Evaluation of Consolidation Results by the Settlement Rate Approach

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ABSTRACT

Analysis based on the settlement rate testing is a promising interpretation tool which enables obtaining basic consolidation parameters, particularly the consolidation coefficient c_v and displacement at the end of primary consolidation δ_{EOP}. Among the many factors which interfere with the filtration process of consolidation, the most important are initial compression and rheological effects. This article presents the results of experimental studies of clayey paste. Three types of curves based on the time-compression data were analysed. The disadvantageous effects of interfering factors was taken into account, the effects were eliminated by the application of an appropriate interpretation approach. Consolidation coefficient c_v values were obtained for theoretically separated consolidation phases. The distinction of sections with negligible secondary consolidation and initial compression effects for the consolidation curves was recognised as the primary criterion of analysis correctness.

KEYWORDS: consolidation, coefficient, settlement rate, velocity

INTRODUCTION

Predicting the magnitude of settlement of a structure founded on the consolidated layer requires the knowledge of the real value of the coefficient of consolidation c_v. The primary factors determining the resulting c_v value include: time under load, load application method, overburden load history, drainage conditions, thickness of the consolidated layer. It should be mentioned that laboratory testing does not allow to take these factors into account. Over the last 50 years, several arduous and time-consuming attempts were made at developing the appropriate methodology and interpretation standards for consolidation studies. The studies related to the standardisation of time-compression data analysis are of great learning value: Šuklje (1957), Parkin (1978); Sridharan (1981); Sridharan et al. (1987); Sridharan, Prakash (1993); Tan (1996); Mesri et al., (1999a); Tewatia (1998a), Tewatia et al. (2007); Tewatia et al. (2011, 2012); Dobak (1986); Al-Zoubi (2010). Analysis using the experimental settlement velocity v = (dδ/dt) also referred to as the rate of settlement enables the production of consolidation characteristics for a given increment and for any time period, without knowing the load history. Furthermore, it provides much useful information for describing the soil behaviour in field conditions as well as predictions for the current and future time-compression dependency for various scenarios, times under load and drainage conditions. This article presents the results of experimental studies of clayey paste. The disadvantageous effects of interfering factors was taken into account, the effects were eliminated by the application of an appropriate interpretation approach. Consolidation coefficient c_v values were obtained for theoretically separated consolidation phases. The distinction of sections with negligible secondary consolidation and initial compression effects for the consolidation curves was recognised as the primary criterion of analysis correctness.

LIMITATIONS OF LABORATORY CONSOLIDATION STUDIES

Testing using an oedometer or consolidometer are bound by limitations, resulting in discrepancies with the applied theory as well as between the parameter values measured in the field and the laboratory experiment results. The limitations are due to the currently leading Terzaghi's theory of filtration consolidation and the resulting simplification assumptions as well as laboratory factors related to the construction of the testing apparatus. The soil considered to be compliant to the Terzaghi’s theory can be only viewed as such in individual consolidation process phases. The generally accepted division recognises three phases: initial compression, filtration (primary) consolidation and secondary consolidation. Tewatia (2007) analysed the rate of settlement for soils with significant content of the clay fraction, organic soils and bentonite-sand pastes and distinguished six consolidation settlement phases. The first phase is initial compression resulting from the moment of applying the load to the sample. The next is the first filtration phase, with the least impact of rheological effects. The calculated c_v are the highest and can be considered true, the soil is believed to conform with the theory and can be described as *“Terzaghi’s soil”*. The third phase is a transition period between the first and second filtration phases, in which the soil changes from one type of Terzaghi’s soil into another due to the progressing rheological effects. The second filtration phase, in some soils, manifests as having constant c_v values for a high progress of settlement. Typical for the next transition phase is the increasing effect of the creep of soil skeleton and obtaining different current c_v values for different *“Terzaghi’s soils”*. The last phase is pure creep, easy to notice using the δ-log t and δ-dδ/dt curves.

This distinction points out the starting of the secondary consolidation during filtration, due to the excess pore water pressure. From the methodological point of view, it is justified to treat the progressing creep (initiating the secondary consolidation phase) and the accompanying changes in the soil skeleton microstructure as the indicator of ending the domination of the hydrodynamic process. Terzaghi (1925) described secondary consolidation (creep) as gradual transfer of load from the water bonds around the skeleton grains to the mineral bonds with the accompanying slow viscous flow or creep. The particles of clay minerals are brought together, increasing the effective viscosity. This view was refuted by Leonards and Girault (1961). Their experiment with non-polar porous fluids showed that the effect of this type of substitution was not significant and further concluded that the viscosity of the oriented water particles does not significantly affect the occurrence of secondary consolidation. Another concept appeared, proposed by Tan and further developed by Barden, indicating that the rate of adaptation of mineral grains under load is related to the viscosity of the adsorbed water bond (layer). Barden (1965) formulated a model of consolidation in which plasticisation (creep) was related to the non-linear function of viscosity approaching the Bingham plasticity type. Crawford (1964), Wahls (1962) found it to be a continuous process, starting at the moment of applying load. The study of Youshikuni, et.al. (1995) based on the elastic-viscous, rheological model of soil proved experimentally that the rheological effects appear in the initial phase of primary consolidation and that they progress in time together. This face is a fundamental problem for the interpretation of laboratory consolidometric studies. It is also justified to take into account the impact of apparatus effects from the rigidity of the pressure system, deformation of the consolidometer cell upon load application, friction between the consolidating soil and the side surface of the cell. There are also multiple problems with recognising the moment of settlement stabilisation caused by unforeseen vibrations and micro-shocks.

