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Overconsolidation and microstructures in Neogene clays from the Warsaw area

Ryszard KACZYŃSKI

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The main objective of the study was determine the loading history and establish the current state of consolidation of Neogene clays, to study their lithological and microstructural properties, and to define their geological-engineering properties. To accomplish this task, series of laboratory and field tests were performed. The tests were made on clays taken from pits excavated for underground stations and tunnels (A-14–A-15) in Warsaw and from 2 borehole cores taken from the Stegny experimental field. The tests showed that: the clays are historically overconsolidated with an OCR ratio of 25–50 and their current state of preconsolidation is OCR = 2–14; their range of clay microstructures, observed for the first time, are matrix-turbulent and turbulent-laminar and there was a clear anisotropy of quantitative parameters of the pore paces, these parameters varying with depth. The engineering-geological characteristics (physical and mechanical properties) of the clays were assessed. The results of the study can be used directly to evaluate the Neogene clays of the Warsaw area for their suitability as a subsoil for engineering projects and indirectly to accomplish the same with other overconsolidated soils, particularly in regard to the study methodologies applied and described.

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INTRODUCTION

The Neogene clays currently constitute, and will increasingly often constitute, the subsoil for building structures. Presently ten-storey and higher buildings are built with a number of levels of underground garages. An underground railway is currently under construction in Warsaw. Proper recognition of soil behaviour under load requires identification of microstructure (porous space quantitative parameters) and maximum current pre-consolidation load (i.e. such that the soil still "remembers"), as well as calculation of the overconsolidation ratio, because the shear strength envelope before and after exceeding the memorised loads is not identical. The character of compression curves also changes.

The test material constituted the Neogene clays of the Warsaw area: of the uplands in the vicinity of the A-14 and A-15 underground railway stations, and in Vistula River valley in the area of the Oligocene water borehole in the neighbourhood of Czarnomorska Street in the Stegny district.

GEOLOGICAL SETTING OF THE NEOGENE CLAYS

The Neogene clays occur across much of Poland, usually under an overburden of Quaternary deposits of varying thicknesses. They represent the youngest Neogene interval (the Late Miocene and the Pliocene) and are often referred to as the Neogene clays. Within the lake basin where clays settled, Dyjor (1970, 1992) distinguished the following zones:

— a central zone with three main lithostratigraphic units (lower: grey clays, middle: green clays, and upper: flame-coloured clays);

— offshore (Fore-Sudetic) zone;

— zone adjacent to Fore-Sudetic area;

Wichrowski (1981) gave detailed descriptions of the Pliocene clays in the three best-researched parts of the sedimentary basin (Fig. 1):

— northeastern part (region A);

— central part (region B);

— southwestern part (region C).

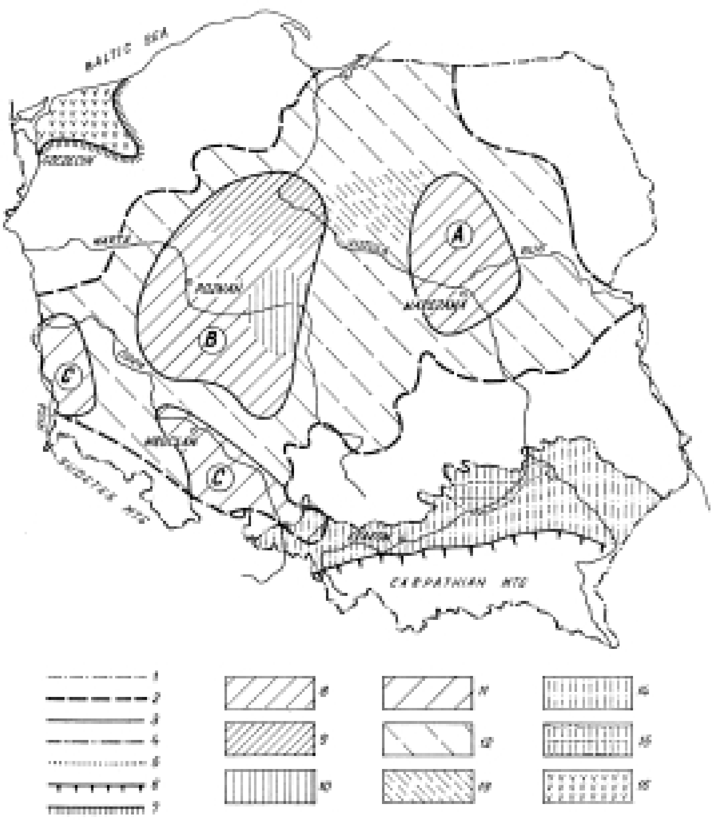


Fig. 1. Map of occurrence of the analysed Neogene clays in Poland (Wichrowski, 1981; Kaczyński and Grabowska-Olszewska, 1997; Grabowska-Olszewska, 1998)

1 — Polish border; 2 — limit of occurrence of Neogene clays of the Poznań series; 3 — boundary lines of regions A–C; 4 — limit of occurrence of Miocene clays of the Carpathian Foredeep; 5 — boundary between clays of different activities; 6 — Carpathian Thrust; 7 — limit of occurrence of Oligocene clays and Neogene clays of the Poznań series; 8 — regions A and B, PE medium (PE — potential expansivness), high and very high, activity A = 0.75–1.25; 9 — region B, PE very high, activity A = 0.75–1.25 and A = 1.25–2.0; 10 — region B, PE high and very high, activity A = 1.25–2.0; 11 — region C, PE medium, high and very high, activity A < 0.75; 12 — anticipated PE medium, high and very high; 13 — anticipated PE very high, Miocene clays on the Carpathian Foredeep; 14 — PE medium, high and very high, activity A = 0.5–1.0; 15 — PE medium, high and very high, activity A = 1.0–4.0, Oligocene clays; 16 — PE very high, activity A = 0.75–2.0

Sedimentation of the Neogene clays shows a distinct periodicity with interbedding of clay and silty sandy units. Over large areas clays were subjected to glaciotectonic dislocations which led to creation of folds, decolbments, displacements — often rearranging the typical sequence of strata. In geological sections different lithostratigraphic units may occur at the same depth.

