0–48.0	20.5–41.0	14.0–48.0
				$\bar{x}$	29.3	29.4	29.3
				σ	8.84	6.506	7.838
				V	30.2	22.1	26.8
	method UU	total normal stress	angle of internal friction, Φ_{uu} [°]	R	6.0–25.5	6.0–16.0	6.0–25.5
				$\bar{x}$	11.8	10.1	11.0
				σ	5.008	2.480	4.123
				V	42.1	24.6	37.5
			cohesion, C_{uu} [kPa]	R	0.5–43.5	14.5–39.0	0.5–43.5
				$\bar{x}$	24.0	26.2	25.0
				σ	9.127	8.361	8.843
				V	38.0	31.9	35.4
		effective normal stress	angle of internal friction, Φ'_{uu} [°]	R	11.0–28.5	13.5–23.5	11.0–28.5
				$\bar{x}$	18.3	18.4	18.4
				σ	4.775	3.496	4.227
				V	26.1	19.0	23.0
			cohesion, C'_{uu} [kPa]	R	2.0–43.5	12.5–32.0	2.0–43.5
				$\bar{x}$	23.7	22.3	23.0
				σ	8.793	7.365	8.186
				V	37.1	33.0	35.6
Primary stress, σ_{zy} [kPa]				R	27.0–58.0	27.0–94.0	27.0–94.0
				$\bar{x}$	35.5	50.6	42.5
				σ	9.772	24.395	19.626
				V	27.5	48.2	46.2

Explanations as in Tab. 1

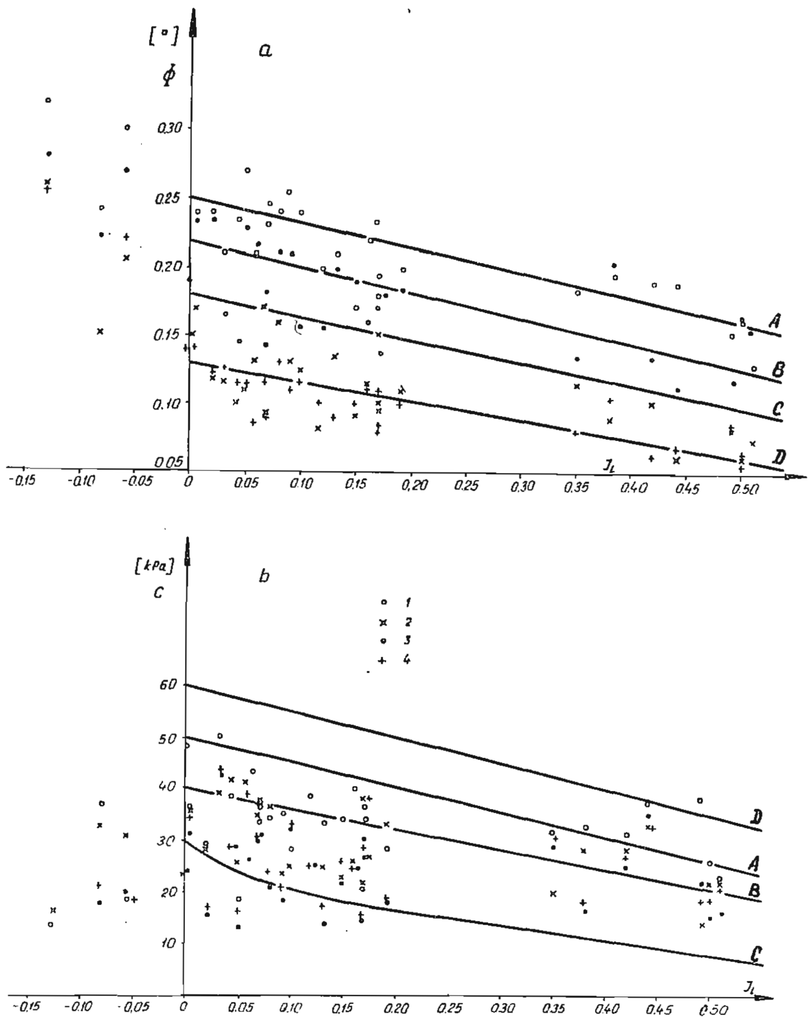

Fig. 9. The graphical representation of the results of investigations: the angle of internal friction (a) and cohesion (b) of the boulder clays of Vistula Glaciation at the nomographs given by Polish standard PN-81/B-03020

