Research Article

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Verification of compressibility and consolidation parameters of varved clays from Radzymin (Central Poland) based on direct observations of settlements of road embankment

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Abstract: Formation of varved clays is characterized by specific compressibility and consolidation features, which are difficult to assess. The construction of an expressway through the area of varved, glacial sediments (Vistula glacial period) required careful analysis of the soil reaction to the increasing load caused by growing embankment. The settlement analyses conducted in relation to the schedule of load increase during construction allowed to verify the deformability assessment of the compressible clays. In order to quantify the compressibility and consolidation parameters of clays, an iterative calculation model was created. The method of the “inverse solution” was used to define optimized values of deformability parameters. The observed delayed reaction of the soil to applied load allowed to assess the nature of consolidation. Comparison of the parameters obtained from the model with the results of laboratory and field tests allowed to evaluate drainage characteristics during consolidation of varved clays as well as to introduce correlation coefficients for interpreting compressibility parameters on the basis of CPT tests.

Keywords: varve soils, Warsaw Ice-Dammed Lake basin, compressibility, consolidation parameters, settlement of embankments, inversion solution

1 Introduction

The accurate deformability prognosis of soft soils under various objects (such as highways and railways, dikes,

housing building etc. around the world) is necessary for the safe design of foundation solutions. The selection of deformability and consolidation parameters as well as calculation methods is of a great importance. Very often, as a comparable experiences, the laboratory and field compressibility tests results must be verified with the results of behavior monitoring of existing facilities. It allows to increase the precision of forecasts, but at the same time it must be correlated with lithological types of the substrate.

In the latest scientific literature, the interesting examples of back analysis application to predict corrected course of parameters on the basis of soft soils settlements may be found. In reviewed papers the analysis was based on the course of settlement or pore distribution observed under load of embankments or buildings. Different methods of analysis based generally on exponential curve fitting methods [1, 2] were discussed there, with the application of developed consolidation theory: elasto-viscoplastic constitutive model [3], coupled flow and deformation in unsaturated soils [4] and Burgers creep model [5]. The results of these analysis were expressed in different parameters and demanded adequate initial parameters from laboratory and field tests.

The values of the obtained parameters reflect the geological and engineering characteristic of the analyzed soils. These were: estuarine, normally consolidated deposit from Brisbane in Australia [2], sludge and mucky soils from different province in China coastal [1], alluvial soft clay in Japan [3] weathered Mud rock in China [5]. It is obvious that in soft soils [6] the solution of each engineering task must be strictly correlated with its location and geological and engineering conditions. Evaluation of proper values of compressibility and consolidation parameters has a wider significance, for example in designing of subsoil reinforcement by preconsolidation [7].

Some investigations are dedicated to analysis of standard conditions [8] and specific behaviour of soils which depends of their origin [9, 10].

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The case presented in this article concerns the characteristics of the course of consolidation and further forecasts of the soil settlement under the rapid road traffic in northeastern vicinity of Warsaw (Poland). The analyzed section of the road was built on a specific substrate - varved clays - with distinct characteristics in relation to the soft soil discussed commonly in the literature.

Compressibility and consolidation characteristic of varved clays is a complex issue due to structural sensitivity, specific character of post-sediment structural bonds, no consolidation in geological past and anisotropy of mechanical and filtration properties within thin (several mm), alternate layers. In comparison to clays of different origin, these soils show different nature of deformability, what has been confirmed by the results of laboratory and field tests presented in a number of publications [11, 12]. However, these publications do not often take into account that the compressibility depends on stress and changes in the soil consistency.

For accurate predictions of settlements, it is necessary to analyze in details the relationship between the compressibility characteristics obtained from:

- direct laboratory tests,
- indirect empirical correlations on the basis of soundings (e.g. CPTu, DMT)
- field observations of soil settlements under load.

Comparison of above-mentioned three types of data allows not only to predict the settlements but also to assess factors conditioning the course of strain under load for such a specific formation as varved clays. The typical area of occurrence of varved clays, so-called Warsaw Lake Basin, was chosen for the study where sedimentation developed in the initial stages of the Vistula glacial period. Later, the erosion in the outer zone of the glacier removed some of the deposits, leaving structurally undisturbed several-meter-long clayey, varved sediments in the lower parts of the basin. Their behaviour under loads transmitted by the embankment as well as by later expressway operation was a subject of further analysis of this study.

