Slovak Geol. Mag., 10, 4 (2004), 305 – 312

Permeability of fine-grained soils

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Abstract. In our study we tried to compare several methods of laboratory determination of coefficient of permeability, which is the principal property characterizing sealing properties of soils. We also tried to evaluate relationships of coefficient of permeability with other engineering geology parameters.
Permeability of 26 fine-grained Quaternary and Neogene soil samples from Western Slovakia was determined in triaxial apparatus and in oedometer by calculation from the time behavior consolidation using square root method and logarithmic method. Permeability was also estimated from grain size distribution by empirical formulas.

The results showed that coefficients of permeability obtained from triaxial and oedometer tests are similar and comparable. Coefficient of permeability obtained by the square root method was very similar to triaxial coefficient of permeability and their relationship is linear. Logarithmic method showed greater differences in comparison with the triaxial test results. Coefficient of permeability showed very good correlation with consistency index, liquid limit, index of plasticity and volumetric moisture content. Coefficient of permeability from grain size distribution is not advisable for cohesive soils.

Key words: sealing properties, coefficient of permeability, triaxial tests, oedometer tests.

Introduction

Proposal for an EU Directive (1997) concerning the design of sanitary landfills prescribes an extra protection against the percolation of leachate using a geological barrier of clay (Baumann et al., 1997). Construction of a proper landfill is necessary for protection of soils and groundwater from the pollution migration. Sealing systems play an important role in landfill construction in creating a long-term protection against pollutant transport into the environment.

Slovak technical standard STN 83 8106 - Landfill sealing suggests parameters of materials suitable for landfill sealing (mineral, geomembrane, combined and others). Materials suitable for the mineral sealing are fine-grained sediments: clays and silts from low to high plasticity and sandy soils (silty sand and clayey sand). The standard suggests to built-in soils with fine-grained particles (< 0,06 mm) $\geq$ 20 to 30 %, $I_P \geq 7$ to 10 %, gravel content (> 2 mm) $\leq$ 30 %, maximum grain sizes 63 mm. It also recommends the use of bentonite or other smectite clays. Organic matter content must be lower than 5% (this is not relevant for stable organic matters, such as coal dust or slag, etc.) Clay activity should be within (0,5 - 1,0) interval. Homogeneity and suitability is required to be verified by laboratory tests: grain size, moisture content, Atterberg limits, maximum dry density (Proctor standard) and laboratory test of permeability.

Permeability is a primary factor governing the performance of sealing systems. Membranes made out of soils with sealing properties should have the desired effect. Coefficient of permeability is the most important property determining the suitability of natural sealants. According to the Slovak technical standard – Laboratory determination of soil permeability, materials are considered impermeable if their coefficient of permeability is below 10^{-8} m.s^{-1}. Jullien et al. (2002) state that the permeability of soils in the sealing systems has to remain below 10^{-9} m.s^{-1} under all circumstances.

Permeability is an inherent property of a solid material and by the definition it is a measure of the rate of fluid flow through a porous material under a unit hydraulic gradient. The coefficient of permeability is a constant of proportionality relating to the ease with which a fluid passes through a porous medium.

Accurate determination of the coefficient of permeability is very important. There are several methods for assessment of the coefficient of permeability. Generally, we recognize direct and indirect laboratory methods. Coefficient of permeability can be determined directly by field tests (Matys et al., 1990). Field tests are time-consuming and require more advanced equipment for determination of coefficient of permeability. Laboratory tests, using a permeameter or a triaxial apparatus, are the simpler and generally more available methods for direct and more accurate determination of coefficient of permeability, but on the other hand the tested specimen is only a limited part of soil mass. Calculation from the time behavior consolidation, estimation from the empirical formulas and geophysical tests are indirect methods. All methods cannot be used generally; each method is suitable for different types of soils.

Záleský (1995) conducted comparative tests of coefficient of permeability on a low plasticity clay (w_L = 32,1 %,

w_P = 18,3 %, w_{opt} = 15,5 %, ρ_s = 2730 kg.m^{-3} a $\rho_{d,max}$ = 1816 kg.m^{-3}). He provided tests on high dimensional permeameter (sample dimensions 2 x 2 m), modified field permeameters (with diameter 50 and 100 mm) and laboratory tests in a pressure chamber with falling head (sample height 50 mm) and from time behavior consolidation in oedometer (height 30 mm and diameter 100 mm). They got good correlation between all methods with coefficient of permeability between 8×10^{-10} m.s^{-1} and 3×10^{-10} m.s^{-1}, except the oedometer tests, which yielded almost one order higher permeability coefficient 4×10^{-9} m.s^{-1}.

Baumann et al. (1997) studied coefficient of permeability in oedometer on high plasticity clay Rodby Havn used as a sealing for landfill layers in Denmark. The diameter was 30 mm and height 20 mm. Resulting coefficient of permeability of 5×10^{-12} m.s^{-1} confirmed propriety of its use in sealing barriers.

Garbulewski et al. (1995) also used oedometer and triaxial tests to determine coefficient of permeability of high plasticity swelling clay. They used specially adapted oedometer, allowing monitoring of permeability changes with saturation of the sample. They observed rapid decrease of the coefficient of permeability in time, in the modified oedometer, (for t = 0, k = 1×10^{-7} m.s^{-1} and for t = 60 000 s, k = 1×10^{-11} m.s^{-1}). Triaxial tests showed relationship between coefficient of permeability and water content (for w = 15 % k = 1×10^{-12} m.s^{-1} and for w = 35 % k = 1×10^{-8} m.s^{-1}). Author did not correlate the results between oedometer and triaxial tests.

