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4. Evaluation and Comparison of Results of Soil Permeability Determination by Hydrodynamic Tests, Laboratory Tests and Empirical Methods within the Project of Environmental Burdens Monitoring

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Abstract: The study presents the results of the research from the geological task "Contaminated sites monitoring on selected localities in Slovak Republic" carried out at the State Geological Institute of Dionýz Štúr in the period of 2013 – 2015. The aim was to use the acquired knowledge on hydraulic parameters of the environment from hydrodynamic tests to evaluate the permeability of the environment. Within the construction of new wells, disturbed soil samples were also taken to determine the physical properties of the soils in the laboratory. Coefficients of hydraulic conductivity were determined in the laboratory on undisturbed samples. Another objective was to compare the values of the coefficients of hydraulic conductivity determined during pumping tests in boreholes, in laboratory conditions in a triaxial permeameter, in a constant head permeameter and a falling head permeameter and by empirical methods from grain-size distribution. In conclusion, the comparison of individual results of determination of the coefficient of hydraulic conductivity by different methods is presented. The resulting comparison shows that no significant correlations were found between the values obtained from pumping tests and laboratory methods. The pumping tests evaluate the permeability of the geological (or borehole-screened) environment in general, while the laboratory tests evaluate only the point value of the coefficient of hydraulic conductivity at a given sampling point. It is therefore necessary to evaluate the results on a case-by-case basis, taking into account the specificities of the method and the method of sampling for laboratory permeability tests. The coefficients of hydraulic conductivity determined in laboratory compared to results from empirical methods show good correlations, which confirms the dependence of permeability on the grain-size distribution of the soil.

Key words: permeability, coefficient of hydraulic conductivity, pumping tests, triaxial test, permeameter, grain size distribution, correlation

4.1 Introduction

Permeability is a very important property of the geological environment when assessing the spread of contaminants. The permeability of a porous medium is its property of permeating liquid or gas. The geological environment has the ability to receive, store, and conduct groundwater (Mucha & Šestakov, 1987).

One of the main activities within the solution of the geological task "Monitoring of environmental burdens in selected localities of the Slovak Republic" carried out at the State Geological Institute of Dionýz Štúr (SGIDŠ) in the period from 2013 to 2015 was the realization of drilling and related works for construction of the basic monitoring objects suitable for monitoring of groundwater quality and changes in groundwater chemical composition in areas of individual environmental burdens. The research sites are located throughout the Slovak Republic. Altogether there were 161 sites. 669 new monitoring boreholes were built at individual sites and another 156 boreholes were reconstructed. After the boreholes were cleaned, 6-hour orientation pumping tests were carried out in most boreholes in accordance with the Slovak technical standard STN 73 6614 (1984), which verified a borehole functionality. On the basis of pumping tests documentation, the hydraulic parameters of the rock environment around the active part of a borehole were determined. Upon completion of the pumping test, a recovery test was carried out, which lasted until the groundwater level had stabilized. During the pumping test, groundwater level, specific electrolytic conductivity and water temperature were monitored at regular intervals. In total, 638 hydrodynamic tests were carried out. One of the results of the hydrodynamic tests was also the determination of the coefficient of hydraulic conductivity of the environment around the well. Within the construction of new wells, disturbed soil samples were also taken to determine the physical properties of the soil in the laboratory. On undisturbed samples, the coefficients of hydraulic conductivity were determined in the laboratory in a constant head permeameter, falling head permeameter or triaxial. The coefficients of hydraulic conductivity were also calculated by empirical methods based on the results of the grain-size analysis.

The aim of this study is to compare the coefficients of hydraulic conductivity determined from the hydrodynamic field tests with the values of the laboratory coefficients of hydraulic conductivity (in the triaxial and constant and falling head permeameter) and the coefficients of hydraulic conductivity determined from grain-size analysis by empirical methods. We tried to find dependencies between methods, depending on the type of soil, their genesis, or grain composition.

The coefficient of hydraulic conductivity (k_f) is the most important parameter in groundwater flow calculations. Its reliable evaluation is necessary for accurate calculation, modelling and evaluation of intergranular flow in porous environment. A number of methods are used to determine the coefficient of hydraulic conductivity. Hydrodynamic tests in wells or in situ permeability tests are conducted in the field. Laboratory evaluation includes permeability tests in permeameters or triaxial devices. Empirical formulas serve to evaluate the value of the coefficient of hydraulic conductivity from the grain-size distribution of soils. In the case of in situ tests, the precise evaluation of the coefficient of hydraulic conductivity is limited by the uncertainties in the geometry of a soil layer under investigation and in the hydraulic boundary conditions. In laboratory tests, it is difficult to obtain representative samples; the size of the test samples is limited; therefore such samples do not fully represent the original layer in situ. The use of empirical equations is not suitable for low permeability soils such as clays and silts, but allows a quick and cost-effective estimation of the coefficient of hydraulic conductivity for soils such as sand and gravel. Comparison of the results of the determination of the coefficient of hydraulic conductivity by different methods was discussed by several authors.

The assumption that permeability is constant is not reasonable at shallow depths, in soils where porosity changes with depth, in normally consolidated soils or under heavy loads. Clarke et al. (1997) point out that laboratory measured permeability may not always correspond to in-situ permeability. Usually, a laboratory test of clay permeability lasts from two weeks to several months when using a low hydraulic gradient. It is possible to accelerate the test by increasing the hydraulic gradient, which causes seepage induced swelling creating a significant variation in effective stress and void ratio in a specimen. To avoid this using of back pressure is recommended.

Lee & Chang (2007) compared the results of laboratory falling head tests on soil samples from the borrow pits used as construction materials of Hwaong sea dike (7 tests) and in situ permeability tests performed directly at the Hwaong sea dike (27 constant hydraulic gradient tests). Silt sands and clays of low plasticity were sampled as disturbed and artificially compacted The results confirmed significant differences between the laboratory coefficient of hydraulic conductivity and the in situ permeability. The differences between the results are caused due to the differences in the samples, the inhomogeneity of the soil in the embankment and the possibility of water flow in all directions in field tests, whereas in laboratory conditions the flow is only onedirectional.

Elarabi & Elfaki (2011) compared laboratory and field permeability tests on borehole samples at the new Khartoum International Airport (KNIA). The results showed a significant difference between the permeability measured in the laboratory and the permeability values in the field by one to four orders, attributing the unrepresentative nature of the laboratory sample to soil under natural conditions. Nevertheless, they found a very good correlation between the laboratory permeability and the relative coefficient between field and laboratory permeability. The authors stated that the ratio decreases at higher values of the coefficients of hydraulic conductivity determined in the laboratory.

Sobolewski (2005) presents an overview and classification of coefficients of hydraulic conductivity determination methods and devices commonly used in Poland. In particular, he focuses on experimental methods and modern measuring instruments that serve to determine the coefficients of consolidation and filtration in cohesive soils. He also suggests introducing changes in methodology that would allow the values of coefficients of hydraulic conductivity determined in situ and from laboratory tests to be comparable. Determining the value of the coefficient of hydraulic conductivity is a complicated and complex engineering task. It is a property of soil, which is changing most significantly. The variations can be in the range of several orders, even in the case of relatively homogeneous layers. There is a huge number of laboratory and field tests to determine the coefficient of hydraulic conductivity. Each method has its advantages but also disadvantages, so the choice of the method depends on the actual situation.

Nagy et al. (2013) investigated various methods for determining the coefficient of hydraulic conductivity of silt sand and silt sand using Khafagi probe, Menard probe, water filtration method. They used a constant head and falling head permeability tests in laboratory. They also used an empirical method of calculating the coefficients of hydraulic conductivity from the grain-size distribution using the equation proposed by Hazen (1895). They accentuate the reliability of individual methods, the capability to sense the layer boundaries and their estimation accuracy. Based on the obtained results, the authors state that they cannot say, what the coefficient of permeability of the soil is, but only state the value obtained from a certain type of measurement. Even in this case one must take into account the disturbance of the sample, the method errors, etc.