The propose of the study was to present methodical experiments regarding the verification and forecasting consolidation behaviour of varved clays which are considered as geologically specific soil. Those analyzes were supposed to refer to optional methods of determining compressibility and consolidation parameters. In particular, it concerned the relationship between back analysis results and the results of laboratory tests carried out under incremental loading (IL) and continuous loading (CL) with adaptation to changes in the load. The correlation of cone resistance obtained from CPTu tests with the val-

ues of compressibility modulus M determined during laboratory tests was determined. Such analyzes were focused on the possibility of applying the results of soundings in the spatial assessment of variability of the deformation parameters of varved clays.

2 Geological and engineering conditions

2.1 Geomorphological location

The typical area of occurrence of varved clays, so-called Warsaw Lake Basin [13] (Figure 1), was chosen for the study where sedimentation developed in the initial stages of the Vistula glacial period [15, 16]. Later, the erosion in the outer zone of the glacier removed some of the deposits, leaving structurally undisturbed several-meter-long clayey, varved sediments in the lower parts of the basin [16–18]. Their behaviour under loads transmitted by the embankment as well as by later expressway operation was a subject of further analysis of this study.

The analysed research area is located within Warsaw Basin which is located on so-called Radzymin terrace (Radzymin-Marki level), which has been created during the Vistula glaciation period [15, 16]. Its core is made of varved clays which origin is connected directly with sedimentation stagnation [14]. This terrace is now a flat and extensive plain with an accumulative and erosive character. At the end of Pleistocene, it has been remodelled by aeolian processes, which caused the formation of irregular dunes and dune banks [16]. In the upper part of the profile, about 1-2 meters thick river sands remodelled by aeolian processes may be observed. The lower part of the profile is represented by clays, silty clays, clayey sands and clayey silts (Figure 2).

2.2 Soil conditions - soil structure and thickness of layers

The geological profile has been recognized down to the depth of the impact of loads generated by the expressway. It is represented by horizontally oriented, quite uniform, non-cohesive river deposits and varved clays of glacial origin [14, 17].

The first layer is represented by medium-compacted, yellow-gray fine or locally medium sand. Density index I_D varies between 0.50 and 0.70. The thickness of these sed-

Figure 1: Study area location at the background of Warsaw Ice-Dammed Lake basin.

Figure 2: Representative geological cross section.

iments is approximately 1.0-2.0 m. These soils have good permeability with a filtration coefficient $k \approx 5 \cdot 10^{-5}$ m/s.

Below, 3-7 m layer of cohesive lake soils is observed. Their structure is an effect of periodical sediment supply, clearly segregated during the sedimentation process. As a result of these specific conditions, the varved texture is observed along almost the entire profile. The main type of soil that forms this complex is horizontally laminated, silty clay - so-called varved clays. The structural conditions play a very important role in consolidation process. This influence is expressed in the clear anisotropy of the filtration parameters that determine the dissipation conditions of the excess pore pressure caused by the load increase. It should be mentioned that these soils were fully saturated (degree of saturation $S_r \approx 1.0$). The way, the direction as well as the velocity of the pore water outflow determines the rate and conditions of consolidation. Varved clays are characterized by significantly higher water permeability in the horizontal direction than in the vertical one. These are low permeable soils, with filtration coefficient $k \approx 5 \cdot 10^{-10}$ m/s. In the perpendicular direction, the water flow rate is significantly lower. Silty clays and silts are less common in the profile and occur in the upper part of clayey formation, where varved texture has been lost or has not been developed. Sometimes some thin lamellas of sands are present in this part of the profile. Such complex

formation under the expressway embankment demands much more care during the earthworks. Below clayey complex, again river deposits is observed in the profile, represented by medium and fine sands. These deposits have been formed during Eemian interglacial period and have been deposited as very thick, compacted layer with a density index $I_D = 0.80$.

