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Physical and mechanical properties of ice-dammed clays in Sochaczew and Radzymin areas in the light of *in situ* tests

Piotr Zawrzykraj

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The paper presents results of engineering geology studies of ice-dammed clays from Sochaczew and Radzymin areas in Poland. Measurements were performed *in situ* in Plecewice near Sochaczew and Mokre near Radzymin where open pits of varved clays are localized, and brought an assessment of physical and mechanical parameters of the soil, discussed in the paper. The tests were performed using static probe, Marchetti dilatometer, geoelectrical probe, and field vane tests. Using these instruments, a complex assessment of physical and mechanical parameters of the soil, including, among others, the compressibility modulus, shear resistance, the coefficient of pre-consolidation, and the coefficient of earth pressure at rest was performed. The paper also presents the geological environment of ice-dammed clays in the area of Warsaw.

Key words: varved clays, physical and mechanical properties, dilatometer test (DMT), cone penetration test (CPT), geoelectrical profiling (PE), *in situ* tests

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Piotr Zawrzykraj. Institute of Hydrogeology and Engineering Geology, Warsaw University, Żwirki i Wigury 93, Warsaw, Poland. E-mail: Piotr.Zawrzykraj@uw.edu.pl

INTRODUCTION

Recent advancements in technology of *in situ* geological-engineering tests made them a baseline of and frequently the most objective approach to investigation of physical and mechanical properties of soil. The high reliability of *in-situ* testing made this method the baseline of geological engineering testing of soil for the needs of planned construction works. CPT probes are now widely used. Because of its advanced capabilities, the dilatometric DMT sounding has gained increasing credibility. Owing to their specific operations mode, these state-of-the-art tools are able to provide a lot of valuable data on soil properties.

Testing of soils in their natural environment enable:

- characterization of a large portion of the soil volume by a continuous determination of the parameters measured, and determination of the depth of the supporting subsoil;
- direct *in-situ* investigation of the mechanical properties of soil; the tests yield objective results because they are performed at a large scale and in the natural environment of the soil tested;
- investigating the properties of soil in its natural stress state and in the location where the soil will work;
- obtaining data on construction subsoil in a rapid and relatively non-expensive way.

Owing to these benefits, *in-situ* testing becomes nowadays the preferred method of soil testing.

Researchers in Poland have been experimenting with *in-situ* testing methods on Polish soils for quite a while now. Analysis of results poses challenges that include interpretation problems, applicability of phenomenology formulae, and credibility of correlations. These issues are also discussed in the paper.

SUBJECT OF RESEARCH

The paper dwells on ice-dammed clay from the regions of Sochaczew and Radzymin in Poland. These clays are sediments originating from the North-Polish glaciation period. The soils are formed as high-plasticity varved clays, laminated in characteristic horizontally-laminated patterns which reflect their specific sedimentation conditions. Their thickness in the area of Warsaw varies from a few to a dozen of meters.

Varved clays from the so-called Warsaw Ice-Dammed Lake, related to the most recent glaciation, are widespread in the Mazovia Province. They frequently become the subsoil of constructions. It seems relevant, then, to present their physical and mechanical characteristics which can be useful for construction projects. The most important parameters are the compressibility modulus, shear resistance, the coefficient of earth pressure at rest, and the coefficient of consolidation.

Varved clay is a natural sediment and as such is inhomogeneous. Its peculiar, varved structure can easily be seen in the vertical profile. Easily noticeable is its bi-colour layer pattern composed of bright silt and dark clay layers. The structure features numerous secondary varves and lamines, as well as cracks and crioturbations (in the roof), as shown in Figs. 1 and 2.

Fig. 1. Varved clay, Plecewice, depth 6 m

Fig. 2. Varved clay, Mokre, depth 9 m

Based on literature data, one can conclude that the mineral composition of varved clay does not vary. It is mainly composed of illite minerals (mostly illite), quartz, carbonates, and ferric oxides and hydroperoxides.

GEOLOGICAL CONDITIONS OF OCCURRENCE OF ICE-DAMMED CLAY

Varved clay makes an appreciable portion of soil within the Warsaw Valley. The results presented in the paper concern the clay created in an ice-dammed lake during the Vistula Glaciation. The lake was formed because of the lack of a run-out of water residing in a large, shallow basin by the head of a continental glacier in the present-day Warsaw Valley. The basin with a well-developed, rich shoreline was an accumulation place of compact, plastic varved clay of a chocolate colour, with a high calcareous content. Its characteristic structure and varved texture is a result of periodic changes in the supply of material to the lake under the conditions of periglacial climate (Myślińska, 1965; Merta, 1978). The age of the ice-dammed formations used to be a subject of animated dispute, which was resolved by stratigraphic tests of the overlying organic deposits (Eemian interglacial period). The varved clays were formed in ice-dammed lakes during the Vistula Glaciation.

