Comparison of permeability testing methods

Comparaison des différentes méthodes sur les tests de perméabilité

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ABSTRACT: Coefficient of permeability is known as the most variable soil property Its value can vary over an order of magnitude even in case of relatively homogenous layers. So determining this value is a complicated, complex engineering task. There is a vast number of laboratory and in situ tests to determine the permeability coefficient. Each method has its own advantages, drawbacks and limitations, so different methods should be preferred in different situations. The permeability coefficients of a sandy silt and a silty sand layer have been determined by means Khafagi probe, Menard probe, water filtration method, constant head laboratory test and falling head laboratory test. The permeability coefficients have also been estimated by the equation proposed by Hazen (1895). The measured values are summarized and evaluated in the paper. Special emphasis is given on the reliability of the methods, on the capability to sense the layer boundaries and their estimation accuracy.

RÉSUMÉ : Le coefficient de perméabilité est connu comme étant la propriété du sol la plus variable. Sa valeur peut varier, même dans le cas de couches relativement homogènes. Ainsi, la détermination de cette valeur est une question difficile, une tâche d'ingénierie complexe. Il existe de nombreux laboratoires et des tests *in situ* pour déterminer le coefficient de perméabilité. Chaque méthode a ses avantages, ses inconvénients et ses limites, ainsi certaines méthodes doivent être privilégiées en fonction du contexte. Les coefficients de perméabilité d'un limon sableux et d'une couche de sable silteux ont été déterminés par la méthode Khafagi, par l'essai pressiométrique Ménard, par la méthode constante et tomber test de perméabilité à la tête. Les coefficients de perméabilité ont également été estimés par l'équation proposée par Hazen (1895). Les valeurs mesurées sont résumées et évalués dans le document. L'accent est mis sur la fiabilité des méthodes, sur la faculté de détecter les limites des couches et sur la précision de leur estimation.

KEYWORDS: coefficient of permeability, laboratory test, in situ test

1 INTRODUCTION

Coefficient of permeability (also known as hydraulic condictivity, denoted by 'k') is a highly variable soil property. Previous studies have shown that its coefficient of variation can be as high as 240 % (Lumb, 1966., Uzielli, 2008., Mlynarek, 2010.). Additionaly the chosen tetsting method has also high influence on measured results.

The two main factors that determine the order of magnitude of the permeability coefficient are: grain size and cleavage (secondary interstices). These two properties can already have significant spatial variability, but other influencing factors make the determination of permeability coefficient even more complex. The impact of the factors listed below is inferior, but still not insignificant:

- grain shape and orientation,
- quantity and connection of interstices,
- uniformity coefficient,
- water content and saturation conditions before seepage begins,
- the properties of the passing liquid (water),
- hydraulic conditions (hydraulic gradient, Reynolds number etc.),
- transient phenomena (migration, wash-out and wash-in of grains).

Section S3 of Annex S to EUROCODE 7: Geotechnical Design Standard highlights the role of saturation, which may cause a change of up to three orders of magnitude in the coefficient of permeability of certain soil types.

It is fair to say therefore that the coefficient of permeability of soils can depend on a large number of factors of different character, which is why general relationships (formulas or graphs) based on a few simple quantities are not expected to provide accurate k values. Based on these considerations, it is not a good practice to use values taken from tables of universal validity. No one can guarantee, for instance, that soils with the correlation feature I_p=30% have identical coefficients of permeability at all sites.

1.1 *Background*

There is no method specified either as a Hungarian Standard or in a Technical Guideline for calculating the coefficient of permeability. Coefficient of permeability values can be determined by on site or laboratory measurements or indirectly from empirical correlations based on grain size distribution. Small as it is, even a country such as Hungary has failed to come to a common understanding about the test.

Kézdi (1976) expresses a preference for laboratory tests for determining the coefficient of permeability and indeed the following laboratory methods are available for determining the value of k:

- by constant water head test
- by falling water head test,
- by capillary permeability test, and
- from a consolidation test.