2.3 Hydrogeological situation

Previous studies have shown the presence of 2 aquifers in the direct substrate of the studied investment.

The first one, despite its small thickness, is the main “water problem” because of its shallow occurrence and considerable extent. This aquifer significantly impedes the construction of the first layers of road embankment. The operation of vibratory plates and vibratory rollers in moist or saturated zones leads to soil liquefaction and becomes ineffective.

The second aquifer occurs at a depth of approximately 4-9 m and is characterized by confined groundwater level that stabilizes at a depth of about 2-3 meters below the surface. Due to the isolation by impermeable clays the groundwater pressure is about 20-50 kPa. This aquifer occurs to a depth of 20-30 m. These sediments are well per-

meable, with a filtration coefficient of approximately $k \approx 5 \cdot 10^{-5} \text{ m/s}$. The hydrogeological situation (piezometric levels, saturation, water permeability of layers, groundwater table system) affects the way and direction of pore water outflow during consolidation.

2.4 Physical parameters

The basic parameter giving some information about the mechanical properties of clays is liquidity index I_L . The obtained I_L values indicated that investigated clays are mainly stiff (Figure 3). Locally, in the upper part of the profile, down to about 1 m clays may be plastic. The clays in the study area are normally consolidated as they had not been subjected to any geological loads apart from the current load of the overburden deposits. This aspect is very important in compressibility assessment of these soils and their consolidation. The formation is subjected to new loads caused by the embankment and is compressed in the elastoplastic manner with a clear evidence of creeping during the consolidation process. It is a manifestation of the reconstruction of the structure in confrontation with the new impact, which these lands were not subjected to in their history.

Figure 3: Frequency and percentage of plasticity index I_L , for the studied varved soils.

The clays from Marki and Radzymin show moderate expansion properties (swelling and shrinkage), despite having a high content of clay fraction (on average 60%). This is due to the mineral composition, where the dominant mineral is illite (about 50%) [19]. The other components are kaolinite, quartz and carbonates which are char-

acterized by low activity and hydrophilicity. Natural moisture conditions ensure structural stability of varved clay in terms of their potential expansive features.

The studies of the expressway substrate indicate that the varved clays are generally stiff. In parts with more permeable silts, they can become plastic, which is indicated by higher values of water content.

3 Methods

3.1 Determination of compressibility and consolidation parameters on the basis of settlements monitoring of expressway substrate

To determine the parameters of soil deformability on the basis of so-called “inverse solution” method it was necessary to characterize the changes in stress and settlements in a function of time and to determine the procedure of iterative calculations leading to the optimization of the value of compressibility modulus as well as primary and secondary consolidation coefficient. The starting point for the calculations was the analysis of the variability of these parameters presented in the scientific literature, standards as well as based on the results of laboratory verification tests conducted for the purposes of this study.

Deformation of varved clays in the light of previous experience

Varved clays are characterized by variable compressibility depending mostly on their structure and particle size distribution as well as applied load [18, 19]. The values of compressibility modules adopted in the literature and standards for non-consolidated cohesive soils deposited outside moraines are usually higher than the results for varved clays. Primary compression of soils from Zielonka (the site next to analysed one) is at a constant level of about 15 MPa in the range of stresses up to 0.4 MPa (Figure 4).

Strengthening the structure obtained during the initial load is observed at a stress of 0.5 MPa and gradually decreases when reaching the value of the previous maximum load of 0.4 MPa. This indicates high structural sensitivity of analysed clays and several times less compressibility of dark layers (with a higher content of clay fractions) in relation to light, silty layers. Primary compression obtained in this study was about 2 times lower than the standard data provided by Wilun [20]. Consolidation

Figure 4: Compressibility varved clay from Zielonka evaluated by oedometer tests (data after [8]).

features of varved clays are not widely recognized due to specific drainage conditions (thin, repeated, silty laminae cause the faster pore pressure dissipation and a complex creep mechanism).