The monitoring well screen and filter pack may cause significant head losses, which are not taken into account when interpreting the permeability test data performed in the monitoring wells. Baptiste & Chapuis (2014) have defined the equivalent coefficients of hydraulic conductivity of conventional PVC screens by hydraulic tests in a water tank. The tests have shown that gas microbubbles, which are a common problem in monitoring wells contribute to increasing parasitic head losses. They used closed-form equations and numerical models to explain by how much a field permeability tests in monitoring wells underestimate an aquifer coefficient of hydraulic conductivity due to parasitic head losses in the screen and the filter pack. The value of the local coefficients of hydraulic conductivity can only be correctly measured in the monitoring well only if it is significantly lower than the maximum value of the coefficient of hydraulic conductivity of the monitoring well obtained in the water tank. The measuring capacity of a monitoring well for large slots in perforation and de-aerated water could by two order higher in comparison to small slots in field conditions for poorly designed and installed monitoring well. When assessing groundwater flow conditions at any location, permeability data must be assessed with caution, as permeability tests could be performed in poorly designed and installed monitoring wells with limited measurement capacities. The result of such case is an underestimation of the coefficient of hydraulic conductivity values and thus an underestimation of the seepage and contamination propagation rates.

4.2 Methods

The technical work included drilling, sampling and hydrodynamic testing. Soil samples were taken during drilling operations. A total of 1,979 disturbed soil samples, 299 undisturbed samples and 313 groundwater samples were collected. Sampling and transport of samples were performed in accordance with STN EN ISO 22475-1. Laboratory determination of geotechnical properties of soils and rocks was carried out at SGIDŠ in the laboratory of the Department of Engineering Geology (Kordík & Slaninka et al., 2015).

Hydrodynamic tests

After the boreholes were cleaned, the pumping tests were carried out for 6 hours in accordance with STN 73 6614 (1984). Upon completion of the pumping test, a recovery test was carried out, which lasted until the groundwater level stabilized. During the pumping test, groundwater level, specific electrolytic conductivity and water temperature were monitored at fixed intervals. In total, 638 hydrodynamic tests were carried out. In the case of a high level of groundwater pollution, the pumping test was not carried out.

Transmissivity (T) and coefficient of hydraulic conductivity (k_f) values were obtained by Jacob's modified nonequilibrium method for adjusted drawdown curves method (Cooper & Jacob, 1946) or by type curve analysis (Moench, 1985).

An example of the pumping test record is shown in Fig. 4.1.

Laboratory tests

Laboratory tests were carried out on the samples in the laboratory of engineering geology of SGIDŠ to determine the basic physical characteristics of soil samples and to determine the permeability.

Grain-size analysis

The grain-size analysis (soil particle size analysis) is used to determine the distribution of soil particles and to express their percentage in the soil. The measured data are plotted in a semi-logarithmic graph. This graph expresses the relationship between the percentage (y-axis) and the average of the individual grain fractions (x-axis). The graphical representation, grain-size distribution curve, represents the weight or percentage grain content of the individual fractions from the dry total weight. The grain-size distribution is a basic parameter in the classification of soils and is also used for indirect determination of permeability (coefficient of hydraulic conductivity) using the empirical relationships. The size of the soil grains ranges from 0.001 to 200 mm (STN 72 1172, 1968). The grain-size was determined by two methods, the

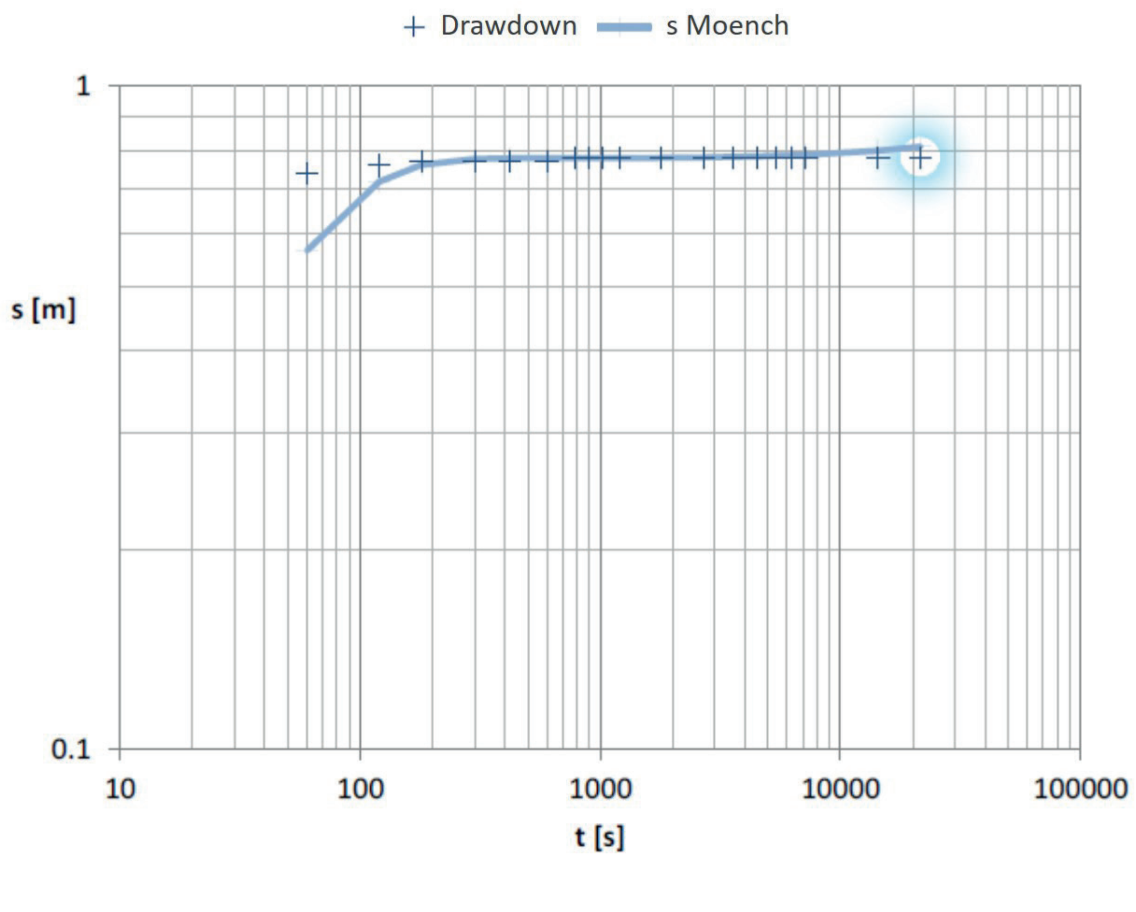

Fig. 4.1 Pumping test in well VN21-2 chart (locality Nové Mesto nad Váhom – landfill)

sieving method for particles larger than 63 μm and the sedimentation method using a hydrometer for particles smaller than 63 μm.

Permeability – coefficient of hydraulic conductivity k_f ($m.s^{-1}$) determination

Laboratory methods for the coefficients of hydraulic conductivity determining are based on the Darcy's filtration law, in which there is a direct proportion between the hydraulic gradient and the filtration rate in the laminar flow of fully saturated soil. The measurement is performed in apparatuses under constant or falling head. The head (hydraulic gradient) is considered to be constant if, during the test, the difference in pressure of the water flowing into the sample and flowing out does not change. We talk about the falling head, when the pressure levels on of the inflow and outflow levels decrease during the test.

On intact samples, the coefficients of hydraulic conductivity were determined in a triaxial chamber with pore pressure measurement and in a constant head and a falling head permeameter.

Coefficient of hydraulic conductivity determination in triaxial chamber (STN 72 1020)

The permeability was determined in a triaxial GDS (Geotechnical Digital System) with automatic control. The device permits constant hydraulic head permeability tests on 38 mm diameter samples and is equipped with hydraulic pumps to apply chamber, saturation and axial pressure. Test specimens with a diameter of 38 mm and heights from 19 mm to 50 mm were used. A weighed soil sample with a precisely measured volume was mounted on a lower base fitted with a saturated filter plate. The base drainage system was filled with de-aerated distilled water and sealed. A saturated filter plate and an upper base with a drainage tube were mounted on the upper face of the test sample. A rubber sleeve (membrane) was mounted on the sample jacket, which was fastened to the jacket of both bases by flexible sealing rings. After the sample was prepared, the chamber was mounted and filled with de-aerated water. Sample prepared for triaxial test permeability is shown in Fig. 4.2.

