Large-scale Rowe cell experimental study on coefficient of consolidation of coal mine tailings

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Abstract. Tailings are the co-product of mining activities which is usually deposited in the form of slurry with high water content and compressibility. Consolidation properties of tailing materials are important for any disposal and storage actions, posing significant challenges in mining industry. In the present study, laboratory experiments were performed to investigate the compressibility and consolidation properties of coal mine tailings. The investigation were carried out on material with different grain-sizes upon application of incremental loads in a large-scale Rowe cell. The samples were collected from open pit Turów Coal Mine in Poland. Remolded samples were manufactured in laboratory as three batches of different size-ratio between fine and coarse particles, i.e. 0.5, 0.75, 0.25. Simultaneous measurements of settlements together with pore water pressure were used for determination of coefficient of consolidation, c_v. For this purpose gradient method was used which is applicable for whole the consolidation curve including secondary consolidation.

1 Introduction

Mining industry every year produces vast amount of fine-grained mine dumps (tailings) that are commonly in slurry form. This kind of materials which consist of sand and fine particles are generally deposited hydraulically and may cause many environmental and ecological problems. Because tailings deposition may affect the environment through many different mechanisms, such as heavy-metal, radionuclide and process chemical toxicity, hyper-sedimentation, changes in grain size and angularity, changes in topography, sediment plumes and turbidity, storage issues become meaningful. It is also well known that the mechanical stability of the tailings mass is very problematic [1]. Essentially, predicting of long term settlements for this kind of materials is just as important. Reasonable approach for solving long-term problems should takes account of large strains and self-weight of the soil [2-5]. To take meaning the self-weight consolidation followed by the sedimentation process it is necessary to evaluate the coefficient of consolidation, c_v of the tailings at different stress levels [6]. The objective of this laboratory investigation was to use optimised c_v value for the simulation of one-dimensional consolidation test.

In this study, dump soil with modelled particle size distribution was selected for laboratory experiments. Tertiary (Oligocene) clay with admixture of clastic rocks (sands

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and gravels) from an open pit Turów Coal Mine was used to prepare the slurry. Remolded slurry samples were manufactured as three batches of different size-ratio between fine and coarse particles, χ=D_{fine}/D_{coarse}, i.e. 0.25, 0.50, 0.75. Consolidation tests using a large-scale Rowe cell with application of incremental loads were undertaken to characterize stress-strain-time behavior. In this work, an attempt is made to obtain optimised value of c_v which can be treated as best fit value, that corresponds to the whole consolidation curve including secondary consolidation. Determined discrepancy between measured and simulated degrees of consolidation versus time curves was used to evaluate a test results.

2 Material and method

2.1 Mine tailings

The dump soil used in this study were obtained from Turów Coal Mine that is located in south-west of Lower Silesia, Poland. Specific gravity of the soil used for a composing of tailing slurry is determined as per CEN-ISO-TS 17892-3 and is obtained as 2.76. The liquid limit is performed according to CEN ISO/TS 17892-6 and the plastic limit is determined according to ISO/TS 17892-12. Liquid limit of the tailing is determined to be 31.4%, and its plasticity index is obtained as 12%. Therefore soil was found to plot above an A-line in the plasticity chart (Fig. 1a) and was classified as sandy low plasticity clay (saCIL) as per European Soil Classification System (ESCS) [7]. Fig 1b presents typical grain-size curve.