Stress state

For the analysis of the soil deformation, 6 road profiles were selected, in representative regions where, according to geological and engineering data, higher settlements could be observed. Schedules of the load stages during the embankments formation were individual for each profile. Mostly 4 to 6 consecutive layers of embankment were constructed in a relatively short time, ranging from 55 to 135 days and reaching about 80 to 95% of the planned height. The last layer was formed after a longer period of 60 to 185 days. Settlement observations at such load schedule allowed to model the contribution of quasi-immediate compressibility and the effects of primary and secondary consolidation.

In the stress state modelling, trapezoidal strip load was applied to the subsoil, where the width of the embankment crown was 36.7 m. At the maximum embankment height of 7 m and slope of 1:1.5, the width of the embankment bottom reached 60 m. Depending on the terrain configuration and grade line of the embankment crown, the value of stress transferred to the subsoil ranged from $q=75$ to $q=145$ kPa. Stresses from the embankment load were determined in each case for 7 vertical profiles using an algorithm based on the Boussinesq's assumption and the superposition principle. The calculations were carried out at

least down to the depth $z_{\max}$ in accordance with the commonly accepted condition $\sigma_{zq} = 0.3\sigma'_{z\gamma}$ and an additional requirement that the analysis should include the full thickness of the compressible layer, i.e. the complex of varved clays.

Analysis of settlements monitoring

The restrictive guarantee requirements for line investments impose restrictions on the acceptable settlements in a 5 year period counting from the date of expressway commissioning. This increases the awareness of contractors, and thus the need to monitor the settlements already at the construction stage. Displacement/strain monitoring of the subsoil is usually carried out by means of classical levelling with the usage of deep plate/disk benchmarks. The benchmarks consist of a rigid steel plate with the column of measuring tubes placed on it in the friction reducing cover. Before starting the construction of the embankment, a plate is placed on the soil surface and its initial/zero position is determined by geometrical levelling. Then, the embankment layers are constructed and a vertical column of measuring tube is installed on the plate. As the next layers of embankment are formed, the measuring tubes are extended by further modules. Knowing the elevation of the top of the measuring tube in connection with the number of column extension modules allows precise positioning of the plate, and thus the determination of settlements. It should be noted that such measurement does not take into account the settlement of the embankment, but only the settlement of the subsoil (substrate).

The analysis of the measurement of the elevation of the top of the measuring tube allows also to determine the rate of embankment construction by determining the rate of changes in the length of the measuring column. The accuracy of the load increase from the embankment enables to predict the consolidation coefficient.

For the purpose of this study, such an analysis was carried out. For each measurement profile, the settlements monitoring was based on a plate benchmark measurements. Regular measurements have been carried out during the construction of the embankment for over 250 days. The frequency of measurements depended on the rate of forming a given section of the embankment. The measurements allowed to determine the total settlements of the subsoil. The rate of load increase was determined on the basis of changes in the length of the measurement column, which allowed to determine consolidation parameters. An example graph for a disk benchmark settlement observa-

tion with the identification of embankment constructions stages was shown in Figure 5.

Figure 5: Exemplary results of settlement monitoring.

On the graph, the load stages and the rate of deformation may be observed. In the initial phase just after applying the load, there was a sudden increase of strain, which should be associated with elastic deformation of the soil. Then the rate of changes decreased. This stage corresponds to filtration consolidation. This is followed by a stabilization phase, when the deformations take a character of creeping.

3.2 The iterative procedure of compressibility and consolidation parameters determination

In the analysis of the settlements course, the following strain types are distinguished:

- initial S_i ,
- consolidation S_c ,
- secondary S_s

Initial strains (S_i) result from quasi-elastic, almost immediate deformations of the soil and cause the mobilization of the increase of the excess pore pressure. They are observed in a short time after applying the load.

Consolidation strains (S_c), result from the dissipation of excess pore pressure, created after applying the load. The rate of uniaxial primary consolidation depends on volume changes and soil permeability characteristics as well as on the location of drainage layers.

Secondary strains (creeping) of the soil skeleton (S_s), are caused by plastic properties of the skeleton, related to the increase of the effective stress. Creeping depends on the rheological properties of the soil and the load value. Although the effect of creeping reduces in a logarithmic scale, it is observed during a long time. It should be emphasized that all of these stages may occur simultaneously, but with different intensity at a particular stage of settlement process.