METHODOLOGY OF TESTING IN THE BARDEN-ROWE CELL

The testing was performed using the EL25-0700 hydraulic consolidometer made by ELE International. The diagram is presented in fig. 1. The applied incremental loading (IL) system had increment paths of 100 and 200 kPa. The analysed soil was placed in the Barden-Rowe type cell and treated with external load in the conditions of equal strain and single-side drainage. Stress was transferred to the top surface of the sample by applying the hydrostatic pressure of water placed in a rubber membrane. A 3 mm plastic drainage ring and a round steel disk for equal soil strain were applied directly on the sample. A displacement sensor with the tolerance of 0,002 mm was used to measure the vertical axis deformation of the sample δ. Two additional systems were connected to the cell: a pore pressure system and a back pressure system. The pore pressure was measured centrally on the bottom surface of the sample at the impermeable base of the cell. All pressure hoses were deaerated before commencing the test. The filling of the entire cell space over the sample with water was checked using the venting screw. In the case of water deficit, water was replenished via the compensation pressure hose.

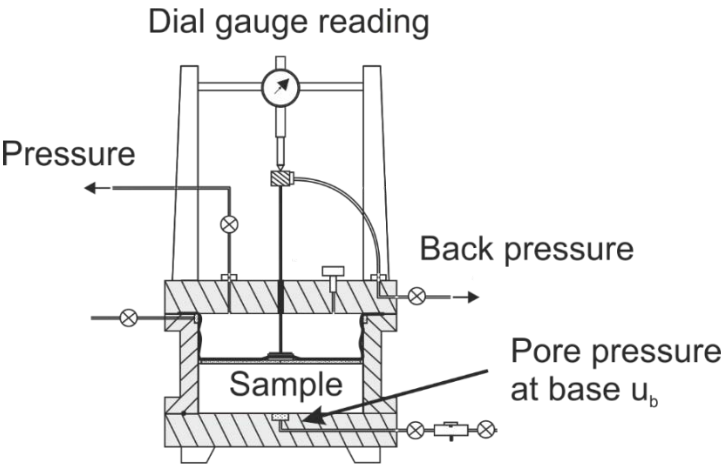


Figure 1: Arrangement of Barden-Rowe cell.

METHODOLOGY OF CONSOLIDATION RESULTS BY THE SETTLEMENT RATE APPROACH

The rate of consolidation depends on the rate of dissipation the excess water pressure in the pores generated by applying the load. It should be noted that, this rate depends on soil permeability, geometry of the pore water migration pathways, etc. The fundamental consolidation formula is expressed with the equation

$$\frac{\partial u}{\partial t}=c_{vc}.\frac{\partial^2 u}{\partial z^2} \quad (1)$$

Equation (1) describes the change of pore water pressure with depth and time u(z,t). The mathematical solution of equation (1) in double-side drainage conditions is an adaptation of the standard diffusion equation and can be solved by expansion using the Fourier series:

$$U=1-\frac{8}{\pi^2}\left\{\exp(-\pi^2\frac{T}{4})+\frac{\{\exp(-9\pi^2\frac{T}{4})\}}{9}+\frac{\{\exp(-25\pi^2\frac{T}{4})\}}{25}+.....\right\} \quad (2)$$

The approximation of the dimensionless time factor T provided by Fox (1948) is equation (3):

$$T=\frac{\pi}{4}U^2 \quad (3)$$

The degree of consolidation U is related to experimental settlement δ with the following dependency:

$$U=\frac{\delta-\delta_0}{\delta_{100}-\delta_0} \quad (4)$$

In the case of single-side drainage, the approximation of equation (2) provided by Lun and Parkin (1985) is applicable:

