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Coal Sludge Permeability Assessment Based on Rowe Cell Consolidation, and Filtration Investigations

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Supplementary materials of the part: Theory background

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2. Theory background

2.1. Soil consolidation

The theory of consolidation for a soil medium deals with the issues related to the change in pore water pressure in the soil, and the change in effective stresses, with a simultaneous decrease in the loaded zone of the soil. Consolidation is, therefore, the process of decreasing soil volume under the influence of a load applied due to the dissipation of excess water pressure and its outflow from the soil pores. Consolidation depends on the filtering properties of the soil and results in soil settlement ([35] after [36]).

The basic model of consolidation, according to Terzaghi, considers the ground as a two-phase medium (fully saturated state - the pores of the ground are filled with water - a state achieved in the process of saturation, which precedes consolidation). Thus, consolidation is a long-term process, and its duration depends on many factors.

The equations determining the total soil settlement due to primary consolidation do not provide information on the rate of this process, and the theory of Terzaghi (1925) is the first solution to consider the rate of uniaxial consolidation of saturated soils [37]. Its assumptions and detailed analysis and solutions of the basic equation are presented by [38,39], among others.

2.1.1. Saturation

The saturation process aims to saturate the sample by filling all the pores in the ground with water. This process involves a gradual increase in water pressure in the soil pores to dissolve the air bubbles. This phenomenon is described by Henry's law [40]. For semi-permeable soils, gravitational saturation only slightly increases the water content in the sample. Therefore, to fill all pores with water is necessary to apply an equalizing pressure (back pressure), which allows maintaining a constant value of effective stress in the sample during the saturation process. The parameter controlling the degree of sample saturation is the Skempton parameter, which defines the ratio of the increase of water pressure in the soil pores in the rise of the total pressure applied to the sample. The values of this parameter are included in Table S1.

Table S1. The values of parameter B at the end of the saturation process

B - value	Data source
0.95 <0.95*	ISO/TS 17892-5:2004 Geotechnical investigation, and testing - Laboratory testing of soil - Part 5: Incremental loading oedometer test [41]
0.95 0.9**	BS 1377-6 1990 Methods of test for soils for civil engineering purposes. Consolidation, and permeability tests in hydraulic cells, and with pore pressure measurement [43]
0.8 - SaSi 0.7 - Si 0.4 - Cl	Jastrzebska, and Kalinowska-Pasieka, 2015 [40]

* If it can be shown that a 50% increase in the back pressure does not increase the B parameter, or if its lower value gives satisfactory pore water pressure measurements.
** under condition that this value remained unchanged after the consolidation, and backpressure three consecutive increases

2.1.2. Characteristics of soil consolidation

The basic parameters describing the consolidation process are the time factor, the coefficient of dissipation of pore water pressure in the soil (degree of consolidation), and the consolidation factor.

The time factor is given to determine the average value of the consolidation degree of a given layer or to determine the value of the consolidation degree at a given depth. The value of the time factor depends on the consolidation ratio, time, and flow path (a). For example, when drainage occurs in both directions, the value of the time factor increases by a factor of four [36,42].

$$T_v = \frac{c_v t}{L^2} \quad (1)$$

The value of the time factor depends on the degree of consolidation (U_z) (2),(3), hence T_v can be calculated from the following relation:

$$dla\ U_z \in \langle 0{,}60\%\rangle, T_v = \frac{\pi}{4}\left(\frac{U\%}{100}\right)^2 \quad (2)$$

$$dla\ U_z > 60\%,\ T_v = 1{,}781 - 0{,}933 log(100 - U\%) \quad (3)$$

The dependence of variation of the time coefficient on the value of the consolidation degree is presented in tabular form by the same authors.

Degree of dissipation of water pressure in soil pores (degree of consolidation)

British Standard BS 1377-6 1990 [43], defines the pore pressure dissipation rate in soil pores (4) as the ratio of the pore pressure difference between the start of the consolidation phase (u1), and the consolidation time t(u), to the pore pressure difference between the start (u1), and the end of the consolidation phase (u2):

$$U = \frac{u_1 - u}{u_1 - u_2} \cdot 100\% \quad (4)$$

In the literature describing the consolidation process (the methodology of its investigation, methods of development, and analysis of results), the authors rarely refer to the degree of pore water pressure dissipation. In contrast, there appears the concept of consolidation degree [36,37,38,44], defined as the ratio of the difference between the excess pore water pressure at the beginning of the consolidation process (u0), and the excess pore water pressure during the consolidation time t (ut), to the initial excess pore pressure (u0). The relationship described is represented by the equation below.

