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# Engineering-geological evaluation of Mio-Pliocene clays in the Warsaw area, central Poland

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ABSTRACT:

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Mio-Pliocene clays will increasingly constitute the subgrade for building structures, not only in the Warsaw region, but within the whole of central Poland, where the depths of their occurrences range from 2 to 100 m below ground-level and their average thickness is 50 m. In their geological history these clays became overconsolidated. They include numerous weakness surfaces, are sensitive to the influence of exogenic processes, and can be classified as soils of specific properties. It is necessary to take into account the state and history of loads when testing these soils. This paper deals with the testing of overconsolidated soils. It contains full characteristics of the engineering-geological properties of the Mio-Pliocene clays of the Warsaw area.

On the basis of the determined properties, the load-bearing capabilities of unweathered and weathered clays as the construction subgrade have been analysed. Special attention was paid to the quantitative expression of the influence of wetting (swelling), structure disturbance, and occurrences of shear strength weakness surfaces (cohesion and angle of internal friction). In the case of clays, it is possible that horizontal stresses are higher than vertical stresses ($K_0$ = 0.74-1.44). The behaviour of clays occurring in slopes has been assessed. Laboratory and field (static penetration and dilatometer) test results are presented. Obtained results can be used directly for the evaluation of Mio-Pliocene clays as a construction subgrade, and indirectly for other overconsolidated soils, especially in the context of testing methodology.

**Key words:** Physical-mechanical properties, Sensitiveness, Exogenic processes, Subgrade.

## INTRODUCTION

For thousands of years soil has been used as the subgrade for building structures, takes part in load bearing, sometimes it loads a structure itself or constitutes a construction material. Initially human activities were based on intuition and gathered experience. Numerous catastrophic failures of structures constituted some of the sources of experiences. In the course of time, with the accumulation of experience, basic laws of a more general nature were formulated. The following can be distinguished among the most important ones still used today:

- Mohr-Coulomb soil failure criterion;
- principle of effective stress, Terzaghi soil consolidation equation and their modifications.

The construction subgrade is that part of the lithosphere which is directly influenced by building structures. The thickness of the subgrade zone varies, depending on the structure type in question (e.g. dwelling house, dam, embankment, dump, slope, mine pit etc.), from a few to hundreds of metres.

Each foundation of a building structure causes a disturbance, an alteration of the existing stress state. Before a structure is founded in soil, there exists the so-called original stress resulting from the soil's own weight; this stress increases with depth. Stress resulting from structures are most always greatest at the level of founding and decrease with depth. Stresses appearing in soil resulting from structure foundation, the so-called additional stresses, must be safely carried by the soil. In real situations, the state of the so-called limit equilibrium must not be exceeded in the subgrade.

In the course of designing engineering structures – with certain assumptions adopted, two limit states are usually checked (first and second).

The first limit state (load-bearing capacity failure) is checked to make sure that the planned load resulting from the structure will not exceed the soil resistance (strength). The second limit state (serviceability limit state design) is checked to determine whether or not the computed structure settlement will exceed allowable deformations determined for the given type of structure (EUROCODE 7 – Geotechnics – 1997). Solving stability problems requires knowledge of the parameters that enable the above limit states to be checked. The most important soil parameters are soil shear strength (angle of internal friction, cohesion) and compressibility modulus. The angle of internal friction and cohesion constitute the constants of the equation of the

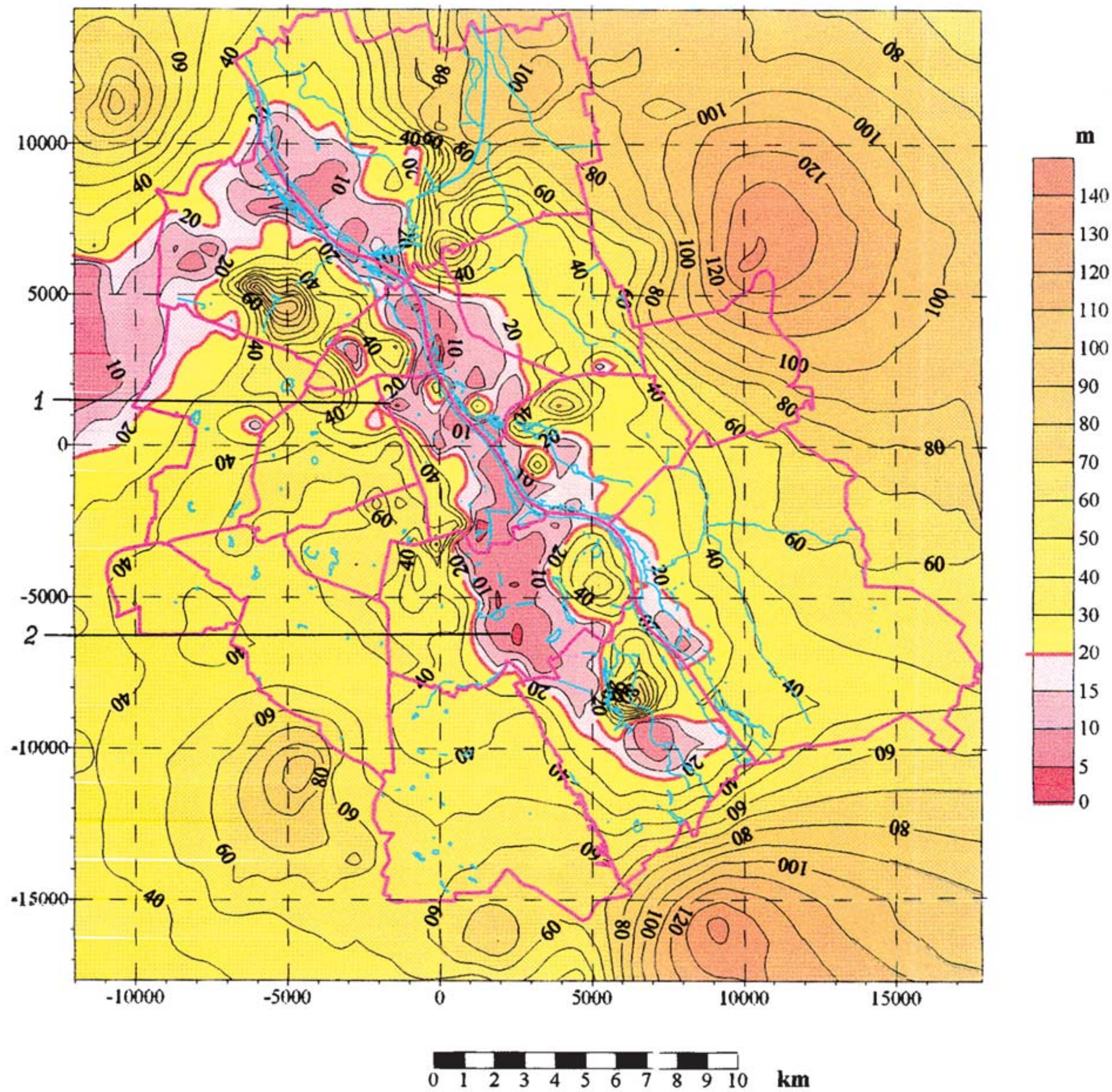


Fig. 1. Map of the depth of Mio-Pliocene clays in the Warsaw area (PIG-Atlas 2000). 1 – Warsaw underground, A-14 station; 2 – experimental Warsaw-Stegny plot, red lines – Warsaw districts' borders, blue lines and spots – surface waters

straight line representing the envelope of shear strength (Mohr-Coulomb failure criterion). The compressibility modulus enables the serviceability limit condition to be chacked.