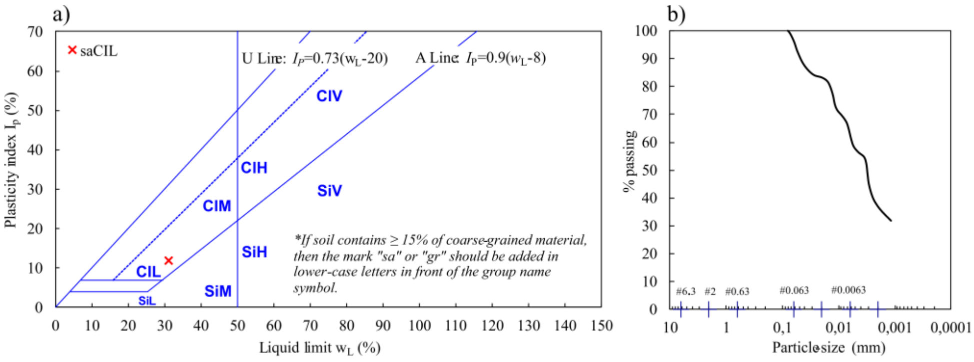

Fig. 1. Classification of tailings dump soil used in the present study: a) plasticity chart; b) particle-size curve.

2.2 Testing procedure

The large-scale Rowe cell used in this study allows for both vertical and radial flow tests and direct permeability measurements. The pore water pressure was measured centrally on the bottom surface of the sample at the impermeable base of the cell. Consolidation tests were conducted with uniform stress distribution and double-sided drainage conditions. During the tests, the filters were designed to prevent leaching and squeezing the slurry from the cell. For experiments saturation of soil sample with distilled water was led in stages with subsequent diaphragm loads (cell pressures) of 25, 50, 100, and 200 kPa, at respective back pressures of 15, 40, 90 and 190 kPa. The values explained above were chosen by reference to the loading scheme. For each step the B-value was calculated as the ratio of the increase of the excess pore water pressure to the applied stress increment according to procedure given by Head [8]. For all tests, the B-value was between

0.97 and 0.99. The tests with a uniform stress distribution and double-sided drainage conditions were conducted, and 200 kPa back pressure was maintained during the tests. Diaphragm loads of 225, 250, 300 and 400 kPa were used for the tests, giving effective pressures of 25, 50, 100 and 200 kPa, so that load increment ratio (LIR) of 1.0 were achieved.

The tests in the large-scale Rowe cell were carried out on the sediment obtained from the slurry of clay, silt and coarse fractions. In order to obtain pure clay, kaolinite slumps were to be crushed and rubbed with distilled water by a mesh diameter of 0.0063 mm, the thicker fractions remaining on the sieve were collected for determination particle size distribution. The clay slurry was left for 2 days sedimentation, then clarified water was removed from the top surface and the clay was dried at 105-110°C. In order to evaluate an effect of particle-size distribution on the consolidation behavior, the tests were carried out on samples consisting of mixtures of several fractions in various proportions [9]. The modelling of the sample grain composition consisted of the three stages: pulping the proper weight of the dried clay in the mortar, preparation of weights of specific fractions (0.1 mm $<\varphi<1.0$ mm). Three reconstituted samples were manufactured in laboratory as three batches of different size-ratio between fine and coarse particles, $\chi=D_{fine}/D_{coarse}$. The first sample (T1) consisted of 25% fines and 75% mixture of coarse grains (χ=0.25). In the second sample (T2), the fines content constituted as 50% (χ=0.50). In the third sample (T3), the proportions of the mixture components were reversed: 75% fines and 25% mixture of the remaining fractions (χ=0.75). The weights obtained in different proportions were mixed with the amount of distilled water that allowed to create a homogeneous slurry, which was poured into the consolidation cell. The thick sample of 40 mm height by 151.4 mm diameter was tested in a large-scale experiments. Fig. 2 presents influence of coarse particles content on tailings compressibility. As can be seen, the increase in the content of coarse fractions in the sample reduces amount of settlement and indicates a higher stiffness of the material.