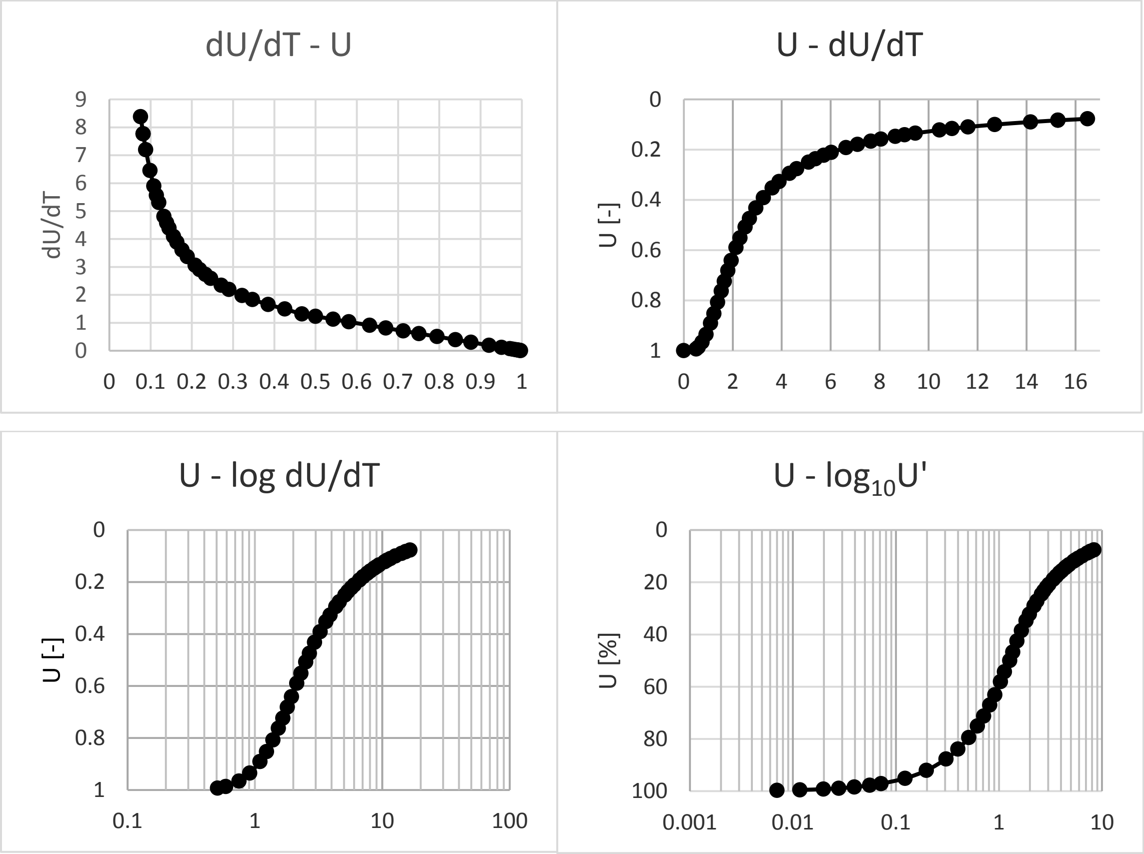
$$U=\frac{2}{\sqrt{\pi}}.\sqrt{T} \quad (5)$$

The theoretical velocity (progress) of consolidation $\dot{U}=dU/dT$ is derived from the degree of consolidation U. Depending on the degree of consolidation, the following approximations can be applied:

$$\dot{U} = \frac{1}{\sqrt{\pi T}} \qquad T \approx 0.197 (U \leq 50\%) \qquad (6)$$

$$\dot{U} = 2e^{-\left(\pi^2 T/4\right)} \qquad T > 0.197 (U > 50\%) \qquad (7)$$

The resulting dependencies $dU/dT_v - U$, $U - dU/dT_v$ and $U - \log dU/dT_v$ are presented in figure 2.


dU/dT - U

U - dU/dT

U - log dU/dT

U - $\log_{10}$U'

Figure 2: Theoretical relationships obtained from laboratory data.

The analysis was based on the fitting procedure between the observed and theoretical dependencies for the individual degrees of consolidation U. For instance, for the dδ/dt-δ curve, where the experimental linear section was fitted with the relevant theoretical section of the dU/dT-U dependency curve (U≥52.5%).

Table 1: Characteristics of experimental curves after Al.-Zoubi M. (2010), Tewatia S.K. (1998, 2012)

dδ/dt-δ	δ-dδ/dt	δ-log$_{10}$dδ/dt
$\frac{d\delta}{dt}=\frac{2.468}{H^2}\left(\delta_p-\delta_t\right)$ $m_2=\frac{2.468}{H^2}$ $\delta_p=-\frac{c_2}{m_2}$ $c_v=\frac{m_2 H^2}{2.468}$	$\delta=\frac{2c_v\left(\delta_{100}-\delta_0\right)^2}{\pi H^2}\left(\frac{dt}{d\delta}\right)+\delta_0$ $m_1=\frac{2c_v\left(\delta_{100}-\delta_0\right)^2}{\pi H^2}$ $\Delta H=\left(\delta_{100}-\delta_0\right)=\frac{\delta_{70}-\delta_0}{0.70}$ $c_v=\frac{m_1\pi H^2}{2\left(\delta_{100}-\delta_0\right)^2}=\frac{\pi}{2}\frac{m_1}{\left(\Delta H/H\right)^2}$ $m_1=const\Rightarrow c_v=const$	$\frac{d\delta}{dt}=-\frac{c_v\left(\delta_0-\delta_{100}\right)}{H^2}\dot{U}$ $s_1=-\left(\delta_0-\delta_{100}\right)\frac{dU}{d\log_{10}\dot{U}}$ $\Delta H=s_{50}=\left(\delta_{100}-\delta_0\right)$ $c_v=-\frac{0.2566\left(\frac{d\delta}{dt}\right)_{16.19}H^2}{s_{50}}$

Based on the characteristics of the experimental consolidation curves (table 1) provided by Al-Zoubi (2010), Tewatia (1998, 2007) from IL testing, the consolidation coefficient was determined for four samples: T1.CH1, T1.CH4, T1.CH5, T1.CH6.