In recent years, multi-floor structures have frequently been designed, often with a few storeys of underground parking. An underground railway is under construction in Warsaw. Because of the deep excavations and high loads involved it is necessary to know soil parameters determined under a wide range of stresses in order to enable determination of the state of horizontal stresses (pressures: active, passive, and at rest). Those parameters are determined in laboratory and field tests.

This project comprised testing of Warsaw Mio-Pliocene clays: in the upland terrain in the vicinity of the underground railway segment between the stations A-14 and A-15; and in the Vistula river valley in the area of Oligocene water intake near Czarnomorska Street in the Stegny district.

## GEOLOGICAL CONDITIONS OF OCCURRENCES OF MIO-PLIOCENE CLAYS IN THE WARSAW AREA

Warsaw is situated on the NE flank of the rim synclinorium. During the Tertiary, the Cretaceous depression (the Warsaw Basin) was filled with sandy-clay deposits. The youngest part of the Tertiary – the Pliocene – is represented by the deposits of a shallow, periodically evaporating basin. The Mio-Pliocene deposits in the Warsaw area (Text-fig. 1) are strongly deformed – many folds of different amplitudes and discontinuous deformations occur here (Text-figs 2-3). The topmost part of the Mio-Pliocene deposits is situated at various levels; the difference may locally exceed 100 m. A distinct, longitudinal upwarp (NNW-SSE), several kilometres long, and 0.5-2.0 km wide, is observed in the region. The top of the Mio-Pliocene deposits within this upwarp exceeds 100 m a.s.l., and approaches the land surface. Several elevations and depressions have been distinguished within the upwarp. The thickness of the Mio-Pliocene deposits reaches a few dozen metres, locally as much as 100-150 m, but 50 m on average. The age and origin of the Mio-Pliocene deformations have not yet been precisely determined. They probably formed in stages, during several glaciation periods. The Pliocene clays in the Warsaw area are covered with Quaternary deposits, including anthropogenic ones, of variable thickness (FRANKOWSKI & *al.* 2000; BARANIECKA 1979; SARNACKA 1979, 1980).

On the underground railway segment in the vicinity of stations A-14 to A-15 Mio-Pliocene clays occur between 2 and 10 m below ground-level (100-113 m a.s.l.), while in the Vistula valley, in Stegny, they occur between 4 and 5 below ground-level (82-75 m a.s.l.). In a soil mechanics context, the mass of Mio-Pliocene clays must be classified as a non-homogeneous, anisotropic and discontinuous medium. The most important are discontinuity surfaces – cracks (slickensides). Creation of slickensides, i.e. brittle fracture combined with displacement, must have occurred when the sediment was already relatively consolidated and its degree of saturation was close to 1.

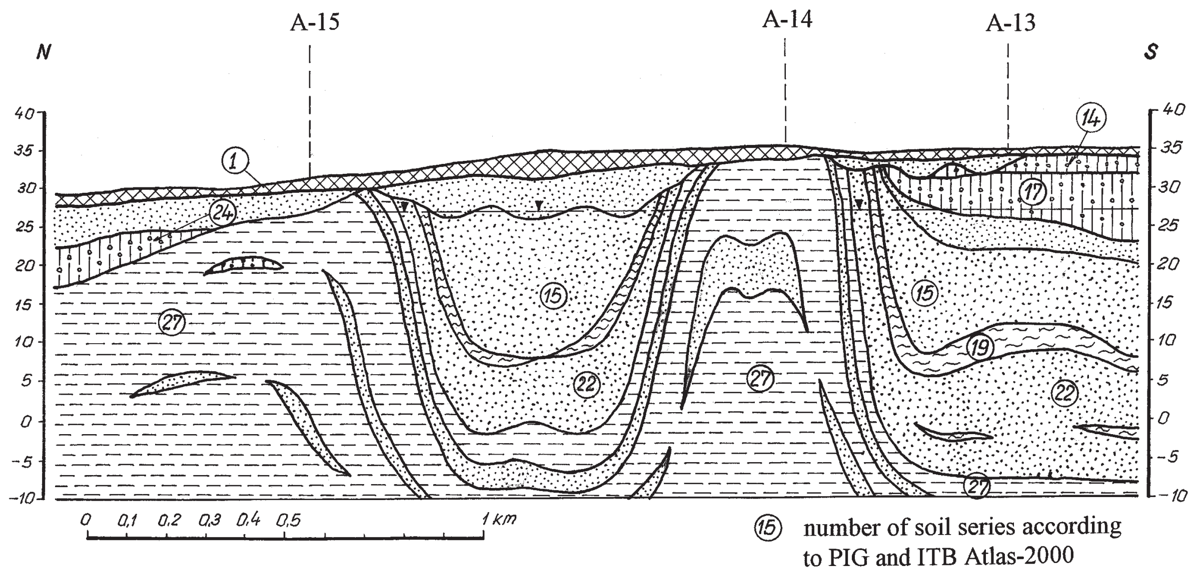


Fig. 2. Exemplary geological profile on the section between stations A-13 and A-14 of the Warsaw underground (according to KOWALCZYK & *al.* 1996)

## LITHOLOGIC-MINERALOGICAL AND MICROSTRUCTURAL CHARACTERISTICS OF THE MIO-PLIOCENE CLAYS

The Mio-Pliocene clays are represented mainly by the complex of clayey soils, with subordinate amounts of silty clayey soils of limnitic origin. In the vertical profile of the clays a few sedimentation cycles, from sands to clays, are observed. The whole complex of Pliocene clays comprises:

- clays, silty clays: 60-70%;
- silts: 10-25%;
- sands: 10-20%.

Based on published data (FORTUNAT 1960, KŁĘBEK & ŁOSZEWSKI 1981, WYSOKIŃSKI 1999, STAMATELLO 1955, PIASKOWSKI 1963, FRANKOWSKI & *al*. 2000) and the author's own research, the average granulometric composition of the clays has been determined. This composition (700 analyses) is as follows:

- clay fraction (<2 μm): 40%;
- silt fraction (2-50 μm): 45%;
- sand fraction (>50 μm): 15%;

(coefficient of variability V = 30-120%).

Mio-Pliocene clays in vertical, and occasionally in horizontal profile change their colour. Bottom levels are rather grey, occasionally greenish. In the middle part green (sometimes blue) hues with numerous yellow or reddish stains predominate (DYJOR 1992, WICHROWSKI 1981), while towards the top sand colours appear with abundant red, brown, rusty and black stains (variegated / flame-coloured clays).

The mineral composition of the clays consists primarily of clay minerals and quartz, with subordinate feldspars and micas, as well as siderite, pyrite, gypsum, marcasite, goethite and hematite. The $CaCO_3$ and organic matter contents do not exceed 5%, and 1% respectively. Among the clay minerals, mainly mixed-layers minerals of the beidellite-illite and kaolinite series are encountered (WYRWICKI & WIEWIÓRA 1972, WICHROWSKI 1981, KACZYŃSKI & *al*. 2000, KACZYŃSKI 2001a,b). The mineral composition of Mio-Pliocene clays from various locations in Warsaw may be presented as follows:

- Stegny clays B50-80>>110-45>K5-10;
- underground railway clays B65-85>>110-30>K0-20.

Warsaw Mio-Pliocene clays are characterised by transitory types of microstructures (KACZYŃSKI & GRABOWSKA-OLSZEWSKA 1997):

- matrix-turbulent, and
- turbulent-laminar.

Turbulent microstructure indicates a significant share of epigenetic processes in the formation of the microstructures of the clays. In contacts between microaggregates type FF (face-to-face) is predominant. The microstructures are usually not very well orientated, but are sometimes highly orientated. Pores are usually anisotropic, and fissure pores occur. In the Stegny vertical profile a distinct change in the quantitative parameters of porous space is observed below 8 m. Porosity, size of pores and form index decreases, while the number of pores and the anisotropy coefficient increases (KACZYŃSKI, in press).