Warsaw is located in the northwestern (peripheral) part of the basin. This setting is associated with a lower clay content; according to Fortunat (1960) clays constitute only *ca.* 30% here. The Neogene deposits across almost all of the Warsaw area are present below an overburden of Quaternary deposits. The Neogene top surface in Warsaw (Fig. 2) is not even; numerous uplifts and dips are observed, chiefly in the NNW-SSE direction; their genesis is linked to glaciotectonics and erosion processes. The relief on the clay top surface approaches 100 m. Occasionally the Neogene top surface comes to the ground surface (e.g. City Centre elevation); the outcrop of clays on the edge of the upland on the Vistula left bank occurs below a thin overburden of Quaternary and anthropogenic deposits (Żoliborz and Babice Stare). The Babice Stare–Żoliborz–City Centre elevation is secondarily uplifted due to glaciotectonic processes. The Neogene clay roof in these zones reaches the 110 m a.s.l. datum, while elsewhere it extends down to between –20 m and –40 m b.s.l. At the underground railway segment within the area of the A-14 to A-15 stations the Neogene clays occur at depths 2–10 m below surface (100–113 m a.s.l.), while in the Vistula valley, in Stegny, at depths of 4–5 m below surface (82–75 m a.s.l.). The average thickness of the Neogene clays is *ca*. 50 m, reaching a maximum of as much as 100–150 m in

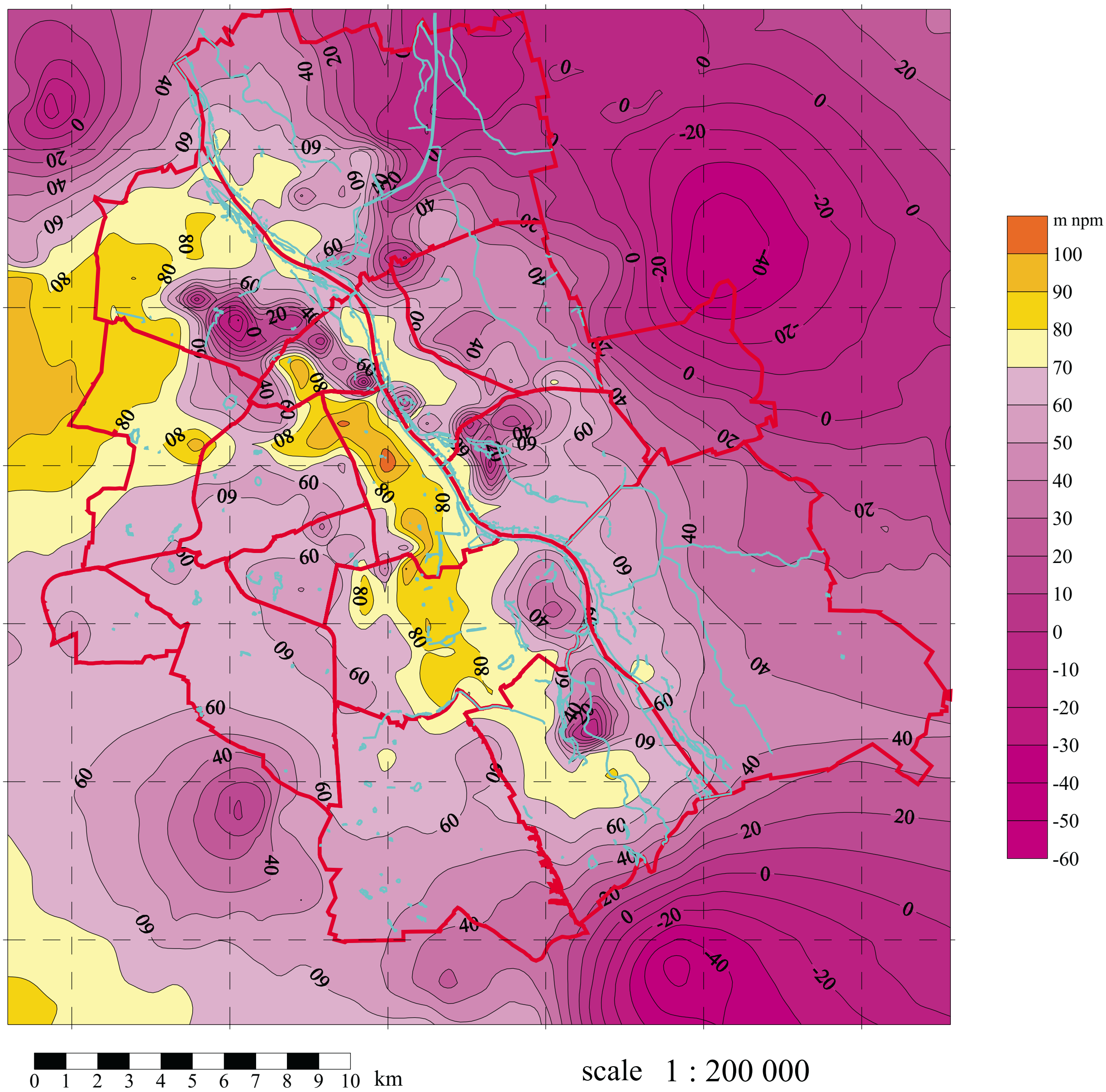


Fig. 2. Map of the top surface of Neogene clays from the Warsaw area (according to Frankowski *et al.*, unpubl.)