METHODS

Determination of the physical and mechanical properties of the soil was performed using the following equipment:

– Marchetti Dilatometer, an instrument that facilitates obtaining of soil parameters from *in-situ* tests. Its usability to geological-engineering *in-situ* tests is supported by numerous publications presented at international conferences (Marchetti, 1980, 1999; *The Flat Dilatometer Test*…, conference proceedings, 2001). Its use is recommended by the European and American field-test geotechnical standards;

– static probe CPT–CPT sounding is in widespread practical use (Lunne, 1997). Static probe is a baseline instrument for *in-situ* measurements of subsoil parameters at numerous research institutions worldwide. Technology development resulted in new models of advanced cones, which provide higher sampling rates and use digital technology for automatic data registering;

– field vane probe PSO-1, designed mainly for testing weak soils of high liquidity. The varved clay discussed in the paper occurs predominantly in a low plasticity state. The author decided to measure the shear resistance of varved clay, using this probe because it is able to provide precision measurements of the shearing force exerted on the soil by the vane, and because the friction resistance of the side surface of the rod is minimized owing to the use of a leading casing rod;

– geoelectrical pProbe (PE), a prototype geoelectrical probe for assessment of the content of clay fraction (and hence of the soil type) based on the measured electrical resistance. Promising results were obtained for measurements of varved clay (Zawrzykraj, 2005). A correlation $\Omega = f(\ln f_i)$ between the electrical resistance of the soil and the content of clay fraction was discovered. The square of correlation coefficient obtained was equal to $R^2 = 0.75$. Because of the small range of the soil volume measured in a single measurement, the probe offers a high resolution, and the results are not affected by errors caused by the influence of nearby layers.

The mechanical parameters of the test soil were determined in each of the measurement points by performing two dilatometric tests, two static tests, one PSO test, and one profiling with the use of a geoelectrical probe. Subsequently, statistical analysis of the results was performed, which brought conclusions on the entire complex of the ice-dammed clay, and its characteristics are presented in Table 1. Detailed plots showing the variability of properties of varved clay in vertical profiles are shown in Figs. 3 and 4.