## BASIC PHYSICAL-MECHANICAL PROPERTIES OF THE MIO-PLIOCENE CLAYS

The lithological physical-mechanical properties as well as the mineral composition and microstructure of the clays formed during a long and complicated geological history, when the clays underwent several cycles of loading and unloading. This resulted in the clays becoming overconsolidated (not totally decompressed). Equalisation of water pressure in pores is retarded with respect to stress decrease, so the clays have never become totally decompressed (except for the layer near the surface). The greatest influence upon the process of consolidation of the clays was the first glacier of the South-Polish glaciation, approximately 1000 m thick. In comparison to contemporary load from soil overburden (at 5-20 m below ground-level) the examined clays were overconsolidated during their history, with the overconsolidation ratio $OCR_{hist}$ = 25-50.

The basic physical-mechanical properties of clays, apart from granulometric composition, are:

- parameters of consistency;
- parameters of density and saturation;
- shear strength;
- deformability.

Warsaw Mio-Pliocene clays demonstrate significant variability in the analysed properties caused mainly by:

- a varied granulometric composition resulting from sedimentation conditions;
- presence of glacitectonic deformations causing deterioration in the strength and deformability parameters;
- hydrogeological conditions resulting in differing degrees of saturation.

The basic properties of the Mio-Pliocene clays depend on the clay fraction content; thus, the parameters of the Stegny clays are closely similar to those of clays from other parts of Warsaw. Their natural water content is almost equal to the total, and the degree of

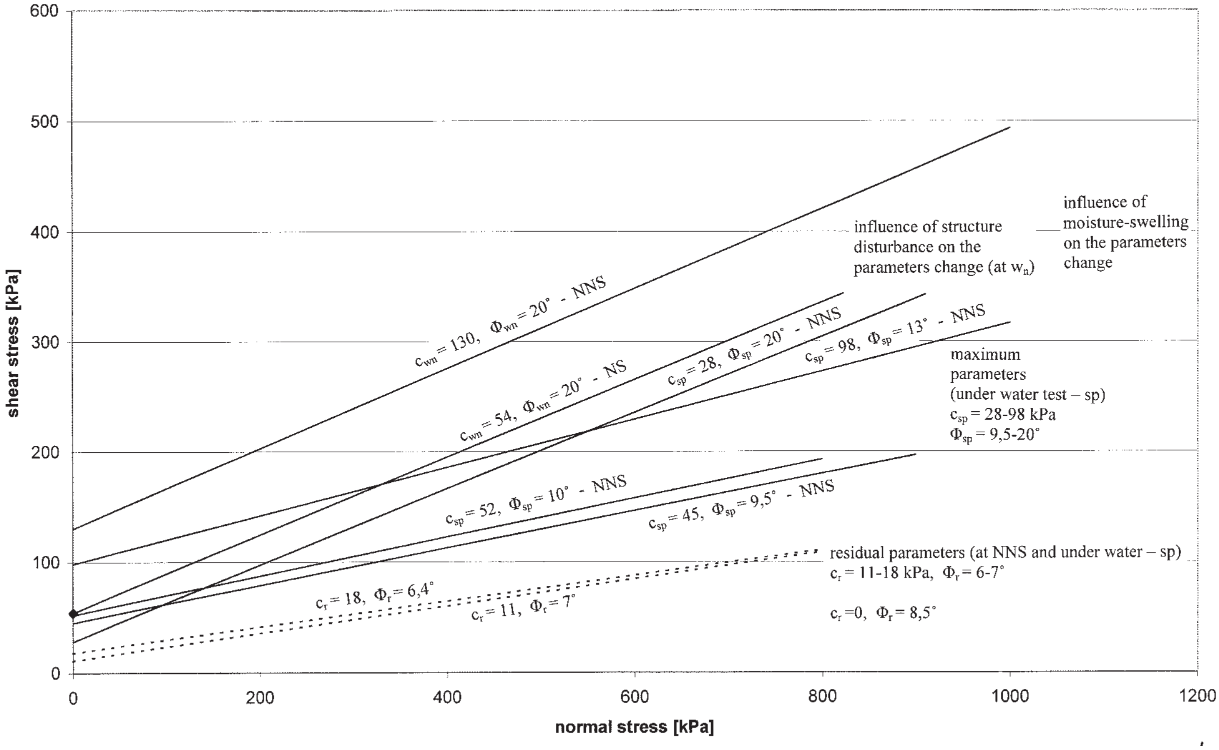


Fig. 4. Shear strength envelopes of Mio-Pliocene clays. Direct apparatus. Warsaw-Stegny. Undisturbed samples NNS, disturbed samples NS, under water ($s_p$) and at natural water content ($w_n$)

| Localization, depth b.g.l. [m] | | Water content $w_n$ [%] | Bulk density $\rho$ [Mg/m$^3$] | Degree of saturation $S_r$ [-] | Total cohesion c [kPa] | Total angle of intern.friction $\phi$ [°] | Effective cohesion c' [kPa] | Effective angle of intern.friction $\phi$' [°] |
|---|---|---|---|---|---|---|---|---|
| 1 | | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Stegny: 4.9-5.6 | | 33.89 - 38.12 | 1.85 - 1.88 | 0.98 - 1.01 | 40 | 10 | 30 | 13 |
| Stegny: 6.8-7.6 | | 29.22 - 31.01 | 1.94 - 1.96 | 0.99 - 1.04 | 60 | 11 | 25 | 13 |
| Stegny: 10.0-10.7 | | 20.35 - 21.05 | 2.01 - 2.04 | 0.90 - 0.94 | 70 | 13 | 55 | 16 |
| Stegny: 11.0-11.7 | | 27.54 - 28.12 | 2.02 - 2.05 | 1.04 - 1.07 | 70 | 13 | 50 | 17 |
| TUBE: Stations A-14 | 0-15, 11.5-12.0 | $\overline{28.3}$ | $\overline{2.02}$ | ~1 | 36 ± 9 | 6.5 ± 1.5 | 30 ± 10 | 8 ± 0.5 |
| | 0-16, 17.0-17.2 | $\overline{19.7}$ | $\overline{2.13}$ | 0.99 | 51 ± 21 | 18 ± 2 | 46 ± 22 | 18 ± 2 |
| | 0-15, 20.5-20.8 | $\overline{24.5}$ | $\overline{2.03}$ | 0.98 | 82 | 6 | - | - |
| A-15 | pit, 14.0 town hall | 23.45-24.12 | 2.00-2.06 | 0.96-1.03 | 63 | 10 | 50 | 15 |
| ONZ Circle: 48.5 - 48.7 | | $\overline{20.8}$ | $\overline{2.13}$ | ~1 | 160<br>35$^x$ | 6 | - | - |

$\overline{28.3}$ – average value, 35$^x$– value for clay with weakness surface

Table 1. Strength parameters of Mio-Pliocene clays with undisturbed structure and natural water content. Triaxial test – Trx CIU

| Depth [m] | CPT static sounding [MPa] | DMT dilatometric sounding [MPa] |
|---|---|---|
| 4.40 | 0.46 | 0.37 |
| 5.00 | 0.60 | 0.37 |
| 7.00 | 0.79 | 0.35 |
| 9.00 | 1.39 | 0.69 |
| 11.00 | 1.05 | 0.89 |
| average: | 0.858 | 0.534 |
| $\sigma'_p$ CPT: DMT = 0.858:0.534 = 1.60 | | |

Table 2. Preconsolidation pressure $\sigma'_p$

| Depth [m] | CPT [MPa] | DMT [MPa] |
|---|---|---|
| 4.40 | 6.2 | 5.6 |
| 5.00 | 8.1 | 5.3 |
| 7.00 | 9.3 | 4.1 |
| 9.00 | 12.5 | 6.7 |
| 11.00 | 8.7 | 7.3 |
| average: | 8.96 | 5.8 |
| OCR CPT: DMT = 8.96:5.8 = 1.54 | | |