RESEARCH MATERIAL

The testing was performed on a sediment of clay suspension, based on Krakowiec clays. The samples from Chmielów (Poland) were collected from Miocene clay formations representing pre-Carpathian sink deposits. These soils developed the form of grey clays, locally with a green or ash-grey tint. These clays, sometimes with sand interbeddings and inserts are a part of the complex of Miocene pre-Carpathian sink Sarmatian deposits. The physical parameters and grain-size fractions of the soil used to made the pastes is presented in the table 2 and 3.

Table 2: Basic physical properties

Soil type	Density of solid particles ρ_s [g/cm^3]	Liquid limit LL [%]	Plastic limit PL [%]	Water content w_n [%]
Low plasticity clay	2.72	65.02	24.6	21.77

Table 3: Grain-size fraction

Soil type	Gravel fraction [%]	Sand fraction [%]	Silt fraction [%]	Clay fraction [%]
Low plasticity clay	0	14	38	48

The pastes with plasticity approaching the liquid limit were made from dried and mortar-ground soil mass combined with water to form a uniform consistence. The next stage of sample preparation was preliminary, one-week consolidation in consolidation rings with the continuous load of 100 kPa. It should be noted that the resulting clay paste is not easily permeable to water and air. The soils do not saturate which can be a result of changing the structure by applying the load as well as very small sizes of the capillaries, narrow migration pathways and a significant amount of suspended capillary water which prevents a free flow of water in the pores area. This tendency was confirmed by Dobak, Pająk (2008) by point out the decreased pore pressure values, leading to discrepancies between the actual test and its theoretical assumptions. The tested soil is also characterised by low hygroscopicity and swelling potency.

RESULTS AND DISSCUSSION

The estimated values of the coefficient of consolidation cv is crucial to settlement analysis. The values obtained from three different curves for two load increments – 200 and 400 kPa are presented in table (4) and figure (3). Furthermore, table (4) contains the results calculated using the Casagrande graphical procedure. When testing the pastes, a uniform structure was made to match the conditions of the Terzaghi's theory of filtration consolidation, e.g. medium composed of two phases: solid and liquid. As pointed out by Dobak, Pająk (2008), the structurally converted to match optimum conditions clay material is typically used as a raw material for constructing artificial insulation barriers and sealing layers for disposal grounds. The assumed range of consolidation loads fully overlaps with the stress values within high storages.

Table 4: Comparison of c_v values obtained from $d\delta/dt-\delta$, $\delta-d\delta/dt$, $\delta-\log_{10}(d\delta/dt)$ and those from Casagrande procedure.

$d\delta/dt$ - δ			δ - $d\delta/dt$			δ - $\log_{10}(d\delta/dt)$			logt		
sample	c_v [m^2/y]	σ	sample	c_v [m^2/y]	σ	sample	c_v [m^2/y]	σ	sample	c_v [m^2/y]	σ
T1.CH1	3.69	200	T1.CH1	2.37	200	T1.CH1	1.75	200	T1.CH1	1.04	200
	1.24	400		0.92	400		0.61	400		0.59	400
T1.CH4	2.55	200	T1.CH4	2.25	200	T1.CH4	0.55	200	T1.CH4	1.5	200
	1.18	400		1.04	400		0.22	400		0.6	400
T1.CH5	2.53	200	T1.CH5	1.89	200	T1.CH5	2.26	200	T1.CH5	1.29	200
	0.91	400		0.89	400		0.78	400		0.68	400
T1.CH6	2.53	200	T1.CH6	1.59	200	T1.CH6	1.88	200	T1.CH6	1.22	200
	0.78	400		0.75	400		0.83	400		0.37	400