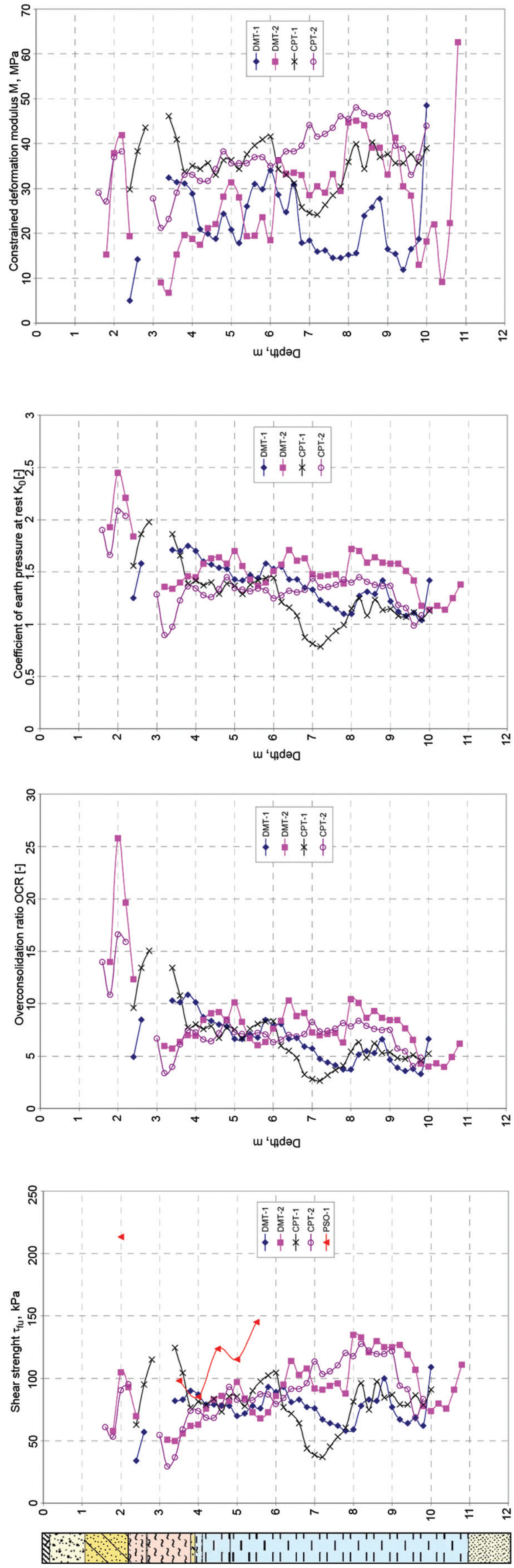

Fig. 3. Results of the *in situ* tests, Plecewice

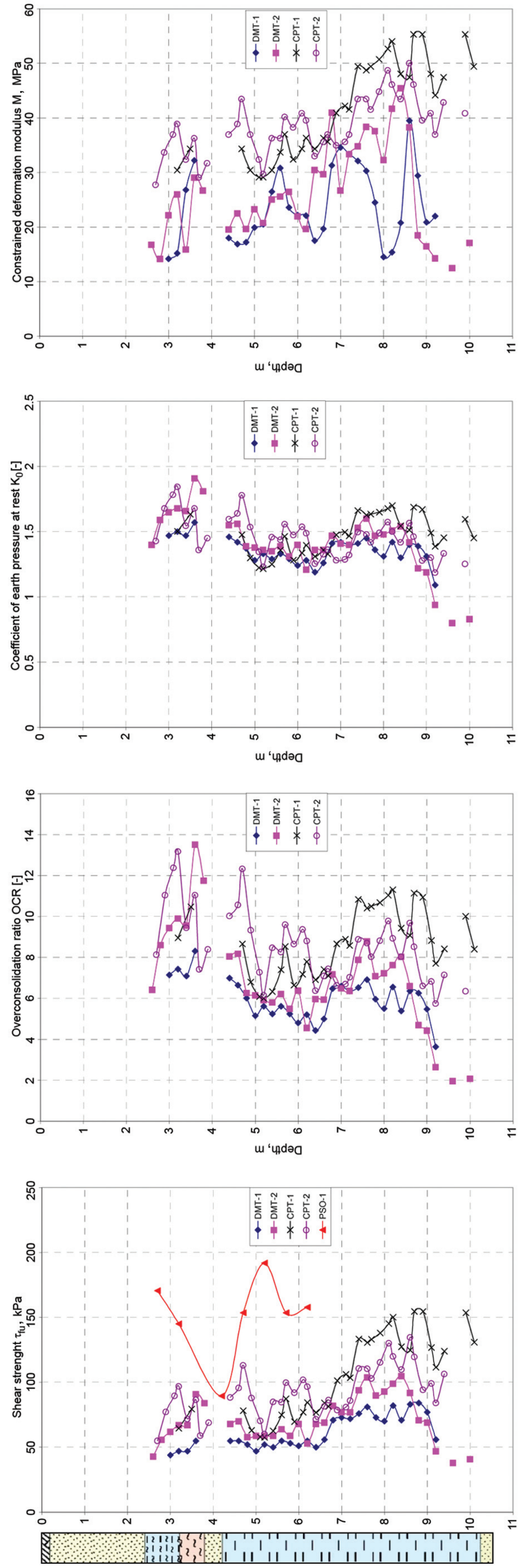

Fig. 4. Results of the *in situ* tests, Mokre

Table 1. **Descriptive statistics of parameters of ice-dammed clay in Plecewice near Sochaczew and Mokre near Radzymin**