1 — Warsaw underground, A-14 station; 2 — experimental Warsaw-Stegny plot; red lines — Warsaw districts' borders; blue lines and spots — surface waters

zones of glaciotectonic dislocations (Wysokiński, 1999; Frankowski *et al.*, unpubl.).

LITHOLOGICAL CHARACTERISTICS OF THE NEOGENE CLAYS

GRANULOMETRIC AND MINERAL COMPOSITION

The Neogene clays comprise a succession of clays and underlying sandy-silty deposits of lacustrine origin. Test results of properties of clays from the Warsaw area can be found in many publications (e.g. Stamatello and Rossman, 1955; Fortunat, 1960; Piaskowski, 1963; Kłębek and Łoszewski, 1981). A couple of thousand analyses have been made, thought only *ca.* 1000 have been published. The granulometric composition, according to published data and my own analyses are shown in Tables 1 and 2.

The mineral composition of the Neogene clays has been examined by many authors. Generally it is quite monotonous. The main components are clay minerals and quartz. Feldspars and micas are subordinate; moreover there are present: siderite, pyrite, gypsum, marcasite, goethite and hematite causing intensive cherry-red colouring; and also hydrated oxides producing

Table 1

Granulometric composition of Neogene clays

Statistical parameters	Fraction content [%]			Kind of soil
	Clay < 2µm	Silt 2–50µm	Sand 50–2000µm	
Range of variability	28–89	11–64	0–29	clay, silty clay, silty clay with sand
Arithmetical mean	56	37.5	6.5	
Standard deviation	19	17	8	
Variability of coefficient	34	46	75	

Number of tests = 25–30

yellow and rust colours. Generally in flame-coloured clays trivalent iron (Fe^{3+}) is present, while in grey, blue-grey and green clays divalent iron is found in varying quantities. Calcium carbonate contents do not exceed 5%, and organic matter does not exceed 1%. Mineralogical studies carried by Wyrwicki and Wiewióra (1972), Wiewióra and Wyrwicki (1974), Wichrowski (1981), Wyrwicki (1998 and unpubl.) and Łuczak-Wilamowska (2002) indicate that clay minerals in the Pliocene deposits are represented by mixed-packet minerals of the beidellite-illite series.

Examination of the mineral composition of clays from the Stegny and Warsaw underground railway line were carried out using derivatographic analysis (differential thermal analysis — DTA). *Modern Setaram Labsys TG-DTA/DSC 1600* instruments were used. The test procedure according to Wyrwicki (1996) was used to determine quantitative composition. Analysis of the Stegny clays (Table 3) indicate as follows:

— clay minerals constitute the dominant component (40–80%), consisting of: beidellite — B, illite — I and kaolinite — K in varying proportions,

— in the Stegny vertical section (to 12 m b.g.l.) the content of clay minerals decreases with depth (80–40%), as does the content of illite (44–9%), while the content of beidellite (53–80%) and kaolinite (3–11%) increases,

— the second most abundant mineral is quartz, and its content together with other thermally inactive materials increases with depth from 13 to 57%,

— goethite only occasionally occurs (1.2–6.3%), as does organic matter (0.2–0.8%); their content decreases with depth.

The compositions of underground railway line clays are similar to those of Stegny, though the content of beidellite reaches 85%, while that of kaolinite reaches 30%, and the content of illite can be zero.

MICROSTRUCTURES

The Neogene clays were examined as regards quantitative microstructural analysis using a scanning electron microscope (SEM), using procedures described by Grabowska-Olszewska *et al*. (1984), Osipov *et al*. (1989), Sokolov (1990), Kaczyński and Trzciński (1997) and Trzciński (1998). In these analyses it was possible to determine the microstructure type as well as quantitative morphometric and geometric parameters (Table 4. Figs. 3 and 4). Scanned clay microstructure images were prepared using a SEM and computer with STIMAN'S software.

The Warsaw Neogene clays are characterised by transient — mixed microstructural types, with matrix, turbulent and laminar microstructure (Kaczyński, 2000, 2001). Matrix and laminar microstructure can be either syngenetic or epigenetic, while the turbulent one is epigenetic only it forms mainly under the influence of gravitational compaction. Matrix microstructure is characterised by the occurrence of uniform clay material (matrix) where silt or sand grains are distributed in a chaotic pattern (Sides, 1972). Laminar microstructure is characterised by well-developed grading and a high degree of orientation of microstructural elements. In the case of turbulent microstructure, clay particles float around sandy or silty grains. Analysis of photographs of the examined soils indicate the following main types:

— matrix-turbulent microstructure,

— laminar-turbulent microstructure.