Rózsa (1977) rejects the laboratory method and recommends pumping from a well to determine the coefficient of permeability:

"The coefficient of permeability is one of the physical properties that cannot be determined at the required accuracy using laboratory methods. Frequently, a 10-50 fold accuracy of

the k factor would be sufficient, but even that is beyond the scope of laboratory tests."

The handbook of groundwork prefers pumping tests performed on site, but fails to mention what to do in layers above the ground water tables. Kovács (1972) takes a different view and recommends using the grain distribution curve.

"Based on a brief description and a critical analysis of laboratory and on site tests, it is underlined once more that formula based calculation should normally be recommended as the method for determining the coefficient of permeability, not only because this is the simplest technique but also because its reliability reaches and in most cases even surpasses that of other methods. In-laboratory and on-site measurements are justified only in case it is our intention to describe a unique stratification property of a layer. That would require laboratory analysis of undisturbed drill cores, advanced percolation tests or pumping tests using several observation wells."

The coefficient of permeability of a rather large basket of soil types, i.e. ones not characterised by grain size distribution, is left undetermined this way. The following remarks allow us to conclude that there the industry lacks consensus on how to determine the coefficient of permeability value.

Section S3 "Evaluation of test results" of the annex to the EUROCODE 7 standard specifies the following requirements for evaluating test findings:

„There are four widely used methods to determine the coefficient of permeability (hydraulic conductivity):

- field tests, such as pumping and borehole permeability tests;
- empirical correlations with grain size distribution;
- evaluation from an oedometer test;
- permeability tests on soil specimens in the laboratory."

So it can be concluded that there are many laboratory and in situ methods to obtain the coefficient of permeability. However there is no universally applicable method; each method is valid within certain limits, which we need to identify to render investigations easy to target and plan.

Measurements have tended to take the form of site investigation as soil mechanics have developed in the past 15-20 years. That way multiple damage to samples can be avoided and results will better reflect local conditions. It is internationally accepted that local investigation provides more accurate site specific values. The question arises whether or not this statement also holds for the determination of coefficient of permeability values.

1.2 *Aims of study*

We set out to determine the coefficient of permeability of transitional and fine grained soils (ranging from fine sand through sand meal and miry sand to silt). The following boundary parameters were assumed for the purposes of our test series:

- We selected methods whose range of validity matched in principle the type soil selected for the tests.
- Homogeneous isotropic strata were assumed for the purposes of the test despite the likelihood of periodic sedimentation of coarser and finer grains during layer formation, and an apparently homogeneous layer may be composed of a network of more conductive and more watertight lenses seams.
- Potential filtration anomalies at layer boundaries are ignored.
- The increased conductivity due to atmospheric effects and human intervention of a layer of top soil, which can be up to 0.6-0.8 m thick, is also neglected.
- Most tests determine the coefficient of permeability on a relatively small sample of soil. It would, however, be a mistake to generalise the value achieved that way for the whole layer represented by the sample.

2 TESTING METHODS

The following methods were used to measure the coefficient of permeability of fine grained and transitional soils on site:

- Horizontal permeability can be measured with a Menard probe inserted into a vertical bore hole. The radial infiltration of water into the soil is facilitated by packers and by the injection of water below and above the measurement section.
- Water absorption test across a trickling head lowered through a Khafagi probe to determine the coefficient of permeability. Soil conditions are taken into account for the purposes of dimensioning the trickling head to be used and the calibrated container.
- Depending on ground water level, one or more boreholes may be lowered for pumping or water absorption. Soil conditions must be taken into account for determining the layout and dimension of the boreholes. Serious errors may occur if the liner fails to connect properly to the hole bottom, as water will not only trickle into the soil across the bottom but along a sleeve of unknown length.

Equipment of constant or falling water head may be used in laboratory measurements depending on the coefficient of permeability.