Table 3. Overconsolidation ratio OCR

saturation is >0.95. The clays are characterised by a semi-compact consistency, only occasionally by a hard-plastic consistency. Priklonski's coefficient of consolidation is 1.09 on average, indicating greatly compacted clays. The range of values and arithmetic means of each parameter are as follows:

- density 2.66-2.78, 2.71 $Mg/m^3$ on average;
- bulk density 1.85-2.13, 2.00 $Mg/m^3$ on average;
- porosity 35-49%, 41 % on average;
- void ratio 0.54-0.97, 0.41 on average;
- natural water content 19.2-35.6%, 27.6 % on average;
- liquid limit 37.5-96.4%, 69.5 % on average;
- plastic limit 22.5-41.0%, 30.5 % on average;
- plasticity index 19.4-58.0%, 38.9% on average;
- liquidity index from –0.27 to –0.24, –0.09 on average;
- activity 0.39-1.27, 0.70 on average;
- degree of saturation >0.95
- 700 analyses.

The shear strength of the clays were determined by testing in apparatuses:

- direct apparatus (Text-fig. 4) at a velocity of 0.01 mm/h;
- triaxial apparatus (Table 1) in the Trx CIU method (isotropic consolidated, undrained, with pore water pressure measurement) at a velocity of 1%/h;

In the natural state clays are characterised by high parameters:

- total (maximal) cohesion of 66-130 kPa (direct apparatus) and 36-160 kPa (triaxial apparatus);
- total angle of internal friction of 9-20° (direct apparatus) and 6.5-18° (triaxial apparatus);

| Localization and depth of sampling [m] b.g.l. | Orientation of sample | Water content $w_n$ [%] | Bulk density $\rho$ [Mg/m$^3$] | Degree of saturation $S_r$ [-] | Consolidometric modulus of compressibility $M_k$ in the range of: 0.05-0.1 MPa | 0.1-0.2 MPa | Consolidation coefficient [m$^2$/s] |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Stegny | vertical | 35.11 - 36.75 | 1.86 - 1.87 | 0.98 - 1.01 | 5.6 - 6.6 | 9.2 - 13.1 | $9.3x10^{-8}$ - $5.4x10^{-6}$ |
| 4.9 - 5.6 | horizontal | 34.41 - 35.08 | 1.86 - 1.87 | 0.97 - 0.99 | 4 - 11 | 7.0 - 11 | $4.6x10^{-8}$ - $9.8x10^{-8}$ |
| Stegny | vertical | 32.39 - 33.10 | 1.95 | 1.05 - 1.06 | 8.2 | 9.4 | $8.4x10^{-8}$ |
| 6.8 - 7.6 | horizontal | 30.15 - 31.20 | 1.94 - 1.95 | 1.00 - 1.03 | 9.9 | 9.9 | $4.8x10^{-8}$ - $1.6x10^{-7}$ |
| Stegny | vertical | 26.45 | 2.03 | 1.05 | 13.3 - 23.7 | 14.2 - 18.1 | $2.7x10^{-7}$ - $4.0x10^{-7}$ |
| 9.0 - 9.7 | horizontal | 26.85 | 2.01 - 2.02 | 1.04 | 13.3 - 19.9 | 6.6 - 8.2 | $9.5x10^{-8}$ - $1.1x10^{-7}$ |
| Stegny | vertical | 27.25 - 27.40 | 2.00 - 2.01 | 1.02 - 1.03 | 16.6 | 19.8 - 19.9 | $4.0x10^{-6}$ - $4.1x10^{-6}$ |
| 11.0 - 11.7 | horizontal | 27.05 - 27.52 | 1.99 - 2.01 | 1.00 - 1.04 | 5.5 - 6.6 | 15.9 | $3.3x10^{-7}$ - $8.7x10^{-7}$ |
| Tube: | vertical | 23.75 - 24.20 | 1.99 - 2.00 | 0.95 - 0.96 | 6.1 - 10.0 | 15.5 - 26.3 | $3.6x10^{-8}$ - $3.4x10^{-7}$ |
| town hall ~14 | horizontal | 23.95 -24.25 | 1.99 | 0.95 | 4.5 - 5.3 | 12.6 - 12.8 | $4.5x10^{-8}$ - $7.5x10^{-8}$ |

Table 4. Consolidometric modulus of compressibility of Mio-Pliocene clays [MPa]

- effective cohesion of 25-50 kPa (triaxial apparatus);
- effective angle of internal friction of 13-18° (triaxial apparatus);

The above parameters, especially the effective cohesion, clearly indicate overconsolidation of the analysed clays. During compression in the triaxial apparatus, the majority of samples collapsed along definite slide surfaces. Only a small part of the clays deformed plastically. In the case of overconsolidated clays, on reaching the maximum value of the principal stress deviator, a distinct drop in shear stress occurred. Maximum strength was reached at 3-6% of the relative deformation. The angle of shearing ranged between 50° and 60°. In many cases, the clay water content after the tests was higher than the original value. During the testing, almost always with the increase in deformation, the conditions of shearing become steady at the so-called residual strength. The strength of clays with weakness surfaces is characterised by residual strength parameters:

- residual angle of internal friction of 6-7° at a residual cohesion of 11-18 kPa; or
- residual angle of internal friction of 8.5° at a residual cohesion of 0 kPa.

Tests of clay deformability were performed by the continuous load (CL) method at a constant rate of strain (CRS) in a high-pressure consolidometer according to the methodology given by HEAD (1992), HOLTZ & *al*. (1986) and in ASTM D 4186. The velocity of strain did not exceed 0.003 mm/min. The following parameters were determined: preconsolidation pressure $\sigma'_p$, overconsolidation ratio OCR ($\sigma'_p : \sigma'_{z\gamma}$; $\sigma'_{z\gamma}$ – overburden pressure), coefficient of consolidation $c_v$, consolidometric modulus of original compressibility $M_k$. The preconsolidation pressure (CASAGRANDE 1932) is much higher than the overburden pressure $\sigma'_p > \sigma'_{z\gamma}$ meaning that at present the soil "remembers" a higher load than that from the present overburden. Regardless of the method of determination, the overconsolidation ratio OCR = 1-14 (Tables 2, 3).

The consolidometric modulus of original compressibility $M_k$ is dependent upon the range of load and the direction of the load force. For the Warsaw Mio-Pliocene clays the following results were obtained (Table 4):

- for 0.05-0.10 MPa load range $M_k$ = 4.0-23.7 MPa;
- for 0.10-0.20 MPa load range $M_k$ = 6.6-26.3 MPa;
- $c_v = 3.6 \times 10^{8} \div 5.4 \times 10^{-6}$ m²/s.

It should be pointed out that clays are less compressible in the vertical direction than in the horizontal direction. The basic physical-mechanical properties of the Mio-Pliocene clays are generally compared with the properties of Tertiary clays of marine origin.