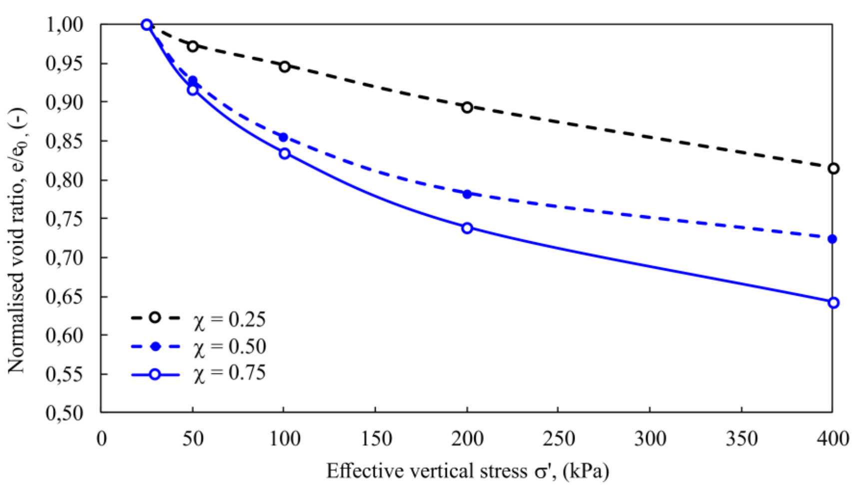

Fig. 2. Normalised compression curves for different size-ratio between fine and coarse particles.

3 Gradient Method for coefficient of consolidation

In the mathematical optimisation gradient method (GR) is a first-order iterative algorithm for finding the minimum or maximum of a function which plays an important role in solving many inverse problems. Using inverse analysis a given model is calibrated by iteratively changing input values until the simulated output values match the observed data. In the work presented herein coefficient of consolidation, c_v is assessed according to Terzaghi's one-dimensional model. An inverse problem in consolidation is defined as the process of calculating from a set of observations the accurate value of c_v that produced them and could be resolved by the (GR) method. Fig. 3 shows visualisation of this approach used for simulation idealised results from consolidation test.

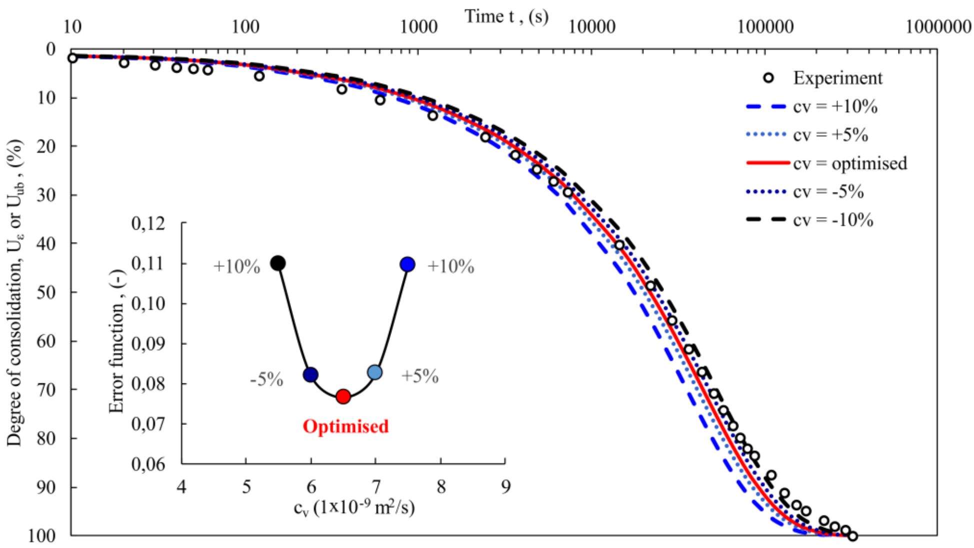

Fig. 3. Principles of gradient method for one-dimensional consolidation.