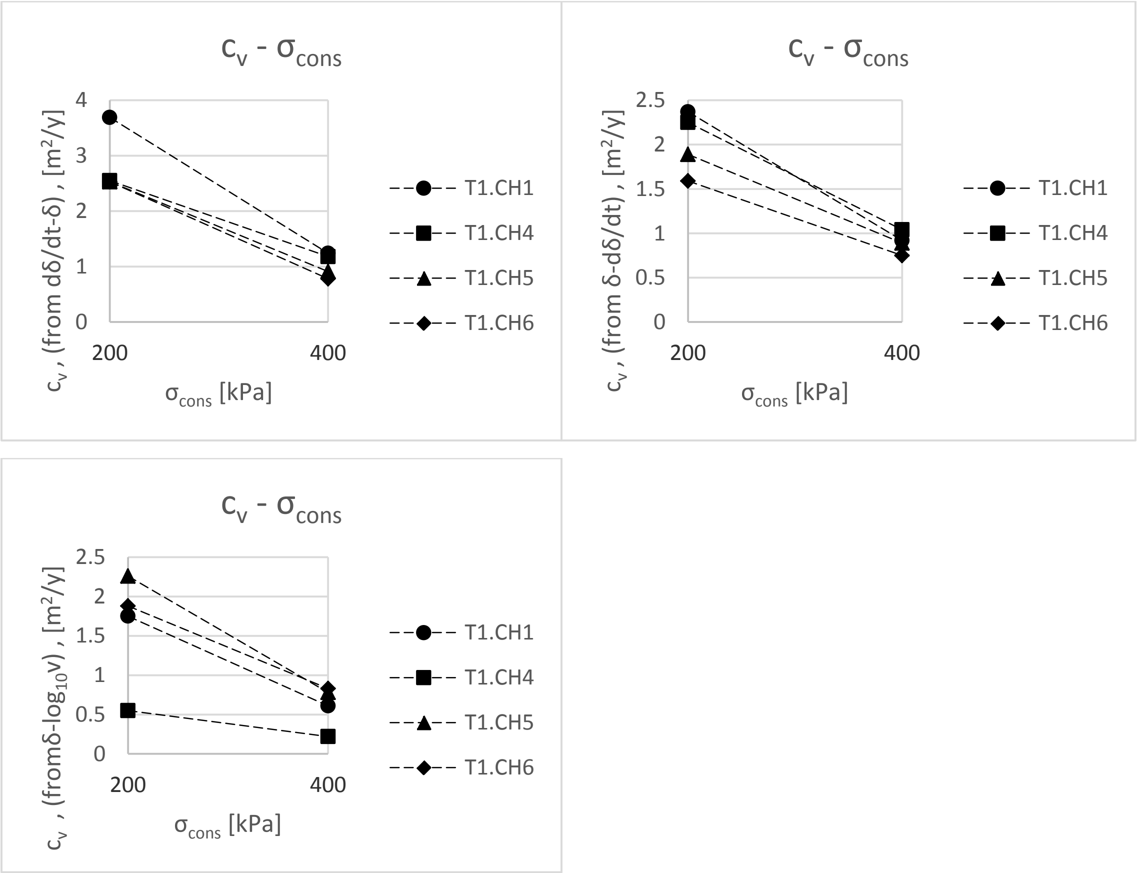


Figure 3: Variation of coefficient of consolidation obtained from dδ/dt-δ , δ-dδ/dt , δ-$\log_{10}$(dδ/dt) curves with consolidation pressure.

During the analysis of consolidation curves dδ/dt-δ , δ-dδ/dt , δ-$\log_{10}$(dδ/dt) and the coefficient of consolidation values determined with them, a tendency to monotonically decrease the cv with the increase of the load was observed. This specific property was also observed by Woźniak (2006) for the same type of clay pastes with the classic graphic interpretation methods of Casagrande and Taylor, Scott method and quasi-constant procedure. The selected dδ/dt-δ , δ-dδ/dt , δ-$\log_{10}$(dδ/dt) curves included in the interpretation are presented in fig. (4), (5) and (6).

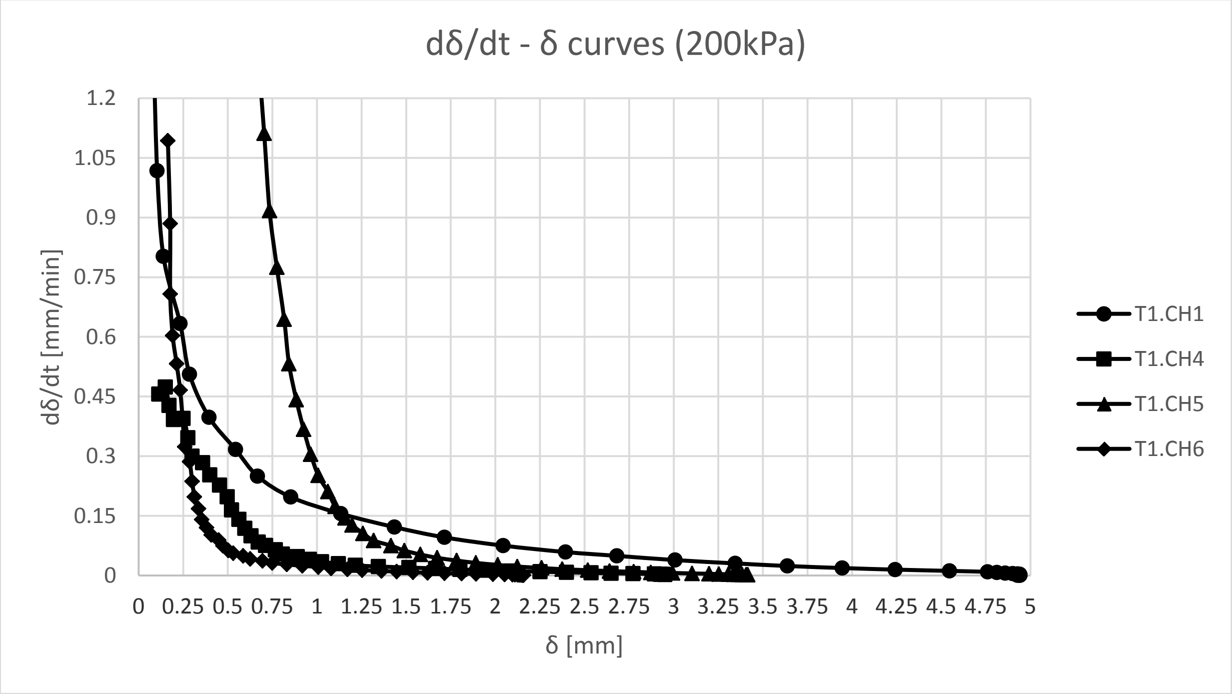


Figure 4: Typical dδ/dt-δ curves for reconstituted krakowiec clay.