On the basis of the values of stress occurring in the subsoil and the assumed compressibility modulus, immediate settlements S_i were determined for non-cohesive soils characterized by negligible filtration resistance.

The modelling of consolidation settlements S_c of varved clays was conducted by determining changes in the degree of consolidation in time, based on the assumed value of the consolidation coefficient c_v and assuming the drainage of the layer both through its top and bottom. Knowledge of changes in the degree of consolidation in time allowed to predict the rate of the settlement. Compressibility and consolidation characteristics consistent with the results of observations were obtained by model calculations using different values of M_0 and c_v parameters.

The iterative way of obtaining compressibility and consolidation characteristics was carried out in three stages.

- I on the basis of the value of quasi-stable settlements (in particular from the one before last stage of embankment formation), the value of the compressibility modulus for the given calculation profile corresponding to those settlements was calculated.
- II the course of settlements obtained from monitoring was compared with a set of optional consolidation curves corresponding to different values of c_v . The convergence of the inclinations of the theoretical and measurement curves was the criterion for choosing the best fitting.
- III after reaching approximately 95% of filtration consolidation, a secondary compressibility coefficient $C\alpha$ was considered in further settlement simulations as follows:

$$S_s = C\alpha \cdot \log \left(\frac{t_f}{t_p} \right) \cdot \frac{2H}{1 + e_0}$$

where:

$C\alpha$ – secondary compressibility coefficient $C\alpha = \frac{\Delta e}{\Delta \log t}$,

$C\alpha = C\alpha \epsilon \cdot (1 + e_0)$

t_p – time, 95% of initial consolidation

t_f – time, the end of the prediction period

$2H$ – the thickness of the drained-from-both-sides layer

The prediction of total settlements in analysed profile was conducted as a simulation of the load at separate stages. The rate of loading was determined on the basis of successive “raising” of the height of plate benchmarks. That was why the process of loading ran in a stepwise manner by forming 1m thick layers. Nevertheless, this way of

Table 1: Long-term prediction of the settlements of the embankment's subsoil.

Section	A				B				C			
Load [kPa]	163				140				157			
Clay layer thickness [m]	4.8				3.3				3.9			
Settlement	Si	Sc	Ss	S	Si	Sc	Ss	S	Si	Sc	Ss	S
Time	[cm]				[cm]				[cm]			
End of construction	5.4	6.5	0.2	12.0	3.4	3.4	0.8	7.6	4.2	6.9	1.0	12.1
5 years	6.4	10.1	1.1	17.6	4.1	4.4	1.9	10.3	4.8	8.5	2.3	15.6
30 years	6.4	10.1	2.8	19.3	4.1	4.4	3.0	11.5	4.8	8.5	3.6	16.9

Section	D				E			
Load[kPa]	140				116			
Clay layer thickness [m]	5.2				5.2			
Settlement	Si	Sc	Ss	S	Si	Sc	Ss	S
Time	[cm]				[cm]			
End of construction	2.1	9.3	0.5	11.7	1.6	7.6	0.3	9.5
5 years	2.7	11.4	2.2	16.3	2.2	9.8	2.0	14.0
30 years	2.7	11.4	4.0	18.1	2.2	9.8	3.8	15.8

simulating the load corresponded quite well with the real response of the substrate. On the basis of information on the earthwork progress, the updated embankment heights and associated loads were determined, assuming the average weight of each embankment layer at the level of 20-21 kN/m³.

After obtaining the value and the settlement rate at each stage of the embankment formation, subsequent loads were introduced to the model resulting from the stage of works completion. In the last stage (about 450 days from the beginning of construction process), the model included additional operational loads with a substitute value of 25 kPa.

tions, it was about 15% of predicted final settlement over 5 years and up to 26% in the 30-year perspective.

It was important for the analysis and further comparisons to determine the optimum values of the compressibility modulus and consolidation coefficient on the basis of “inverse solution” method.

Table 2: Consolidation parameters of the varved clay layer determined by the “inverse solution” method of modelling.