Švábik (2001) compared permeability of four high and intermediate plasticity clays from Devínska Nová Ves and Levice in triaxial apparatus and oedometer. He found a good correlation between the two methods (maximum difference was 5.10^{-12} m.s^{-1}).

In this paper we compare different methods of Permeability determination for fine-grained soils. Permeability was determined by test of permeability in triaxial apparatus, in oedometer (logarithmic and square-root method) and by using empirical formulas based on grain size distribution. Empirical methods were used only for comparative purposes, since they are not suitable for clays. Grain size distribution, plasticity and liquid limits, bulk density and specific density were determined to classify the samples. Other physical properties, such as porosity, clay activity, organic matter content, carbonate content, saturation degree, etc. were also estimated to characterize engineering properties of the samples.

Materials

Twenty-six samples from localities from western Slovakia around town Skalica (Skalica, Holíč, Vradište, Kátov, Kopčany), Nové Mesto nad Váhom (Turecký vrch) and Trnava were tested in laboratory to evaluate different laboratory and empirical methods of determining of coefficient of permeability. Samples are Quaternary and Neogene fine-grained sediments.

Area around Skalica is geologically constituted of Neogene sediments, mainly from Holíčske Súvrstvie formation composed predominantly by calcareous clays, claystones and siltstones. These are sediments of basin facies of culminating transgression. Genetically heterogeneous Quaternary sediments of different thickness represented mainly by fluvial, proluvial and eolian sediments cover almost whole area.

Area around Trnava is composed of Neogene and Quaternary sediments. Neogene sediments create pre-Quaternary sublayer, represented by Panonian (greenish and yellow brown calcareous clays with sand and fine gravel layers), Pontian (coarse to boulder gravels, sands with gravel admixtures and clayey layers) and Levantian (medium to coarse gravels, scarcely sands) sediments. Quaternary is composed mostly by eolian origin sediments – ochre-yellow, fine sandy loess and loess loams. Thickness of the loess cover reaches up to 26 m. Fluvial sediments create fillings of fluvial bottomland of streams and deluvial sediments (washed loess, having mostly clayey character and darker colored), on the valley slopes (Salai, 1984).

Turecký vrch area is represented by rock complexes from middle Triassic to Quaternary. Neogene in the Turecký vrch area protrudes only on few places, represented by basal conglomerates and sandstones of Egenburg-Otnang cycle. Quaternary sediments are represented by various types of Eolian sediments (Pleistocene) represented by light yellow to brown colored loess, loess silts and clays. These sediments are wide spread and up to 14 meters thick (Matejček, 2003).

Tested samples are classified as low to very high plasticity clays. One sample is classified as very high plasticity clay, 9 samples as high plasticity clay, 1 sample as sandy clay, 12 samples as medium plasticity clay and 3 samples as low plasticity clay. Table 1 shows the classification of particular samples.

Methods of determination of the coefficient of permeability

Tests in triaxial apparatus, calculation from the time behavior consolidation (Casagrande's and Taylor's methods) and estimate from the empirical formulas were employed in determining of the coefficient of permeability.

Determination by the permeability test in triaxial apparatus

Determination of coefficient of permeability in a permeameter or a triaxial apparatus is based on the Darcy's law (linear resistance law), which applies generally for steady water flow in soils. It is given as:

$$v = k.\, i \qquad (1)$$

and corresponding flow rate

$$q = k.\, i.\, A, \qquad (2)$$

where q is quantity (m^3) of fluid flow in a unit time t (s), k is coefficient of permeability (m.s^{-1}), $i = \frac{h}{l}$ expresses the hydraulic gradient, h is total head difference along the flow path of length or height of the tested sample l (m)

Table 1. List of samples and their classification.

No.	Probe	Depth (m)	Locality	Description	Class	Symbol	Consistency	Clay/Loess
3492	JV-12	2,5	Vradište	very high plasticity clay	F8	CV	stiff	Clay
3498	JV-13	5,4	Skalica	high plasticity clay	F8	CH	firm	Clay
3504	JV-2	2,6	Holíč	high plasticity clay	F8	CH	stiff	Clay
3512	JV-1	8,6	Kopčany	high plasticity clay	F8	CH	stiff	Clay
3513	JV-3	1,2	Holíč	high plasticity clay	F8	CH	stiff	Clay
3514	JV-3	1,4	Holíč	high plasticity clay	F8	CH	stiff	Clay
3517	JV-3	6,8	Holíč	intermediate plasticity clay	F6	CI	stiff	Clay
3523	JV-4	4,5	Holíč	high plasticity clay	F8	CH	stiff	Clay
3524	JV-4	6,2	Holíč	high plasticity clay	F8	CH	stiff	Clay
3525	JV-5	7,7	Holíč	intermediate plasticity clay	F6	CI	firm	Loess
3526	JV-5	11	Holíč	intermediate plasticity clay	F6	CI	firm	Clay
3527	JV-6	3,5	Kopčany	low plasticity clay	F6	CL	firm	Loess
3528	JV-6	3,3	Kopčany	intermediate plasticity clay	F6	CI	stiff	Loess
3529	JV-6	8,7	Kopčany	low plasticity clay	F6	CL	firm	Loess
3533	JV-7	8	Vradište	intermediate plasticity clay	F6	CI	firm	Clay
3535	JV-8	3,6	Kátov	high plasticity clay	F8	CH	firm	Clay
3540	JV-9	1,1	Skalica	sandy clay	F4	CS	firm	Clay
3711	VT-4	14,2	Turecký v.	intermediate plasticity clay	F6	CI	hard	Loess
3712	VT-4	16,7	Turecký v.	intermediate plasticity clay	F6	CI	hard	Clay
3713	VT-4	24,4	Turecký v.	intermediate plasticity clay	F6	CI	hard	Loess
3717	VT-4	25,5	Turecký v.	intermediate plasticity clay	F6	CI	stiff	Clay
3719	VT-1	2,9	Turecký v.	intermediate plasticity clay	F6	CI	hard	Loess
3726	VT-5a	13,7	Turecký v.	intermediate plasticity clay	F6	CI	hard	Clay
3783	T2	3,1	Trnava	low plasticity clay	F6	CL	hard	Loess
3784	T3	4,5	Trnava	intermediate plasticity clay	F6	CI	stiff	Loess
3785	T4	6,1	Trnava	high plasticity clay	F8	CH	stiff	Loess