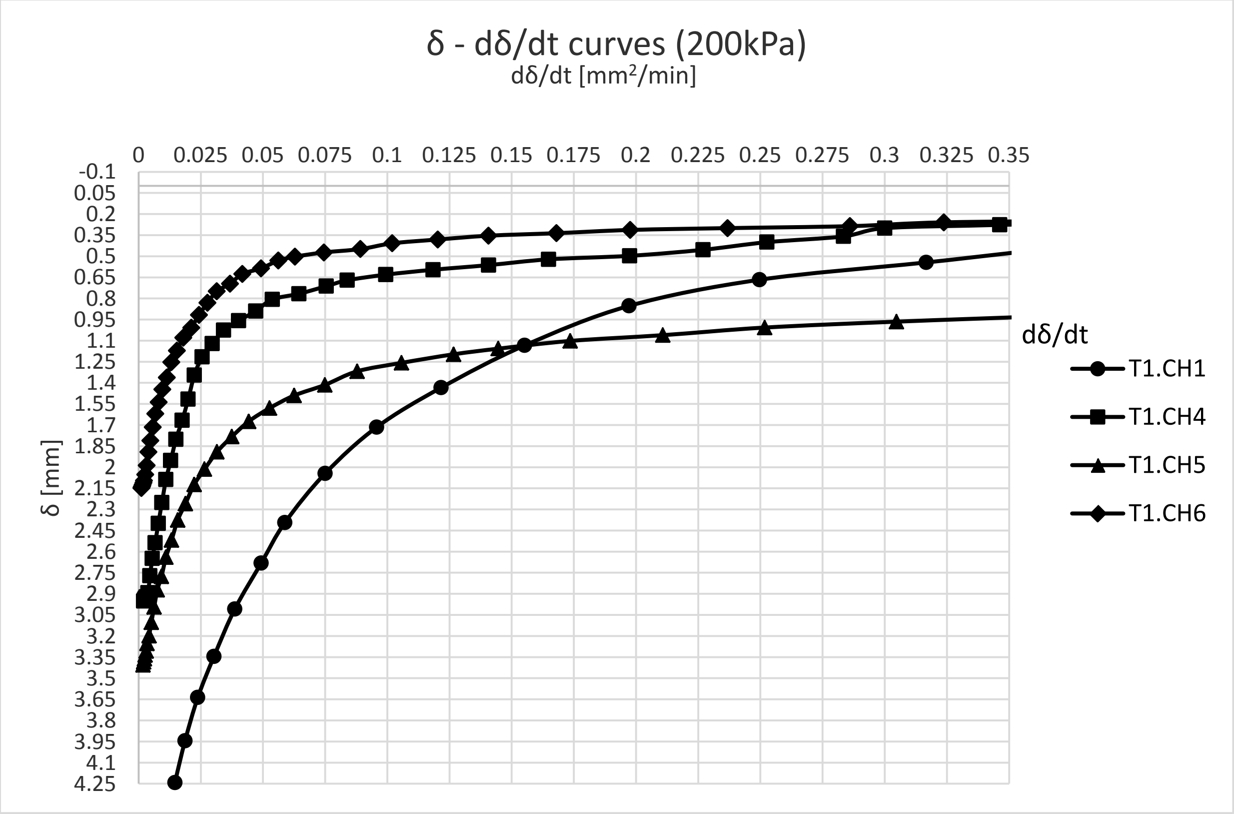


Figure 5: Typical δ-dδ/dt curves for reconstituted krakowiec clay.

