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Formation of engineering properties of soils during geological history

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A quantitative evaluation of the present behaviour mainly of clay under load is given. The soils examined acquired their present properties in the course of a long and often complex geological history when they attained the state of overconsolidation (non-decompressed to the end). Examined were glaciolacustrine clays, boulder clays, Mio-Pliocene clays and Miocene clays. The results obtained were compared with data for the Eocene London Clays taken from professional literature. Field and laboratory tests permitted to define the basic properties of these soils, the parameters of their "geological history" and stress-strain interdependence. Special attention was given to the effect of exogenic factors on the strength and deformability of the soils. The zonality of the weathering profile was defined.

Key words: geological history, engineering behaviour of soils, overconsolidation, properties, weathering, stress-strain

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INTRODUCTION

Not infrequently modern engineering constructions have several underground storeys and several tens of storeys above the ground. For deep excavations and great loads, of crucial importance is the knowledge of soil parameters (engineering behaviour) reliably defined for a wide range of loads and enabling the definition of the horizontal component of stress state. The engineering behaviour is greatly influenced by the geological compaction-unloading history and the overall geodynamic factors and phenomena. The shape of the stress–strain relationship strictly depends on the present consolidation stage of soils.

In this paper, field and laboratory results are presented for typical clayey soils known to occur in Poland. These data have been obtained from projects granted by the Committee for Scientific Research (KBN) and doctoral theses defended at the Department of Engineering Geology, Warsaw University. Subjected to examinations were Quaternary clays (glaciolacustrine), boulder clays, Mio-Pliocene clays and Miocene Clays.

For comparison, data for Eocene London Clays are cited.

OVERCONSOLIDATION OF SOILS

The structure and properties of soil in its natural state are the result of the physical and chemical processes and phenomena that have occurred during geological history in the course of sedimentation, consolidation and diagenesis as well as in later changes. A considerable part of soils shows features characteristic of soils much more consolidated than implied by their present position (depth of occurrence), which means they are overconsolidated, the overconsolidation ratio being OCR = $\sigma'_{\mathrm{pmax}} : \sigma'_{\mathrm{zy}} > 1$ (σ'_{pmax} – preconsolidation stress, σ'_{zy} – overburden pressure). In the literature (Szczepański, 2005), two types of preconsolidation are distinguished: proper (mechanical) preconsolidation and apparent preconsolidation related to structural acquisition. The formation of properties, the state of normally consolidated and overconsolidated soils are shown in the three successive graphs (Fig. 1 a, b, c)**.** The function $e = f(\sigma')$ coupled with soil schemes illustrates the behaviour of soil under compaction-unloading during sedimentation-erosion, repeated compaction caused, for example, by a glacier and other factors. It should be emphasized that σ'_{pmax} is the overconsolidation pressure presently memorized by the soil.

In addition to compressibility lines, shear strength lines $\tau_f = \sigma_n' \operatorname{tg}\Phi' + c'$ are shown in Fig. 1c. The functions are noticeably different depending on whether the soil is normally consolidated or overconsolidated. The limit for these behaviours is σ'_{pmax}. In overconsolidated soils, cohesion $c' \neq 0$. $K_0 = \sigma_h' : \sigma'_v$ The coefficient of earth pressure at rest σ_n', σ'_v – effective horizontal and vertical stresses for overconsolidated soils – exceeds 1 which is of crucial significance in case of foundation work in deep excavations.