In order to carry out an inverse analysis, the function that could evaluate the error between the experimental and theoretical solution, and then minimize this function should be defined. In the engineering literature, the simple scalar error functions is commonly adopted to be able to solve optimization problems [10], [11]. In this work expression for an error function is as follows:

$$Error(x) = \frac{\sum \frac{\left|U_{n,i} - U^*_{n,i}\right|}{U_{n,i}} \times w_{n,i}}{\sum w_{n,i}} \tag{1}$$

where: $U_{n,i}$ is the experimental degree of consolidation; $U^*_{n,i}$ is the theoretical degree of consolidation and $w_{n,i}$ is the range around each theoretical point $U^*_{n,i}$ characterizing the divergence.

$$w_{n,i} = \frac{U^*_{n,i} - U^*_{n,i-1}}{2} + \frac{U^*_{n,i+1} - U^*_{n,i}}{2} \tag{2}$$

To reduce the influence of the factors which affect the error function such as experimental consolidation curve shape, number of measurement points and the scale effects on the fitness between the experimental and the simulated results, weight to each calculation point was adopted. The accuracy of the prediction of the consolidation behavior by the (GR) method strongly depends on the large number of test data points. As stated by Levasseur

[12] the objective error calculated by this kind of function is a dimensionless variable and can be used for measuring the fitness between simulated and objective curves. Above-mentioned equation (1) was used for comparison between measured data and simulation.

4 Consolidation behavior of tailings

The experimental data, for all increments, were converted into degree of consolidation, U and non-dimensional time factor, T_v and then values of c_v were determined using an optimisation technique. The relationship between the degree of consolidation calculated on the basis of strain data and non-dimensional time factor, T_v can be derived using Terzaghi's theory as:

$$U_\varepsilon = 1 - \sum_{m=0}^{m=\infty} \frac{2}{M^2} \exp\left(-M^2 T_v\right) \tag{3}$$

where: $M = (2m+1)\pi/2$ and m is an integer.

On the other hand, when excess pore pressure is measured at the base of soil sample, one can use following expression for degree of consolidation at the base:

$$U_{ub} = 1 - \sum_{m=0}^{m=\infty} \frac{2}{M} \sin M \exp\left(-M^2 T_v\right) \tag{4}$$

The non-dimensional time factor, T_v is defined as follows:

$$T_v = \frac{c_v t}{H^2} \tag{5}$$

where: c_v is the coefficient of consolidation and H is the sample height.

The term "consolidation" is used herein to designate the one-dimensional time-dependent process, and it includes both hydrodynamic effects (primary consolidation) and viscoplastic component of compression (secondary consolidation). Typical relationships between degree of consolidation based on observed strains along with pore water pressures and the logarithm of time for the consolidation pressure increment of 25–50 and 200–400 kPa is shown in Fig. 4.

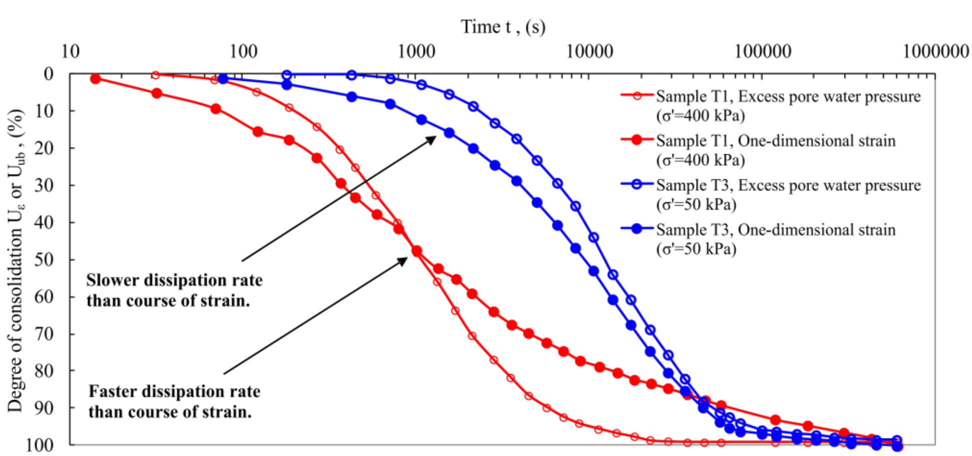

Fig. 4. Typical consolidation rates of coal mine tailings for two different load increments.