We have also determined the value of coefficient of permeability indirectly (by empirical correlation based on grain size distribution) to compare and verify local measurements. Different authors have identified different relationships to be used in the indirect method of calculation and have partially combined these methods with a variety of status descriptors. A shared feature of these methods involves plotting a grain size distribution curve typically identifying the grain diameter (d_{10}) associated with ten mass percentages passing and this value is normally on the power of two. This paper presents the results received from calculations using formula (see Figure 2).

3 TEST LOCATION, SOIL TYPES

Tests were performed at five locations, but this paper only covers the findings testing section 54+260 of the left bank of the Danube near Ráckeve. The tests were performed on the protected side 10 meters from the toe of the flood control dyke. Exploratory drilling identified the following order of layers:

- the upper layer from 0.0 to 3.4 m contains yellow and yellowish grey silt with silty sand of low water content ($7\% < w < 14\%$) and with moist density at around $\rho = 1.76$ g/cm^3. The grain size distribution curve shows that the fine content makes up 80-90% of soil particles. The coefficient of uniformity vary between C_u = 8.6-12.3 (see figure 1).
- the layer from 3.4 to 5.0 m contains sand with grey silt. The water content of this well graded layer is 20% on average. Wet bulk density is around $\rho = 1.86$ g/cm^3. The layer is understood to be much looser than the one above. The examination of grain size distribution suggests that the sand fraction makes up 70-75% with silt at 25-30% (see figure 1). The coefficient of uniformity is at C_u = 30-33.

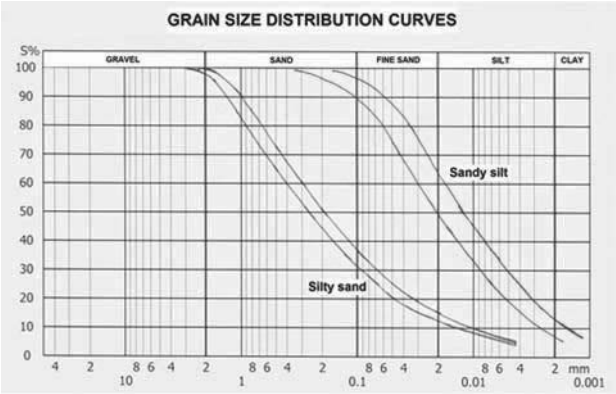

Figure 1. Grain size distribution curve envelopes of the tested soils

4 TEST RESULTS

The results of the performed permeability tests are summarized in Figure 2.

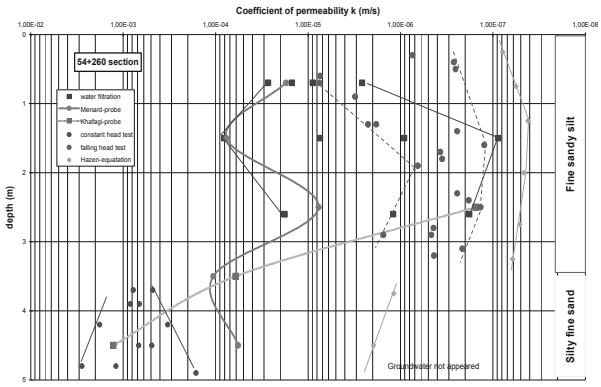

Figure 2. Measured permeability coefficients

The following conclusions can be drawn from a practical comparison of various measurement methods on the basis of determining the applicability of the methods (see Figure 2).