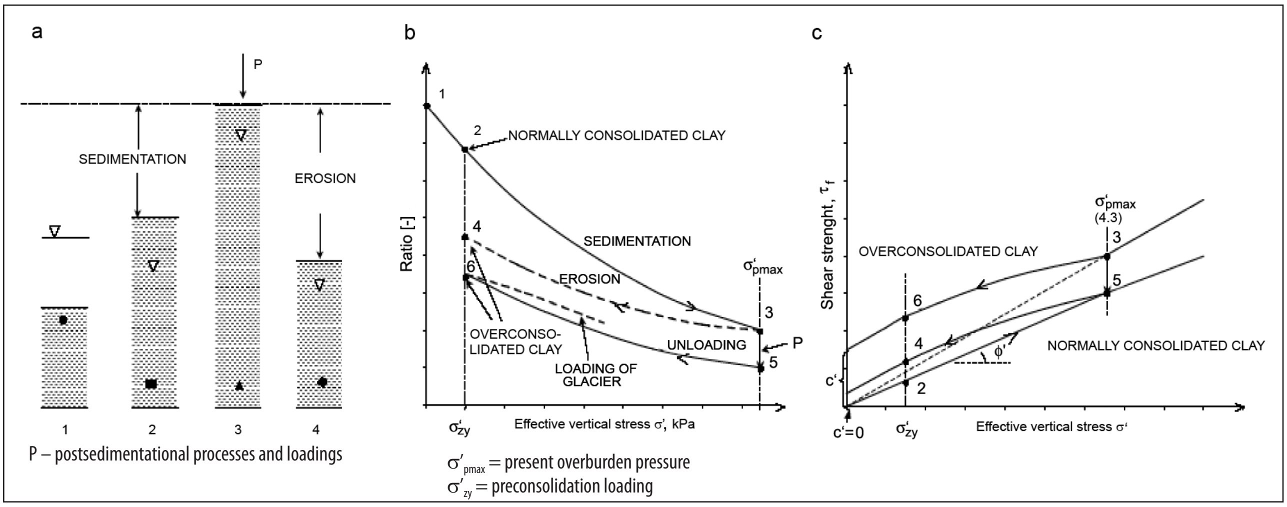

Fig. 1. Schematic geological history of overconsolidated clays: *a* – sedimentation, erosion, diagenesis and postsedimientiational processes, *b* – composition and loading, *c* – shear strength as a function of loading und unloading (to take pattern publication: Skempton, 1961, 1964; Bjerrum, 1967; Fleming et al., 1970 with supplements – see Taylor, Crips, 1987)

GEOLOGICAL SETTING OF CLAY OCCURRENCE

Engineering-geological studies were carried out on Quaternary and Tertiary clays:

- glaciolacustrine clays – North Polish glaciation
- boulder clays – Middle Polish glaciation
- Miopliocene clays
- Miocene clays
- London Eocene clays.

Glaciolacustrine clays. Sedimentation of glaciolacustrine clays of Cental Poland (Mazowsze) took place in several separated basins during the Riss glacial period. They occur directly on the surface; their average thickness has been evaluated to be about 4–5 m. They are usually underlain by sands and glacial tills. The clays represent typical glaciolaustrine sediments, their mineral composition is fairly monotonous. Dark varves are fine-grained and richer in clay minerals, and bright varves are coarser and richer in detrital mineral.

Boulder clays. The processes forming the physical-mechanical properties of boulder clays have acted generally in various ways in different morphological and climatological conditions of clay sedimentation, not identical in the successive phases of glaciation, and in different conditions of postgenetic alteration of these clays. The boulder clays of Middle Polish Glaciation (Warsaw area) in most cases achieved full consolidation (overconsolidated state OCR > 1, liquidity index $I_L \leq 0$). Boulder clays consist of heterogeneous material, belong to individual moraines and often are of different colours (grey, brown and red-brown). In most boulder clays analysed, illite and minerals of the mixed package group are the main clay minerals. Only in a small number of cases montmorillonite with some illite prevailed. Chlorite and koalinite were present as admixtures. Skeletal, skeletal-matrix and matrix microstructures are characteristic of the boulder clays investigated.

The Mio-Pliocene. Mio-Pliocene clays of the Poznań series occur over a considerable area of Poland and are overlain by a Quaternary drift deposit of varying thickness. In the Warsaw region, the depth of their occurrence ranges from 2 to 100 m below ground-level, and their average thickness is 50 m. The Mio-Pliocene deposits are strongly deformed; many folds of different amplitudes and discontinuous deformations occur here. The analysed clays in the Warsaw area are covered with Quaternary deposits including anthropogenic ones of varying thickness. Mio-Pliocene clays are represented mainly a the complex of clayey soils, with subordinate amounts of silty clayey soils of limnic origin. Warsaw Mio-Pliocene clays are characterized by transitory (Grabowska-Olszewska, Osipov, Sokolow, 1984; Grabowska-Olszewska (ed.), 1998) types of microstructures: matrix, turbulent and turbulent-laminar (Fig. 2). Among the clay minerals, mainly mixed-layer minerals of the beidellite-illite and kaolinite series are encountered (Kaczyński, Grabowska-Olszewska, 1997). These clays are overconsolidated (Borowczyk, Szymański, 1995; Izbicki, Stachoń, 1989; Szymański, 2000; Kaczyński, 2003).