The development of the formula mentioned above leads to the following identity (5):

$$U_z = \frac{u_0 - u_t}{u_0} = \frac{(u_1 - u_2) - (u - u_2)}{(u_1 - u_2)} = \frac{u_1 - u_2 - u + u_2}{u_1 - u_2} = \frac{u_1 - u}{u_1 - u_2} \quad (5)$$

Hence (6):

$$U_z = U \quad (6)$$

Consolidation ratio

The consolidation coefficient c_v is a parameter that defines the speed of soil settlement. Its value generally decreases with increasing soil liquidity limit. The range of variation of c_v for a given liquid limit of soil is quite wide [37]. The consolidation coefficient c_v is used to calculate the value and rate of consolidation deformation of soils under load [45]. The value of the consolidation coefficient may be determined by the analytical method - from the solution of Terzaghi's equation (7) or by the use of empirical methods in which, for a given load increment of the tested sample, the characteristics of experimental and theoretical consolidation curves are compared, the so-called curve fitting process. Consolidation curves are more readable if the consolidation time is plotted on a logarithmic scale or presented as a square root [38].

$$c_v = \frac{k}{\gamma_w m_v} = \frac{k M_0}{\gamma_w} \quad (7)$$

Many literature sources distinguish two graphical methods for determining c_v under laboratory conditions in uniaxial consolidation tests [37,38]. One is the logarithmic-time method proposed by [46], and the other is the square root method suggested by [47]. In [43], in addition to the methods above, the third graphical method using the pore pressure dissipation factor is also defined. The general procedures for determining c_v by the methods mentioned earlier are included in Table S2.

Table S2. Methods for vertical consolidation coefficient determination

Method	Vertical consolidation coefficient [m2/s]	Method's description
The log time method (Casagrande Method)	$c_v = T_v \cdot \frac{h^2}{t_{50}}$ $T_v = 0{,}196$ t_{50} for U = 50%	Tv – time factor for U = 50% [-], t50 – time of 50% consolidation [s], h – sample height corresponding to 50% consolidation taken from consolidation curve [m].
The root time method (Taylor Method)	$c_v = T_v \cdot \frac{h^2}{t_{90}}$ $T_v = 0{,}848$ t_{90} for U = 90%	Tv – time factor for U = 90% [-], t90 – time of 90% consolidation [s], h – sample height corresponding to 90% consolidation taken from consolidation curve [m].
The pore water pressure dissipation method (Robbinson Method)	$c_v = T_v \cdot \frac{h^2}{t_{50}}$ $T_v = 0{,}279$ t_{50} for U = 50%	Tv – time factor for U = 50% [-], t50 – time of 50% consolidation taken from PWP dissipation curve [s], h – sample height egual to half height of the Row'e cell [m].
U – degree of consolidation [%]		

2.1.3. Phases of the soil consolidation

Immediately after the load is applied to a cohesive soil, due to the movement of free water molecules to more firmly bound water zones, the pore pressure in pore-filling water increases, and it takes up the entire load increment. The excess water is squeezed out of the higher-pressure areas into the lower-pressure areas. This process continues until the pore water pressure in the soil is equalized, there is no outflow of water from the sample, no displacement of soil particles, so no consolidation occurs.

When the drainage is unblocked, the water moves out of the loaded zone (filtration consolidation), with a simultaneous increase in the effective stress of the soil skeleton. When the structural strength of the soil is exceeded (up to 0.15 MPa), the pore pressure increases again; water is squeezed out of the pores (structural consolidation). When the consolidation process is complete, the pore water pressure equals the hydrostatic pressure that existed before the soil load was increased. Thus, the effective stresses increase by the whole increment of soil pressure.

Many researchers have observed that the different phases of deformation overlap and proceed simultaneously - the phase of deformation associated with structural consolidation already occurs during filtration consolidation [36,48,49].

2.2. Soil water permeability

Movement of water in the ground

Under natural conditions, the water flow in the ground is caused by the earth's gravitational forces, which tend to level off the differences in the level of water in the ground [49]. Thus, the movement of water in the ground can be determined or undetermined in time [34,50]. The motion in which water particles in adjacent layers move parallelly to each other and the direction of the water flow is referred to as laminar motion. The basic law on which the dynamics of water flow in porous media is based, assuming laminar motion, is Darcy's law, also called the linear filtration law [50].