Section	A	B	C	D	E
c_v [m ² /s]	$7 \cdot 10^{-7}$	$1 \cdot 10^{-7}$	$5 \cdot 10^{-7}$	$1 \cdot 10^{-7}$	$5 \cdot 10^{-7}$
M_o [kPa]	7700	7100	7100	7100	5900

4 Results and discussion

4.1 Derived parameters in predicting settlement of varved clays

Long-term settlement predictions

The selected calculation profiles characterized the thickness variation typical for the test site, affecting the nature of deformability. The Table 1 presents the results of modelling the course of immediate and consolidation settlements based on monitoring. Additionally, a medium-term (5-year) and long-term (30-year) forecast was included.

Attention should be paid to the relatively significant values of settlements due to creeping. In the analyzed sec-

It is worth to mention that similar characteristics were obtained in the analyzed profiles, which may indicate a relatively homogeneous consolidation behaviour of the complex of varved clays.

The trapezoid nature of load affects the expected range of settlement differences in particular sections of the embankment. The scale of settlement increase for particular stages of embankment construction including the forecast of settlements during the 5 and 30 year operation of the route was presented in Figure 6. The settlements when the route was completed were marked in red, after 5 years of operation - green, and after 30 years – purple.

Figure 6: Prognosis of settlement in time (profile A).

4.2 Evaluation of compressibility of varved clays on the basis of field soundings

Field tests conducted for the purposes of this study enabled direct acquisition of penetration characteristics, which can then be associated with mechanical parameters. To predict the deformability of the soil, it is necessary to know the local structural and genetic features and the geological history of the sediment. It is crucial for linking the empirical relationships available in the literature with the studied soil as well as for making a conscious, correct choice of correlation. Another way to choose the right relationship is to obtain own research results based on the direct determination of the most important mechanical parameters. This approach was chosen in this case. The CPTu static probes were the basis for the assessment of *in situ* parameter values and mechanical variability of varved clays (Figure 7).

Based on the cone resistance q_t , it was possible to estimate the oedometric modulus M based on the following formula:

$$M = \alpha \cdot (q_t - \sigma_{v0}) \text{ [MPa]} \text{ [21], where:}$$

α – empirical coefficient [–]

q_t – corrected cone resistance [MPa]

σ_{v0} – total primary stress at the depth of the test [MPa]

Direct observations of soil deformations caused by the gradual formation of the embankment and the results from consolidometer tests on varved clays allowed to indicate the actual values of compressibility modulus M within the range of expected loads.

The increase of the additional stresses from the growing embankment covered the entire layer of varved clays.

This was due to the width of the embankment bottom, which was about 60 m, and at the same time much smaller thickness of varved clays (about 6–8 m) occurring approximately 1 m below the bottom of the embankment. Therefore, it was assumed that similar degree of consolidation and deformation was observed along the whole profile of clays. Thus, the average cone resistance q_t represents the actual (measured) compressibility/deformability of the embankment's subsoil. The distribution (histogram and basic statistics) of received q_t values for varved clays was presented in Figure 8.

The obtained deformation modules M ranged between 5.9 and 7.7 MPa. Knowing the average value of q_t for varved clays in vertical profile (taking into account the total initial stress σ_{v0}), which was calculated as 1.18 MPa, the following equation was transformed:

$$\alpha = M / (q_t - \sigma_{v0});$$

and the following values were received:

$$\text{for } M = 5.9 \text{ MPa } \alpha = 5.9 / 1.18 = 5$$

$$\text{for } M = 7.7 \text{ MPa } \alpha = 7.7 / 1.18 = 6.5$$

The obtained empirical coefficient α (5 – 6.5) allowed to predict the compressibility modulus M , for varved, non-consolidated clays based on the values of the cone resistance q_t in the load range up to 150 kPa.

Direct observations of road embankment settlements and compressibility tests in the consolidometer allowed to obtain optimal selection of the fitting coefficient. In the current study, the obtained values of the compressibility modulus were quite low. To compare, the values of the M_{DMT} parameter presented in the literature [22] in relation to this type of sediments obtained from Marchetti dilatometer tests, reached average values of 25 MPa. This example shows how post-depositional processes and

Figure 7: Results of CPTU soundings.