Para-meter	Statistics	Plecewice near Sochaczew							Mokre near Radzymin						
		Type of test							Type of test						
		DMT1	DMT2	CPT1	CPT2	PSO			DMT1	DMT2	CPT1	CPT2	PSO		
						τ_{fmax}	τ_{fmin}	S					τ_{fmax}	τ_{fmin}	S
M, MPa	Average	**21.6**	**27.8**	**35.2**	**37.2**				**23.9**	**26.0**	**41.8**	**38.5**			
	Max	34.0	62.6	46.1	48.1				39.5	45.5	55.3	50.1			
	Min	5.0	6.8	24.1	21.3				14.2	12.5	29.1	27.8			
	Number	35	43	37	39				29	34	33	40			
	Standard deviation	7.0	11.3	5.0	6.5				6.8	8.7	8.7	5.1			
	Coefficient of changeability	0.3	0.4	0.1	0.2				0.3	0.3	0.2	0.1			
t_{fu}, kPa	Average	75.0	91.4	80.2	87.9	130.0	47.6	2.7	61.8	70.7	104.5	92.7	151.7	62.7	2.5
	Max	100.0	135.0	124.4	127.6	213.3	68.2	3.1	84.0	105.0	154.7	134.8	191.9	106.5	3.6
	Min	34.0	50.0	37.0	29.6	85.3	34.1	2.3	44.0	38.0	57.8	55.1	89.6	42.7	1.6
	Number	35	43	37	39	6	6	6	29	34	33	40	7	7	7
	Standard deviation	12.6	22.9	19.6	23.5	41.7	11.1	11.1	12.7	17.5	31.7	18.5	29.1	19.8	0.6
	Coefficient of changeability	0.2	0.3	0.2	0.3	0.3	0.2	4.1	0.2	0.2	0.3	0.2	0.2	0.3	0.2
OCR	Average	**6.5**	**8.4**	**6.7**	**7.6**				**6.0**	**6.9**	**8.7**	**8.6**			
	Max	10.9	25.8	15.1	16.6				8.3	13.5	11.3	13.2			
	Min	3.3	4.0	2.6	3.4				3.6	2.0	6.0	5.8			
	Number	35	43	37	39				29	34	33	40			
	Standard deviation	2.1	3.8	2.9	2.7				1.0	2.4	1.6	1.8			
	Coefficient of changeability	0.3	0.5	0.4	0.3				0.2	0.3	0.2	0.2			
K_0	Average	**1.4**	**1.5**	**1.3**	**1.4**				**1.4**	**1.4**	**1.5**	**1.5**			
	Max	1.8	2.5	2.0	2.1				1.6	1.9	1.7	1.8			
	Min	1.0	1.1	0.8	0.9				1.1	0.8	1.2	1.2			
	Number	35	43	37	39				29	34	33	40			
	Standard deviation	0.2	0.3	0.3	0.2				0.1	0.2	0.2	0.2			
	Coefficient of changeability	0.1	0.2	0.2	0.2				0.1	0.2	0.1	0.1			

To obtain a qualitative assessment of the profile of varved clay, geophysical studies were performed using a new, prototype probe to measure soil resistance (Borowczyk, Porzeżyński, 2003). Measurements of the electrical resistance of the soil were performed using a probe attached to the last rod of the CPT probe. The geoelectrical probe was inserted into a hole resulting from a CPT sounding performed previously. The measuring terminal used to measure soil resistance was fitted with symmetrically distributed electrodes, i.e. it had two measuring electrodes (MN) and two supply electrodes (AB) (Fig. 5).

Fig. 5. Prototype geoelectrical probe for electrical soil resistance

One has to keep in mind that the measured resistance depends on many factors, such as (Borowczyk, Królikowski, 1959; Fajklewicz 1972):

– the water content of the soil – the resistance is reduced with increasing moisture;

– the mineral composition of the soil skeleton: some minerals may have a high conductivity;

– mineralization of pore water: a higher mineralization increases conductivity;

– the type of the soil, i. e. granulation, which is directly related to porosity and water content.

Hence, the correlations obtained must be treated with caution, keeping in mind that they may apply only to similar soils. The probe can be used for *in-situ* detection of the soil type. In the case of varved clay in the Warsaw Valley from the last glaciation, the mineral composition of the soil is uniform and the mineralization of the pore water is not diversified (Bojakowski, 1982;

Myślińska, 1974). The soils are of a similar origin, were formed in similar conditions and in the same geological period, they feature similar mechanical and physical properties. Therefore, in author's opinion, they make a perfect test environment for the mentioned geoelectrical probe which should be widely used for the qualitative and quantitative reconnaissance of the soil type (of the content of clay fraction), its diversification within a geological unit, and of the natural water content of varved clay. Using an appropriate methodology and relevant equipment for *in-situ* testing, one can expect promising perspectives for employing the geoelectrical probe presented in the paper. Extension of such studies will facilitate its application to other types of soil as well.