## SENSITIVENESS OF CLAYS TO EXOGENIC PROCESSES

The properties of overconsolidated clays are time-dependent, since their water content increases with time, the pore water pressure dissipates, and the effective strength decreases. Equalisation of pore pressure in unloaded clays is delayed in relation to the decrease in stress. In the topmost part of the clays, a layer of weathered clay forms which is subjected to total or partial deconsolidation. The properties of clays under the influence of various factors (mainly exogenic) deteriorate in relation to their original subgrade. The tested clays were sensitive above all to changes in water content, and to disturbance of their structure. Depending on their initial water content, they either swell or soak. The results of the swelling test were:

- coefficient of free swell FS = 4-16%,
- swelling pressure $\sigma_{sp}$ = 15-280 kPa,

indicating that the Mio-Pliocene clays in their natural state may be classified as soils of low to extremely high swellability (Text-fig. 5). Clays with a low water content soak. Air-dry clays avalanche-disintegrate from 40 to 100% within 1 hour, while clays with water content close to natural increase their mass in the soaking test, but flake and crack somewhat. Decrease in shear strength (cohesion c and angle of internal friction Φ) resulting from swelling of the clays (sp) in relation to their natural water content ($w_n$) based on laboratory tests can be expressed as follows (Text-fig. 4):

- $c_{sp} = 0.55\text{-}0.70\ c_{wn}$;
- $\Phi_{sp} = 0.70\text{-}0.90\ \Phi_{wn}$.

The problem of the influence of clay swelling on the strength parameters was analysed in the paper of Warsaw University of Technology (PRACA ZBIOROWA 1997) and by BUKOWSKI & RYMSZA (1997), and the following relations were obtained:

- $\Phi_{sp} = 0.70\ \Phi_{wn}$, $\Phi'_{sp} = 0.85\ \Phi'_{wn}$;
- $c_{sp} = 0.25\ c_{wn}$, $c'_{sp} = 0$; where: c', Φ' – effective cohesion and angle of internal friction.

The influence of disturbance of clay structure (NS) on its cohesion in relation to clay with an undisturbed structure (NNS) can be determined as:

- $c_{NS} = 0.4\ c_{NNS}$.

Disturbance of structure causes mainly a decrease in cohesion, while the angle of internal friction remains relatively unchanged. The thickness of clays altered as

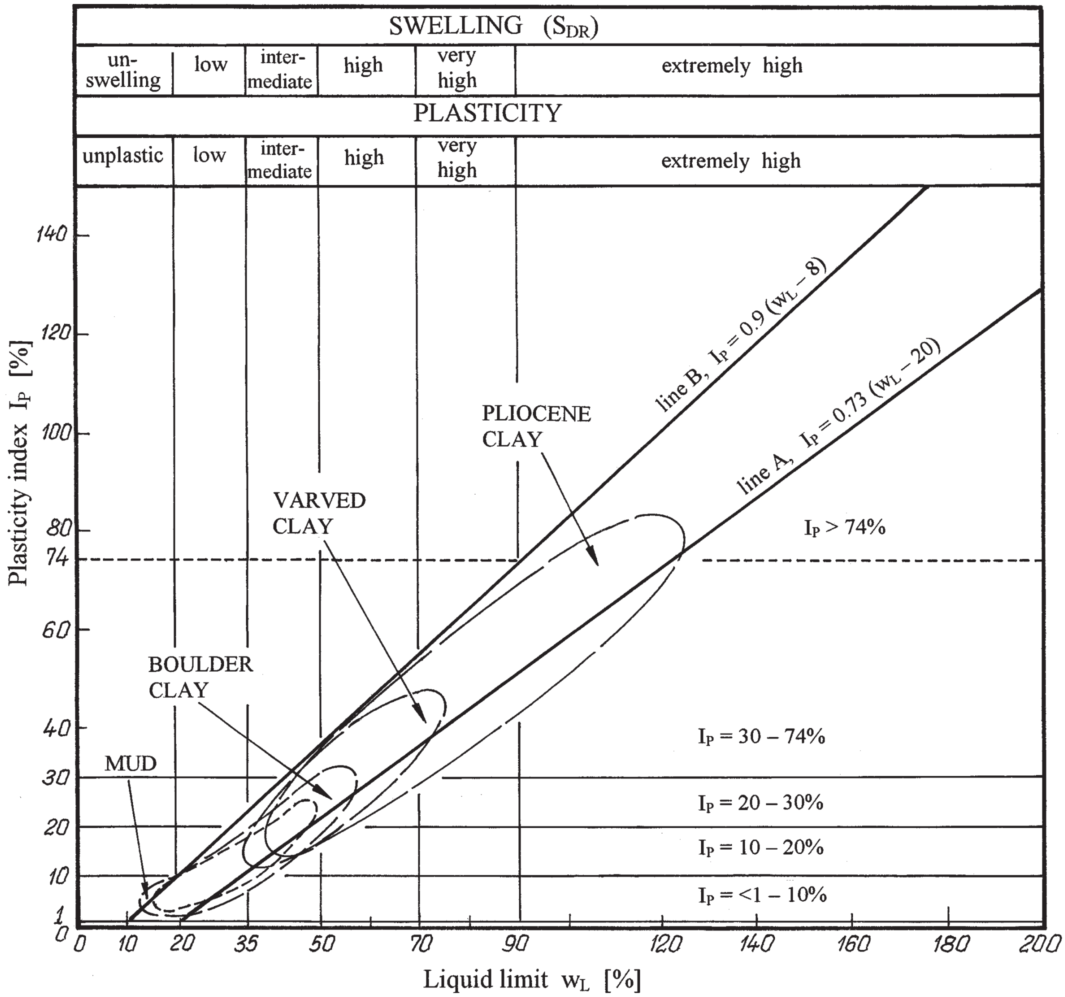


Fig. 5. Swelling and plasticity of Mio-Pliocene clays and other cohesive soils from Warsaw – nomogram according to Casagrande (modified by GRABOWSKA-OLSZEWSKA 1998)

the result of exogenic processes in Warsaw area can be defined as ca. 1 m.

## EVALUATION OF THE MIO-PLIOCENE CLAYS AS A CONSTRUCTION SUBGRADE

Evaluation of soils as the subgrade in designing building structures, and use of appropriate protections must be strictly related to the soil properties. As for vertical load, unweathered Mio-Pliocene clays (in their natural state) show relatively high strength parameters – they constitute load carrying subgrade, i. e. it is possible to found on them the majority of typical building structures. In the unweathered state the clays are overconsolidated soils. The distinct role of preconsolidation load $\sigma'_p$ must be stressed in the shape of the stress-strain relationship, the course of the shear strength line, and in the obtained values of pore water pressure. Clays

| OCR | Φ'= 13° | Φ'= 14° | Φ' = 15° | Φ'=16° | Φ'=17° |
|---|---|---|---|---|---|
| 1 | 0.78 | 0.76 | 0.74 | 0.72 | 0.71 |
| 2 | 0.91 | 0.90 | 0.90 | 0.87 | 0.87 |
| 3 | 0.99 | 0.99 | 1.00 | 0.98 | 0.98 |
| 4 | 1.06 | 1.06 | 1.07 | 1.06 | 1.06 |
| 5 | 1.11 | 1.12 | 1.14 | 1.13 | 1.13 |
| 6 | 1.16 | 1.17 | 1.20 | 1.19 | 1.19 |
| 7 | 1.20 | 1.21 | 1.24 | 1.24 | 1.25 |
| 8 | 1.23 | 1.25 | 1.29 | 1.29 | 1.30 |
| 9 | 1.26 | 1.29 | 1.31 | 1.33 | 1.34 |
| 10 | 1.29 | 1.32 | 1.36 | 1.37 | 1.38 |
| 11 | 1.32 | 1.35 | 1.39 | 1.40 | 1.42 |
| 12 | 1.35 | 1.38 | 1.41 | 1.44 | 1.46 |
| 13 | 1.37 | 1.40 | 1.42 | 1.46 | 1.49 |
| 14 | 1.39 | 1.43 | 1.44 | 1.49 | 1.52 |

Table 5. Pressure coefficient at rest $K_0$ = f(Φ', OCR) according to Schmidt formula; Φ' – effective angle of internal friction, OCR – overconsolidation ratio

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Stegny - poletko                D M T  :  - 12.04.2000                    Reg 11