Fig. 4.2 Permeability in triaxial permeameter

Permeability was measured on totally saturated and consolidated samples. The saturation occurred simultaneously with the consolidation of the sample. The chamber pressure was always at least 20 kPa greater than the saturation and test pressure during both the saturation and consolidation and during the permeability measurement itself. The final saturation pressure was chosen according to the initial degree of saturation. The chamber and saturation pressures increased simultaneously until the final size of the chamber and saturation pressures was reached. The loading rate was not higher than 3 kPa per minute. At saturation, the amount of water received by the sample over time was automatically recorded. The final saturation pressure and chamber pressure were maintained until the volume of water received by the test sample was less than 0.2% of its initial volume in 24 hours. Upon completion of consolidation, as soon as water began to flow through the sample, permeability measurements were started while maintaining a constant value of the hydraulic inclination. The volume of flowed water V_w and its temperature were measured at least 5 times at suitably selected time intervals t. The length of the time interval was adapted to the permeability of the test soil. For more permeable soils the measurement intervals were usually from 2 to 10 minutes, for less permeable soils from 1 to 2 hours The permeability measurements were carried out until the flow rate stabilized. The difference in pressure altitudes h was chosen so that the hydraulic gradient did not exceed 100 during the test.

At the end of the measurement, the water supply pressure sources were disconnected, the chamber pressure source was also disconnected, and the water was drained from the chamber. The samples were removed and, if possible due to the nature of the sample, the volume and weight of the sample after the test was determined.

Coefficient of hydraulic conductivity was calculated according to the formula:

$$k_f = \frac{Q \,.\, L}{A \,.\, h \,.\, \Delta t} \cdot [m \,.\, s^{-1}]$$

where Q is the volume of water in m^3, L is the height of the sample before the test in m, A is the cross-section of the sample in m^2, h is the difference of pressure levels in m, and t is the time interval of the measurement in s.

Coefficient of hydraulic conductivity measured at temperature ϑ is marked as k_ϑ. For comparative value k_{10} is calculated according:

$$k_{10} = \frac{1.359}{1 + 0.0337 \,.\, \vartheta + 0{,}00022 \,.\, \vartheta^2} \cdot k_\vartheta = \alpha \,.\, k_\vartheta \; [m \,.\, s^{-1}) \,]$$

The values of the α coefficient are set in the range of 5 to 25 °C, given in STN 72 1020 (1991). The temperature is determined as the average temperature to which it refers and at the end of the interval from which the coefficient of hydraulic conductivity was evaluated.

The resulting coefficient of hydraulic conductivity value is the average of all stabilized values. As stabilized values of coefficient of hydraulic conductivity those values are considered, which do not differ more than 20% of their average value. Physical parameters of the samples before and after the test were calculated according to the applicable relationships of soil mechanics.

Constant head permeability test

In the constant head permeability test water flows through a cylindrical-shaped soil sample with a constant differential pressure. The test is performed in a chamber whose dimensions were 116.5 mm high and 101.4 mm diameter. The permeameter is equipped with an adjustable water tank that allows a constant head flow during the test. For testing, deaerated water at a constant temperature is used. Before starting the flow measurement, the soil sample must be saturated. During the test, the amount of water flowing through the sample at given time intervals is measured.

Coefficient of hydraulic conductivity can be calculated as:

$$k_f = \frac{Q \,.\, L}{A \,.\, \Delta h \,.\, \Delta t}$$

where *L* is the height of the sample, *A* is the cross-section of the sample, *Δh* is the pressure level difference, *Q* is the volume of flow-through water, *Δt* is the time interval.

Falling head permeability test

A falling head permeability test means water flow through a soil sample in a chamber with a height of 116.5 mm and a diameter of 101.4 mm attached to a burette that provides a hydraulic height and also allows measurement of the volume of water passing through the sample.

Before starting the flow measurement, the soil sample is saturated with de-aerated water. The burette is filled to the specified height. The test is then started and the water flows through the sample until the water in the burette reaches the lower limit. The time taken to fall from the upper level to the lower level is recorded. The procedure is repeated several times until the recorded time varies by less than 10% (Head, 1981).

Coefficient of hydraulic conductivity is calculated as:

$$k_f = \frac{a \,.\, L}{A \,.\, \Delta t} \,.\, \log \left(\frac{h_0}{h_1}\right)$$

where *L* is the height of the soil sample, *A* is the cross-sectional area of the sample, *a* is the cross-sectional area of the burette, *Δt* is recorded time, h_0 and h_1 are upper and lower water levels in the burette.

The resulting values of the coefficient of hydraulic conductivity, which were determined at a given temperature in the laboratory k_ϑ, were calculated to a comparative value of 10 °C k_{10}. Permeameter for constant and falling head tests is shown in Fig. 4.3.

Fig. 4.3 Permeameter for constant and falling head test

Empirical methods

Since the permeability of the porous rock depends on the relative grain content of the various sizes, the granularity of the rock is also reflected in its coefficient of hydraulic conductivity. Different ways of deriving the coefficient of hydraulic conductivity from the grain-size distribution curves were developed. These are used for noncohesive sedimentary rocks, especially for sandy and gravel soils (Dananaj, 2004).

These methods are indirect, based on the size and shape of the particles, so it is necessary to establish a grain-size distribution curve that captures the amounts of the individual grain fractions. Several equations are used to relate the permeability of soils (especially sands) to their granular composition and other classification values. The best known are the Hazen equation, which is simple and based on the grain-size distribution curve and the Kozeny equation and its Carman modification. Other methods are, for example, Jaky, Terzaghi, Orechova, American formula, Seelheim, Zieschang, Beyer, Zauerbrej, Zamarin, Schlichter, Krüger, Palagin. These methods are particularly suitable for sands and their use is not suitable for fine-grained soils. Coefficients of hydraulic conductivity were determined from the grain curves using the GeoFil computer program, which uses the above mentioned methods.

Carman – Kozeny method puts permeability into a relationship with grain-size, porosity, particle shape, specific surface and water viscosity. The formula is valid only for sands, but sometimes is extrapolated for fine-grained soils to approximately determinate their permeability (Head, 1981):

$$k_f = \frac{\rho_w \, . \, g}{C. \, \eta_w \, . \, S^2} \, . \, \frac{e^3}{1+e}; \; C = 5 \, . \, f$$

or *(simplified for spherical grain shape)*

$$k_f = \frac{1}{5} \, . \, \frac{g \, . \, n^3}{\gamma \, . \, (1-n)^2} \, . \, \frac{d_e}{\alpha} \quad ,$$

where e is porosity index, ρ_w is water density, γ is volumetric gravity, g is gravity acceleration, η_w is water viscosity, S is surface area, C is shape coefficient (= 5 for spherical shape), f is angularity coefficient (1.1 – 1.4), n is porosity, d_e is effective grain diameter and α is pore shape coefficient.

Seelheim, American formula and Orechova put coefficient of hydraulic conductivity into relationship with grain-size expressed by diameters d_{50}, d_{20} and d_{17}.

Seelheim is valid for soils with fraction less than 0.063 mm content < 35%

$$k_f = \frac{0.357 \, . \, (d_{50})^2}{100}$$

American formula is valid for soils with effective grain diameter ($0.01 < d_{20} < 2.0$)

$$k_f = \frac{0.36 \, . \, (d_{50})^{2.3}}{100}$$

Orechova formula is valid for soils with fraction less than 0,063 mm content < 35%.

$$k_f = \frac{640 \, . \, (d_{17})^2}{86{,}400} \, .$$

4.3 Results

Rocks of different ages and origin were found in the areas of monitored localities. Most of the sites were Quaternary and Neogene rocks. Palaeogene, Mesozoic and Palaeozoic rocks were also found in some localities.