As can be seen on Fig. 4 estimated rates of consolidation differ each other. In general all specimens indicated a large amount of secondary consolidation revealing itself as a linear relationship between strain and logarithm of time in the advanced stages of the process.

4.1 Validation of the model predictive ability

Analysis revealed that good agreement between experiments and simulations was generally archived by Terzaghi model only in specific stages of consolidation with the set parameters optimized by (GR) method. Figure 5 gives an example of the comparison between experimental and simulated rate of consolidation in terms of pore water pressures. In the method using a direct comparison of the measured and predicted consolidation behavior, validation of the model predictive ability could be directly verified. Using (GR) method one can establish range on consolidation curve where the simulated behavior agrees with experimental observations. As expected viscoplastic component of total strain (creep) become increasingly relevant during dissipation of pore water pressure after certain degree of consolidation U_{ub}. The modeling results is depicted in the dimensionless graph as a divergence between the curves after U_{ub} = 58%. As can be seen creep effects slow down dissipation process. Consequently, good agreement between experimental and theoretical curves can be recognized as primary consolidation in which hydrodynamic effect is dominant and creep is negligible. By fitting simulated curve to the whole experimental data points, Terzaghi's model is regarded as indicator of any discrepancy from purely hydrodynamic behavior. This remark is rather phenomenological than analytical approach. Because Terzaghi's model assumes uncoupled consolidation equations, excess pore water pressure and strain are determined separately (no hydro-mechanical coupling). Hence, simultaneous modeling of the development of strain along dissipation pore water pressure is not possible. To overcome this limitation advanced elasto-viscoplastic models combined with Biot's theory [13], e.g. rate-dependency based elastic-viscoplastic ANICREEP model [14] or rate-dependent with no pure elastic domain Creep-SCLAY1 model [15] may be used. However, hydro-mechanical coupling will not be discussed further in this work.

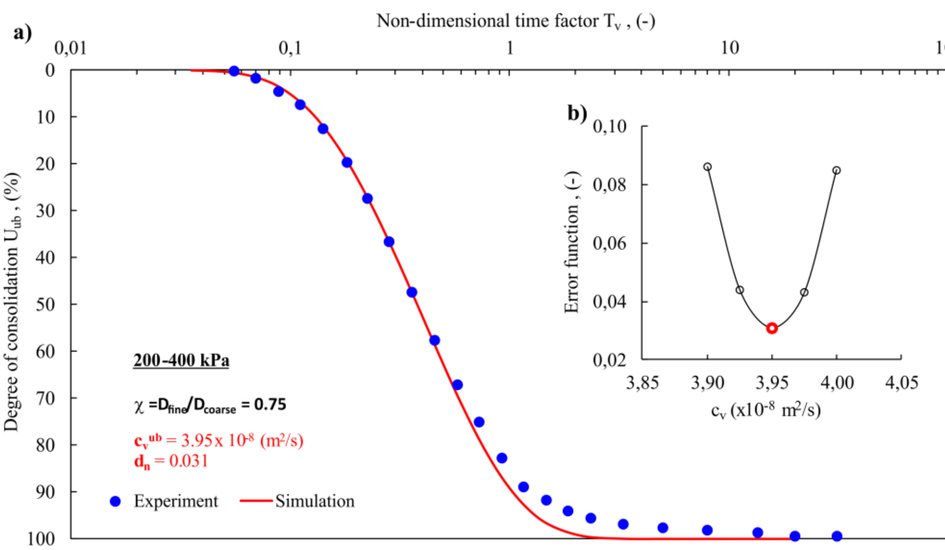

Fig. 5. Comparison between simulated and experimental results of Rowe cell test on sample T3: a) relationship between U_{ub} and T_v; b) parabolic changes of error function together with targeted consecutive c_v values due to iteration.