I_L — liquidity index; angle of internal friction determined using: 1 — box shear apparatus, 2 — compression triaxial apparatus Q_r, 3 — compression triaxial apparatus *UU*, 4 — compression triaxial apparatus *UU'*; A — cohesive, consolidated morainic soils; B — other cohesive, consolidated soils and cohesive, nonconsolidated morainic soils; C — other cohesive, nonconsolidated soils; D — clays (independent on geological origin)

Graficzne przedstawienie wyników badań kąta tarcia wewnętrznego (a) i spójności (b) glin zwałowych zlodowacenia Wisły na nomogramach z normy PN-81/B-03020

I_L — stopień plastyczności; kąt tarcia wewnętrznego oznaczony za pomocą: 1 — aparatu skrzynkowego, 2 — aparatu trójosiowego ściskania Q_r, 3 — aparatu trójosiowego ściskania *UU*, 4 — aparatu trójosiowego ściskania *UU'* ; A — grunty spoiste morenowe skonsolidowane; B — inne grunty spoiste skonsolidowane oraz grunty spoiste morenowe nieskonsolidowane; C — inne grunty spoiste nieskonsolidowane; D — iły (niezależnie od pochodzenia geologicznego)

— most of the samples of boulder clays were deformed plastically (the deformation of the "barrel" type), without the distinct diminishing of the deviator stress with the increase of the deformation. This type of destroying was characteristic for the samples of clays (I_L = 0.0–0.50).

— part of the samples (I_L < 0 and I_L = 0.0–0.25) were destroyed along the evident sliding surfaces. The surfaces were uneven; in the cases of the increased amount of clay fraction they were glimmering with evident sliding marks.

The pressure of water in the pores of the boulder clays investigated at the moment of destroying was always positive and in most cases it showed high values in the relation to the pressure used in the investigation chamber.

The statistical set of the parameters of the shear strength is given in the Tab. 3. Fig. 9 is the graphical image of the results for the cohesion and the angle of internal friction of the boulder clays of Vistula Glaciation at the background of the nomographs given in Polish standard PN-81/B-03020.

The results obtained show the distinct influence of the methods of investigations used on the parameters of shear strenght. If we treat the samples of boulder clays investigated as a whole (one geological bed), then the angle of internal friction and the cohesion are included in the limits 19–42%, while the boulder clays of Leszno Phase are distinctly less differentiated.

The parameters determined in the box shear apparatus (method 1) are:

— the angle of internal friction (Φ_{sk}) equals 13.0–32.0°; average 21.5°;

— the cohesion (C_{sk}) amouts to 13.5–50.5 kPa, average 32.8 kPa. These are the highest values achieved.

The results achieved in the compression triaxial apparatus by the method Q_r (the shearing of one sample repeated many times — method 2) are characterized by the greatest variability. The angle of internal friction (Φ_{Qr}) 6–26°, average 12.1°, is lower than the values achieved in the box shear apparatus and the cohesion (C_{Qr}) 14–48 kPa, average 29.3 kPa, is approaching the values achieved in the box shear apparatus.

The parameters of shearing strength (method 3) were computed separately for the effective normal stresses and total normal stresses. These parameters are as follows:

— for the total normal stresses the angle of internal friction (Φ_{uu}) 6.0–25.5°, average 11°; the cohesion (C_{uu}) 0.5–43.5 kPa, average 25.0 kPa;

— for the effective normal stresses the angle of internal friction (Φ'_{uu}) 11.0–28.3°, average 18.4°; the cohesion (C'_{uu}) 2.0–43.5 kPa, average 23.0 kPa.