Only the Quaternary and Neogene sediments were processed in the Laboratory of engineering geology.

The Quaternary is represented by anthropogenic, fluvial, deluvial, eluvial, proluvial, aeolian, polygenetic, organogenic and glacifluvial sediments. The counts of soil samples by their genetic origin are shown in Tab. 4.1.

Tab. 4.1 Genetic classification

Genesis	Formation	Count
Anthropogenic	Quaternary	80
Deluvial	Quaternary	295
Eluvial	Quaternary	58
Aeolian	Quaternary	23
Fluvial	Quaternary	1,170
Glacifluvial	Quaternary	4
Proluvial	Quaternary	48
Polygenetic	Quaternary	65
Organogenic	Quaternary	1
Sedimentary	Neogene	416
Volcanic	Neogene	1
Effusive	Neogene	6
Sedimentary	Palaeogene	80
Sedimentary	Mesozoic	29
Sedimentary	Permian	2
Metamorphic	Palaeozoic	2

A total of 2,315 disturbed and undisturbed soil samples were processed. Moisture content was determined on all of them and granulometric analysis for soil classification according to STN 72 1001 on 2,313 samples. Consistency limits were determined on 56 samples.

A total of 3 samples of boulder fraction (200 – 60 mm), 722 gravelly, 368 sandy and 1,220 fine-grained soils were tested. The numbers of soils according to the classification based on STN 72 1001 are given for gravelly soils in Tab. 4.2, for sandy soils in Tab. 4.3 and for fine-grained soils in Tab. 4.4.

Tab. 4.2 Classification of gravelly soils

Class	Symbol	Classification (STN 72 1001)	Count
G1	GW	Well graded gravel	29
G2	GP	Poorly graded gravel	56
G3	G-F	Gravels with admixture of fine-grained soil	363
G4	GM	Silty gravel	21
G5	GC	Clayey gravel	253
Overall		Gravelly soils	722

Tab. 4.3 Classification of sandy soils

Class	Symbol	Classification (STN 72 1001)	Count
S1	SW	Well graded sand	1
S2	SP	Poorly graded sand	57
S3	S-F	Sand with admixture of fine-grained soil	84
S4	SM	Silty sand	18
S5	SC	Clayey sand	208
Overall		Sandy soils	368

Tab. 4.4 Classification of fine-grained soils

Class	Symbol	Classification (STN 72 1001)	Count
F1	MG	Gravelly silt	2
F2	CG	Gravelly clay	66
F3	MS	Sandy silt	28
F4	CS	Sandy clay	313
F5	ML	Silt of low plasticity	42
	MI	Silt of intermediate plasticity	
F6	CL	Clay of low plasticity	513
	CI	Clay of intermediate plasticity	
F7	MH	Silt of high plasticity	3
	MV	Silt of very high plasticity	
	ME	Silt of extremely high plasticity	
F8	CH	Clay of high plasticity	253
	CV	Clay of very high plasticity	
	CE	Clay of extremely high plasticity	
Overall		Fine-grained soil	1,220

Based on the results of granulometric analyses, the computer programme GeoFil was used to determine the coefficients of hydraulic conductivity values by empirical methods from grain curves. The program uses the methods Hazen1, Hazen2, Orechova, American formula, Seelheim, Zieschang, Beyer, Zauerbrej, Kozeny1, Kozeny2, Zamarin1, Zamarin2, Zamarin3, Zamarin4, Schlichter1, Schlichter2, Schlichter3, Kruger, Palagin, Carman – Kozeny. The programme automatically selected the appropriate methods for the soil type. The criteria are defined by the program itself and cannot be influenced except for the approximate porosity setting. The total number of coefficients of hydraulic conductivity for each method is shown in Tab. 4.5.

Permeability and bulk density were determined on intact and reconstituted samples. The permeability in the triaxial permeameter was determined on 218 samples. The permeability in the constant head permeameter was determined on 58 samples. The permeability in the falling head permeameter was determined on 19 samples. In statistical processing, the results of the coefficient of hydraulic conductivity determination in the constant head permeameter and falling head permeameter were evaluated together with the result from triaxial permeameter.

The results of engineering geological properties determinations and values of coefficients of hydraulic conductivity determined by various methods were summarized in the database of all project data. The evaluation was based on a total dataset of 2,281 samples, which included the physical properties of soils together with the results of the determination of the coefficient of hydraulic conductivity by empirical methods and laboratory determination of the coefficient of hydraulic conductivity. From hydrodynamic tests in boreholes it was possible to determine coefficients of hydraulic conductivity in 254 cases. Based on the determination of the main collector, the results from the laboratory determination for the soil type were subsequently assigned to the well.

In this dataset, the results of determined coefficients of hydraulic conductivity were compared directly with each other, as well as depending on the grain-size, soil type or genesis.

By direct comparison between the values of the coefficients of hydraulic conductivity determined by hydrodynamic and laboratory tests, only twelve data could be compared, since only in these cases data from both tests were available. This was due to the fact that for the laboratory determination of the coefficient of hydraulic conductivity the impermeable soils were preferably taken. The results of this comparison are shown in Fig. 4.4. It is clear that the differences are considerable, in the order of several orders, which is also confirmed by the weak exponential relationship with the correlation coefficient R = 0.36455. The results from hydrodynamic tests generally give a higher k_f value than laboratory tests.

Tab. 4.5 Number of coefficients of hydraulic conductivity calculated by empirical methods (in $m.s^{-1}$)

Method	Hazen1	Hazen2	Orechova	American	Seelheim	Zieschang	Beyer
Min	$2.13x10^{-08}$	$8.49x10^{-09}$	$1.40x10^{-08}$	$8.94x10^{-10}$	$7.32x10^{-09}$	$3.95x10^{-09}$	$4.30x10^{-09}$
Max	$2.45x10^{-01}$	$1.96x10^{-01}$	$2.77x10^{-01}$	$3.88x10^{-01}$	$9.36x10^{-01}$	$2.57x10^{-01}$	$2.08x10^{-01}$
Count	854	860	1,416	1,531	1,516	861	866
Method	**Zauerbrej**	**Kozeny1**	**Kozeny2**	**Zamarin1**	**Zamarin2**	**Zamarin3**	**Zamarin4**
Min	$1.86x10^{-09}$	$5.23x10^{-08}$	$1.63x10^{-07}$	$4.58x10^{-09}$	$1.16x10^{-10}$	$7.27x10^{-11}$	$1.13x10^{-09}$
Max	$9.05x10^{-02}$	$6.98x10^{-02}$	$5.27x10^{-03}$	$2.20x10^{-01}$	$3.29x10^{-02}$	$1.48x10^{-02}$	$5.46x10^{-03}$
Count	909	941	943	868	864	855	858
Method	**Schlichter1**	**Schlichter2**	**Schlichter3**	**Kruger**	**Palagin**	**Carman – Kozeny**	**Average**
Min	$6.52x10^{-09}$	$2.34x10^{-08}$	$6.07x10^{-10}$	$6.59x10^{-09}$	$1.69x10^{-10}$	$2.25x10^{-09}$	$2.30x10^{-09}$
Max	$5.40x10^{-02}$	$2.99x10^{-02}$	$2.90x10^{-02}$	$8.19x10^{-02}$	$1.11x10^{-01}$	$5.74x10^{-02}$	$2.22x10^{-01}$
Count	869	869	867	872	945	2,240	2,246