Miocene clays occur in the Carpathian Foredeep which is part of the Para-Tethys basin. In Poland, near the Tarnobrzeg area, these clays occasionally occur on the surface or under a fairly thin overburden. More often, however, they are overlain by a younger-Quaternary drift deposit (loess, alluvium, tills, slope wash material). The characteristic feature of the marine Miocene sediments is the occurrence of bentonite and bentonitic clays. The Miocene clay sediments are represented by marine, montmoryllonitic and illitic, marly, overconsolidated, laminated clays. From the engineering-geological point of view, the massif of the Miocene Clays should be treated as a heterogeneous, anisotropic and discontinous medium. The soil massif is cut by weakness surfaces which may be divided into two types: sedimentary surfaces and discontinuities. The maximum thickness of Miocene sediments has been recorded along the axis of the Fordeep and at the Carpathian Thrust and evaluated to be as high as 3–4 km, in the Tarnobrzeg area being 50–100 m (Kaczyński, Grabowska-Olszewska, 1997).

London Clays. Two Eocene marine basins are known to occur in South Eastern England – the London basin in the north and the Hampshire basin in the south, both forming a part of the larger North Sea Basin. In these basins, clay sediments known as London Clay occur, with rich fauna, mainly nummulitic, and tropical plants. The London Clay series is characterized by a distinct layering and contains, among others, pyrite, selenite and septaria concretions. The clays are cohesive, with fissure lines visible in hand specimen and numerous microdiscontinuities noted under the microscope (Fookes, 1966; Tchalenko, 1968). The total thickness of this series is 100–130 m (Crips, Taylor, 1977; Ward, Samuels, Buttler, 1950).