and A is cross sectional area (m^2) Coefficient of permeability (Mucha, et al., 1987) is calculated after modification to:

$$k = \frac{q.l}{A.h.t}, \ (m.s^{-1}) \qquad (3)$$

Coefficient of permeability was determined in a triaxial cell apparatus by "Constant head permeability test", measuring the flow of water through the sample, according to the Manual of Soil Classification and Compaction Tests (Head, 1992) and Slovak technical standards. The triaxial test determination with a pore pressure apparatus gives substantial control over the hydraulic gradient h/l across the sample. Magnitude of the gradient was from 30 to 100. Measurements until steady values of coefficients of permeability k were obtained. Coefficient of permeability for temperature 10°C k_{10} was calculated according the Slovak technical standard STN 72 1020.

Determination from the time behavior consolidation in oedometer

Laboratory test of consolidation of soils in oedometer is a model test of one-dimensional consolidation (Lambe, 1969). A compressible water saturated specimen is loaded evenly, water is embossed into the porous plates on both sides. Consolidation is not just a hydraulic process. A certain immediate deformation occurs after the loading in the initial phase of the curve, which is generally explained by the soil framework structure deformation and compression of minor air bubbles. The so-called secondary consolidation, which reaches more important portion only for the clayey soils, occurs at the end phase after expected termination of the initial hydraulic consolidation and is explained by the long-term plastic flow of the soil.

For each load increment the amount or (dial reading) that the sample has compressed at the end of a series of elapsed time in minutes is recorded as part of the data. A total time for a sample to consolidate under a load increment must be 24 hours or more (Bowles, 1992). There are several methods for taking time versus dial readings. Casagrande's and Taylor's methods are the most widely used. In the Casagrande's method, shown on Figure 1 the data are presented as a semi logarithmic plot of dial readings versus time (time on the log scale) in minutes and in the Taylor's method one uses a plot of dial reading versus $\sqrt{t}$ (in minutes). From such plots we obtain the dial reading corresponding to the end of primary consolidation (or the end of 100 percent consolidation) U or D_{100} . Time elapsed when this occurs is T. It is also necessary to obtain a dial reading at the beginning of the test. Data reduction for the Casagrande's method usually requires using a D_{50} (dial reading at U = 50 %) and corresponding time t_{50} (Figure Cassagrande's method). The time at U = 50 % is used to estimate the coefficient of consolidation c_v from the test. This value is used to estimate rate of settlement as follows:

$$c_v = \frac{0{,}049.(h_{50})^2}{t_{50}}, \ (m^2.s^{-1}) \qquad (4)$$

Taylor's method presented on Figure 2 uses D_{90} (dial reading at $U = 90$ %) and corresponding time t_{90} to calculate the coefficient of consolidation (Figure Taylor's method) according to:

$$c_v = \frac{0{,}212.(h_{90})^2}{t_{90}}, \ (\mathrm{m^2.s^{-1}}) \qquad (5)$$

where h_{50} and h_{90} is height of the specimen at 50 and 90 % of the primary consolidation.

Since the coefficient of consolidation is defined:

$$c_V = \frac{k.E_{oed}}{\gamma_w}, \qquad (6)$$

where γ_w is water unit gravity, E_{oed} is oedometric modulus, c_v can be used for calculation of coefficient of permeability after modification to:

$$k = \frac{c_v.\gamma_w}{E_{oed}}, \ (\mathrm{m.s^{-1}}) \qquad (7)$$

Laboratory tests of consolidation of soils in oedometer were performed according to the Slovak technical standard STN 72 1027. Load of 400 kPa was used to determine oedometric modulus E_{oed}, coefficient of consolidation c_v and coefficient of permeability k for all samples. Loads of 100 kPa and 200 kPa were used for several samples as well. Coefficient of consolidation was evaluated by both Casagrande's and Taylor's method.