The results (method 3) are generally lower than the results achieved using method 1. The angle of internal friction expressed in the effective normal stresses approximates the angle determined in the box shear apparatus ($\Phi'_{uu} \approx \Phi_{sk}$).

The results of determinations of the shear strength, and especially the average values for the angle of internal friction and cohesion, allow for the presentation of the following dependence between the parameters of the soil and the method of their determination:

$$C_{sk} \geq C_{Qr} > C_{uu} > C'_{uu} \quad , \quad \Phi_{sk} \geq \Phi'_{uu} > \Phi_{Qr} \approx \Phi_{uu}$$

The analysis of the results achieved does not allow to observe the distinct differences of the angle of internal friction and cohesion between the boulder clays of Pomeranian and Leszno phases.

The analysis of the values achieved for the angle of internal friction and cohesion at the background of the nomographs given in the Polish standard PN-81/B-03020 (treating the boulder clays tested as nonconsolidated — the group B) shows that (Fig. 9):

— The angles of internal friction Φ_{sk} are grouping around the straight line A. Nearest to the straight line B are the angles Φ'_{uu}, determined in the compression triaxial apparatus (the determination of *UU* — method 3). The angles of internal friction Φ_{Qr} and Φ_{uu} are distinctly lower than the values proposed by the standard.

— The cohesion of the boulder clays is changeable and depends less on the changes in the water content (the liquidity index). The results achieved in the box shear apparatus (C_{sk}) follow the line B.

The physical-mechanical and ocassionally structural properties of boulder clays occurring outside Poland have been presented in the following papers: A. W. Bishop (1971), A. McGown et al. (1974, 1975, 1977), D. G. McKinlay et al. (1975), A. W. Skempton, J. D. Brown (1961), P. R. Vaughan, H. J. Walbancke (1975).

SUMMARY AND CONCLUSIONS

The processes forming the physical-mechanical properties of the boulder clays have acted generally in various ways in the different morphological and climatological conditions of the sedimentation of clays, not identical in the successive phases of glaciation, and in different conditions of postgenetical alteration of these clays. Such conditions caused the relatively great mutability of properties of the basement of boulder clays of Vistula Glaciation. In the light of the field investigations made in 30 observation points in the Polish Lowland (Fig. 1), and the laboratory investigations (Tab.1–3) made in the subsurface zone of boulder clays (to 5 m below terrain surface), the following conclusions can be drawn:

1. The physical-mechanical properties of the boulder clays of Vistula Glaciation were formed during the last 20 000 years (Leszno and Pomeranian phases), when the boulder clays in most cases did not achieve full consolidation. They remain in the nonconsolidated state (the degree of natural consolidation K_d and the degree of consistency I_k do not generally exceed 1) and liquidity index I_L = 0.0–0.50. According to the terms used in the Polish standard PN-81/B-03020, the boulder clays may be considered as belonging to the B group.

2. In most boulder clays analysed illite and the minerals of the mixed-packet group are the main clay minerals. Only in small number of cases montmorillonite with some illite was prevailing. Chlorite and kaolinite exist as the admixture. Skeletal, skeletal--matrix and matrix microstructures are characteristic for the boulder clays investigated. The skeletal and skeletal-matrix microstructures are characteristic for the boulder clays of both Pomeranian and Leszno phases. In the clays of Leszno Phase the matrix microstructures are not observed (Pl. I–III). The use of the computer technics

to the structural investigations enabled for the quantitative evaluation of the photographs taken using the scanning electron microscope rendering possible the numerical expression of so called "packing" of the clay particles in the cohesive soil.