The results of SEM quantitative analysis appear as follows:

— the porosity of the clays varies from 37 to 52%. At depths down to to 8 metres (in the Stegny section) the porosity is: 43–52%, while below 8 m it decreases to: 42–37%,

— the number of pores N varies from 347×10^3 to 73×10^3 and is not distinctly correlated with the porosity n. To a depth of 8 m the number of pores is smaller, and their average surface S_{av} (4.4–15.0) is larger, so they are bigger. Below 8 metres there are more pores, and they are smaller (S_{av} = 2.6–7.5), except

Table 2

Average granulometric composition of Neogene clays according to different authors

Fraction contents [%]	Piaskowski, 1963	Frankowski *et al*., (unpubl.)	KBN Grant UW-2000 (unpubl.)	Average composition
Clay fraction	~30	39	~56	40
Silt fraction	~50	45	~37.5	45
Sand fraction	~20	19	~ 6.5	15
Number of tests	636	25–27	25–30	~ 700

Table 3

Results of differential thermal analysis of Neogene clays

Samples		STG 5		STG 7.2		STG 12.5		Stegny Warneńska St. depth 10.0–10.7		Stacja A-15 Bankowy Sq. depth 7.0		A-14/B-15 tunnel inlet depth 6.0		Station A-14 depth 5.0	
Clay minerals [%]	proportion B:I:K [%]	$B^{53}=(I^{44}+K^{3})$		$B^{68}>>(I^{26}+K^{6})$		$B^{80}>>>(K^{11}+I^{9})$		$B^{50}=(I^{30}+K^{20})$		$B^{73}>>(I^{18}+K^{9})$		$B^{60}>(K^{30}+I^{10})$		$B^{85}>>>K^{15}$	
including:		80.0		64.3		41.8		67.8		57.0		74.6		91.0	
- beidellite		42.4		43.7		33.4		33.9		41.6		44.8		77.4	
- illite		35.2	80.0	16.7	64.3	3.8	41.8	20.3	67.8	10.3	57.0	7.4	74.6	–	91.0
- kaolinite		2.4		3.9		4.6		13.6		5.1		22.4		13.6	
Gethite		6.3		1.4		1.2		4.9		1.2		7.4		8.6	
Organic matter		0.8		0.5		0.2		0.5		0.4		0.5		0.4	
Quartz+thermally inactive components		12.9		33.8		56.8		26.8		41.4		26.8		–	
Total		100.0		100.0		100.0		100.0		100.0		100.0		100.0	

B — beidellite, I — illite, K — kaolinite

from the STG-12 sample (which contains significantly less clay fraction),

— the total area of pores S_t, throughout the Stegny section, has an approximately constant value of 870×10^3 µm^2 to 1091×10^3 µm^2,

— the average form index K_{fav} of pores reaches higher values at the depths down to 8 m. This is because the pores are more oval-shaped than those in deeper-lying clays,

— the coefficient of microstructural anisotropy K_a to a depth of 8 m b.g.l. reaches lower values (12–28%) in relation to clays lying deeper (15–38%). This indicates a higher degree of orientation of microstructure in clays occurring below 8 metres depth.

BASIC ENGINEERING-GEOLOGICAL PROPERTIES OF THE NEOGENE CLAYS

The following engineering-geological properties of soil can be classified as basic:

— consistency parameters,

— parameters of density and saturation.

Detailed parameters are given in Tables 5 and 6.

Analysis shows that the physical parameters of the Stegny clays are very close to parameters characterising other clays from Warsaw (mainly from the underground railway line). Moreover, it was observed that:

— the natural water contents w_n are close to total water contents at full saturation: w_r, $w_n \approx w_r$; the degree of saturation S_r is most often above 0.97, at average $S_r \approx 1$,

— natural water contents w_n are usually lower (only occasionally higher) than the plastic limit w_p, whereas $w_s < w_n < w_p < w_L$ indicate that clays are characterised by a semi-compact consistency (liquidity index is –0.09 on average), and only rarely have hard-plastic consistency (w_s denotes shrinkage limit),

— average parameters denoting natural compactibility of clays are within the following limits: natural bulk density = 2.00 Mg/m^3, dry bulk density = 1.60 Mg/m^3, porosity = 41%, void ratio = 0.70 — which indicates that there were external loads during their geological history,

— Prikłoński's consolidation coefficient $K_P = 1 - I_L$ is on average equal to $K_P = 1 - (-0.09) = 1.09$, indicating overcompacted soils, i.e. over consolidation,

— the colloidal activity A is on average equal to 0.70-0.80, placing the examined soils close to normally active,

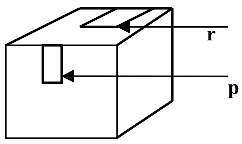
— in the Stegny vertical section at depths to 12 m below the ground, the rise of volumetric density from 1.88 to 2.10 Mg/m^3, and the decrease of porosity from 49 to 40% was observed with increase of depth.

Table 4

Quantitative investigations of the microstructure (SEM) of Neogene clays

Parameters of porous space	Location										
	STG 5p	STG 5r	STG 6.3p	STG 7.2p	STG 7.2r	STG 8p	STG 9.6p	STG 10p	STG 11.3p	STG 11.3r	STG 12p
Porosity n %	45.6	52.0	43.0	49.2	51.3	42.0	37.4	45.3	45.8	45.3	37.1
Number of pores N x 10^3	158	172	226	73	197	269	342	347	134	144	74
Average diameter of pores D_{av} µm	1.15	1.11	0.99	1.82	1.13	1.08	0.79	0.95	1.35	1.53	0.81
Total pore area S_t x 10^3 µm^2	1059	1108	993	1091	1181	1036	870	1020	1003	1043	202
Average pore area S_{av} µm^2	6.70	6.45	4.40	15.02	5.98	3.85	2.55	2.94	7.49	7.23	2.72
Total pore perimeter P_t x10^3 µm	1375	1479	1653	1006	1681	2264	2152	2393	1365	1601	467
Average pore perimeter P_{av} µm	8.70	8.61	7.32	13.86	8.51	8.42	6.29	6.89	10.20	11.10	6.27
Average form index of pores K_{fav}	0.522	0.470	0.517	0.453	0.517	0.506	0.489	0.500	0.432	0.437	0.501
Prevailing direction of pore orientation α °	28.3	9.5	176.6	4.9	1.8	18.9	173.2	11.7	171.9	178.5	103.5
Anisotropy coefficient of microstr. K_a %	12.8	29.3	20.5	18.4	28.3	25.9	29.6	38.0	32.3	25.8	15.4
Range of microstructure orientation	medium	high	medium	medium	high	high	high	high	high	high	medium

p — vertical orientated sample,
r — horizontal orientated sample
STG 5p — the place (STG — Stegny) and depth (5m) of sampling