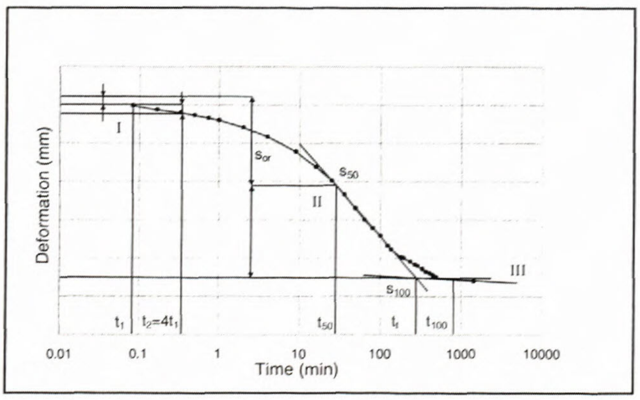

Figure 1. Casagrande's method diagram

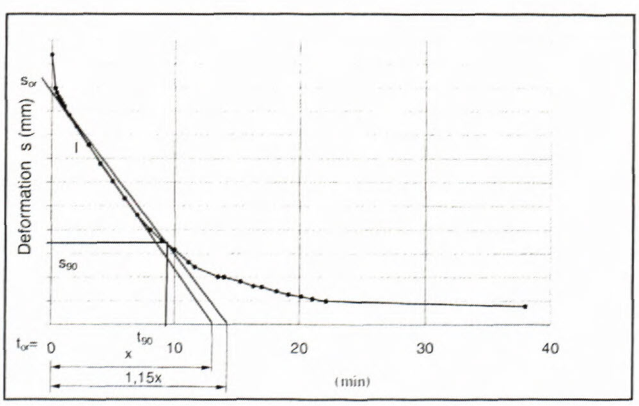

Figure 2. Taylor's method diagram

Determination from the Empirical equations

Grain size of soil is reflected in coefficient of permeability, because the permeability of the porous soil depends on the relative content of the grains of different sizes (Head, 1990). Different ways of coefficient of permeability determination from the grain size curve have been therefore developed. These are used for loose sedimentary soils, especially for non-cohesive sediments. They were used only for comparative purposes, even they are not suitable for fine-grained soils.

These methods are indirect, they are based on the size of particles, and it is therefore necessary to determine the grain size curve, which gives the amounts of particular grain size fractions. Several equations, which relate the permeability of soils and their grain size and other classification values, are used. Hazen's, Kozeny's and Carman's modification of the Kozeny's equation belong among the most known. Other are Jáky, Terzaghi, Orechová, American equation, Seelheim, Zieschang, Beyer, Zauerbrej, Zamarin, Schlichter, Krüger, Palagin, etc.

Empirical equations determined by Carman-Kozeny, Seelheim, Orechova and American formula were also used to determine to estimate coefficient of permeability for each soil.

Carman-Kozeny

Relates permeability with grain size, porosity, grain shape, surface area and water viscosity. The formula is intended only for clean sands, but it is sometimes extrapolated for finer soils to obtain an approximate indication of their permeability (Head, 1990):

$$k = \frac{\rho_w.g}{C.\eta_w.S^2}\frac{e^3}{1+e}; \quad C = 5.f \quad \text{or} \qquad (8)$$

$$k = \frac{1}{5}\frac{g.n^3}{\gamma.(1-n)^2}\left(\frac{d_e}{\alpha}\right)^2$$

(modified for spherical shape of grains), (9)

where e is void ratio, g is acceleration of free fall, ρ_w is water density, η_w is water viscosity, S is surface area, C is shape factor (5 for spherical shape), f is angularity factor (f range 1,1 – 1,4), n is porosity, γ is unit gravity d_e is effective grain diameter and α is pore shape factor.

Seelheim, American equation and Orechová relate coefficient of permeability just to the grain size distribution represented by grain size diameters d_{50}, d_{20} and d_{17}.

Seelheim

$$k = \frac{0{,}357.(d_{50})^2}{100},$$

valid for soils with grains (0,063 mm < 35 %) (10)

American equation

$$k = \frac{0{,}36.(d_{20})^{2.3}}{100},$$

valid for soils with (0.01 mm < d_{20} < 2.0 mm) (11)