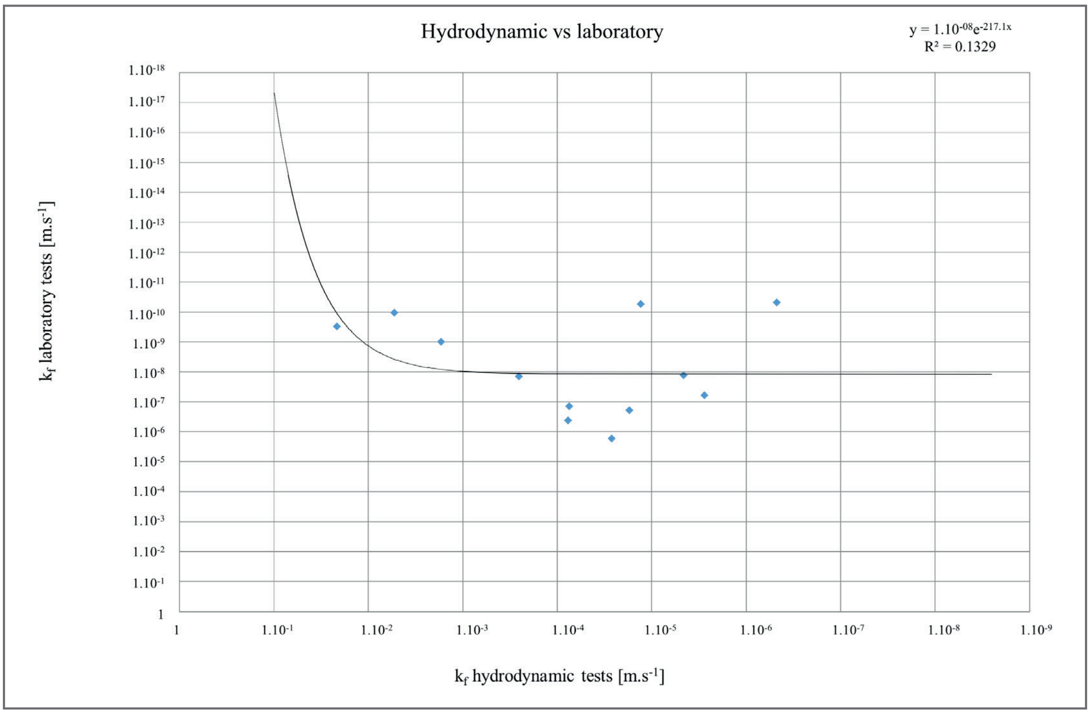

Fig. 4.4 Comparison between values of coefficients of hydraulic conductivity determined by hydrodynamic and laboratory tests

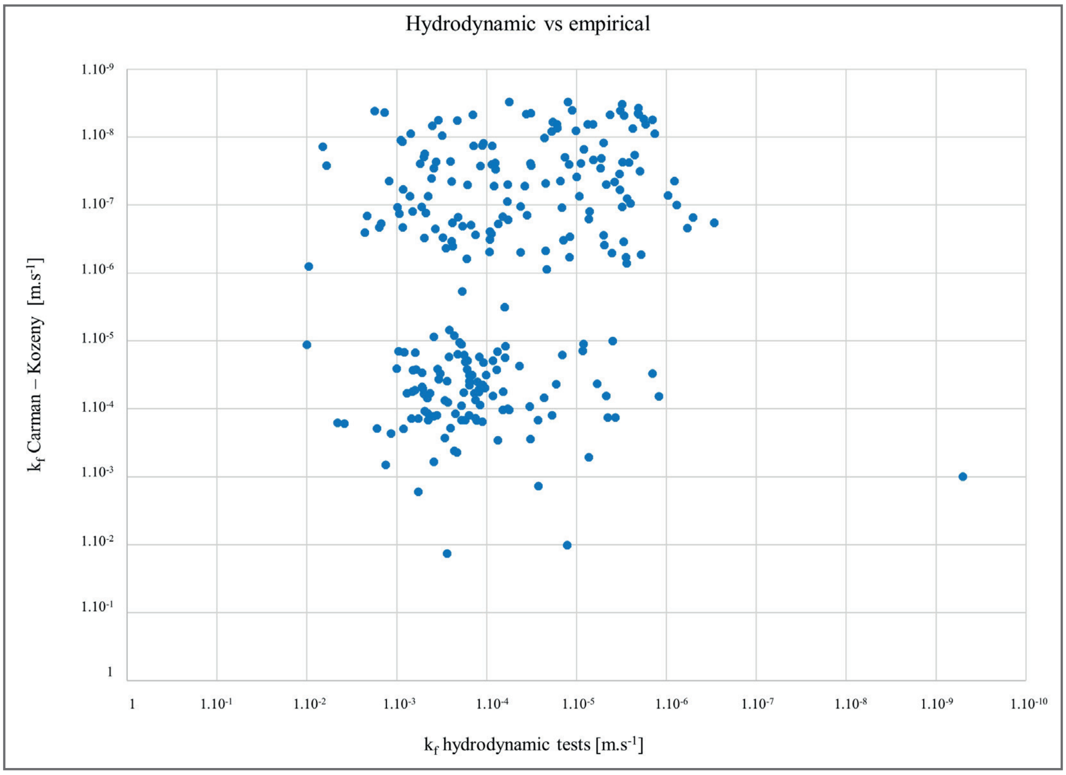

Fig. 4.5 Comparison between values of coefficients of hydraulic conductivity determined by hydrodynamic tests and Carman – Kozeny empirical method

To compare the coefficients of hydraulic conductivity from hydrodynamic tests and from empirical relationships, the average values per well were calculated from the determined values of the coefficients of hydraulic conductivity obtained from empirical formulas to increase the impact of heterogeneity of the whole environment and "simulate" the cross–section of the well geological profile. The Carman – Kozeny method, which was calculated for almost all samples, was used for the evaluation. The resulting graph is shown in Fig. 4.5. No correlation is seen, as well.

The values of coefficients of hydraulic conductivity determined by hydrodynamic tests and mean values calculated from all empirical methods were also compared. The samples were divided into 4 groups according to the percentage of clay particles (< 0.002 mm). The first group

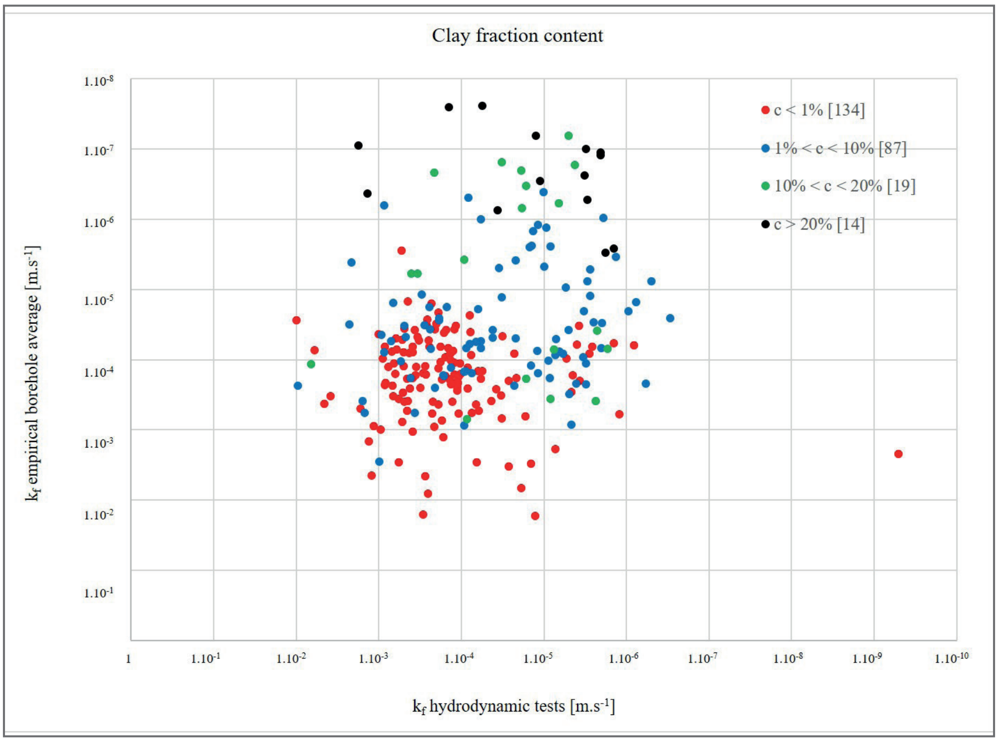

Fig. 4.6 Comparison between the values of coefficients of hydraulic conductivity determined by hydrodynamic tests and from grain-size distribution curves in dependence to clay fraction content

