Variability of physical and mechanical properties of varved clays of Warsaw ice-dammed lake in light of *in situ* tests

The paper presents an analysis and variability of selected physical and mechanical properties of varved clays. The test results were related to the conditions and sedimentary zones as well as to regional lithological and structural variability. The occurrence of varved clays of the Warsaw ice-dammed lake on the background of geological and geomorphological conditions was described. The sedimentary conditions and structure of the studied clays observed in the natural exposures are discussed in detail.

The research programme included a series of field tests in seven experimental sites which represent the area of varved clays deposition in the Warsaw ice-dammed lake. Four stations were established on each experimental site, where basic tests were carried out.

Selected mechanical properties of clays were determined by the CPT/CPTu, DMT and PBP/PDP tests. Electrical resistivity was determined with RCPT profiling. The BAT piezometer allowed measuring pore pressure and permeability of varved clays. The primary and shear wave velocity were determined using the seismic cone penetration test (SCPT).

Among the tests performed on the selected experimental sites, there were the tests carried out in the horizontal direction with the use of the Menard pressuremeter and Marchetti dilatometer. They were the basis for determination index of anisotropy of mechanical parameters of clay and stress state analysis of the soil mass.

The author compared the physical and mechanical properties of varved clays with lithological types and their location within the sedimentary basin. Then, the results were related to particular facies types. The relations between parameters obtained as a result of various research techniques were also presented and their statistical comparison was made.

As a result, the ranges of values of the following parameters were determined:

- mechanical cone resistance q_c,
- sleeve friction for mechanical cone $f_{s(m)}$,
- corrected electrical cone resistance q_t,
- sleeve friction for electrical cone $f_{s(e)}$,
- pore pressure behind tip cone u_2,
- shear wave velocity V_s,
- primary wave velocity V_p,
- compressibility modulus from dilatometer test M_{DMT},
- undrained shear strength c_{uDMT},
- coefficient of horizontal permeability k_h,
- pressuremeter modulus E_M,

– creep pressure p_f,
– limit pressure p_l,
– electrical resistivity ρ,
and their statistical characteristics were presented and compared.

The results provide the mechanical and physical characteristics of varved clays from:
- northern area – representing the proximal zone of the ice-dammed lake and layer type A (according to Merta, 1978);
- eastern area – representing the intermediate zone and layer type B;
- western area – representing the distal zone and layer type C.

Almost all of the analysed mechanical and physical properties demonstrated a clear correlation with the ice-dammed sedimentary zone. The permeability parameters (i.e. coefficient of horizontal permeability) and undrained shear strength determined from the dilatometer test showed the highest sensitivity and diversity referring to lithogenetic types of clays. Other parameters also indicated differentiation depending on the sedimentary zone and the clay type and its structure. The observed effects are certainly legible, as they have been established according to a unified methodology, using a single set of research tools and operator. In this way, possible deviations caused by the influence of the human factor in the aspect of constancy of the test methodology were minimized. Performing tests right next to each other with various measuring systems, i.e. based on mechanical, piezoelectric, pneumatic and hydraulic systems, was a way of crosschecking of values and variability parameters within the studied areas of the ice-dammed lake. All methods showed similar trends in the range of values obtained and at the same time in the range of variability referring to the zones of glaciolacustrine lake.

Analyses of horizontal variability of the test results within a single experimental station, experimental site and deposition area indicate that the studied clays revealed significant variability of mechanical properties, despite the horizontal lithological homogeneity observed and characteristic for varved clay profiles. The observed variability of parameters expressed by the coefficient of horizontal variability reaches 10–40 %. Histograms and basic statistics representing the variability of mechanical properties within the experimental sites were presented. The variability parameters were related to the sedimentary area in the glaciolacustrine basin. This enabled reliable estimation of engineering geological parameters. The CPT/CPTu/DMT tests allowed measuring parameters in the whole soil profile, which enabled measuring variability on a large scale and almost continuous characteristics of mechanical or physical properties of soils on site. They present the complex nature of the geological structure and become an appropriate scope for understanding the problem of significant deviations of a few measurements from the real range variability of soil characteristics (representativeness of individual measurements against the variability of a feature).

Varved clay turned out to be an excellent model, which made it possible to assess the state stress using standard *in situ* methods in a new way. The solution of this issue, based on the classical approach using Marchetti's empirical formulas, needs to be corrected due to the significant impact of diagenetic processes indicated by the author in his previous studies (Zawrzykraj, 2004, 2007). The horizontal dilatometer test, which was used for this purpose, verified the values of horizontal stresses in the varved clay. Comparison of the variability of mechanical properties with the electrical resistivity indicated indirectly the important and measurable influence of diagenetic factors that affect the current mechanical behaviour of soil. For the first time, the scale of this phenomenon was documented in a numerical way using *in situ* tests. It was possible because of the varved texture of clay and its small horizontal structural variability. The usefulness of a varved soil for model analyses should be emphasized, where horizontal lithological uniformity is important to search for relations between different tests and for considerations concerning the reasons for observed discrepancies in mechanical parameters determined at the same depths. Among the common geological units, varved clay is the most homogeneous lithologically (in horizontal direction) soil type.