The assessment of filtration properties is also related to the direction of water movement in the soil. The three basic directions of water movement in nature are horizontal, vertical downwards, and vertical upwards. Horizontal water flow is usually found at the top of an impermeable layer. The vertical downward flow usually occurs when the seeping of sub-soil water through the layer of low permeable soil below takes place, while the vertical upward flow occurs when pumping water from the bottom of the excavation as well as during construction works in the low permeable layer, the bottom of which is under the pressure of the interstitial water present below. Water permeability of soils is the ability of water to pass through the network of channels formed by the pores of the ground. The measure of water permeability of the ground is the filtration coefficient (water permeability coefficient), which according to Darcy's filtration law defines the relationship between the hydraulic gradient, and the speed of water flow through the pores of the ground [49].

The physical properties of the flowing water that affect the water permeability of soils are its temperature, viscosity, specific gravity, mineralization, soil texture as well as methods and conditions of measurements [34].

Methods for the determination of the filtration coefficient

The value of the filtration coefficient is determined based on empirical and analytical formulas), laboratory, and field tests, as well as mathematical, physical, and numerical modeling.

The choice of the method for determining the filtration coefficient depends, to a large extent, on the size of the grains, particles, and the associated properties of the soil under investigation. Permeability coefficient determination methods can be divided into:

- analytical, and empirical formulas – based on the grain size distribution (Hazena, and Kozeny-Carman formulas [51,52]; Hazen, Slichter, Terzaghi, Beyer, Sauber, Krueger, Kozeny, Zunker, Zamarin, USBR, Alyamani, and Sen, Shepherd, and Loudon [53]; Terzaghi, Kozeny, Carman, Zunker, and Chapuis [54–56]; Hazen [57]; Kruger [58]),
- laboratory, and field tests (in situ permeameter test [59]; Filtration Column [58]; ZWKII apparatus [60]; Oedometer [61], Rowe Cell [39,62])
- modelling (mathematical, physical, numerical: using DEM [50]; Using FEM [20]; Using LEM, FEM[61]).

Laboratory tests

Laboratory methods for the determination of the filtration coefficient should model the main directions of water flow in the soil. The flow rate measurement methods used in laboratory studies can be divided into direct and indirect methods (taking into account both constant and variable hydraulic gradient). A list of instruments used in individual methods is presented by [48].

Indirect methods are mainly based on the theory of filtration consolidation. The filtration coefficient of coal sludge (8) determined by this method depends on the value of the consolidation coefficient and the uniaxial compressibility modulus, and its value is calculated from the formula below:

$$k = \frac{c_v \gamma_w}{M_0} \quad (8)$$

The determination of the filtration coefficient of waste coal sludge by the direct method was carried out with a constant hydraulic gradient, and vertical direction of the filtration flow: from top to bottom. The filtration coefficient (k)(9) was calculated when steady-state filtration conditions were achieved using the formula in [42]:

$$k_v = \frac{1{,}63qL}{A\left((p_1 - p_2) - p_c\right)} \cdot R_t \cdot 10^{-4} \quad (9)$$

Due to their granulometric composition, the studies on water permeability of fine-grained wastes such as coal sludge should be carried out by the methods designed for cohesive soils in devices such as triaxial apparatus, consolidometers (e.g. Rowe cell), or specially adapted edometers. The construction and operation principles of the most commonly used instruments for determining the coefficient of permeability of semi-permeable formations are exhaustively described in the following publications [63–65].

6. Notation

The following symbols are used in this paper:

A - cross-sectional area of the sample,

B - Skempton parameter,

CS - coal sludge,

cv - coefficient of consolidation, m^2/s

γ_w- water weight,

k - coefficient of permeability, m/s

L - sample length, m, mm

M_0 - one-sided primary compressibility modulus of the soil,

m_v - volumetric compressibility factor of the soil,

pc - pressure loss in the system for flow rate q [kPa],

q - the average rate of water flow through the sample [ml/min],

Rt - temperature correction factor for water viscosity,

t - consolidation process duration time (time elapsed since the load was applied), s

u - pore water pressure after time t,

U - degree of dissipation of water pressure in the pores of the ground,

u_0 - excess pore water pressure in the soil at the beginning of the consolidation phase,

u_1 - pore water pressure at the beginning of the consolidation process,

u_2 - pore pressure in the soil at the end of the consolidation phase,

u_t - excess water pressure in the soil pores during consolidation time t,

Δu - increase in pore water pressure in the soil [kPa],

$\Delta\sigma_1$ - increment of vertical consolidation pressure [σ_1kPa],

Uz - degree of consolidation,

Δp = (p1 - p2) - the difference between the pressure of water entering the sample, and the the pressure of water leaving it [kPa].

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