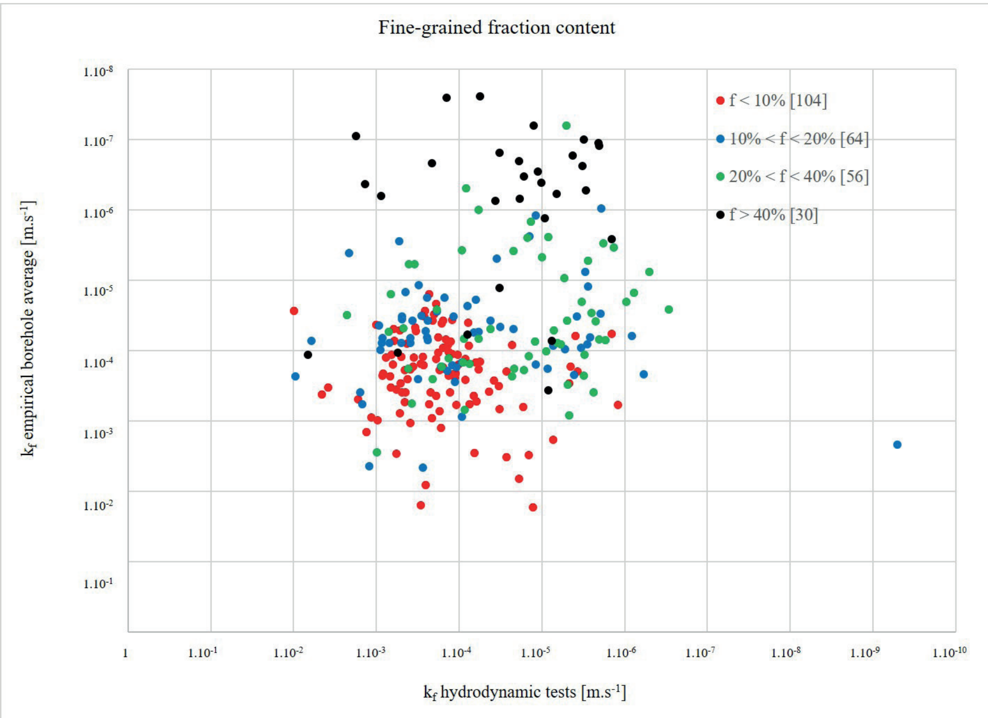

Fig. 4.7 Comparison between the values of coefficients of hydraulic conductivity determined by hydrodynamic tests and from the grain-size distribution curves in dependence to the content of fine-grained fraction

represented the samples with clay content less than 1%, the second from 1% to 10%, the third from 10% to 20% and the fourth above 20%. This comparison is shown in Fig. 4.6. Again, there was no apparent correlation for any of the four groups.

A similar comparison was also made with a fine grain fraction (< 0.063 mm). The samples were divided into 4 groups according to the percentage of fine-grained particles. The first group represented the samples with a fine particle content of less than 10%, the second group from 10% to 20%, the third group from 20% to 40% and the fourth group above 40%. This comparison is shown in Fig. 4.7. Even this comparison did not bring any significant correlations.

Comparison with respect to soil type is shown in Fig. 4.8. It is clear from the figure that, there is no significant correlation.

Another comparison was made for samples divided by genetic origin (Fig. 4.9). Again, no significant correlations can be seen based on genetic types.

Fig. 4.10 shows a comparison of the coefficients of hydraulic conductivity from hydrodynamic tests and the difference between the coefficient of hydraulic conductivity of hydrodynamic tests and the coefficient of hydraulic conductivity of empirical methods depending on the clay fraction content. With such a distribution it can be

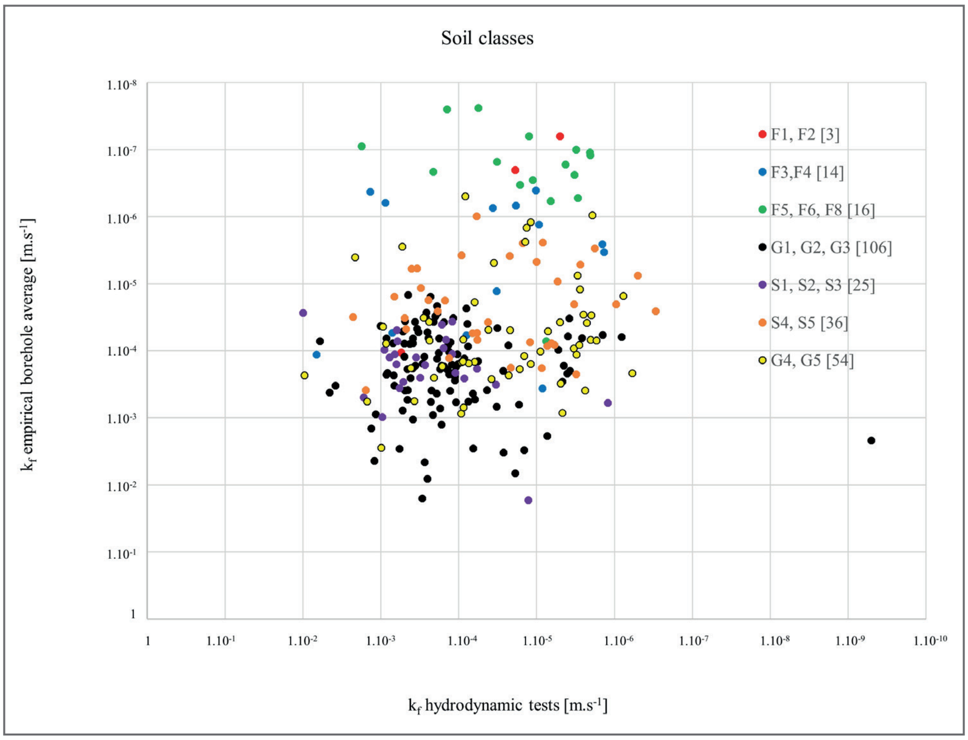

Fig. 4.8 Comparison between the values of the coefficients of hydraulic conductivity determined by hydrodynamic and from the grain-size distribution categorized by soil type

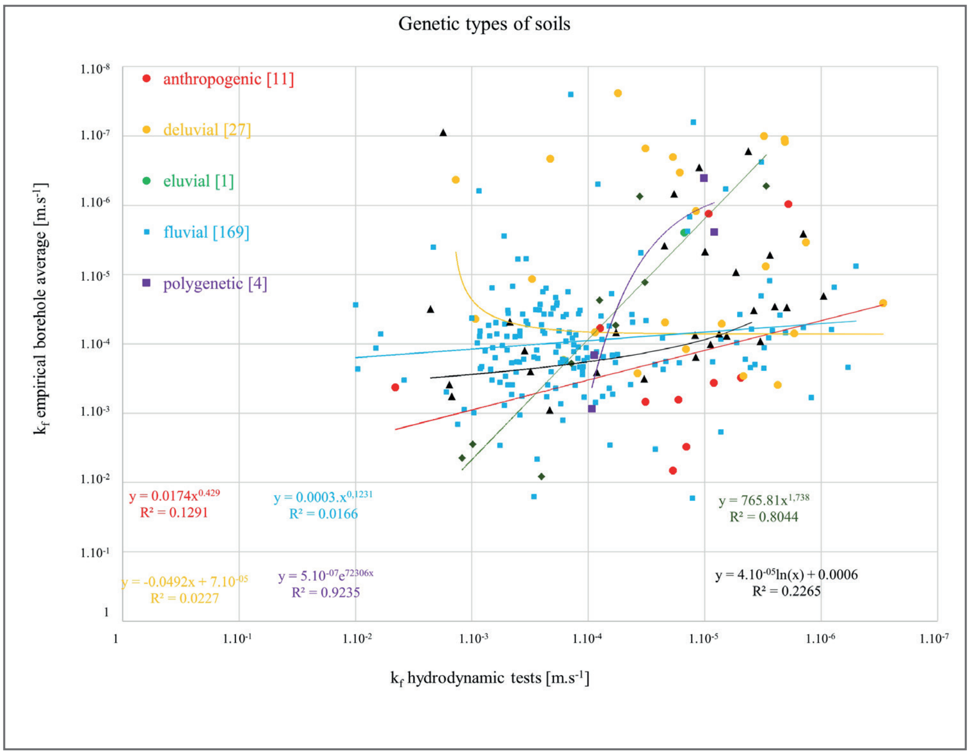

Fig. 4.9 Comparison between the values of coefficients of hydraulic conductivity determined by hydrodynamic tests and from the grain-size distribution based on genetic origin

seen that the greatest differences are with soils having the lowest clay content.