OVERCONSOLIDATION OF THE NEOGENE CLAYS

LOADING HISTORY

During early Quaternary times the Neogene clays were covered by sandy-gravel alluvial deposits (without Scandinavian material) few to twenty metres thick. Pleistocene ice sheets covered the Warsaw area at least three times, as indicated by three main tills. Analysis of the publications of Domosławska-Baraniecka and Gadomska (1965), Mojski and Domo - s≥awska-Baraniecka (1965), Brykczyńska and Brykczyński (1974), Sarnacka (1979, 1980, 1992), Ruszczyńska-Szenajch (1985), Morawski and Sarnacka (1989), Lindner (1992), Marks (1992), Baraniecka (1995), Wysoczański-Minkowicz (1995) and the Warsaw University grant, indicate that, during the Quaternary, the clays were loaded by ice sheets of the:

— South-Polish Glaciation: ca. 800–1000 m thick, 660–500 kyrs, i.e. during ca. 160 kyrs;

— Middle-Polish glaciations: Odra stage: *ca*. 500–700 m thick, 320–300 kyrs, i.e. during *ca.* 20 kyrs; Warta stage: *ca.* 200–300 m thick, 150–135 kyrs, i.e. during less than 20 kyrs.

Hence all the ice sheets combined together were *ca*. 2000 m thick and loaded the Neogene clays for *ca*. 200 kyrs, whereas the entire Pleistocene lasted for *ca*. 1 million years. Interglacial periods were longer than glacial ones. The influence of each ice sheet upon the state of clay consolidation was different. Cer-

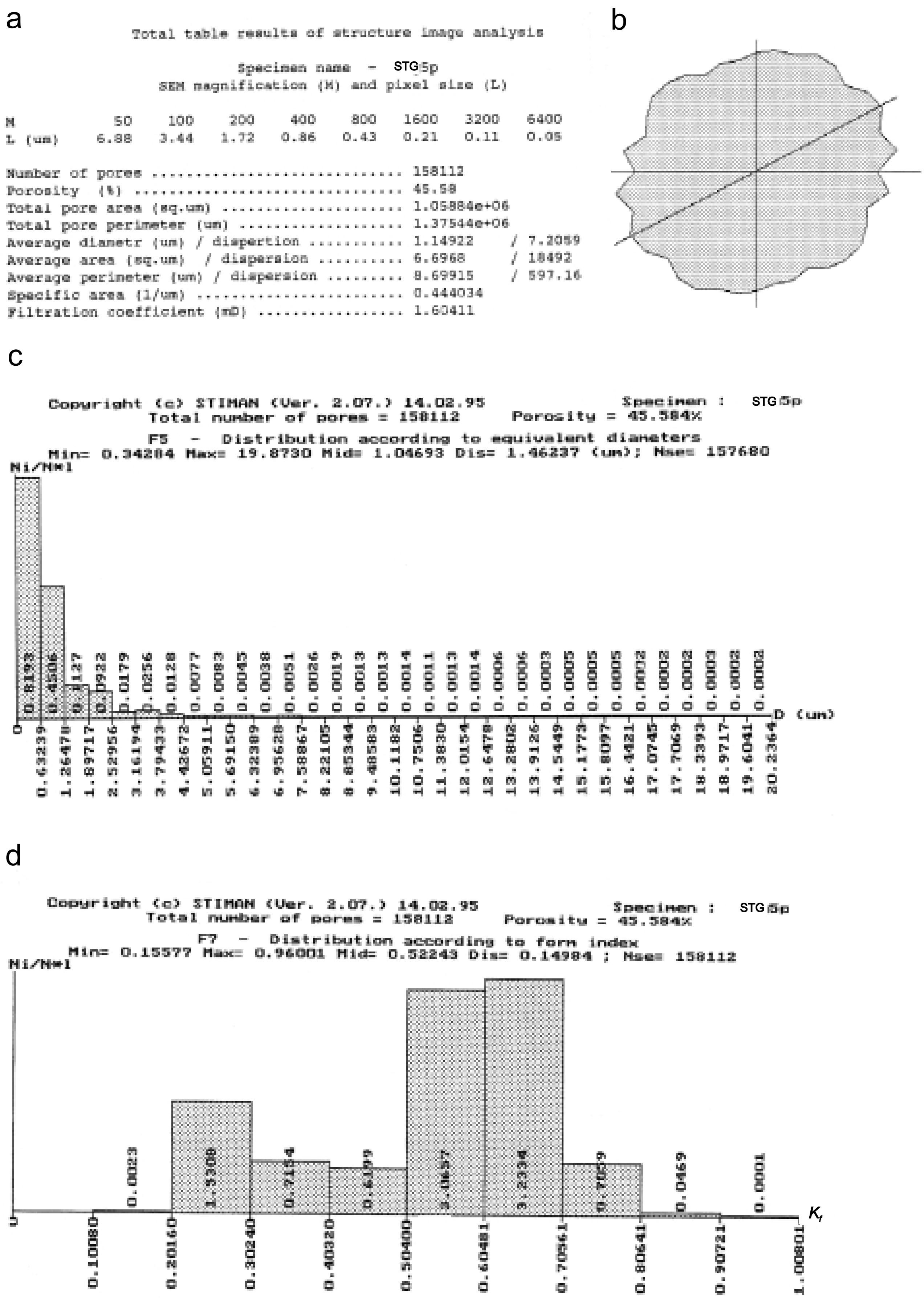


Fig. 3. A typical full computer printout of quantitative microstructural analysis of Neogene clays using STIMAN'S software

a — microstructural parameters of porous space for sample STG 5p; b — diagram showing orientation of structural elements for sample STG 5p; c — histogram of distribution according to equivalent diameter for sample STG 5p; d — histogram of distribution according to form index K_f for sample STG 5p