Table 2. Coefficients of permeability

Sample No.	Coefficient of permeability k (m.s^{-1})										
		Oedometer						Empirical equations*			
	Triaxial	Taylor's square-root method			Casagrande's logarithmic m.			Orechová	American equation	Seelheim	Carman-Kozeny
	k_{10}	k_{100}	k_{200}	k_{400}	Lk_{100}	Lk_{200}	Lk_{400}				
3492	$1.24x10^{-11}$	$1.16x10^{-11}$	$1.96x10^{-11}$	$1.53x10^{-11}$	$8.73\ 10^{-11}$	$1.16x10^{-11}$	$1.72x10^{-11}$				
3498	$1.32x10^{-11}$		$3.74x10^{-11}$	$2.4x10^{-11}$		$4.88x10^{-11}$	$4.07x10^{-11}$			$1.87x10^{-8}$	$1.87x10^{-8}$
3504	$1.04x10^{-11}$		$1.66x10^{-10}$	$1.14x10^{-10}$		$1.21x10^{-10}$	$4.06x10^{-11}$			$1.52x10^{-7}$	$3.48x10^{-9}$
3512	$1.93x10^{-11}$			$3.59x10^{-11}$			$4.7x10^{-11}$	$2.95x10^{-8}$	$4.73x10^{-9}$	$4.31x10^{-7}$	$5.20x10^{-9}$
3513	$8.74x10^{-10}$	$2.73x10^{-9}$	$9.1x10^{-10}$		$3.6\ 10^{-10}$	$4.04x10^{-11}$				$7.21x10^{-8}$	$3.06x10^{-9}$
3514	$2.08x10^{-10}$	$4.71x10^{-10}$	$6.5x10^{-10}$		$2.49\ 10^{-10}$	$2.2x10^{-10}$				$2.19x10^{-7}$	$3.92x10^{-9}$
3517	$2.64x10^{-11}$		$1.17x10^{-10}$	$4.12x10^{-10}$		$2.42x10^{-10}$	$3.12x10^{-10}$	$3.79x10^{-8}$	$3.46x10^{-8}$	$3.99x10^{-6}$	$8.17x10^{-9}$
3523	$3.36x10^{-11}$	$2.40x10^{-11}$	$3.88x10^{-11}$	$3.55x10^{-11}$	$3.07\ 10^{-11}$	$2.97x10^{-11}$	$2.18x10^{-11}$			$1.02x10^{-8}$	$3.49x10^{-9}$
3524	$3.24x10^{-11}$		$1.17x10^{-10}$	$4.24x10^{-11}$		$6.93x10^{-11}$	$4.63x10^{-11}$			$7.37x10^{-9}$	$3.69x10^{-9}$
3525	$7.62x10^{-10}$	$8.02x10^{-10}$	$9.52x10^{-10}$	$5.33x10^{-10}$	$1.5\ 10^{-10}$	$5.32x10^{-10}$	$2.74x10^{-10}$	$1.63x10^{-8}$	$2.14x10^{-9}$	$1.90x10^{-6}$	$5.96x10^{-9}$
3526	$2.67x10^{-10}$	$4.43x10^{-10}$	$4.15x10^{-10}$	$2.96x10^{-10}$	$2.71\ 10^{-10}$	$2.34x10^{-10}$	$1.69x10^{-10}$	$2.53x10^{-8}$	$4.16x10^{-9}$	$1.27x10^{-6}$	$6.26x10^{-9}$
3527	$1.00x10^{-9}$		$7.01x10^{-10}$	$6.65x10^{-10}$		$1.35x10^{-10}$	$1.75x10^{-10}$	$2.15x10^{-8}$	$2.90x10^{-9}$	$9.49x10^{-7}$	$5.88x10^{-9}$
3528	$1.05x10^{-9}$		$2.01x10^{-9}$	$1.11x10^{-9}$		$3.18x10^{-10}$	$3.38x10^{-10}$	$2.14x10^{-8}$	$3.07x10^{-9}$	$1.34x10^{-6}$	$6.13x10^{-9}$
3529	$1.27x10^{-9}$	$1.3x10^{-9}$	$2.17x10^{-9}$	$1.3x10^{-9}$	$4.18\ 10^{-10}$	$6.42x10^{-10}$	$4.53x10^{-10}$	$2.22x10^{-8}$	$3.12x10^{-9}$	$1.37x10^{-6}$	$6.18x10^{-9}$
3533	$2.55x10^{-10}$	$3.21x10^{-10}$	$2.35x10^{-10}$	$2.35x10^{-10}$		$1.44x10^{-10}$	$5.75x10^{-11}$	$4.26x10^{-8}$	$6.51x10^{-9}$	$1.19x10^{-6}$	$6.26x10^{-9}$
3535	$8.91x10^{-11}$	$3.84x10^{-10}$	$1.05x10^{-10}$		$1.18\ 10^{-10}$	$9.07x10^{-11}$			$1.06x10^{-9}$	$2.24x10^{-6}$	$5.48x10^{-9}$
3540	$1.64x10^{-11}$	$4.26x10^{-11}$	$2.75x10^{-11}$		$6.09\ 10^{-11}$	$3.68x10^{-11}$				$4.37x10^{-6}$	$4.76x10^{-9}$
3711	$1.15x10^{-9}$		$3.76x10^{-9}$	$1.32x10^{-9}$		$3.69x10^{-11}$	$1.15x10^{-10}$		$1.97x10^{-9}$	$9.09x10^{-7}$	$5.45x10^{-9}$
3712	$1.74x10^{-10}$		$4x10^{-10}$	$2.09x10^{-10}$		$3.79x10^{-11}$	$7.09x10^{-11}$			$3.55x10^{-7}$	$3.88x10^{-9}$
3713	$7.89x10^{-11}$		$5.93x10^{-11}$	$8.93x10^{-11}$		$7.06x10^{-11}$	$6.43x10^{-11}$	$1.78x10^{8}$	$3.51x10^{-9}$	$1.03x10^{-6}$	$6.0x10^{-9}$
3717	$1.27x10^{-10}$		$2.15x10^{-11}$	$1.46x10^{-10}$		$7.13x10^{-11}$	$3.75x10^{-11}$			$2.58x10^{-7}$	$3.76x10^{-9}$
3719	$2.76x10^{-8}$			$8.72x10^{-9}$			$1.2x10^{-9}$	$8.27x10^{-8}$	$1.9x10^{-8}$	$1.59x10^{-6}$	$6.83x10^{-9}$
3726	$2.70x10^{-11}$			$2x10^{-11}$			$3.55x10^{-11}$		$2.12x10^{-9}$	$7.54x10^{-7}$	$5.17x10^{-9}$
3783	$8.90x10^{-9}$			$6.5x10^{-9}$			$4.07x10^{-10}$	$2.78x10^{-8}$		$2.42x10^{-7}$	$5.35x10^{-9}$
3784	$7.35x10^{-9}$			$6.2x10^{-9}$			$1.83x10^{-10}$	$4.15x10^{-8}$		$1.2x10^{-6}$	$7.79x10^{-9}$
3785	$1.45x10^{-9}$			$1.73x10^{-9}$			$3.38x10^{-10}$	$2.01x10^{-8}$		$7.75x10^{-7}$	$4.59x10^{-9}$

*not advisable for fine-grained soils

Orechová

$$k = \frac{640.(d_{17})^2}{86400},$$

valid for soils with grains (0,063 mm < 35 %) (12)

Tests Results

Obtained coefficients of permeability are shown in Table 2. Values of coefficient of permeability determined in triaxial test are within limits of $2,76\times10^{-8}$ m.s^{-1} to $1,04\times10^{-11}$ m.s^{-1}.