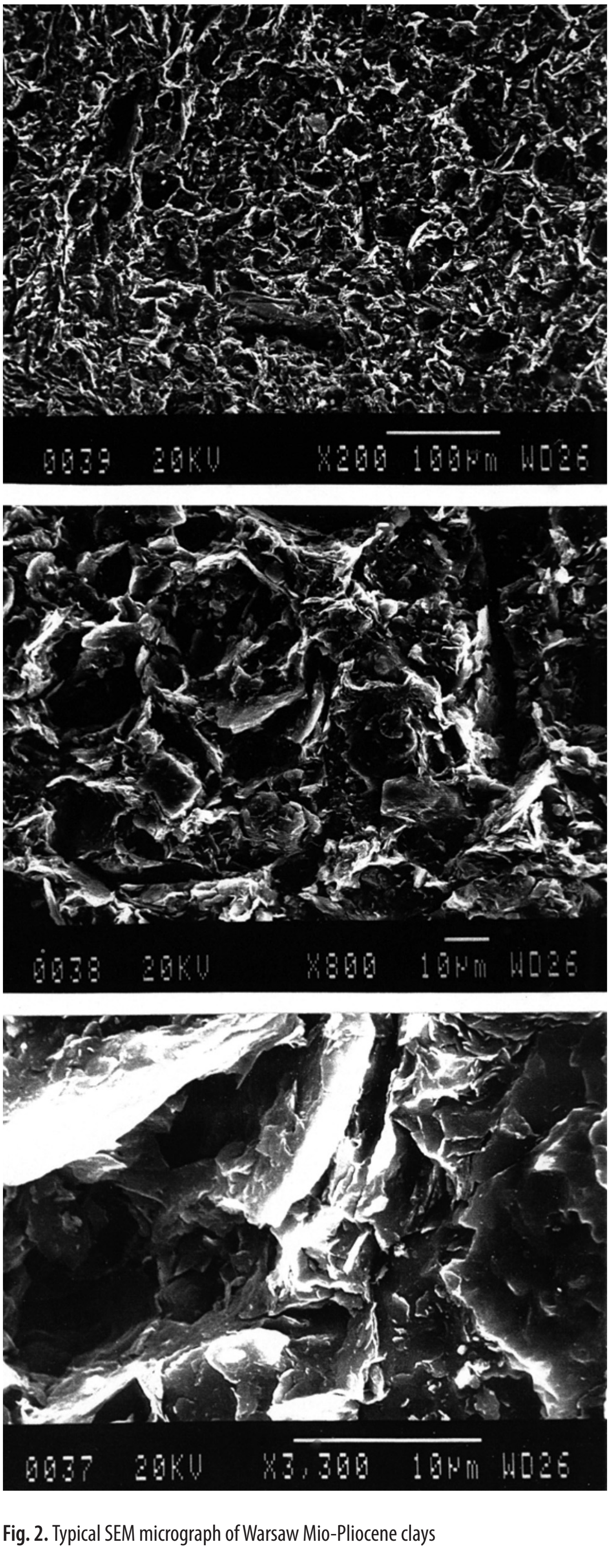

Fig. 2. Typical SEM micrograph of Warsaw Mio-Pliocene clays

ENGINEERING-GEOLOGICAL PROPERTIES OF SOILS

The properties of the clays examined were formed in the course of a long, rather complicated geological history and acquired an overconsolidated state (not fully decompressed). The equalization of water pressure in the pores lags behind the decrease of stress, and therefore the clays, except the close-to-surface layer, are not fully decompressed. The major impact on clay consolidation was exerted by the glacier load (in case of glacial, Mio-Pliocene and Miocene clays), tectonic events (Miocene and Eocene clays), erosion (Miocene and Eocene clays), cementation (glaciolacustrine clays) and drying (all clays). A quantitative illustration of such a history (mainly load) is, among others, the overconsolidation ratio (OCR).

The OCR and the other parameters were determined in the laboratory using the Rowe–Barden (to 2 MPa) consolidometer and the prototype consolidometer (to 20 MPa). Field investigations included CPT and DMT tests. The maximum preconsolidation stress was determined by the Casagrande method. The results obtained are listed in Tables 1 and 2. The overall OCR data fall within 1.4–50.0 (sometimes to 200) range. Noteworthy are the close OCR values for the glaciolacustrine and Mio-Pliocene clays, the glaciolacustrine clays having never been found under the glacier load. In clays deposited in an aqueous environment, the OCR grows with the age of the clays. Worth noting are the high OCR values for boulder clays, i. e. sediments of a different origin. The distribution of the coefficient of earth pressure at rest, K_0, with depth for the Mio-Pliocene (Warsaw) Clays against the background of the London Clays is given in Fig. 3.

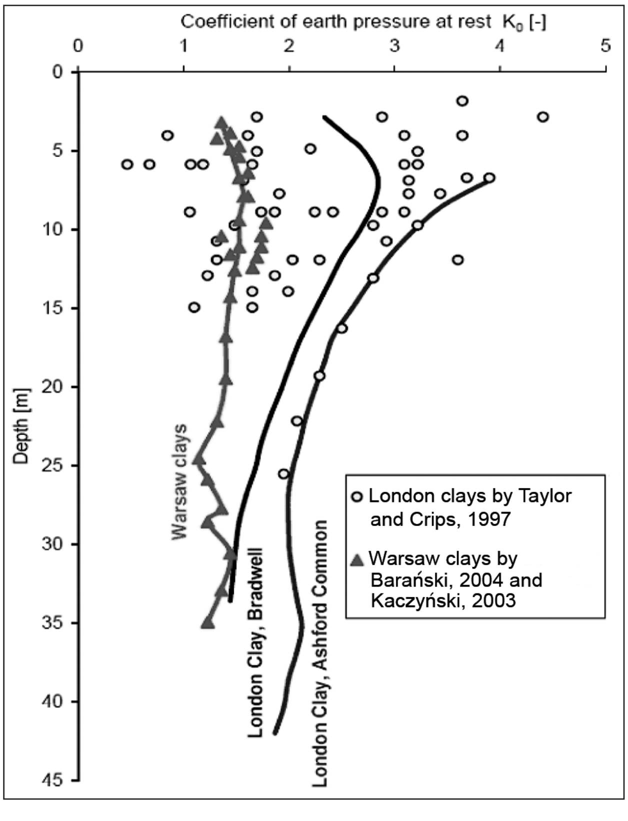

Fig. 3. Distribution with the depth coefficient of earth pressure at rest K_0 in overconsolidated London and Warsaw clays – *in situ* tests

Table 1. **Basic physical-mechanical properties of unweathered and weathered clays**