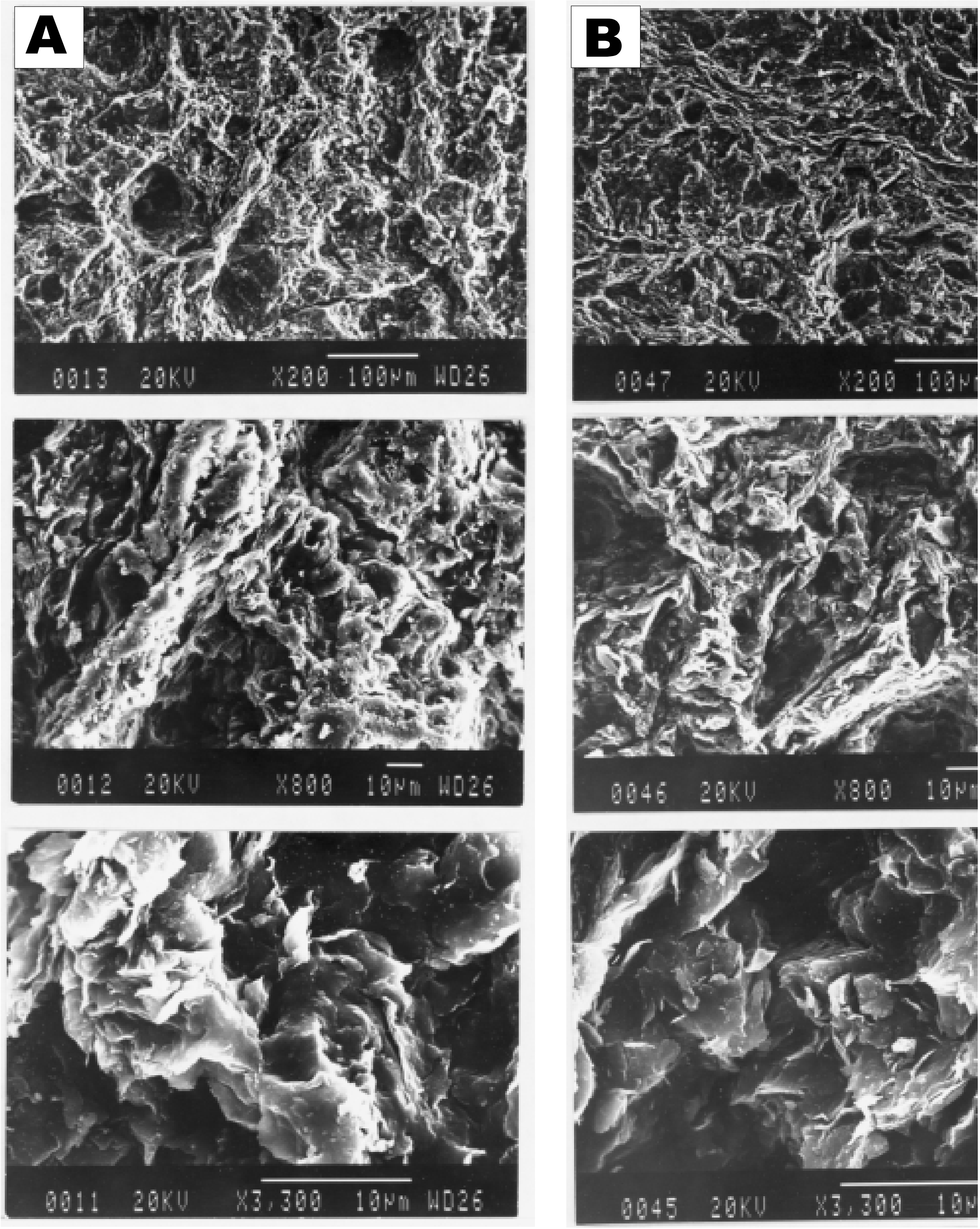
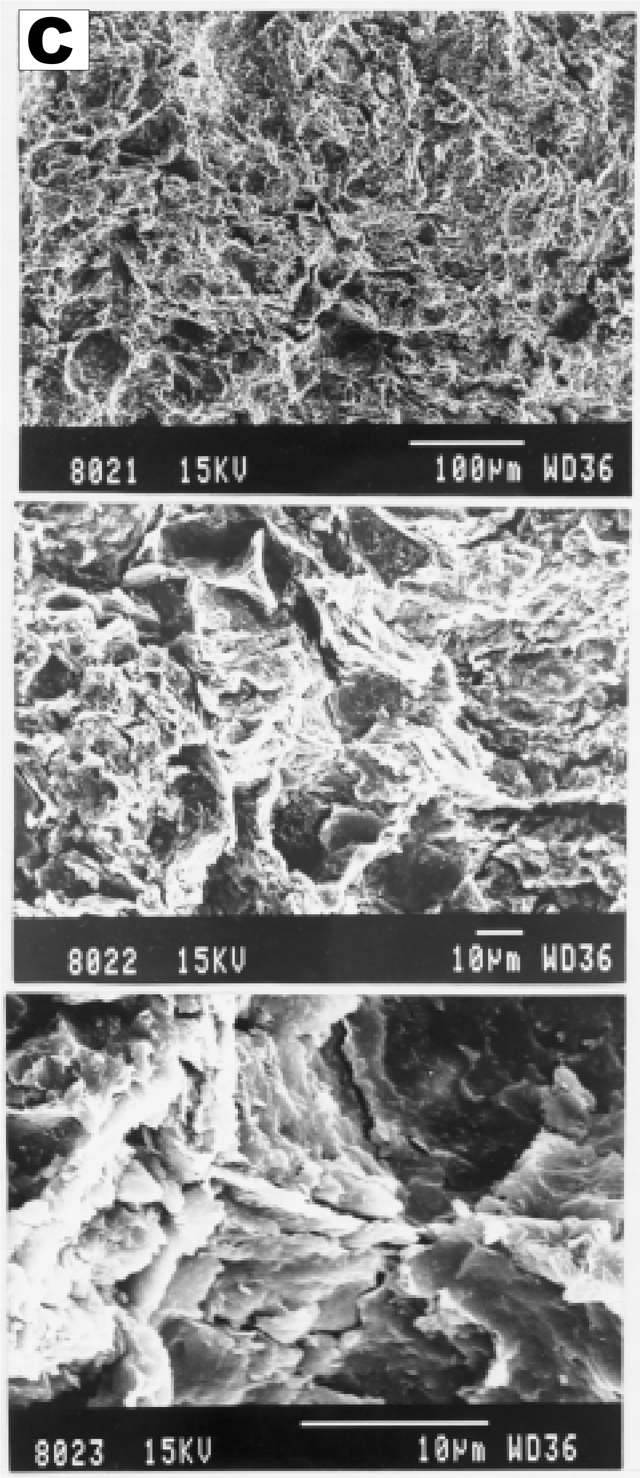