Application of the field vane probe in field studies facilitated direct measurements of the maximum and residual shear resistance. The values of shear resistance obtained were close to the upper limit of the probe capabilities (when the smallest vane was used). Based on the ratio of τ_{max} to τ_{const} for the test soils, the coefficient *S* of structural strength of the soils against dynamical action was determined using the formula:

$$S = \frac{\tau_{max}}{\tau_{const}},$$

where τ_{max} is the maximum shear strenght and τ_{mim} is the residual shear strength.

The results are compiled in Tables 1 and 2.

The data collected facilitated a comparison of the values of shear resistance of soil in the conditions with no water outlet, obtained using various test methods. Figures 3 and 4 show the measurements of this parameter obtained from the CPT, DMT and PSO tests.

As is evident in the figures, the shear resistance values obtained using the PSO probe are on the average twice as high as the results from the static CPT and dilatometric DMT sounding. The PSO test did not cover the entire series of the ice-dammed clays. Testing of the shear resistance in the wall was performed at the upper part of the profile because of considerable problems with inserting the probe into the soil. They were due to increasingly high friction forces at the side walls of the casing rod.

Based on the calculated values of the structural strength *S* and on the classification suggested in the operating manual of the field vane probe, the test soils were classified as resistive against dynamical action; $S \in \{2,4\}$.

One of the most important physical parameters of soil is the filtration coefficient *k*. It affects, among others, the consolidation and settling rate of the soil and influences the choice of strength measurements procedures. It also determines the possibility to use soil as a natural barrier against the migration of contaminants.

Table 2. **Results of field vane tests PSO**

Site	Depth H, m	Maximum strength τ_{max}, kPa	Residual strength τ_{const}, kPa	Structural sensitivity S
Plecewice	2.0	213.3	68.2	3.1
	3.5	98.1	42.7	2.3
	4.0	85.3	34.1	2.5
	4.5	123.7	42.7	2.9
	5.0	115.2	42.7	2.7
	5.5	145.0	55.4	2.6
Average	–	130.1	47.6	2.7
Mokre	2.7	170.6	106.5	1.6
	3.2	145.0	64.0	2.3
	4.2	89.6	46.9	1.9
	4.7	153.5	51.2	3.0
	5.2	191.9	68.2	2.8
	5.7	153.5	42.7	3.6
	6.2	157.8	59.7	2.6
Average	–	151.7	62.7	2.5

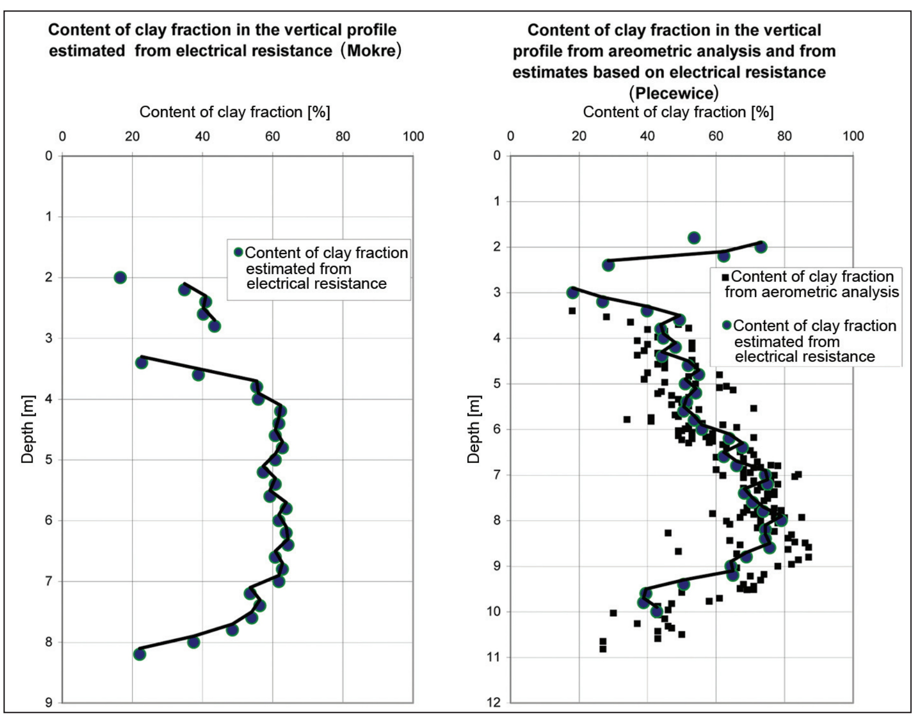

Fig. 6. Content of clay fraction in the vertical profiles, estimated from electrical resistance