Figure 8: Histogram and percentage of cone resistance q_t in the intervals of frequency distribution.

structural (diagenetic) factors during indirect determination of parameters can hide the actual deformability parameters of tested sediments. It is extremely important to verify the universal correlations from the literature by direct tests and to adjust them to local litho-genetic divisions. In the current study, the uncritical adoption of all available formulas may lead to an error in estimating settlements up to 300% of the real value.

4.3 Filtration and rheological conditions of consolidation of varved clays

The character of compressibility of varved clays recorded in uniaxial IL and CL type consolidation studies (Figure 9) indicated the specific sensitivity of these soils to load

Figure 9: Comparison of laboratory and inversion solution for compressibility modulus.

changes. The lowest values of compressibility modulus M_0 were recorded in IL tests, which included standard strain stabilization at each stage of constant load. In CRL studies, M_0 values were usually higher. In some tests (CRL1 and CRL2), the U-shaped character of the $M_0 - \sigma$ relationship was revealed [23], indicating the destruction of natural structural bonds in the interval from 50 to 150 kPa and then the increase in the value of the modules. In some tests (CRL 5 and CRL 6) the mentioned destruction of structures and the associated decrease in the value of modules were observed only after exceeding the stress $\sigma > 150$ kPa. The above-mentioned anomalies confirmed the changes in compressibility trends and indicated a significant variability in the varved clays deformability features. The assessment of compressibility based on the monitored settlement and obtained in the “inverse solution” procedure indicated that for predicting settlements, the M_0 module values should be estimated as 1.5 to 2 times higher than the most frequent results obtained in laboratory tests.

The course of deformation as a function of time indicated the dominant role of creeping in clays. This was illustrated by the analysis of IL test results (Figure 10). On the basis of the $\epsilon - \log t$ graphs, the initial S-shaped part was separated, which could be associated with the primary consolidation and the quasi-linear part of the graph in the advanced stage of deformation described as so-called secondary consolidation. In typical model behaviour, it is assumed that the rate of primary consolidation is conditioned only by pore pressure dissipation. According to Terzaghi's theory, this should be reflected in the constant value of the consolidation coefficient c_v for the entire process. In the analysed research, c_v was calculated at various values of the degree consolidation U [24] related only to the S-shaped part of graph $\epsilon - \log t$ (Figure 11). Only for U ranging from 0.2 to 0.6, similar c_v values were ob-

Figure 10: Curves of consolidation from IL tests.

tained and later their significant decrease was observed for this parameter. That indicated the presence of the creep component also at the initial stage of soil deformation. It can be defined not as a classical primary consolidation, but only as a quasi - seepage phase of IL consolidation, conditioned not only by the permeability of the soil, but also by the increasing participation of skeleton creep. Values of c_v recommended to calculation model should be selected from the part of the $\log c_v - U$ plot, where the values of the consolidation coefficient are approximately constant. Such approach allows in the prognostic calculations to make the actual participation of pore pressure dissipation in the course of settlements more real.

Figure 11: Coefficient of primary consolidation in IL tests.

The method of determining c_v values from IL tests gave comparable results with CRL tests, where the consolidation factor was determined on the basis of changes in pore pressure, and thus the registered effects of water filtration in a consolidated soil. In CRL studies, the initial c_v values changed significantly and were usually overestimated (unsteady phase). In the analyzed examples, that applied to the stress range from 50 to 100 kPa. Further, the c_v values were stabilized, decreasing linearly only as a result of the progressive change in the porosity of the compressed soil. The c_v characteristics obtained from the tests were in the range of $10^{-7} - 10^{-8} \text{ m}^2/\text{s}$. They appeared to be adequate to the ones observed *in situ* and modelled in the deformation calculations for B and D profiles. In case of E, C and A profiles, the settlements were faster, which in the calculation model required the c_v values higher by 5 to 7 times (Figure 12). This difference in laboratory characteristics and modelling results based on field observations may be a result of drainage conditions. Varved clays are characterized by a significant variation in permeability characteristics of dark (clayey, poorly permeable) and light (silty, better permeable) layers. As a result, complex, heterogeneous characteristics of the excess pore water pressure were created. The consolidation delay was the result of the thickness of

Figure 12: Comparison of laboratory and inversion solution for consolidation parameters.

the layers in the whole complex. The obtained comparisons of subsidence monitoring and laboratory test results indicated that the varved structure may result in several times higher effective values of the generalized parameters describing filtration consolidation.