Parameter	**Lacustrine clays**	**Boulder clays**	**Mio-Pliocene clays**		**Miocene clays**		**London Eocene clays****	
	unweathered	**unweathered**	**unweathered**	**weathered**	**unweathered**	**weathered**	**unweathered**	**weathered**
Natural water content, %	29–39	7–22.5	19.2–35.6 (28)	30–45	8.8–37.0	20–45	19–28	23–49
Liquid limit, %	25–88*	15–55	37.5–96.4 (72.3)	to 100	39–82	45–85	50–105 (70)	66–100 (82)
Plasticity index, %	4.5–50*	2.5–25	16,2–58 (40.4)	to 60	17–33	25–60	40–65 (47)	36–55 (44)
Clay fraction content, %	18–88	5–50	28–89 (56)	20–85	15–60	20–65	40–72	–
Bulk density, mg/m^3	1.73–1.98	1.65–2.25	1.85–2.13 (2.00)	1.7–2.0	1.85–2.36	1.6–20	1.92–2.04	1.70–2.00
Undrained shear strength, kPa	30–150	50–300	8–250	to 80	to 1000	to 120	80–800	40–190
Cohesion, kPa	28–70*	20–130	25–55	to 10–25	15–425	5–50	31–252	1–18
Angle of internal fraction, °	19–32*	12–25	12–22	to–13	11–29	2.5–15	20–29	17–23
Oedometric modulus, MPa	7–45	25–500	4–26	1–10	5.9–148	1–20	8–50	–

* E. Myślińska (1965).

** Taylor and Crips (1987).

Table 2. **Parameters of geological history**

Age of clay	**Type of clay**	**Overconsolidation ratio OCR [–]**	**Preconsolidation stress σ_{pmax}, kPa**	**Coefficient of earth pressure at rest K_0 (–)**
Quaternarry	Glaciolacustrine clay	5–9 (2–12)	250–1000	1–2
	Boulder clay	10–50 sometimes to 200	1000–12500	0.5–3.5
Tertiary	Mio-Pliocene clay	2–14	500–1100	0.75–1.44
	Miocene Clay	1.4–20.0	50–3500	> 1.0
	London Eocene Clay (Taylor and Crips, 1987)	4–41	1500–4900	1.5–2.8

The remaining engineering geological parameters adequate to the geological history are listed in Table 2.

SENSITIVENESS OF CLAY TO EXOGENOUS PROCESSES

The equalization of pore pressure in unloaded overconsolidated clays is delayed in relation to the decrease in stress (Bishop, 1972; Chandler, 1969). In the topmost part of the clays, a layer of weathered clay forms, which is subjected to total or partial deconsolidation. The properties, particularly of overconsolidated clays, are time-dependent, since their water content increases with time. The tested clays are sensitive to additional wetting and to disturbing their structure. The swelling pressure $\sigma_{sp} = 10$ (boulder clays) – 1000 kPa (London clay) – indicate that the analysed clays, in their natural state, may be classified as soils of a low to extremely high swelling. Clays soak under the effect of even a low water content. In the soaking test, air-dry clays avalanche-disintegrate from 40 to 100% within one hour, while clays with a water content close to natural increase their mass, and flake and crack slightly.

Based on laboratory tests, the decrease in shear strength (cohesion *C* and the angle of internal friction Φ) that results from the weathering (first of all the swelling) of clays (wt) in relation to their natural water content – non-weathered soils (nwt) – can be expressed as follows:

- Glaciolacustrine
  Mio-Pliocene $C_{wt} = 0.40–0.70\ C_{nwt}$
  Miocene (Fig. 4)
  Clays $\Phi_{wt} = 0.60–0.90\ \Phi_{nwt}$
- London Eocene Clays $C_{nwt} \approx 0.10\ C_{nwt}$
  (Cripps, Taylor, 1981) $\Phi_{nwt} \approx 0.50\ \Phi_{nwt}$

The influence of clay structure disturbance *dis* (remoulded samples) on its cohesion, in relation to clay with an undisturbed structure *und*, may be determined as