3. The physical properties of the boulder clays of Pomeranian and Leszno phases are similar, but for the clays of Leszno Phase somewhat greater compaction (higher density, lower porosity) is observed. The boulder clays of Pomeranian Phase show higher natural water content and higher water-logging. The clays of Vistula Glaciation, compared with the older (especially Middle-Polish Glaciation) glaciations, are characterized by distinctly lower volume density and higher porosity, natural water content and liquidity index, which shows that their consolidation is lower than in the case of older clays.

4. The results of investigations of the angle of internal friction and cohesion of boulder clays indicate the distinct influence of the methods of investigation and the type of apparatus used on the value of the parameters determined. The tests in the box shear apparatus (Φ_{sk}, C_{sk}), in the compression triaxial apparatus (the method of repeated shearing — Φ_{Qr}, C_{Qr} — and the method without consolidation and without outlet for the total normal stress Φ_{uu}, C_{uu} and the effective normal stress Φ'_{uu}, C'_{uu}) allows to establish the following dependencies:

$$C_{sk} \geq C_{Qr} > C_{uu} > C'_{uu} \quad , \quad \Phi_{sk} \geq \Phi'_{uu} > \Phi_{Qr} \approx \Phi_{uu}$$

5. The angles of internal friction and cohesion of the boulder clays of Pomeranian and Leszno phases are very similar. They indicate that at the background of the nomographs included in Polish standard PN-81/B-03020 the values of the angle of internal friction Φ'_{uu} and C_{sk} are gathered around the straight lines marked with the letter B. The rest of the parameters do not fit to the values given in the Polish standard. The physical parameters of the boulder clays investigated, like the parameters of shear strength and deformation, are lower than the data given in the published papers for the boulder clays of older glaciations.

6. The boulder clays containing more than 20% of the clay fraction are susceptible to the action of the exogenetic processes. The soaking and the cyclical swelling and shrinking cause quick desintegration of the soil, changing the properties of its top parts. The lack of suitable protection of the clays used as a base for building leads quickly to the change of the soil with good properties into the weathered soil with generally lower resistance.

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WŁAŚCIWOŚCI FIZYCZNO-MECHANICZNE I STRUKTURALNE GLIN ZWAŁOWYCH ZLODOWACENIA WISŁY NA OBSZARZE POLSKI

Streszczenie

Niniejszy artykuł, z uwagi na liczbę wykonanych badań oraz olbrzymi obszar występowania glin zwałowych zlodowacenia wisły, nie pretenduje do całościowego, regionalnego czy monograficznego ujęcia parametrów geotechnicznych. Może natomiast stanowić przewodnik po ich właściwościach, a także w przyszłości posłużyć do opracowania katalogu właściwości gruntów Polski. Próbki do badań laboratoryjnych pobrano z 30 punktów badawczych, wycięto przez skrawanie w zakresie głębokości 1,5–5 m poniżej poziomu terenu. Wszystkie badania właściwości glin zwałowych wykonano w laboratorium Instytutu Hydrogeologii i Geologii Inżynierskiej UW przez ten sam zespół pracowników.

Gliny zwałowe zlodowacenia wisły występują na terenie Polski północnej zajmując ponad 1/3 powierzchni całego obszaru kraju (fig. 1). Zlodowacenie to zaznaczyło się w terenie trzema wielkimi ciągami moren czołowych. Cechy litogenetyczne gruntów są związane z procesami, które formowały obecny ich stan. Procentowa zawartość poszczególnych frakcji wskazuje na dynamikę procesu wytapiania, transportu i sedymentacji. Pod względem granulometrycznym badane osady są wykształcone (fig. 2) jako: gliny piaszczyste — 40%, gliny zwięzłe — 17%, gliny piaszczyste zwięzłe — 13,5%, iły pylaste — 13,5% oraz piaski gliniaste, gliny i gliny pylaste.