Fig. 4. Typical SEM micrographs of Neogene clays

A — sample STG 5p, matrix-turbulent microstructure; B — sample STG 11.3p, laminar-turbulent microstructure; C — A-14 station of Warsaw



from the Warsaw area

underground, depth 5 m, laminar-turbulent microstructure

tainly the most significant was the load caused by the South-Polish ice sheet, which exerted on the subsoil a thrust of 10 000 kPa (10 Mpa). The Odra and Warta ice sheets acted upon the substrate after longer intervals (interglacial periods), and are of lesser significance. Assuming a historical geological load of 10 MPa and relating it to the present load from soil overburden ranging from 10 to 20 m below ground-level, it is possible to determine that the Neogene clays were overconsolidated in a ratio of OCR_{hist} = 25–50.

CURRENT OVERCONSOLIDATION RATIO

The overconsolidation ratio $OCR = \sigma'_{p\,max}/\sigma'_{z\gamma}$ is equal to the ratio of pre-consolidation stress $\sigma'_{p\,max}$ to geological stress resulting from the depth of sample collection. OCR and $\sigma'_{p\,max}$ was examined in laboratory and field conditions (methods according to Casagrande, 1932; Marchetti, 1980; Holtz *et al.*, 1986; Kulhavy and Mayne, 1990; Robertson, 1990; Gaworek *et al.*, 1993, unpubl.; Szymański, 1993, 2000 and Borowczyk and Szymański, 1995).

The continuous loading (CL) method was used in the laboratory: clay samples were tested in a consolidometer at a constant rate of strain (CRS) of 0.003 mm/min. Methodical details are given in Head (1988) and ASTM D 4186. The results are shown in Table 7, whereas the pre-consolidation stress (the stress that the soil still remembers today) was interpreted according to two methods:

— Casagrande's: $\sigma'_{p\,max}$ = 5.4–11.0 Mpa; OCR = 3.9–14.0;

— Holtz's: $\sigma'_{p\,max}$ = 5.2–8.0 Mpa; OCR = 2.9–10.3

In field tests, the static penetration test (CPT) and Marchetti's dilatometer DMT (Marchetti, 1980) were used. In the section of clays in the Stegny test field, the following range and average values were obtained:

— CPT: $\sigma'_{p\,max\,CPT}$ = 0.46–1.05 (av. 0.86) MPa; OCR_{CPT} = 6.2–12.5 (av. 8.96)

— DMT: $\sigma'_{p\,max\,DMT}$ = 0.37–0.89 (av. 0.53) MPa; OCR_{DMT} = 4.1–7.3 (av. 5.80)

— For average values:

$OCR_{CPT} : OCR_{DMT} = 1.54$

$\sigma'_{p\,max\,CPT} : \sigma'_{p\,max\,DMT} = 1.60$

were: $s'_{p\,max}$ — pre-consolidation stress, CPT — static penetration test, DTM — Machetti's dilatometer.

The results submitted indicate that the values interpreted according to Casagrande are higher than those interpreted by Holtz's method. All laboratory and field tests confirm that the examined clays remember from their geological history loads much higher than the present ones, and it is possible to state that those clays are considerably overconsolidated. The ratio of overconsolidation of clays occurring to a depth of 20 m reaches values up to 15. Pre-consolidation stresses and over consolidation ratios obtained in laboratory tests are generally higher than those from field tests. It was observed also that CPT method values are higher than those obtained by the DMT method.