There were two groups of samples, with different origin: clays (16 samples) and loess and loess-like sediments (10 samples). Clayey samples are varying from intermediate to very high plasticity clays and loess and loess-like soils are characterized only as low and intermediate plasticity clays. Their comparison is presented in Figure 3. Values of coefficients of permeability determined by Taylor's method are labeled as k_{100}, k_{200} and k_{400}, according the load, at which they were measured. Similarly, the values from the Cassagrande's logarithmic method are labeled as Lk_{100}, Lk_{200} and Lk_{400}. Average coefficients of permeability were, as expected, lower for clays and the differences are most obvious for the triaxial test and Taylor's method at 400 kPa, where average value differs by one and a half of order. Higher permeability is caused by structure of loess and loess-like sediments, which controls their properties. Figure 4. shows the comparison of coefficient of permeability obtained by triaxial and oedometric Taylor's test for clays and loess and loess-like sediments separately. Generally Taylor's method gives higher values of coefficient of permeability for clays then triaxial test. Loess and loess-like sediment samples coefficient of permeability values mostly lay over the even line, which means this method gives lower values of coefficient of permeability then the triaxial method. Clays and loess and loess-like sediments also show differences in correlation of coefficient of permeability with other parameters. Clayey soils exhibit good correlation of coefficient of permeability with fraction % 0.5, 1 and 2 mm. For loess and loess-like sediments is characteristic good correlation of coefficient of permeability with fraction % 0.002, 0.005, 0.1, 0.25, 0.5, 1 and 2 mm, consistency index I_C, liquidity index I_L, bulk density ρ_n, specific gravity ρ_s, porosity n, void ratio e, degree of saturation S_r, volumetric moisture content w_o. Coefficient of permeability of loess and loess-like sediments seems to be more dependent on these properties in comparison with clays, because they characterize structure and state of the soil. Permeability of typical clays depends mainly on physical and chemical processes connected with mineralogical composition (clay minerals content). Plot of the Fraction < 0.002 mm content versus plasticity limit is shown on Figure 5. It shows the differences between clays and loess and loess-like sediments in clay activity expressed by the means of Activity index, the ratio of the plasticity limit and fraction < 0.002 mm ratio. Activity index, expressed by Skempton, serves for characterization of the clay behavior (Head, 1992). All of the loess and loess-like sediment samples belong to the group with intermediate clay activity. Clay samples are spread through the low, intermediate and high clay activity zone.

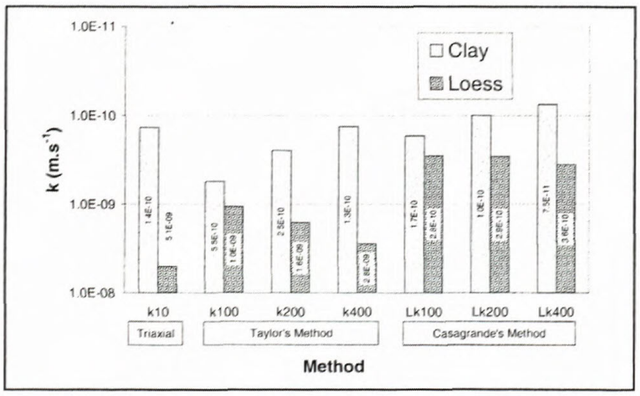

Figure 3. Coefficients of permeability for clays and loess and loess-like soils.

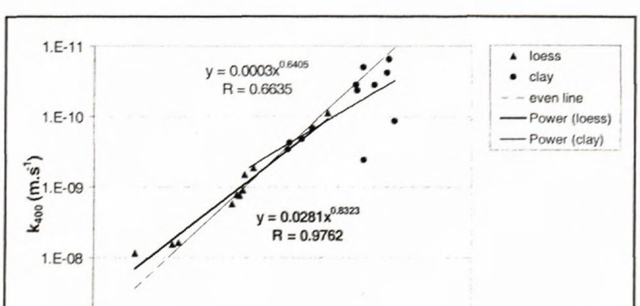

Figure 4. Plot of Triaxial versus Taylor's method at 400kPa plot for clays and loess and loess-like soils.

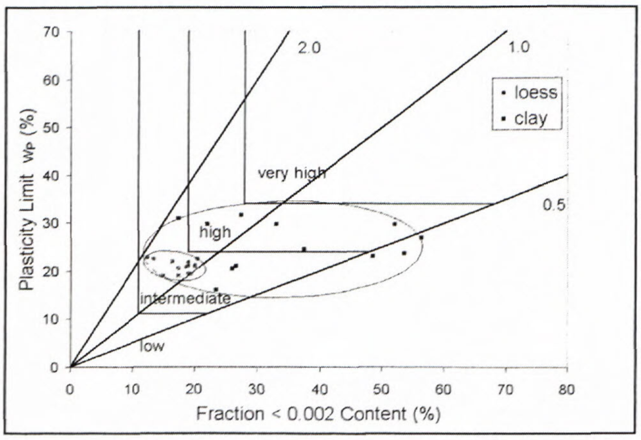

Figure 5. Activity comparison for clays and loess and loess-like soils.