Badania strukturalne wykonane w skaningowym mikroskopie (SEM) pozwoliły wyróżnić mikrostruktury: szkieletową, szkieletowo-matrycową (mieszaną) i matrycową (tabl. I–III). Otrzymane zdjęcia z SEM poddano obróbce komputerowej, otrzymując ilościową ocenę rozkładu wielkości porów i cząstek oraz ich ukierunkowania — orientacji (fig. 6).

Skład mineralny frakcji iłowej ustalono na podstawie badań termicznych i rentgenowskich. W większości próbek glin zwałowych występuje illit lub z grupy minerałów mieszanopakietowych — illit–montmorylonit.

Charakterystykę podstawowych właściwości fizycznych glin zwałowych zestawiono w tab. 2. Gęstość właściwa zmienia się w zakresie 2,63–2,75 g/cm^3. Gęstość objętościowa w stanie naturalnym wynosi 1,78–2,08 g/cm^3. Wilgotność naturalna waha się w przedziale 11,0–25,9%, przy średniej 15,1%. Gliny zwałowe fazy pomorskiej wykazują wyższą wilgotność naturalną i stopień nasycenia porów wodą od glin fazy leszczyńskiej. Granica płynności mieści się w zakresie 14,2–47,1%, a granica plastyczności — 10,2–20,7%. Konsystencja glin zwałowych obu faz jest bardzo zbliżona, wykazując przede wszystkim stan plastyczny i twardoplastyczny oraz sporadycznie półzwarty i miękkoplastyczny. Rozmakanie i pęcznienie wywołuje osłabienie wiązań strukturalnych i prowadzi do ich zniszczenia i powstania powierzchni nieciągłości. Czas całkowitego rozpadu od wilgotności naturalnej zmienia się od 3 min do 24 h, a od wilgotności w stanie powietrzno-suchym — od 1 min do ponad 24 h. Badania pęcznienia przeprowadzono w pierścieniach edometrycznych, a wskaźnik pęcznienia przekracza przeważnie 5%.

Charakterystykę właściwości mechanicznych rozpoczyna odkształcalność, pozwalająca określić równowagę graniczną ośrodka gruntowego. Badania w jednoosiowym stanie odkształceń przeprowadzono w edometrze i konsolidometrze. Wyznaczono moduły ściśliwości obiema metodami, a ponadto współczynnik konsolidacji i obciążenie prekonsolidacyjne.

Wyznaczone paramtery są niezwykle zróżnicowane. Współczynnik zmienności często dochodzi do 75–100%, a moduły ściśliwości wyznaczone w konsolidometrze są niższe od modułów określonych w edometrze.

Podstawową charakterystykę wytrzymałościową stanowi wytrzymałość na ścinanie, z głównymi parametrami: kątem tarcia wewnętrznego i spójnością. Badania przeprowadzono w aparacie skrzynkowym i trójosiowego ścinania (metodą kilkakrotnego ścinania oraz bez konsolidacji bez odpływu z pomiarem ciśnienia wody w porach gruntu).

Większość próbek deformowała się w sposób plastyczny — odkształcenia typu „beczki" szczególnie dla glin w stanie plastycznym i twardoplastycznym. Część próbek glin w stanie półzwartym i twardoplastycznym uległa zniszczeniu po wyraźnych powierzchniach poślizgu.

Kąt tarcia wewnętrznego i spójność wykazują zmienność od 19 do 42%, przy czym wyraźnie mniej zmienne okazują się gliny fazy leszczyńskiej. Analizę kąta tarcia wewnętrznego i spójności na tle załączonych w normie PN-81/B-03020 nomogramów pokazuje fig. 9.

Procesy kształtujące właściwości fizyczno-mechaniczne glin zwałowych spowodowały dużą zmienność właściwości podłoża. W trakcie ostatnich 20 tys. lat nie osiągnęły stanu pełnego skonsolidowania i według terminologii stosowanej w normie PN-81/B-03020 można uznać je za grunty należące do grupy B.