Determination of the filtration coefficient in cohesive soils by *in-situ* tests is a challenging issue. It is difficult to control the boundary conditions (volume and pore pressure changes). The currently used test methods are based, therefore, on the analysis of the rate pore water overpressure dissipation, built up as a result of insertion of probes into the soil. To determine the filtration coefficient in the tests, the author chose to use the Marchetti dilatometer. The DMTA test was performed in Plecewice. Such an approach enables determining the filtration coefficient k_h and the consolidation coefficient c_h (Zawrzykraj, 2004a). The results are listed in Table 3.

Table 3. **Consolidation coefficient c_h and filtration coefficient k_h obtained from DMTA measurements in Plecewice**

Depth, m	T_{flex}, min	c_h, OC, cm²/s	k_h, cm/s
2.2	23	$5.2 \cdot 10^{-3}$	$5.9 \cdot 10^{-9}$
5.6	8.1	$1.4 \cdot 10^{-2}$	$3.2 \cdot 10^{-8}$
6.6	42	$2.8 \cdot 10^{-3}$	$6.1 \cdot 10^{-9}$
7.2	29	$4.0 \cdot 10^{-3}$	$6.2 \cdot 10^{-9}$
8.4	64	$1.8 \cdot 10^{-3}$	$5.4 \cdot 10^{-9}$
9.5	1.7	$7.0 \cdot 10^{-2}$	$3.6 \cdot 10^{-7}$

The results suggest that variations of the consolidation and filtration coefficients in the horizontal direction, obtained from the DMTA measurements, are contained within a relatively narrow range. Outliers are only the c_h and k_h values obtained at the depth of 9.5 m. At this depth, however, the bright-coloured layers are clearly silt and sand interbeddings which directly increase the rate of pore overpressure dissipation.

Analysis of the results suggests the DMTA method to be representative and reliable. Measurements yield the resultant rate of dissipation of excess pore water pressure, because the receptor is the entire surface of the membrane, which is not sensitive to point-like pressure drops. The method yields the average rate of excess pore water pressure dissipation for a soil area equal to the area of the dilatometer membrane. One needs to keep in mind that because of the characteristic structure of varved clays, the measured values of the filtration coefficient are lower than the directly measured values of the horizontal filtration coefficient, which is due to measurement specificity. The results are thus intermediate between the minimum and the maximum values (respectively, in the vertical and horizontal directions).

The lack of the necessity to dig pits and collect soil samples, and a relatively short time needed to perform the measurements make DMTA measurements an easy and relatively rapid method of assessing the consolidation and filtration coefficients in field tests.

CONCLUSIONS

The paper presents results of *in-situ* determination of the physical and mechanical parameters of soil. Complex measurements were performed in two locations (Mokre, Plecewice near Warsaw, Poland) using state-of-the-art instruments, including a Marchetti dilatometer DMT and a static probe CPT. A standard PSO probe and a prototype geoelectrical probe PE were used as well.

The tests and their analysis allowed to determine *in situ*, among others, the modulus of compressibility M, the coefficient of shear resistance τ_{fu}, the coefficient of pre-consolidation OCR, the coefficient of earth pressure at rest K_0, the coefficient of consolidation c_h, and the coefficient of filtration k_h. Application of the geoelectrical probe enabled an assessment of the clay fraction content in varved clay profiles (Fig. 6).

Detailed statistics of the results is presented in Table 1. Variations in the parameters studied as a function of their vertical profiles are presented in Fig. 3 and 4.

The results of measurements of pre-consolidation parameters suggest the study soil to be pre-consolidated (OCR ≈ 6.0–8.7). According to present knowledge, in the geological history there were no factors that could be responsible for such a high pre-consolidation. The studies performed by the author within his Ph. D. project have shown that the actual pre-consolidation is caused by post-sedimentation processes occurring in the soils studied. They include, among others, drying, cementation, diagenesis, and secondary consolidation.

The problem of pre-consolidation is tightly related to the coefficient of earth pressure at rest K_0. Its high values obtained (1.3–1.5) require confirmation by lab testing. This problem is particularly challenging and certainly requires further studies and an appropriate analysis. Nevertheless, in author's opinion, the results obtained are overestimated, probably because of the structure of the sediment developing since the deposition.