A factor directly independent of the drainage conditions is clean creep expressed by the coefficient of secondary consolidation $C_{\alpha\epsilon}$. The results of the conducted research indicated that the parameter $C_{\alpha\epsilon}$ shows changes in time [25]. They were usually expressed by abrupt increases in the inclination of linear sections of the $\epsilon - \log t$ graph (see Figure 10) and indicated the possibility of larger strains at the stage of pure creep than results from a linear approach assumed in the $C_{\alpha\epsilon}$ definition. $C_{\alpha\epsilon}$ values increase at higher loads (Figure 13 and 14).

The lack of long-term geodetic observations was a significant difficulty in predicting the settlements of the subsoil. The highest value of the secondary consolidation coefficient $C_{\alpha\epsilon} = 0.5\%$ was used for calculations and it was twice as large as the average value of this parameter. That estimation referred to the experience from Australia [2] regarding the relationship between the results of laboratory tests and long-term observation of the embankment settlements. According to the comparative analysis, the values of the secondary consolidation coefficient calculated with the back analysis method were up to two times higher than those determined in the course of laboratory tests.

Presented study shows, that realistic forecasting of settlement depends on accurate choice of compressibility and consolidation model. This requires careful analysis of occurrence of varved sediments, the variability of plastic-

Figure 13: Coefficient of secondary consolidation vs stress.

Figure 14: Incremental increase of secondary consolidation parameter vs stress.

ity zones and precise load simulation. The combination of these conditions determines the involvement of permeability and creep factors governing the settlement process.

Advanced laboratory equipment allows to reconstruct various velocities of loading and drainage conditions [26], which have the crucial significance in the creep process. A comparison of laboratory tests and settlement monitoring shows that compressibility, consolidation and creep parameters are variable in the process and should be selected in relation to the analysis of values and velocity of loading.

5 Conclusions

1. The values of settlements in the analysed geological and engineering conditions were conditioned by: the thickness of varved clays, loads resulting from the various height of the embankment as well as the possibility of weakening the soil resulting from the local increase of plasticity. Compressibility of varved clays is very variable, as shown also in the literature. Predicting the settlements based solely on literature data can therefore lead to significant errors.
2. Model calculations based on the analysis of step changes in loads and settlement monitoring results allowed to determine deformation and consolidation parameters of clays based on the behaviour of the actual system: object - soil. The values of the compressibility modulus as well as the primary and secondary consolidation coefficients estimated with the "inversion solution" method provided data for comparisons with material characteristics obtained in laboratory and field tests carried out using various methodologies (IL, CRL, CPT studies)
3. The compressibility parameters obtained with the "inversion solution" method were within a relatively wide range of values obtained in laboratory tests of samples taken directly from the subsoil. For proper selection of module values for predicting settlements, it was necessary to refer to the actual state of stress. The verified values of the compressibility modules of varved clays were most often in the range of 5.900-7.700 kPa and were lower than those reported in the literature. To predict the course of settlements, it is recommended to adopt higher parameters of filtration consolidation than those obtained in laboratory tests. This is due to the anisotropy of the soil and the shorter routes of real drainage in clayey layers.
4. In their geological history, varved clays were not strengthened by natural consolidation (e.g. by the glacier or significant thickness of the overlying sediments). Thus, these sediments were loaded with embankment for the first time and are susceptible to significant and long-lasting rheological deformations. This has been experimentally confirmed in obtaining variable values of the secondary consolidation coefficient depending on the stress and time.
5. The presented modelling methodology provides verified data for the assessment of the behaviour of the subsoil in the perspective of operational standards. In three out of five analysed profiles, the settlement

value of 5 cm can be exceeded after 5 years of road operation. In the other two profiles, settlements of 3 cm have been determined. The obtained modelling results can be treated in the context of Eurocode 7 as a "comparable experience" enabling the determination of "derived" values of parameters characterizing the deformability of varved sediments.

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