PLATE I

Fig. 1. The microstructural surface of the boulder clay, documentation point No. 18; SEM; the skeletal microstructure
Powierzchnia mikrostrukturalna gliny zwałowej; punkt dokumentacyjny nr 18; SEM; mikrostruktura szkieletowa

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PLATE II

Fig. 2. The microstructural surface of the boulder clay, documentation point No. 23; SEM; the skeletal-matrix microstructure
Powierzchnia mikrostrukturalna gliny zwałowej; punkt dokumentacyjny nr 23; SEM; mikrostruktura szkieletowo-matrycowa

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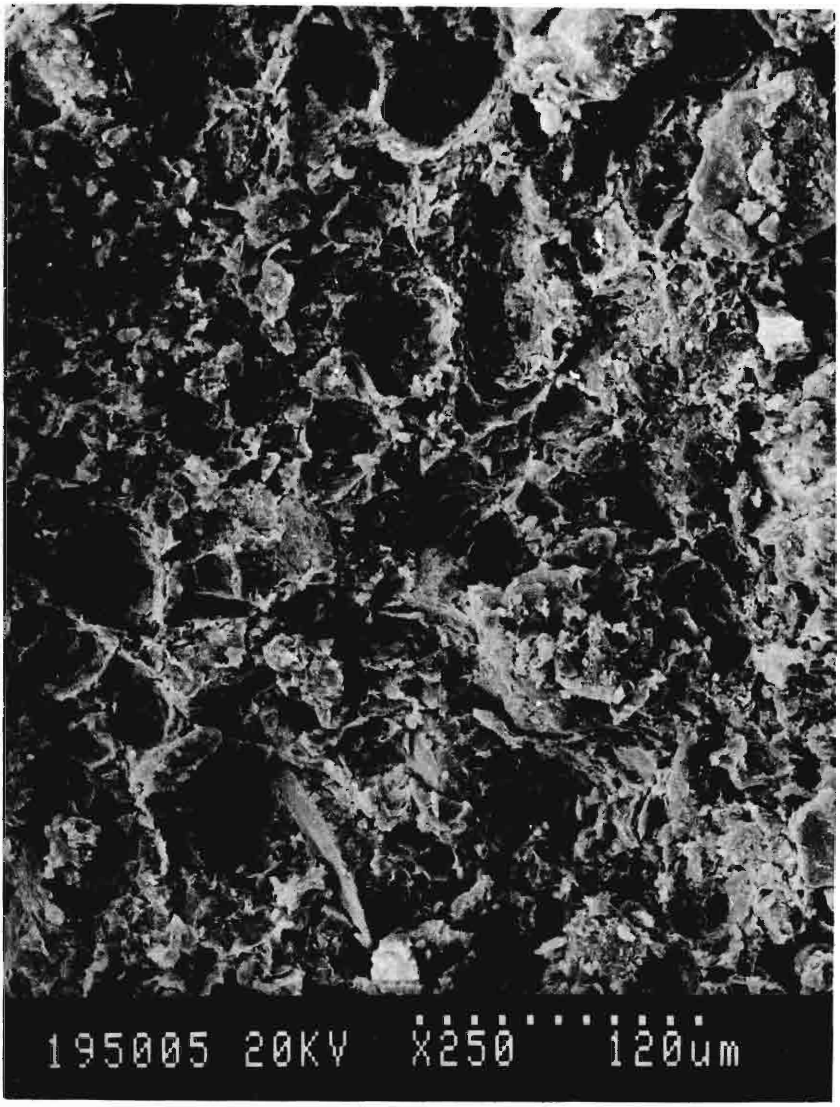
PLATE III

Fig. 3. The microstructural surface of the boulder clay, documentation point No. 5; SEM; the matrix microstructure

Powierzchnia mikrostrukturalna gliny zwałowej; punkt dokumentacyjny nr 5; SEM; mikrostruktura matrycowa



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