WATERTABLE m 2.9

Reduction formulae according to Marchetti, ASCE Geot.Jnl.,Mar. 1980, Vol.109, 299-321
NOTE : OCR = ''relative OCR''. OCR below often reasonable. Accuracy can be improved if precise
       OCR values are available. Then factorize all OCR below by the ratio  OCRreference/OCR

Po     = Corrected A reading            bar      INTERPRETED GEOTECHNICAL PARAMETERS
P1     = Corrected B reading            bar      ----------------------------------
Gamma  = Bulk unit weight/GammaH2O      (-)      Ko = In situ earth press. coeff.        (-)
Sigma'= Effective overb. stress         bar      Ocr= Overconsolidation ratio            (-)
U      = Pore pressure                  bar      q  = Eroded overburden above g.s.       bar
Id     = Material Index                 (-)      M  = Constrained modulus (at Sigma')    bar
Kd     = Horizontal stress index        (-)      Cu = Undrained shear strength           bar
Ed     = Dilatometer modulus            bar
```

| Z (m) | Po | P1 | Gamma | Sigma' | U | Id | Kd | Ed | Ko | Ocr | q | M | Cu | DESCRIPTION |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.60 | 2.2 | 12.6 | 1.90 | 0.10 | 0.00 | 4.84 | 21.0 | 363 | | | | 1163 | | SAND |
| 0.80 | 2.6 | 12.4 | 1.90 | 0.14 | 0.00 | 3.80 | 18.5 | 341 | | | | 1052 | | SAND |
| 1.00 | 2.6 | 13.6 | 1.90 | 0.18 | 0.00 | 4.17 | 14.8 | 381 | | | | 1096 | | SAND |
| 1.20 | 2.7 | 13.3 | 1.90 | 0.21 | 0.00 | 4.03 | 12.3 | 371 | | | | 1000 | | SAND |
| 1.40 | 2.9 | 13.4 | 1.90 | 0.25 | 0.00 | 3.70 | 11.3 | 367 | | | | 961 | | SAND |
| 1.60 | 2.8 | 15.0 | 1.90 | 0.29 | 0.00 | 4.41 | 9.6 | 425 | | | | 1048 | | SAND |
| 1.80 | 2.3 | 12.1 | 1.90 | 0.33 | 0.00 | 4.29 | 7.0 | 341 | | | | 748 | | SAND |
| 2.00 | 2.5 | 13.1 | 1.90 | 0.36 | 0.00 | 4.36 | 6.7 | 371 | | | | 799 | | SAND |
| 2.20 | 2.5 | 12.1 | 1.90 | 0.40 | 0.00 | 3.85 | 6.2 | 334 | | | | 698 | | SAND |
| 2.40 | 2.2 | 10.4 | 1.90 | 0.44 | 0.00 | 3.81 | 4.9 | 287 | | | | 541 | | SAND |
| 2.60 | 1.8 | 9.6 | 1.90 | 0.48 | 0.00 | 4.39 | 3.8 | 272 | | | | 449 | | SAND |
| 2.80 | 2.5 | 12.1 | 1.90 | 0.51 | 0.00 | 3.85 | 4.9 | 334 | | | | 627 | | SAND |
| 3.00 | 1.5 | 9.1 | 1.80 | 0.54 | 0.01 | 4.93 | 2.8 | 263 | | | | 371 | | SAND |
| 3.20 | 1.8 | 11.1 | 1.90 | 0.56 | 0.03 | 5.21 | 3.2 | 323 | | | | 489 | | SAND |
| 3.40 | 1.7 | 11.3 | 1.90 | 0.57 | 0.05 | 5.83 | 2.9 | 334 | | | | 474 | | SAND |
| 3.60 | 1.1 | 7.1 | 1.80 | 0.59 | 0.07 | 6.04 | 1.7 | 210 | | | | 202 | | SAND |
| 3.80 | 1.5 | 6.2 | 1.80 | 0.61 | 0.09 | 3.24 | 2.4 | 163 | | | | 204 | | SILTY SAND |
| 4.00 | 1.8 | 12.3 | 1.90 | 0.62 | 0.11 | 6.41 | 2.6 | 367 | | | | 494 | | SAND |
| 4.20 | 3.8 | 13.8 | 1.90 | 0.64 | 0.13 | 2.75 | 5.7 | 349 | | | | 698 | | SILTY SAND |
| 4.40 | 4.1 | 7.0 | 1.80 | 0.66 | 0.15 | 0.73 | 6.0 | 101 | 1.3 | 5.6 | 3.0 | 201 | 0.58 | CLAYEY SILT |
| 4.60 | 4.7 | 8.4 | 1.80 | 0.67 | 0.17 | 0.83 | 6.7 | 130 | 1.4 | 6.6 | 3.8 | 273 | 0.67 | SILT |
| 4.80 | 4.7 | 8.4 | 1.80 | 0.69 | 0.19 | 0.83 | 6.5 | 130 | 1.4 | 6.3 | 3.7 | 269 | 0.66 | SILT |
| 5.00 | 4.3 | 7.5 | 1.80 | 0.71 | 0.21 | 0.79 | 5.8 | 112 | 1.3 | 5.3 | 3.0 | 218 | 0.59 | CLAYEY SILT |
| 5.20 | 4.3 | 7.3 | 1.80 | 0.72 | 0.23 | 0.74 | 5.7 | 105 | 1.3 | 5.1 | 2.9 | 201 | 0.58 | CLAYEY SILT |
| 5.40 | 4.8 | 8.1 | 1.80 | 0.74 | 0.25 | 0.73 | 6.2 | 115 | 1.3 | 5.8 | 3.6 | 232 | 0.66 | CLAYEY SILT |
| 5.60 | 4.9 | 8.1 | 1.80 | 0.75 | 0.26 | 0.69 | 6.2 | 112 | 1.3 | 5.8 | 3.6 | 225 | 0.68 | CLAYEY SILT |
| 5.80 | 4.8 | 8.6 | 1.80 | 0.77 | 0.28 | 0.86 | 5.8 | 134 | 1.3 | 5.3 | 3.3 | 262 | 0.65 | SILT |
| 6.00 | 5.0 | 8.8 | 1.80 | 0.78 | 0.30 | 0.82 | 6.0 | 134 | 1.3 | 5.5 | 3.5 | 264 | 0.68 | SILT |
| 6.20 | 5.0 | 7.9 | 1.80 | 0.80 | 0.32 | 0.62 | 5.9 | 101 | 1.3 | 5.4 | 3.5 | 197 | 0.68 | CLAYEY SILT |
| 6.40 | 5.1 | 8.2 | 1.80 | 0.82 | 0.34 | 0.65 | 5.8 | 108 | 1.3 | 5.3 | 3.5 | 211 | 0.69 | CLAYEY SILT |
| 6.60 | 4.9 | 9.0 | 1.80 | 0.83 | 0.36 | 0.93 | 5.4 | 145 | 1.2 | 4.7 | 3.1 | 273 | 0.63 | SILT |
| 6.80 | 5.5 | 9.0 | 1.80 | 0.85 | 0.38 | 0.69 | 6.0 | 123 | 1.3 | 5.6 | 3.9 | 244 | 0.74 | CLAYEY SILT |
| 7.00 | 4.7 | 8.4 | 1.80 | 0.86 | 0.40 | 0.88 | 5.0 | 130 | 1.2 | 4.1 | 2.7 | 233 | 0.59 | SILT |
| 7.20 | 7.2 | 10.0 | 1.80 | 0.88 | 0.42 | 0.41 | 7.8 | 97 | 1.6 | 8.3 | 6.4 | 218 | 1.05 | SILTY CLAY |
| 7.40 | 6.5 | 10.3 | 1.80 | 0.89 | 0.44 | 0.64 | 6.8 | 134 | 1.4 | 6.7 | 5.1 | 281 | 0.90 | CLAYEY SILT |
| 7.60 | 7.0 | 10.6 | 1.80 | 0.91 | 0.46 | 0.56 | 7.2 | 126 | 1.5 | 7.3 | 5.8 | 273 | 0.99 | SILTY CLAY |