It should be noted that the values of the compressibility modulus M obtained from CPT sounding are distinctly lower than the values obtained from DMT sounding. A systematic comparison of the two methods with respect to determination of the compressibility modulus is needed. With a larger data sample on hand, one could verify the existence of possible systematic relations. The mean values range within 21.6–41.8 MPa.

Determination of the consolidation coefficient c_h and the filtration coefficient k_h in the Plecewice ice-dammed clay was performed using the DMTA method. The parameters were based on the measured rate of excess pore water pressure dissipation. The overpressure was generated by a penetration of the soil by the dilatometric probe terminal. The consolidation coefficient c_h varies from $1.8 \cdot 10^{-3}$ to $7.0 \cdot 10^{-2}$ cm²/s and the filtration coefficient k_h from $5.4 \cdot 10^{-9}$ to $3.6 \cdot 10^{-7}$ cm/s. The results are comparable to literature data (Krogulec, 1994). Generally, the results obtained are consistent with and typical of very cohesive soils.

Assessing the measurements of the shear resistance τ_{fu} of varved clay, one notices that the results from field vane tests are about two-fold higher than the results from the CPT static probe and from the Marchetti dilatometer. In summary, the shear resistance in the wall varies from 75 to 130.0 kPa (averaged).

A complex characterisation of the physical and mechanical properties of ice-dammed clay in the Warsaw area, performed with the use of state-of-the-art equipment for field tests, is a new approach first published in the Polish literature.

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Piotr Zawrzykraj

LIMNOGLACIALINIO MOLIO FIZIKINĖS MECHANINĖS SAVYBĖS PAGAL *IN SITU* TYRINĖJIMUS SOCHAČEVO IR RADZIMINO RAJONUOSE

Santrauka
Straipsnyje pateikiami inžinerinių geologinių tyrinėjimų, atliktų Plecevico ir Mokro molio telkiniuose Vidurio Lenkijoje, rezultatai. Lauko tyrimuose buvo panaudotas statinis zondas CPTU, dilatometras Marchetti DMT, geoelektrinis zondas PE, mentelių prietaisas VT. Šia aparatūra įvertintas deformacijų modulis, stipris kerpant, perkonsolidacijos koeficientas, šoninio slėgio koeficientas. Pateikiamos Varšuvos rajono limnoglacialinio molio slūgsojimo sąlygos.

Piotr Zawrzykraj

WŁAŚCIWOŚCI FIZYCZNO-MECHANICZNE IŁÓW ZASTOISKOWYCH Z OKOLIC SOCHACZEWA I RADZYMINA W ŚWIETLE BADAŃ POLOWYCH

Streszczenie
Prezentowana publikacja zawiera wyniki badań geologiczno-inżynierskich iłów zastoiskowych z okolic Sochaczewa i Radzymina. Badania zostały przeprowadzone w Plecewicach k/Sochaczewa i Mokrem k/Radzymina, gdzie zlokalizowane są odkrywki iłów warwowych. Parametry fizyczno-mechaniczne otrzymano w toku badań wykonanych w warunkach *in situ*. Badania terenowe zostały przeprowadzone z wykorzystaniem sondy statycznej, dylatometru Marchettiego, sondy geoelektrycznej oraz polowej sondy obrotowej. Przy zastosowaniu wspomnianej aparatury dokonano kompleksowej oceny parametrów fizyczno-mechanicznych, tj. modułu ściśliwości, wytrzymałości na ścinanie, współczynnika prekonsolidacji, współczynnika parcia gruntu w spoczynku i in. W artykule przedstawiono także sytuację geologiczną iłów zastoiskowych występujących w okolicach Warszawy.

Петр Завжикрай

ФИЗИКО-МЕХАНИЧЕСКИЕ СВОЙСТВА ЛИМНОГЛЯЦИАЛЬНЫХ ГЛИН ПО ИССЛЕДОВАНИЯМ *IN SITU* В РАЙОНАХ СОХАЧЕВА И РАДЗИМИНО

Резюме
Представлены результаты исследований, проведенных в месторождениях глин Плецевице и Мокре (Средняя Польша). Исследования проводились с помощью статического зонда CPTU, дилатометра Маргети ДМТ, геоэлектрического зонда PE и крылчатки VT. Установлены следующие показатели: модуль деформации, сопротивление сдвигу, коэффициент переуплотнения, коэффициент бокового давления. Описаны условия залегания лимногляциальных глин в районе Варшавы.