- Mio-Pliocene
  Miocene $C_{dis} \approx 0.4\ C_{wnd}$
  Clays

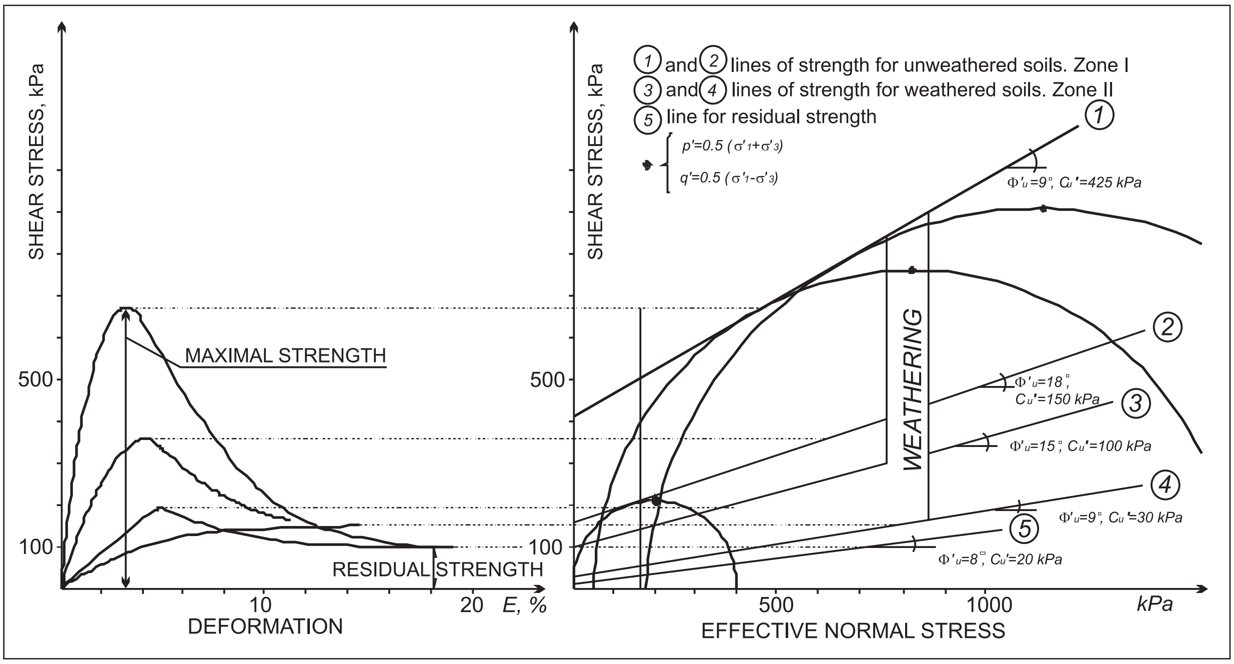

Fig. 4. Parameters of shear strength for Miocene clays from Carpathian Foredeep

The disturbance of structure mainly causes a decrease in cohesion, while the angle of internal friction remains relatively unchanged.

Observations carried out over the whole area of occurrence of Mio-Pliocene and Miocene clays make it possible to separate the weathering profile into two distinct principal zones:

- zone I of clays with their original properties completely changed
- zone II of weathered clays.

The thickness of the weathering profile as a result of exogenic processes in analysed Polish clays may be defined as ~1 m and when lacking covering as 3–5 m.

CONCLUSIONS

The analysed clays are common soils in Central Poland. They occur very often in the zone of interaction between soil and engineering buildings. From the point of engineering-geological assessment, these clays should be included in the group of soils of specific properties, especially susceptible to exogenous processes (weathering). The results of the investigations may be summarized as follows:

1. The cohesive soils (clays) examined are overconsolidated soils which attained their state due to various, sometimes complex, historic geological events. The overconsolidation ratio (OCR) for cohesive soils falls within 1.4–50.0 (sometimes to 200) and 1.4–20.0 for the clay group. As a result of cementation and drying, the glaciolacustrine clays non-loaded by the glacier show the OCR values close to those for the Tertiary clays. Glacial clays as a medium of different origin have very high OCR values.

2. The overconsolidation state includes proper preconsolidation (related to mechanical compaction-unloading) and apparent preconsolidation (resulting from post-sedimentary events and processes, from structurization).

3. In their natural (unweathered) state, clays show high strength and deformability parameters, i. e. a sufficient bearing capacity for standard constructions.

4. In the course of loading and during repeated loading, these clays can soak up water to the point when the memorized preconsolidation stress σ'_{pmax} value is exceeded. Because $K_0 > 1$, the vertical stress should be expected to be higher than the horizontal stress.