| 7.80 | 6.7 | 10.6 | 1.80 | 0.93 | 0.48 | 0.64 | 6.7 | 137 | 1.4 | 6.6 | 5.2 | 287 | 0.92 | CLAYEY SILT |
| 8.00 | 7.3 | 11.8 | 1.95 | 0.94 | 0.50 | 0.65 | 7.3 | 156 | 1.5 | 7.5 | 6.1 | 338 | 1.04 | CLAYEY SILT |
| 8.20 | 7.0 | 11.6 | 1.95 | 0.96 | 0.52 | 0.70 | 6.8 | 159 | 1.4 | 6.7 | 5.5 | 335 | 0.97 | CLAYEY SILT |
| 8.40 | 9.5 | 14.5 | 1.90 | 0.98 | 0.54 | 0.56 | 9.2 | 174 | 1.7 | 10.8 | 9.6 | 419 | 1.45 | SILTY CLAY |
| 8.60 | 8.2 | 12.1 | 1.90 | 1.00 | 0.56 | 0.52 | 7.6 | 137 | 1.5 | 8.1 | 7.1 | 306 | 1.17 | SILTY CLAY |
| 8.80 | 6.8 | 12.6 | 1.95 | 1.01 | 0.58 | 0.94 | 6.1 | 203 | 1.3 | 5.7 | 4.8 | 407 | 0.90 | SILT |
| 9.00 | 7.6 | 11.6 | 1.90 | 1.03 | 0.60 | 0.58 | 6.8 | 141 | 1.4 | 6.7 | 5.9 | 296 | 1.04 | SILTY CLAY |
| 9.20 | 7.7 | 16.4 | 1.95 | 1.05 | 0.62 | 1.22 | 6.8 | 301 | | | | 638 | | SANDY SILT |
| 9.40 | 7.3 | 15.1 | 1.95 | 1.07 | 0.64 | 1.18 | 6.2 | 272 | 1.4 | 5.9 | 5.2 | 553 | 0.97 | SILT |
| 9.60 | 8.6 | 16.1 | 1.95 | 1.09 | 0.66 | 0.95 | 7.3 | 261 | 1.5 | 7.6 | 7.1 | 571 | 1.21 | SILT |
| 9.80 | 8.9 | 13.1 | 1.90 | 1.11 | 0.68 | 0.52 | 7.4 | 148 | 1.5 | 7.7 | 7.4 | 325 | 1.25 | SILTY CLAY |
| 10.00 | 10.2 | 17.2 | 1.95 | 1.12 | 0.70 | 0.73 | 8.5 | 243 | 1.7 | 9.5 | 9.6 | 567 | 1.50 | CLAYEY SILT |
| 10.20 | 9.5 | 16.2 | 1.95 | 1.14 | 0.72 | 0.76 | 7.7 | 232 | 1.6 | 8.2 | 8.3 | 520 | 1.36 | CLAYEY SILT |
| 10.40 | 9.9 | 16.1 | 1.95 | 1.16 | 0.74 | 0.69 | 7.9 | 218 | 1.6 | 8.5 | 8.7 | 491 | 1.41 | CLAYEY SILT |
| 10.60 | 9.3 | 17.6 | 1.95 | 1.18 | 0.76 | 0.98 | 7.2 | 290 | 1.5 | 7.4 | 7.5 | 631 | 1.29 | SILT |
| 10.80 | 9.9 | 15.1 | 1.90 | 1.20 | 0.77 | 0.57 | 7.6 | 181 | 1.5 | 8.1 | 8.5 | 402 | 1.40 | SILTY CLAY |
| 11.00 | 9.5 | 13.6 | 1.90 | 1.22 | 0.79 | 0.48 | 7.1 | 145 | 1.5 | 7.3 | 7.6 | 311 | 1.31 | SILTY CLAY |
| 11.20 | 8.8 | 16.1 | 1.95 | 1.23 | 0.81 | 0.92 | 6.5 | 254 | 1.4 | 6.3 | 6.5 | 524 | 1.18 | SILT |
| 11.40 | 9.6 | 15.1 | 1.95 | 1.25 | 0.83 | 0.63 | 7.0 | 192 | 1.5 | 7.1 | 7.6 | 410 | 1.32 | CLAYEY SILT |
| 11.60 | 8.2 | 14.4 | 1.95 | 1.27 | 0.85 | 0.86 | 5.8 | 218 | 1.3 | 5.2 | 5.3 | 423 | 1.05 | SILT |
| Z (m) | Po | P1 | Gamma | Sigma' | U | Id | Kd | Ed | Ko | Ocr | q | M | Cu | DESCRIPTION |

Fig. 6. Results of dilatometric sounding DMT of Mio-Pliocene clays from Warsaw-Stegny

| Depth [m] | CPT [MPa] | DMT [MPa] |
|---|---|---|
| 4.40 | 1.27 | 1.3 |
| 5.00 | 1.39 | 1.3 |
| 7.00 | 1.45 | 1.2 |
| 9.00 | 1.78 | 1.4 |
| 11.00 | 1.45 | 1.5 |
| average | 1.47 | 1.34 |
| $K_o$ CPT: DMT = 1.47:1.34 = 1.09 | | |

Table 6. Pressure coefficient at rest $K_0$

may become unloaded and "suck" (imbibe) water to the point of exceeding the remembered preconsolidation load (FREDLUND & RAHARDJO 1993).

In terms of strength and strain, unweathered Warsaw Mio-Pliocene clays have high parameters. Effective cohesion $c'_{CIU}$, effective angle of internal friction $\Phi'_{CIU}$, and consolidometric modulus of original compressibility in the range of 0.1-0.2 MPa are:

- $c'_{CIU}$ = 40 kPa (on average);
- $\Phi'_{CIU}$ = 15° (on average);
- $M_{kv}$ = 9.2-26.3 in vertical direction;
- $M_{kh}$ = 6.6-15.9 MPa in horizontal direction.

In designing deep foundations, horizontal stresses play a very important role. They can be determined knowing the pressure coefficient at rest $K_0 = \sigma'_h : \sigma'_v$ ($\sigma'_h$ – effective horizontal stress, and $\sigma'_v$ – effective vertical stress). $K_0$ values calculated from the Schmidt formula: $K_0 = (1 - \sin \Phi')\ OCR^{\sin\Phi'}$, in relation to the effective angle of internal friction Φ' and overconsolidation ratio OCR are given below in Table 5. In the case of the analysed clays, with OCR values of 1 to 14 and Φ' value of 15°, $K_0$ values range from 0.74 to 1.44. The above parameters determined in laboratory tests, are confirmed in field tests: solid sounding CPT, and dilatometric (MARCHETTI 1980, 1999) sounding DMT (Text-fig. 6; Tabs 6, 7). In the Mio-Pliocene clays one must take into account that horizontal stresses are greater than vertical stresses. CPT and DMT tests of the Mio-Pliocene clays were also accomplished by SGGW (Warsaw Agricultural University), Chair of Geotechnics (WOLSKI & *al.* 1993; PRACA BADAWCZO-ROZWOJOWA 1992; SZYMAŃSKI 1996, 2000). The results enable determination of the relationship between parameters obtained in the laboratory and in the field.

| Depth [m] | CPT [MPa] | DMT [MPa] |
|---|---|---|
| 4.40 | 0.069 | 0.058 |
| 5.00 | 0.089 | 0.059 |
| 7.00 | 0.118 | 0.059 |
| 9.00 | 0.207 | 0.104 |
| 11.00 | 0.161 | 0.131 |
| average: | 0.128 | 0.082 |