In Fig. 4.11, there is a comparison of the values of the coefficients of hydraulic conductivity determined in the triaxial permeameter with the average values obtained by empirical methods. The values are significantly different, since the minimum values from the grain-size distribution curves reach values of the order of 10^{-9} m.s^{-1}. The values determined in the triaxial permeameter reach the order values up to 10^{-11} m.s^{-1}. The value of the correlation coefficient R for the given statistical set of 215 samples for the power trend line is 0.452769, with the determination

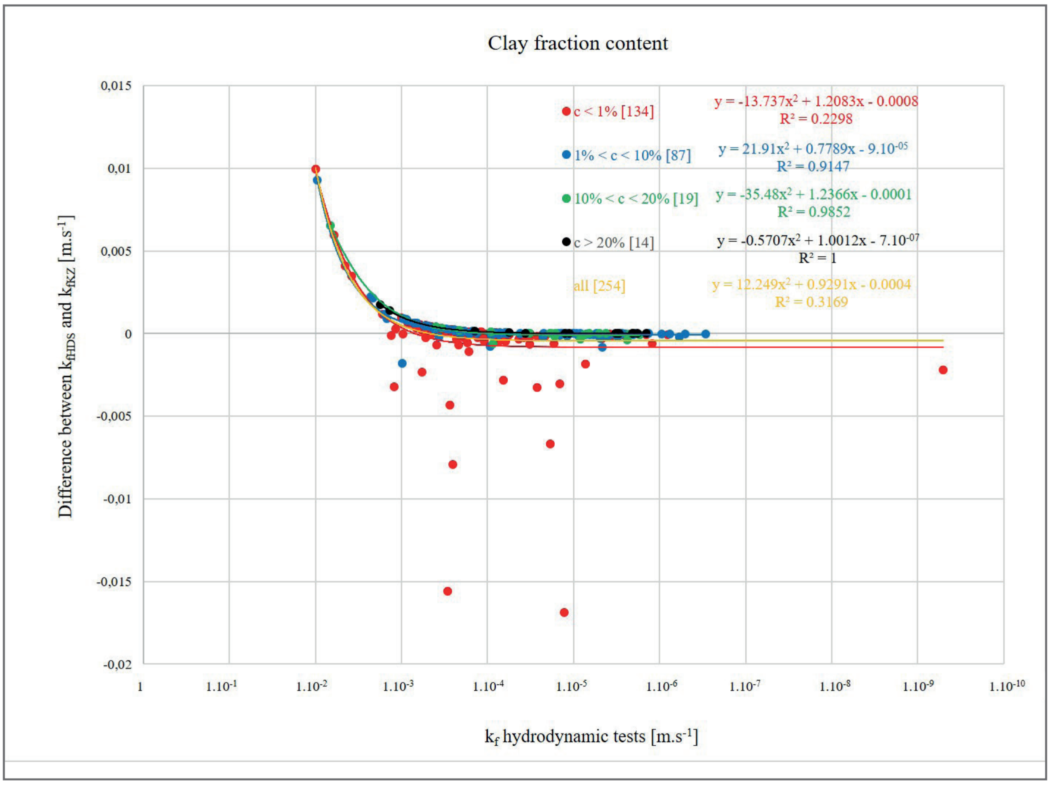

Fig. 4.10 Comparison of the coefficients of hydraulic conductivity from hydrodynamic tests and the difference between the coefficients of hydraulic conductivity from hydrodynamic tests and from empirical methods depending on the clay fraction content

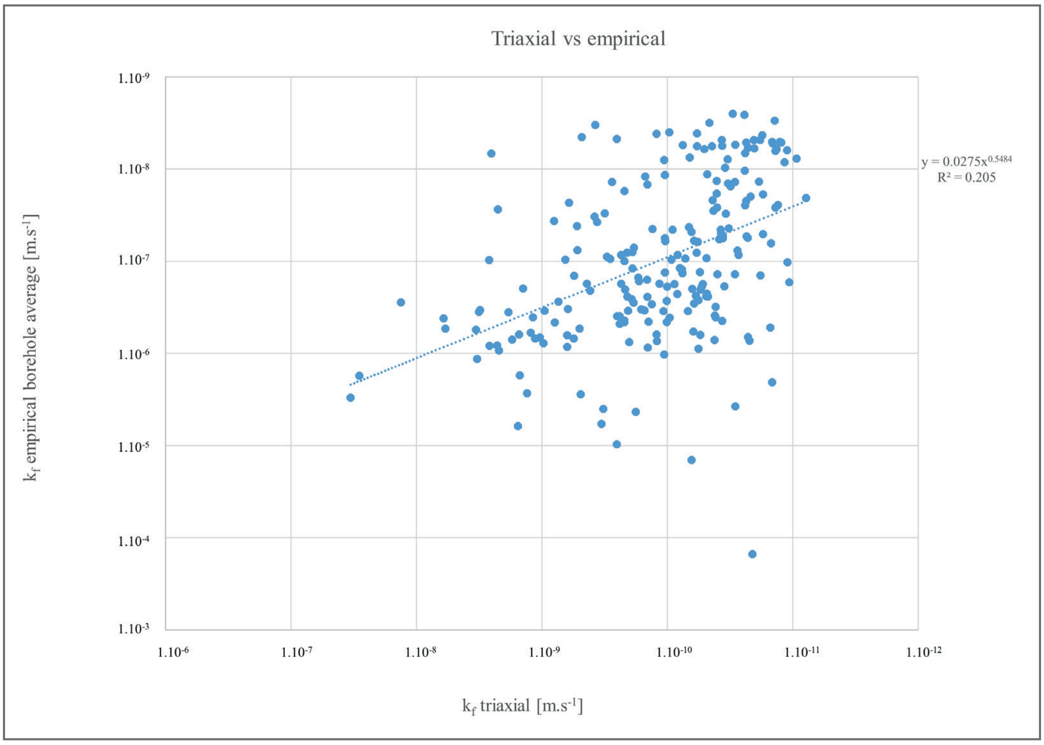

Fig. 4.11 Comparison of the coefficients of hydraulic conductivity determined in a triaxial permeameter with the average values obtained from empirical methods