4.2 Coefficient of consolidation

For each samples, the coefficient of consolidation, c_v was determined by two methods at different stress increments using the optimisation technique. The variation of c_v with the applied effective vertical stress for three different size-ratio between fine and coarse particles, χ is shown on semi-log plot (Fig. 6). It can be seen that the increase in the content of coarse particles significantly influences the obtained results. Based on the data collected in the study presented herein, the values of c_v corresponding to a larger voids ratio (smaller χ), which indicates more permeable material were much higher than those with higher percentage of fines particles (higher χ). Furthermore, determined c_v values depend upon the type of data involved in the analysis. For sample T1 (χ=0.25) c_v calculated on the basis of pore water pressures was found to be higher than those given by strain data. In this case c_v values slightly increased with the increase in applied stress. Further, for each mixture with varying percent of coarse particles, c_v were mostly in reasonable agreement with an exponential trend. On the other hand simulation using strain data shown decrease in c_v with the increase in applied stress for the first two load increments and decrease for the last two. As can be seen from Fig. 6 values of c_v for sample T2 (χ=0.50) fuzzy varying with the applied stress. It is interesting to note that for sample T3 (χ=0.75) observed strain gives higher values of c_v than pore water pressures records, while keeping a similar exponential trend up to effective vertical stress of 200 kPa. Because sample T3 includes percentage of clay fraction three times as much as sample T1, dissipation of excess pore water pressure is delayed in relation to course of strain (i.e. see Fig. 4).

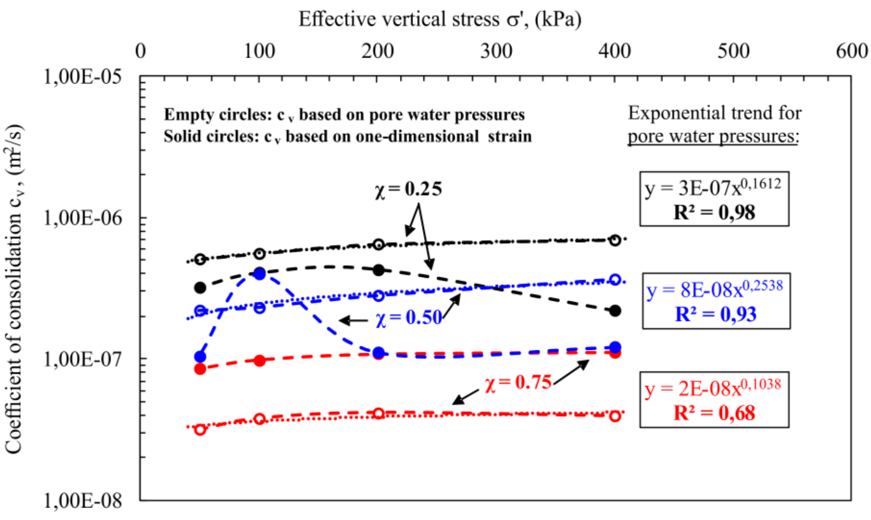

Fig. 6. Variability of c_v according to course of strain and pore water pressures during large-scale Rowe cell experiments on three samples with different size-ratio between fine and coarse particles, χ.

5 Conclusions

Coal mine tailings with different size-ratio between fine and coarse particles were examined to characterize consolidation behavior and in order to determine coefficient of consolidation, c_v. Obtained values of c_v with the help of optimisation technique were used for simulating the large-scale Rowe cell tests. Gradient method (GR) has allowed to determine the coefficient of consolidation, c_v with the smallest value of error function which corresponds to the best fitting of the laboratory data. In this study the error function was assessed for determination discrepancy between experimental and theoretical percentage of consolidation, U. Terzaghi consolidation theory which is only applicable to water pressure dissipation in primary consolidation does not account for secondary consolidation. Gradient method (GR) is beyond this fundamental scope of application and allows to determination a more realistic estimate of c_v as well as check predictive ability of Terzaghi's model. It should be noted that produced c_v by (GR) method is attempted for whole the consolidation curve including secondary consolidation.

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