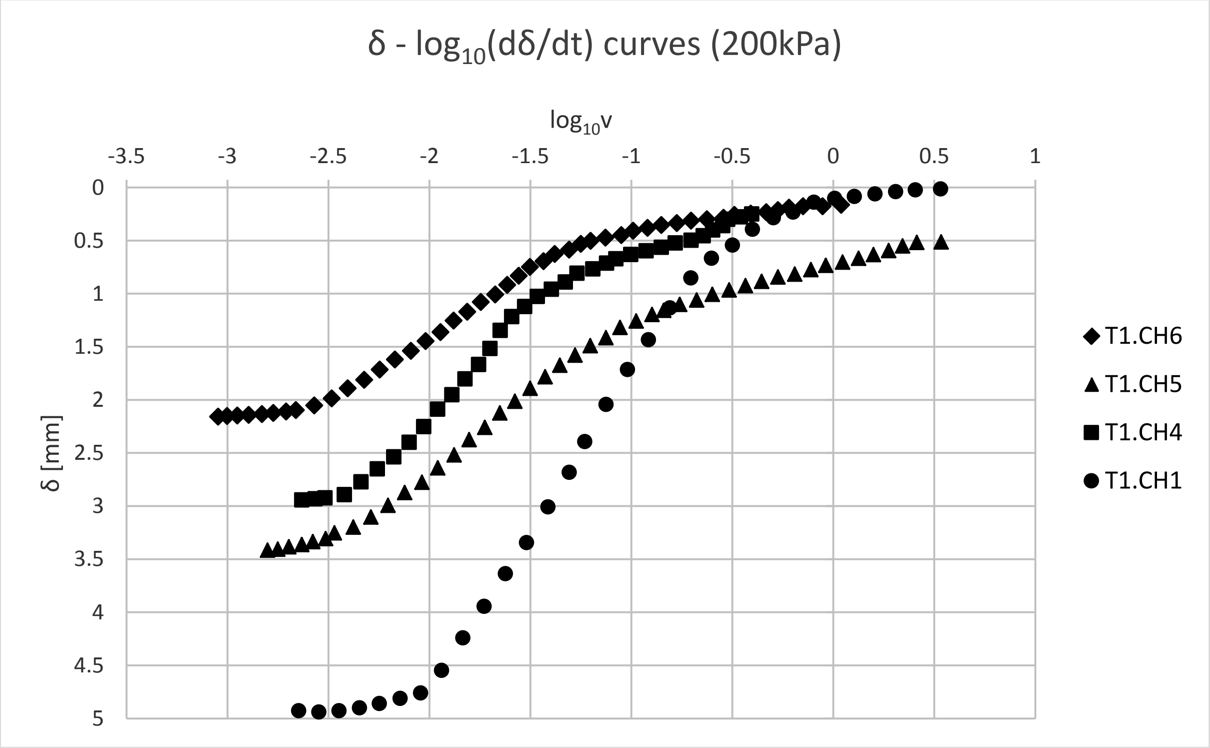


Figure 6: Typical δ-$\log_{10}$(dδ/dt) curves for reconstituted krakowiec clay.

The c_v values resulting from the settlement rate to settlement curve dδ/dt-δ are within the range of 3.69 – 2.53 [m^2/year] for 200 [kPa] and 1.24 – 0.78 [m^2/year] for 400 [kPa]. The c_v values resulting from the settlement to settlement rate curve δ-dδ/dt are within the range of 2.37 – 1.57 [m^2/year] for 200 [kPa] and 1.24 – 0.75 [m^2/year] for 400 [kPa]. The c_v values resulting from the settlement to settlement rate common logarithm curve δ-$\log_{10}$(dδ/dt) are within the range of 2.26 – 0.55 [m^2/year] for 200 [kPa] and 0.83 – 0.22 [m^2/year] for 400 [kPa]. Figures (7), (8) and (9) present comparison of c_v values computed by settlement rate approach.

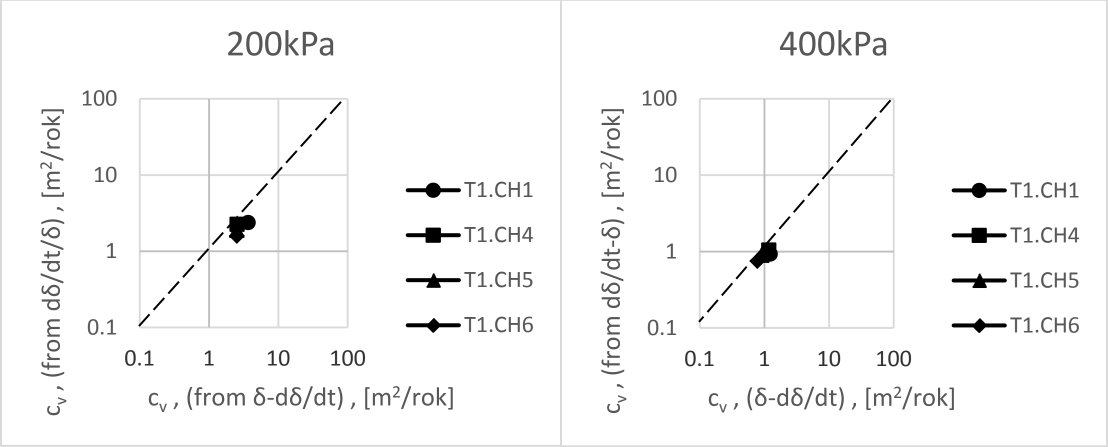


Figure 7: Comparison of c_v values obtained with use dδ/dt-δ curve and δ-dδ/dt curves.