5. As a result of various exogenous processes, in case of saturation and structural disturbances in particular, the engineering properties of clays drastically change. This statement applies mainly to cohesion which in Polish clays shows a substantial decrease even by several tens per cent.

6. Two zones are distinguished in the clay weathering profile:

I – clays with the properties and structure totally different from those of non-weathered clays,

II – clays of a varying weathering degree, their basic original structural features preserved; the thickness of the weathering profile reaches up to 1 m and in case of the lacking external cover 3–5 m.

7. As compared with the Polish Tertiary (Mio-Pliocene and Miocene) clays, the Eocene London Clays deposited in an aqueous environment are more overconsolidated, stronger and less deformable.

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References

1. Barański M. 2004. Evaluation of Pliocene clays behaviour from Stegny in effective conditions. Grant KBN. Nr 5T12B04122. UW Warsaw. 280 p. (in Polish).

2. Bishop A. W. 1972. Shear strength parameters for undisturbed and remoulded soil speciments. In: Parry R. H. G. (eds.). *Rescoe Memorial Symposium on Stress-Strain Behaviour of Soils.*Cambridge University. Oxfordshire. 3–58.
3. Bjerrum L. 1967. Progressive failure in slipes of overconsolidated plastic clay and clay shales. Soil Mechanics Division. *Preceedings ASCE. **93***. 3–49.
4. Borowczyk M., Szymański M. 1995. The use of *in situ* tests for determination of stress history. *Proc. 11th European Conf. Soil Mechanics and Found.* Eng. Copenhagen. 117–123.
5. Chandler R. 1969. The effect of weathering on the shear strenght properties of Keep Marl. *Géotechnique. **19***. 321–334.
6. Cripps J. C., Taylor R. K. 1977. The engineering properties of mudrocks. *Q. J. Engg. Geol**. 7***. 257–296.
7. Fookes P. G. 1966. London Basin Tertiary sediments. *Géotechnique*. ***16***. 260–263.
8. Grabowska-Olszewska B. (ed.). 1998. Applied Geology. Properties of Unsaturated Soils. PWN (in Polish).
9. Grabowska-Olszewska B., Osipov V., Sokolov V. N. 1984. Atlas of Microstructure of Clay Soils. PWN.
10. Izbicki R. J., Stachoń M. 1989. The influence of overconsolidation on strenght properties of tertiary cohesive soils. *Proc. 6th Glacitectonics Symposium. Zielona Góra.* 53–64 (in Polish).
11. Kaczyński R., Grabowska-Olszewska B. 1997. Soil mechanics of the potentially expansive clays in Poland. *Applied Clay Science. Special Issue. **11***. 337–355.
12. Kaczyński R. 2003. Overconsolidation and microstructure in Neogene clays from the Warsaw area. *Geol. Quarterly. **47**(1)*. 43–54.
13. Myślińska E. 1965. Influence of sedimentary conditions and of diagenesis of varved clays of the middle-Polish glaciation from the Mazovian area upon their engineering-geological properties. *Biul. Geol. UW. T. **7***.
14. Skempton A. W. 1961. Horizontal stress in an overconsolidated Eocene clay. *Proc. 5th Int. Conf. SMFE. **I***. Paris. 351–357.
15. Skempton A. W. 1964. Long-term stability of clay slopes. *Géotechnique. **14**(2)*. 77–01.
16. Szczepański T. 2005. Estimation of the consolidation state of chosen clays on the basis of their compressibility parameters. Diss. Doct. UW.
17. Szymański A. 2000. Determination of stress history in cohesive soil on the basis of *in-situ* tests. *Proc. 9th Baltic Geotechnical Conference.* Tallinn. 25–28.
18. Taylor R. K., Crips J. C. 1987. Weaterring Effects: Slopes in Mudrocks and Overconsolidation Clays. Slope Stability. M. G. Anderson, K. S. Richards (eds.) J. Willey & Sons. 405–443.
19. Tchalenko J. S. 1968. The microstructure of London Clay. *Quarterly Jour. of Eng. Geology. **1***. 158–168.
20. Ward W. H., Samuels S. G. Butler M. E. 1950. Further studies of the properties of London Clay. *Géotechnique. **V. IX. N 2***. 33–58.