Table 5

Consistency parameters of the Neogene clays

Location	Clay fraction contents f_i [%]	Natural water contents w_n [%]	Soil consistence			
			Liquid limit w_L [%]	Plastic limit w_P [%]	Plastic index I_p [%]	Liquidity index I_L
Warsaw area	28–89 (56.0)*	19.2–35.6 (27.6)*	37.5–96.4 (69.5)*	20.1–41.0 (30.5)*	16.2–58.0 (38.9)*	–0.27÷0.24 (–0.09)*
Warsaw-Stegny	29–80 (56.3)*	21.1–35.6 (29.4)*	42.0–96.0 (74.6)*	22.5–41.0 (33.4)*	19.4–58.0 (41.2)*	–0.27÷0.08 (–0.10)*

* — average value

CONCLUSIONS

Examinations of the Neogene clays of the Warsaw area at depths to 20 m can be summarised as follows:

1. The Neogene clays during the Quaternary were loaded at least three times with ice sheets. The South-Polish ice sheet — the first and the thickest one (*ca*. 1000 m) had the greatest influence on the consolidation of the clays. With respect to current load from soil overburden (e.g. at depths of 10 and 20 m) the examined clays are historically overconsolidated, and the overconsolidation ratio is OCR_{hist} = 25–50.

2. The presently remembered load maximum pre-consolidation load is significantly higher than the present geological load from overburden. The pre-consolidation ratio, regardless of the method, is $OCR_{current}$ = 2–14.

3. The Neogene clays, during glacial periods (*ca*. 200 kyrs), were probably overconsolidated 25–50 times, and after interglacial periods (almost 500 kyrs) they remember loads 2–15 times higher than the present one.

4. The Warsaw Neogene clays are characterised by transient types of microstructures:

— matrix-turbulent,

— turbulent-laminar.

The porosities of the Neogene clays from Warsaw-Stegny range from 37 to 52%. They are higher (43–52%) to a depth of 8 metres below ground-level, and lower (42–37%) at depths below 8 metres b.g.l. The porosity of vertically oriented clay samples is always lower than that of horizontally oriented ones. The clays are characterised by a void space anisotropy of index K_a = 12–38%. The shape of pores in clays changes with depth from isometric to anisometric. The orientation of structural elements in clays increases with depth.

5. The main component of the Neogene clays comprises clay minerals, and their contents range from 40 to 80%. The clay minerals are: beidellite — B, illite — I, and kaolinite — K. The mineral composition of the clays may be shown as follows:

— in case of the Warsaw-Stegny clays: $B^{50–80} > I^{10–45} > K^{5–10}$;

— in case of the underground tunnel clays: $B^{65–85} > I^{10–30} > K^{0–20}$; and can be defined as of beidellite type. In the Stegny clay profile, an increase in the contents of beidellite and kaolinite, and a decrease of in the illite content was observed together with depth.

6. In lithological terms, the Neogene clays are represented mainly by a succession of clay and subordinate sandy-silty deposits of lacustrine origin. The average granulometric composition is as follows:

— clay: 40%;

— silt: 45%;

— sand: 15%.

Moreover, clays are characterised with natural water contents almost equal to full, their consistency is mostly semi-compact, only occasionally hard-plastic. The consolidation coefficient according to Prikłoński is above 1.

7. An attempt to find the relations between porous space parameters and certain physical properties of the clays proved un-

Table 6

Density and saturation parameters of the Neogene clays

Location	Density [Mg/m^3]			Total water porosity	Void ratio e	Contents w_r [%]	Activity A
	Mass ρ_s	Bulk ρ_o	Dry bulk ρ_d				
Warsaw area	2.66–2.78 (2.71)*	1.85–2.13 (2.00)*	1.37–1.78 (1.60)*	0.35–0.49 (0.41)*	0.54–0.97 (0.70)*	19.2–35.9 (26.0)*	0.39–1.27 (0.700)*
Warsaw-Stegny	2.68–2.73 (2.70)*	1.88–2.10 (1.99)*	1.39–1.66 (1.54)*	0.38–0.49 (0.43)*	0.63–0.96 (0.76)*	23.3–35.1 (28.0)*	0.52–1.02 (0.80)*

* — average value

Table 7

Preconsolidation (load $\sigma'_{p\,max}$) and overconsolidated ratio (OCR) of tested Neogene clays — laboratory and field tests

Localisation, depth b.g.l. [m]	Natural water content w_n [%]	Bulk density ρ [Mg/m^3]	Degree of saturation S_r	Vertical overburden stress σ'_v [kPa]	Preconsolidation stress σ'_{pmax} [kPa]				Overconsolidation ratio OCR			
					Laboratory tests		Field tests		Laboratory tests		Field tests	
					Casa-grande	Holtz	CPT	DMT	Casa-grande	Holtz	CPT	DMT
Stegny: 4.9–5.6	34.41–36.75	1.86–1.87	0.97–1.01	70	1000 540	720 500	0.46–0.60	0.37	14.0 7.6	10.3 7.0	6.2–8.1	5.3–5.6
Stegny: 6.8–7.6	30.15–33.10	1.94–1.95	1.00–1.06	90	540	500	0.78	0.35	6.0	5.6	9.3	4.1
Stegny: 9.0–9.7	26.45–26.85	2.01–2.03	1.04–1.05	110	920 670	590 500	1.39	0.69	8.4 6.1	5.4 4.5	12.5	6.7
Stegny: 11.0–11.7	27.05–27.52	1.99–2.01	1.00–1.04	130	730 820	520 690	1.05	0.89	5.6 6.3	4.0 5.3	8.7	7.3
Underground: Town Hall Station ~14 m	23.75–24.25	1.99–2.00	1.99–2.00	280	1100	800	–	–	3.9	2.9	–	–

CPT — cone penetration test; DMT — Marchetti's dilatometer

successful — accurate function relations have not been found. Never the less the values of the correlation coefficient estimated at 0.6–0.7 suggest that with more tests on more diverse clays mathematical relations may be be attainable.

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