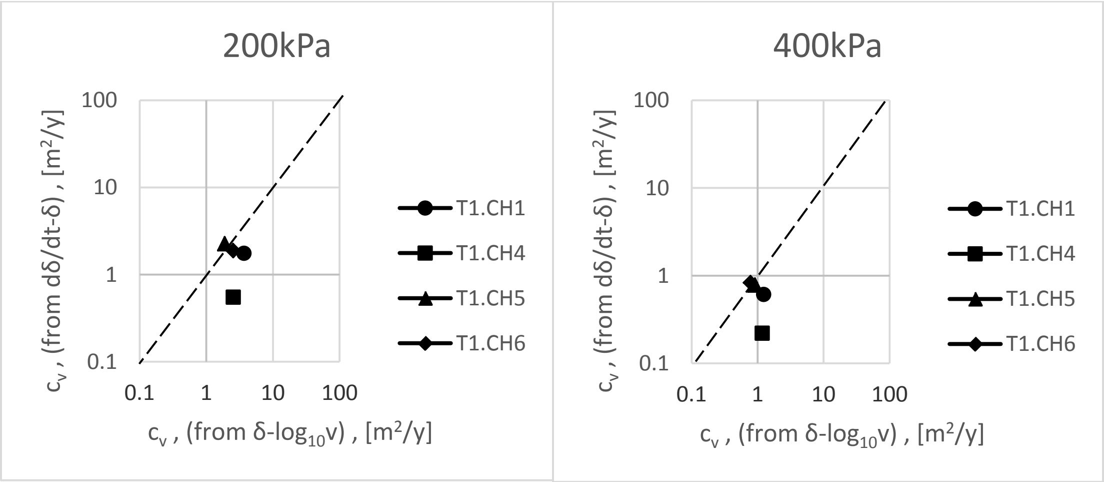


Figure 8: Comparison of c_v values obtained with use dδ/dt-δ curve and δ-$\log_{10}$(dδ/dt) curves.

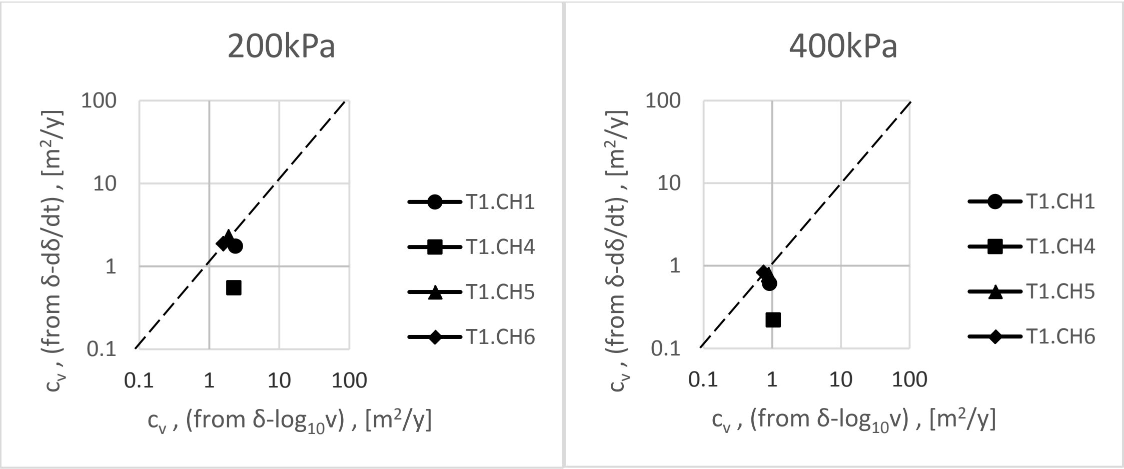


Figure 9: Comparison of c_v values obtained with use δ-δ/dt curve and δ-$\log_{10}$(dδ/dt) curves.

CONCLUSIONS

(1) The values of the coefficient of consolidation cv depend on the rate of settlement which decrease with time in the course of the study. The increasing impact of rheological effects slows down the rate of settlement. The coefficient of consolidation in adopted approach is related to the slope of the linear section of experimental curves dδ/dt-δ, δ-dδ/dt, δ-log10(dδ/dt).

(2) Actual c_v values should be obtained before reaching 60% of the U progress of consolidation. The determination of settlement at the end of primary consolidation δ_{EOP} together with the c_v coefficient of consolidation enables the reduction of testing time and the impact of rheological effects.

(3) Based on the consolidation results using the curves described herein, the resulting values of the c_v coefficient show a high degree of conformity. Particular interdependency was found for

the dδ/dt-δ, δ-dδ/dt curves. In comparison to the c_v values calculated using the graphical Casagrande procedure, the results of the interpretation approach based on settlement progress have higher values.

NOTATION

c_v – coefficient of consolidation

c_2 – δ axis crossing point (dδ/dt–δ curve)

dδ/dt – experimental velocity

H – longest drainage path

m_1 – slope of the linear section of the δ–dδ/dt curve

m_2 –slope of the linear section of the dδ/dt –δ curve

δ_0 – corrected dial gauge reading

δ_{100} – displacement reading at the end of primary consolidation (δ–dδ/dt, δ–$\log_{10}$dδ/dt curve)

δ_p – displacement reading at the end of primary consolidation (dδ/dt–δ curve)

δ_t – displacement reading at any time

s_1 – slope of the theoretical U–log dU/dT curve

s_{50} – slope of the experimental δ–$\log_{10}$dδ/dt curve in the inflecion point

$\dot{U}$ – theoretical velocity of consolidation

U – degree of consolidation

T – dimensionless time factor

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