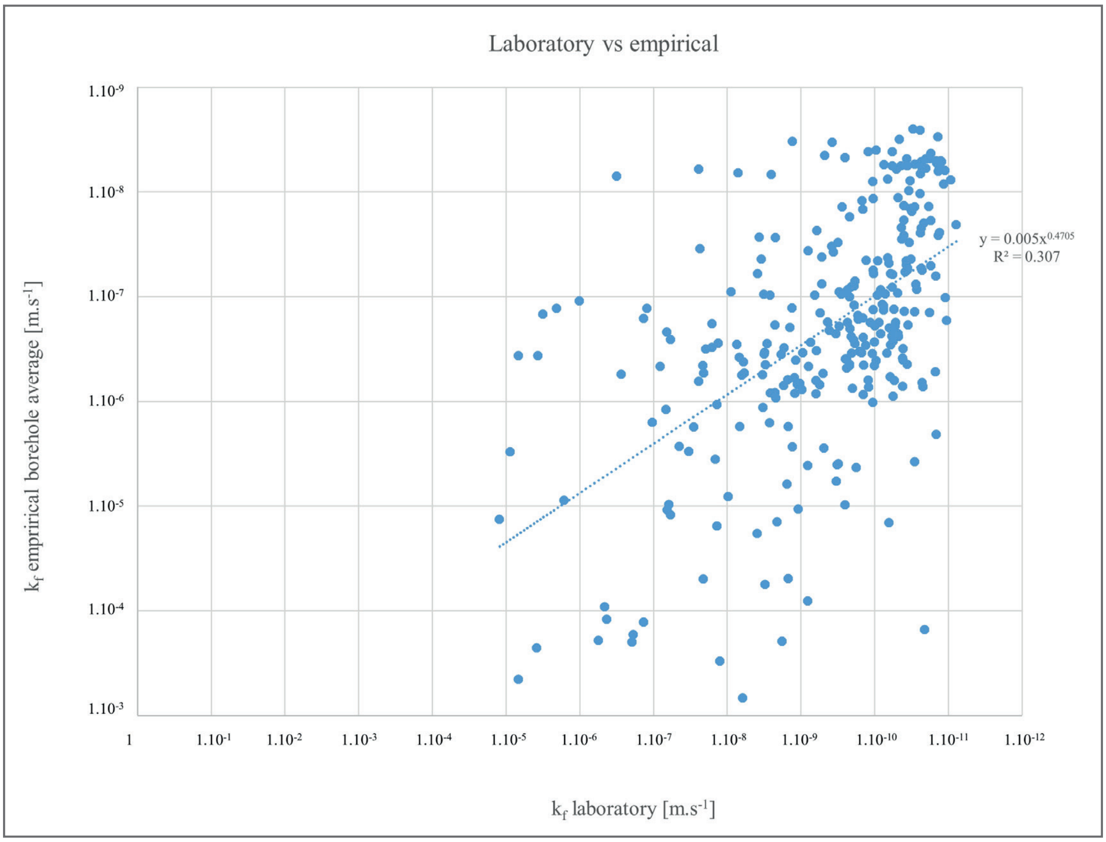

Fig. 4.12 Comparison of the coefficients of hydraulic conductivity in all permeameters with the average values obtained from empirical methods

coefficient R^2 = 0.205 and confirms mutual correlation.

Similar comparison is shown in Fig. 4.12, but in addition to the results in the triaxial permeameter, the results from the constant head and falling head permeameters are included. This set of laboratory determinations is compared with the average values obtained from empirical methods. The value of the correlation coefficient R for the statistical set of 289 samples for the power trend line is 0.554076, which corresponds to the determination coefficient R^2 = 0.307. Again, a good correlation is shown.

The laboratory determination of the coefficients of hydraulic conductivity in a triaxial permeameter and constant head and falling head permeameters compared to the average value obtained from all valid empirical methods gives a good correlation due to the high number of samples in the statistical set, confirming the permeability dependence on the grain-size of the soil. Therefore, the values of the coefficient of filtration from the grain-size distribution curves, especially for coarse-grained soils, give at least an approximate idea of the value of the coefficients of hydraulic conductivity that can be expected from permeability tests in laboratory instruments.

The results of this research showed no correlation between the coefficient of hydraulic conductivity values from the hydrodynamic tests, the laboratory tests and the empirical methods. The differences between the tests were in the magnitude of orders and no trends of interdependence or functional relationships were found.

Similar results were obtained in research of Elarabi & Elfaki (2011), who observed a difference between the permeability measured in the laboratory and the permeability values in the field by one to four orders. Author also attributed the difference to the unrepresentative nature of the laboratory sample to soil under natural conditions. They also found a very good correlation between the laboratory permeability and the relative coefficient between field and laboratory permeability.

Lee & Chang (2007) also found significant differences between the laboratory coefficient of hydraulic conductivity and the in situ permeability. According to them the differences between the results are caused due to the differences in the samples are caused by the inhomogeneity of the soil in the environment and the possibility of water flow in all directions in field tests, whereas in laboratory conditions the flow is only one-directional.

On the contrary Rapp (1965) found a very good correlation between field and laboratory tests. His research was focused specifically on the comparison of field and laboratory methods with sampling adjusted to the research objective.

The reason for our finding is that the geological task “Monitoring of environmental burdens in selected localities of the Slovak Republic” was not focused specifically on the comparison of individual methods of determination of coefficients of hydraulic conductivity. Therefore, sampling of undisturbed samples was not targeted specifically for this purpose, but laboratory samples were taken mostly to determine coefficients of hydraulic conductivity of the fine-grained soils to verify their sealing function. At the same time, the irregular sampling of the soil from the drill core itself is influenced by an error based on the subjectivity of the sampling selection.

The ratio of fine and coarse fraction samples for drill core sampling was predominantly 3/1, which is why the average values of the coefficient of hydraulic conductivity calculated by laboratory methods and empirical methods are burdened by subjective sampling error or error between proportions of fractions with different hydrogeological function.

On the contrary, hydrodynamic tests characterize the environment around well overall and were carried out in order to determine the water-permeability of the environment, which mainly concerns sandy and gravel soils. The disadvantage of these tests, however, was their short duration, which was a 6-hour test, and therefore can only be considered as indicative, because their results affect only the vicinity of the well, which was in many cases affected by drilling technology. Also the permeability tests in well could be performed in poorly designed and installed monitoring wells with limited measurement capacities as was also claimed by Baptiste & Chapuis (2014).

Although a large number of coefficients of hydraulic conductivity values were obtained to compare them, there were not enough relevant data. The numbers of determination of the coefficients of hydraulic conductivity values by the various methods alone do not guarantee comparable results. For laboratory tests, only very small samples with a diameter of 38 mm and a height of 20 to 50 mm in a triaxial instrument or with a diameter of 100 mm and a height of 90 mm in a constant head and falling head permeameters were used. The results of such tests therefore cover only a very small part of the environment and do not take into account the possible occurrence of disturbances in the natural environment of much larger dimensions that alter the sealing properties of soils or, conversely, their ability to permeate water. It can therefore be stated that laboratory methods for determining the coefficient of hydraulic conductivity are useful in the oriented research of specific horizons at which their sealing function is assumed or verified. Conversely, properly performed hydrodynamic tests can be used specifically to characterize the permeability of the geological environment within a perforated well section. At the same time, the methodological differentiation of both values can also influence the economic aspects of environmental burdens monitoring so that there is no unnecessary duplication.

Based on the results obtained, the statement published by Nagy et al. (2013) that they are not able to express what the coefficient of permeability (coefficient of hydraulic conductivity) of soils is, but only state the value obtained from a certain type of measurement was confirmed. They also accentuated the reliability of individual methods, the capability to sense the layer boundaries and their estimation accuracy.

4.4 Conclusions

The main objective was to evaluate the results of the determination of coefficients of hydraulic conductivity using hydrodynamic tests, laboratory tests and empirical methods, to compare them and possibly to find correlations between individual methods. The results of 254 hydrodynamic tests were used to calculate the coefficient of hydraulic conductivity, 218 laboratory permeability tests in a triaxial permeameter, 58 tests in a constant head permeameter and 19 tests in a falling head permeameter were performed and laboratory test results of 2,246 samples were used for coefficient of hydraulic conductivity calculation by using empirical methods.

Comparison of the laboratory determination of the coefficients of hydraulic conductivity in the laboratory apparatus compared to the values obtained from empirical methods gives good correlation due to the high number of samples in the statistical set, confirming the dependence of the permeability on the grain-size distribution of the soil.

The results of the comparison of the coefficients of hydraulic conductivity determined by the hydrodynamic tests and the laboratory methods show that no correlations were found either in comparison of the individual methods, nor in relation to the clay fraction, fine-grained fraction, soil type or its genesis. The reason for this is that the selection of individual samples for laboratory tests focuses primarily on less permeable soils, while hydrodynamic tests characterize the overall environment of a well.

In the future, in the case of further research aimed at comparing the coefficients of hydraulic conductivity from hydrodynamic tests with the values of coefficients of hydraulic conductivity from laboratory tests or empirical methods, more attention should be paid to the correct design of the sampling, in order the selected samples would represent the rock environment of the main collector or more collectors. It is also necessary to focus on the correct performance of hydrodynamic tests, especially in terms of pumping time, and avoid to perform just indicative short-term tests.

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