| $\tau_{fu}$ CPT: DMT = 0.128:0.082 = 1.56 | | |

Table 7. Shear strength in undrained conditions $\tau_{fu}$

Disturbance of the natural structure of clays, occurrences of weakness surfaces, and additional wetting results in significant change in their properties:

- occurrence of weakening surfaces causes a change in strength, from maximum strength to residual strength ($\Phi_R \approx 8.5°$)
- disturbance of clay structure decreases the shear strength by 50-60% in comparison to the undisturbed state.

Additional wetting almost always results in a swelling of the clay, and change in such parameters as:

- bulk density (decrease about 10-20%), porosity (increase to 50%);
- water content (increase to 50%), liquidity index (increase to 100%);
- cohesion, internal friction angle, and compressibility modulus (decrease to 100%).

Weathered clays formed in the topmost layers must be treated as unconsolidated or normally consolidated clays, hence constituting a weak construction subgrade.

Assessment of slope stability requires a very thorough investigation of the properties of the clays in question. In the analysis of equilibrium in soils with weakness surfaces it is necessary to know the shear resistance along the weakness surfaces, as well as their inclination and orientation. Strength along weakness surfaces of discontinuity type is close to minimum residual shear strength. For numerical assessment of shear strength decrease at the transition from maximum to residual value, Bishop's index (BISHOP 1972) is used, which, in the case of the Mio-Pliocene clays reaches 75%. Account must be taken that long-term stability in the Mio-Pliocene clays may be assured only at around or below 10%.

## CONCLUSIONS

The Mio-Pliocene clays from the point of view of engineering-geological assessment should be included in the group of soils of specific properties, especially sensitive to exogenic processes. Soaking, cyclic swelling and shrinking cause fast disintegration of clays. The influence of disturbance the original structure or any of changes in humidity shows very distinctly in shear strength decrease, which results in a significant decline in the subgrade load-bearing capacity. The results of the investigation can be summarised as follows:

1. Warsaw Mio-Pliocene clays are overconsolidated soils (OCR = 1-14), represented by the complex of clayey soils, and by subordinate silty clayey soils of limnitic origin. The main clay minerals are beidellit, illite and kaolinite. The clays are characterised by a semi-compact/hard-plastic consistency, with water contents close to saturated and transient types of microstructures (matrix-turbulent and turbulent-laminar).

2. In their natural (unweathered) state the clays have relatively high strength and deformability parameters – they constitute a load-bearing subgrade. Clays may become unloaded and "suck" water to the point of exceeding the remembered pre-consolidation load.

3. Higher horizontal then vertical stresses must be accounted for in the case of Mio-Pliocene clays. The coefficient of soil pressure at rest $K_0$ = 0.74-1.44.

4. The Mio-Pliocene clays are very sensitive to exogenic processes. Especially in the case of additional wetting or disturbance of the structure, the properties of clays change drastically – porosity, water contents and liquidity index increase, while bulk density, cohesion, angle of internal friction and compressibility moduli decrease. In numerical terms, depending on the parameter concerned, those changes range from 10 to 100%.

5. Weathered layers formed in the topmost part of clays must be treated as unconsolidated, or normally consolidated soils – they constitute an inadequate construction subgrade.

6. Occurrences of weakness surfaces in the clay mass cause a decrease in its strength. Quantitative evaluation of shear strength decline at the transition from the maximum value to the residual value is illustrated by Bishop's index, which reaches 75% in the case of the Mio-Pliocene clays.

In order to protect the Mio-Pliocene clays against disintegration it is necessary to guard them above all against changes in water content by means of appropriate damp-proofing. Unless this is properly accomplished, soil of high parameters transforms into eluvium of low strength parameters.

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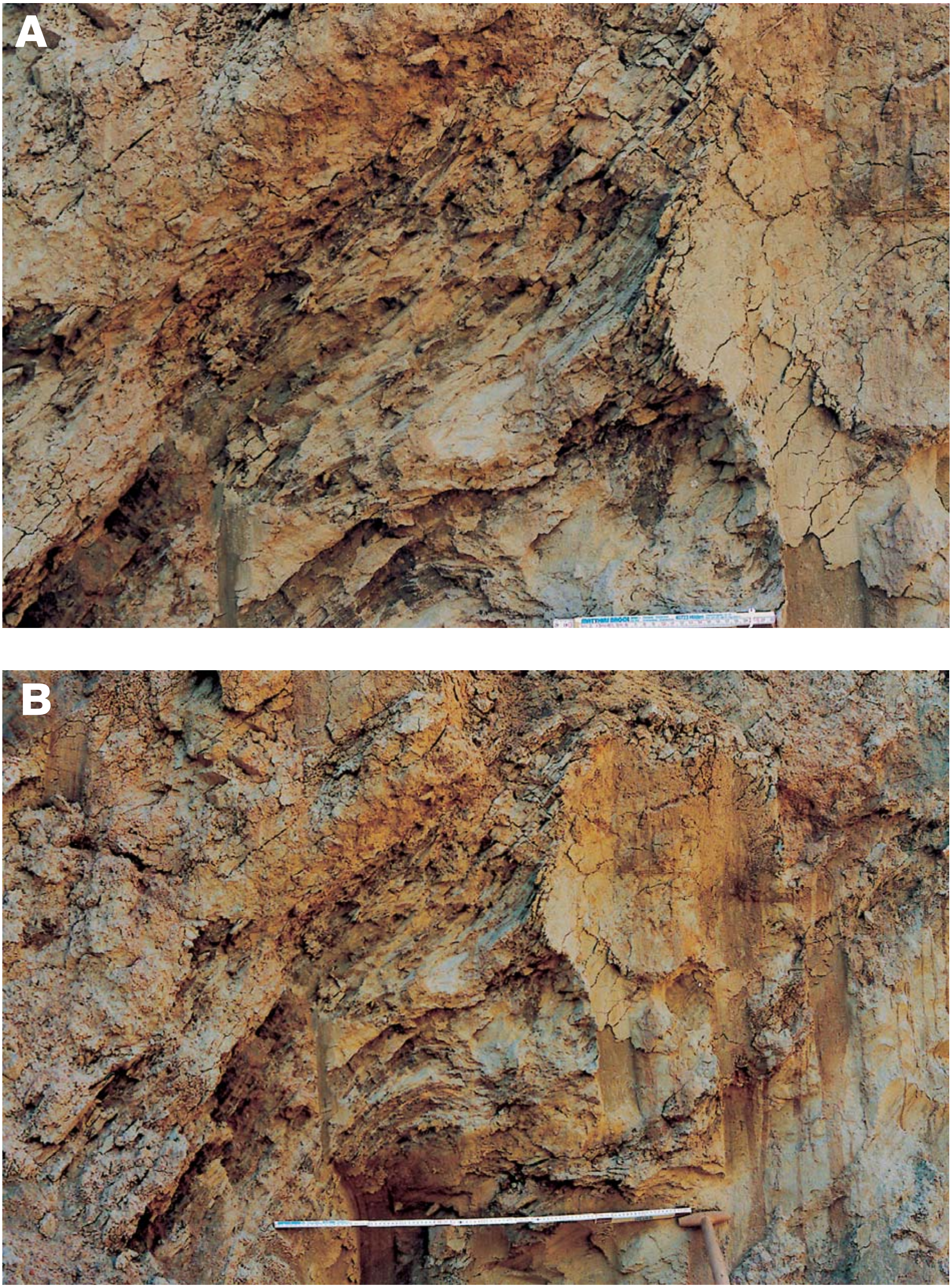


Fig. 3. A. glaciotectonic dislokation (fold) in Pliocene clays (flame coloured); B. magnification of the fold