It is obvious, from the Table 2 that the values obtained by triaxial and oedometer tests, especially Taylor's method are similar and for majority of samples the values of the coefficient of permeability from the triaxial test are lower then those from the Taylor's method. The Differences between coefficients of permeability from the triaxial test and Taylor's method are negligible. They differ only by decimals within one order. Greater difference was observed for samples 3504 and 3517, for which the Taylor's method yielded coefficient of permeability one order grater then the triaxial test ($k_{10} = 1.04\times10^{-11}$ m.s^{-1} / 2.64×10^{-11} m.s^{-1}, $k_{400} = 1.14\times10^{-10}$ m.s^{-1} / 4.12×10^{-10} m.s^{-1}). Sample 3719 (loess) show half of order difference, with lower oedometric test value ($k_{10} = 2.76\times10^{-8}$ m.s^{-1}, $k_{400} = 8.72\times10^{-9}$ m.s^{-1}).

Figure 6. shows plot of k_{10} from triaxial method and k from oedometer (Taylor's and Casagrande's method), for better resolution in log-log scale. The plot shows very good correlation between triaxial and oedometer tests with power relationship and Correlation coefficients R = 0.9975 for Taylor method and linear correlation with R = 0.8844 for Casagrande method. Correlation coefficients higher then 0.6084 represent significant relationship for number of cases n = 26. The significance of the correlation is expressed by a significance level. The two tailed significance level of 0.001 means that the correlation coefficient is significant at 99.9 %. Plot between Taylor's and Casagrande's method on Figure 7. shows power relationship with very good correlation R = 0.8459. For coefficient of permeability lower then 1.10^{-10} m.s^{-1} differences are very low and both oedometric methods give similar values with the triaxial test. For higher coefficients of permeability the differences between the Cassagrande's method and the triaxial method are getting higher with higher coefficient of permeability. Although the Correlation coefficient between the triaxial test and Casagrande's method shows significant relationship, values from Casagrande's test are lower then those from the triaxial test, which is good seen in the comparison with the even line (Fig. 6) and it means, the results are not on the safety side. This does not correspond with the Slovak technical standard STN 72 1027, which recommends to use logarithmic

Taylor's method if both methods could be used for evaluation. This points to the fact that Taylor's method is more accurate than Casagrande's method. Empirical equations showed two to three order higher values, Seelheim method even higher, which means, that empirical equations are not suitable for determination of coefficient of permeability for fine-grained soils.

$$k = 1^{-8}e^{-0,1264.w_o},\ (R = -0.5307). \qquad (16)$$

Second order polynomial equation (R = 0.6413) characterizes relationship between k_{10} and void ratio *e*. Some of above-mentioned relationships are shown on Figure 8. and 9.

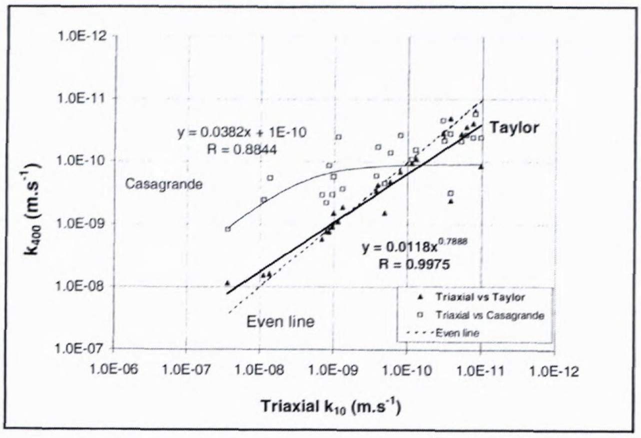

Figure 6. Plot of triaxial k_{10} versus Oedometer Casagrande's and Taylor's method.

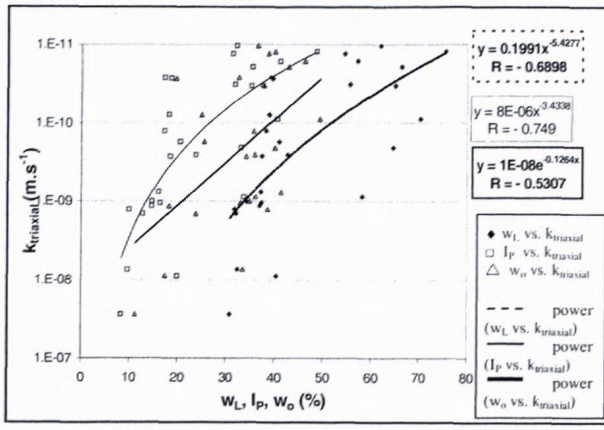

Figure 8. Plot of liquid limit w_L, plasticity index I_P and volumetric moisture content w_o versus triaxial k_{10}.

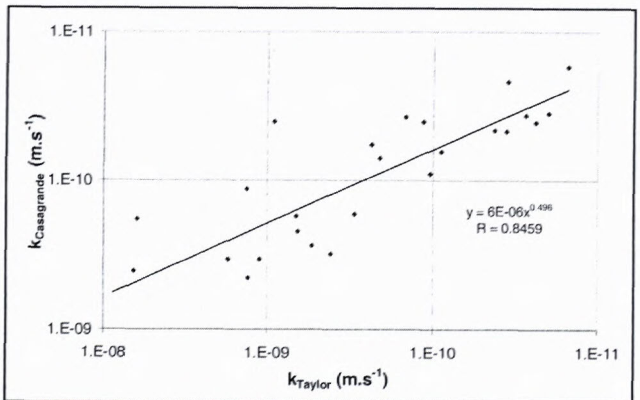

Figure 7. Plot of Taylor's versus Casagrande's method.