Ryszard R. Kaczyński

GRUNTŲ INŽINERINIŲ SAVYBIŲ FORMAVIMASIS GEOLOGINĖS RAIDOS METU

Santrauka

Straipsnyje įvertinama dabartinė molio gruntų fizinė būklė veikiant mechaninei apkrovai. Tyrimai atlikti su limnoglacialiniu, moreniniu moliu, taip pat plioceno ir mioceno moliu. Konstatuota, kad dabartines inžinerines savybes gruntai įgijo ilgos ir sudėtingos geologinės raidos metu, ir tai nulėmė jų perkonsoliduotą būklę. Gauti rezultatai palyginti su Londono eoceniniu moliu, dabartiniais ir lauko metodais nustatytos gruntų fizikinės mechaninės savybės, jų geologinės raidos ypatumai, stiprumo ir deformacijos sąsajos. Įvertintas egzogeninių veiksnių poveikis gruntų stiprumo ir deformacijos savybių vertėms. Išskirtos gruntų dūlėjimo pjūvio zonos. Tyrimais nustatyta, kad perkonsolidavimo rodiklio DCR vertė kinta nuo 1,4 iki 50. Išimtiniais atvejais DCR vertė pasiekia 200. Perkonsoliduotą būklę lemia ne tik mechaninė, bet ir su posedimentaciniais procesais susijusi perkonsolidacija. Egzogeniniai procesai (prisotinimas vandeniu, struktūros pokyčiai) ženkliai keičia gruntų inžinerines savybes. Pokytis sudaro kelias dešimtis procentų. Molio dūlėjimo pjūviuose išskirtos dvi pagrindinės zonos.

Ryszard R. Kaczyński

KSZTAŁTOWANIE SIĘ INŻYNIERSKICH WŁAŚCIWOŚCI GRUNTÓW PODCZAS ICH HISTORII GEOLOGICZNEJ

Streszczenie

Ilościowa ocena obecnego zachowania się iłów pod obciążeniem jest bardzo istotna w analizie nośności podłoża budowlanego. Aktualne właściwości grunty nabyły w trakcie długiej i skomplikowanej historii geologicznej i najczęściej osiągnęły stan przekonsolidowany (nieodprzężony do końca). Badane były iły zastoiskowe (warwowe), gliny lodowcowe, iły mioplioceńskie i iły mioceńskie. Porównano je ze znanymi eoceńskimi iłami londyńskimi. Uzyskane wyniki można podsumować następująco. Współczynnik przekonsolidowania dla badanych gruntów zmienia się w granicach OCR = 1,4–50,0 (niekiedy do 200). Przeksonsolidowany stan obejmuje prekonsolidację właściwą (mechaniczną) wywołaną obciążeniem-odciążeniem oraz prekonsolidację pozorną związaną z postsedymentacyjnymi procesami. W rezultacie egzogenicznych procesów, głównie w wyniku nasycenia wodą i naruszenia struktury, właściwości inżynierskie gruntów drastycznie zmieniają się, obniżenie parametrów osiąga kilkadziesiąt procent. W profilu wietrzeniowym iłów wyróżnia się 2 główne strefy.

Рышард Р. Качиньски

ФОРМИРОВАНИЕ ИНЖЕНЕРНЫХ СВОЙСТВ ГРУНТОВ В ХОДЕ ГЕОЛОГИЧЕСКОГО ОБРАЗОВАНИЯ

Резюме

Оценивается современное состояние глинистых грунтов под воздействием механических нагрузок. Исследования выполнены для лимногляциальных глин, моренных суглинков, плиоценовых и миоценовых глин. Констатируется, что современные инженерные свойства грунты приобрели в ходе долгого и сложного геологического развития. Полученные результаты сопоставлены с данными лондонских эоценовых глин. Лабораторными и полевыми методами определены физико-механические свойства грунтов, особенности их образования, взаимосвязь прочности и деформируемости. Оценивается влияние экзогенных процессов на показатели прочности и сжимаемости. Выделены зоны выветривания в геологическом разрезе. Результаты исследований позволяют установить, что значения показателя переуплотнения OCR изменяются от 1,4 до 50, в исключительных случаях – до 200. Переуплотненное состояние – это не только механическое переуплотнение, но также связанное с постседиментационными процессами. Такие экзогенные процессы, как водонасыщение, изменение структуры, значительно – на несколько десятков процентов – изменяют инженерные свойства грунтов. В разрезах глинистых грунтов выделены две основные зоны выветривания.