Presentation of the parameters for each area separately showed that physical and mechanical characteristics of each of these are distinct. The quantitative description of this differentiation is very important. In this way, probabilistic criteria differentiating structural variability within the glaciolacustrine basin were emphasized. The variation within each experimental site was expressed in aggregated box-and-whisker plots that contain basic statistical parameters, i.e. mean, median, standard deviation, minimum and maximum values.

Summarizing the studies and analyses performed, it was stated that:

- The presented results represent one lithogenetic unit and the analysis of its physical and mechanical properties in relation to the geomorphological location of seven experimental sites.
- All tests were carried out using the same procedures, one set of research tools and by one operator, which ensured high quality and comparability of results. Undoubtedly, this has contributed to the legibility of the presented relationships.
- Physical and mechanical parameters determined under *in situ* conditions for specific areas of glaciolacustrine basin result mainly from their facies differentiation within the ice-dammed lake and post-sedimentary changes. The presented set of data makes it possible to perform two-way geological analyses. Lithofacies identification allows the prediction of engineering geological parameters. Likewise, based on the evaluation of mechanical parameters of clay, it can be deduced about the sedimentary conditions.
- Several examples demonstrated the relationship between mechanical properties determined *in situ* and the area of occurrence of varved clays. On the basis of the collected parameters, the experimental sites were divided since the western and eastern areas were found to be separate.
- Comparison of electrical resistivity of clay profiles from Plecewice with 136 hydrometer analyses gave a relationship and the coefficient of determination R^2=0.90, which allowed predicting the clay content in the western area.
- The investigations showed anisotropy of mechanical parameters of varved clay in light of *in situ* tests carried out by horizontal penetration of the Menard pressuremeter and Marchetti dilatometer.
- It was shown that among the applied *in situ* methods (CPT, CPTu, DMT, PMT), high resolution RCPTu test is the best tool for lithological prediction of clay content in glaciolacustrine soils.
- Horizontal lithological homogeneity documented by the RCPTu test is not compatible with mechanical properties, which directly indicates the presence of other factors generating differentiation of mechanical properties (structural changes, diagenesis and post-sedimentary disturbances).
- Innovative horizontal dilatometer test DMT-H confirmed the inadequacies of Marchetti's formulas for determining horizontal stresses during standard vertical tests.
- Horizontal tests DMT-H allowed determining the real coefficient of earth pressure at rest K_0 in apparent overconsolidated soils. In the author's opinion, this is one of the most important achievements of this dissertation. The horizontal homogeneity of varved clays allows noticing the influence of the eodiagenetic processes on some distortion of overconsolidation parameters (i.e. preconsolidation pressure, overconsolidation ratio) and horizontal stresses due to the use of conventional empirical relations.
- Pore pressure measurements with the BAT piezometer showed that pore water pressure in varved clay tends to be hydrostatic, provided that in the top of clay layer there is a perched water table. This is an important observation that facilitates the interpretation of hydraulic processes within varved clay unit. This assumption should be used in the interpretation of the CPT test results.

Conclusions referring to the nature of material distribution in the ice-dammed lake indicate stable sedimentary conditions, especially in the distal zone. The excellent repeatability and homogeneity of the sediments sequence in the horizontal direction was observed, which was documented by the electrical resistivity measurements of the RCPTu test in the western experimental sites. Therefore,

there were very good conditions for uniform distribution of mineral material and then for calm uniform sedimentation in a distance of at least 30 km.

Measurements of electrical resistivity with high resolution (RCPTu) showed that the clay profiles in Iłów, Plecewice and Kampinos are compatible and represent the same deposits sequence. This is all the more important as it was found only by *in situ* tests (RCPTu profiling). No such comparative studies have been carried out in the studied area so far. It was demonstrated, solely on the basis of electrical resistivity measurements, that compatibility, structural and genetic similarity of the ice-dammed profiles can be correlated, compared and concluded. Without knowledge of the current geological conditions and continuity of the Błonie level on the basis of the electrical resistivity characteristics in the profile, it can be stated that varved clays from Iłów, Plecewice and Kampinos were formed in one basin at the same time. On the other hand, no compatible records of electrical resistivity were found as a result of comparison of the eastern area (Radzymin level) with the western area (Błonie level). The electrical resistivity measurements obtained from the RCPTu test indicate a low local variability (within one accumulation area) and at the same time reveal a significant regional changeability (between accumulation areas).