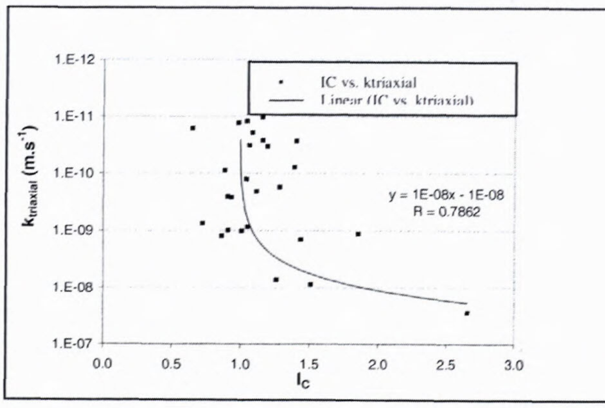

Figure 9. Plot of I_C versus triaxial k_{10}.

Comparison with other physical parameters revealed some interesting relationships. Coefficient of permeability from triaxial k_{10} shows very good linear correlation with consistency index I_C characterized by equation

$$k = I_C.1^{-8} - 1^{-8},\ (R = 0.7862), \qquad (13)$$

bulk density ρ_n (R = -0.7573) and degree of saturation S_r (R = -0.6656).

Coefficient of permeability with liquid limit w_L, equation

$$k = 0,1991.w_L^{-5,4277},\ (R = -0.6898) \qquad (14)$$

and index of plasticity I_P

$$k = 8^{-6}.I_P^{-3,4338},\ (R = -0.749) \qquad (15)$$

show power relationship and relationship of coefficient of permeability and volumetric moisture content w_o is exponential, equation

Conclusions

Following conclusions could be drawn from this investigation:

1. Oedometric determination of Coefficient of permeability yields very similar results to Triaxial permeability test. Both Taylor and Casagrande methods show close relationships to Triaxial test. Power relationship is characteristic for Taylor's method with Correlation coefficient R= 0.9975 and linear relationship characterizes Casagrande's method with R = 0.8844.

2. The best correlation between triaxial and oedometric determination of Coefficient of permeability was found for loads of 400 kPa (for k_{400} R = 0.9020 and for Lk_{400} R = 0.8844, number of cases 22) and 200 kPa (for k_{200} R = 0.8493 and for Lk_{200} R = 0.5380, number of cases 20), lower correlations were for loads of 100 kPa. (for k_{100} R = 0.7708 and for Lk_{100} R = 0.8176, number of cases 10).

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3. Comparison of Taylor's square-root method and Casagrande's logarithmic method showed that Taylor's method gives values closer to those obtained from Triaxial test, the difference is negligible. Values from Casagrande's method are also close to triaxial method, but the differences are higher, especially for samples with coefficients of permeability higher then 1×10^{-10} m.s^{-1}. This is in contradiction to the STN 72 1027, which recommends the use of Casagrande's logarithmic method when both methods could be realized.

4. Methods of determination of Coefficient of permeability from the empirical equations (Carman-Kozeny and Seelheim) brought values more than two orders higher than those from Triaxial and oedometer tests. Since these methods are based only on the grain-size distribution, and partly on porosity or grain shape they do not express actual values of Coefficient of permeability. Empirical equations are suitable mainly for sands and gravels, but their use for fine-grained soils is not advisable, because mineralogical composition and behavior of clay mineral play very important role in these soils, however relationship between coefficient of permeability k_{10} and void ratio e is characterized by significant 2nd order polynomial relationship with R = 0.6413.

5. Coefficient of permeability showed some very high correlations with other parameters. Coefficient of permeability has linear relationship with consistency index I_C (R = 0.7862), bulk density ρ_n (R = 0.7573) and degree of saturation S_r (R = 0.6656). Coefficient of permeability with liquid limit w_L (R = 0.6898) and index of plasticity I_P (R = 0.65696) show power relationship and relationship of coefficient of permeability and volumetric moisture content w_o is exponential with R = 0.6905. These results confirm the dependence of permeability on the physical state of soil, which is characterized by liquid limit, consistency index and index of plasticity, water content in soil (degree of saturation and volumetric moisture content) and bulk density. Good correlation of the coefficient of permeability with liquid limit, consistency index and index of plasticity indirectly shows its relationship to the clay mineralogy.

6. Differences between clays and loess and loess-like sediments are best seen from triaxial test and oedometric Taylor's method results. Average value of coefficient of permeability obtained by triaxial test k_{10} is 1.37×10^{-10} m.s^{-1} for clays and 5.10×10^{-10} m.s^{-1} for loess and loess-like sediments. Taylor's method yielded average values of k_{400} 1.3×10^{-10} for clays and 2.8×10^{-9} m.s^{-1} for loess and loess-like sediments. This is the result of different structure and origin of loess soils and clays. Even though loess and loess-like soils are also fine-grained sediments containing clay minerals, they possess different properties, which was revealed by differences in permeability and other characteristics such as clay activity. The differences between the two groups in comparison of coefficient of permeability obtained by the triaxial test and oedometric Casagrande method hint that oedometric methods are suitable for clayey soils and could be used only as an informative method for loess and loess-like soils.

This laboratory investigation was an attempt to compare different methods of coefficient of permeability determination and it showed comparability of triaxial and oedometric Taylor's method of coefficient of permeability determination, especially for clay soils. Taylor's method is accurate, reliable alternative method for coefficient of permeability determination, which is in accordance with wide use of Taylor's method in USA (Bowles, 1992). Casagrande's logarithmic method yields lower values of coefficient of permeability.

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