- The majority of measurement methods identified the change of soil along the two sides of the formation boundary.
- The results showed higher than expected scatter and the errors seem to be regular in character and attributable to the method of measurement.
- Each method is likely to have a relative error of one order of magnitude, disregarding the examination of samples taken from the vicinity of the surface.
- The error of water absorption was especially large: three orders of magnitude at the depth of 1.7 meters and only two at 2.6 meters. This method seems to lend itself to erroneous measurements.
- The scope of validity of the test performed with falling water head test did not cover the bottom layer, as water flow through the specimen rapidly. As a result equipment maintaining constant water head test had to be used to examine the lower layer.
- Regardless of the type of soil, measurements with the Menard probe returned values varying between $k = 10^{-4} - 10^{-5}$ m/s and it seems to be insensitive to changes of soil. But it must ba also noted that inappropiate device might heva caused the experienced error. Unfortunatley we couldn't repeat the test to reveal the reason of this trend, so these results have not been analyzed in this study.
- The trend of the permeability coefficient determined with the Khafagi probe and by calculations based on the grain size distribution curve is identical to the findings of laboratory measurements. Each of the three methods sensed the rise of the coefficient of permeability at the depth of 3.4 meters.
- Compared to the coefficient of permeability findings of local measurements and laboratory tests, calculations from the grain distribution curve produced slight and more pronounced overestimations for soils of poor and better permeability, respectively.

The tests performed in the 54+260 km section and at other locations demonstrated that Khafagi probes lowered by pumping (or in receiver probes) are best suited to routine tests. The advantages are laid out below:

- potential to use both above and below ground water,
- can be lowered with any type of probe,
- simple device,
- relatively low measurement costs,
- no complicated measurement and evaluation methods,
- relatively rapid measurement,
- measurement length is adjustable to soil,
- measurement findings include both horizontal and vertical coefficients of permeability.

Naturally, the studies described above still keep us in the dark about the exact value of the coefficient of permeability at the location we examined, but we have measured approximations, which we know deviate from true values in a certain direction due to measurement error.

5 CONCLUSIONS

The theories established on the basis of various studies offer a solution for determining the coefficient of permeability for instance on the basis of the grain size distribution curve or for evaluating the findings recorded by the Khafagi probe or the Menard probe, but we can still entertain doubts about whether or not the values determined that way are appropriate, the measurements replicate nature or reveal the k value characteristic of natural permeation. We have conducted local and laboratory measurements of the coefficient of permeability, soil mechanics explorations and identification studied to resolve these questions.

It is necessary to increase the accuracy of measuring the k factor, because the relative error of calculations, processing and geometric dimensioning, etc. is orders of magnitude smaller than what we can determine for the coefficient of permeability. Greater accuracy is required because uncertain measurements lead to unjustified over-dimensioning at times and to running unnecessarily large risks at other times. It is extremely important to know the true value of the k factor to avoid that.
There are several methods for the in-situ determination of the coefficient of permeability. This study and this paper aimed at a practical comparison of the results of the different methods. Figure 3 presents the range of validity of each measured value and method of calculation based on measurement findings and processing the literature. The same figure shows the classification of soil types by permeability for the purposes of various technical interventions.

The studies allow us to establish two important findings:

- There is no universally applicable method and each method of determining the coefficient of permeability has its own range of validity. This principle was adopted in the Hungarian Standard 15295, which was issued in 1999.
- If there the coefficient of permeability of the layers is no material different, it is not practical to use different measurement methods in a single borehole and one must not use different measurement methods at different depths within one and the same layer, because swapping methods may result in measured findings showing

greater differences than the ones actually present in the soil.

Based on the foregoing, one must try to ensure that the value of the coefficient of permeability is determined at least to ± 20-30% accuracy.

When evaluating measured values, one must bear in mind that no measurement is perfect and each method of measurement carries an error, hence each will distort measured values one way or another. Drilling (or pressing the probe into position) may destroy the structure of the soil in in-situ measurements. When drilling in floating sand or sand meal, fresh water should always be replenished and the bit has to be withdrawn slowly enough to prevent the soil from breaking into the borehole due to the emanating piston effect. When performing laboratory measurements of an undisturbed sample, taking samples with a chipped sampler vessel is a dangerous source of errors as we will measure the volume of water flowing past the mantle. When evaluating measured values, one must pay attention to the direction of change in the measured value triggered by the measurement error. A chipped sampler will lead to measuring a larger value of permeability, while the soil compacted by the probe will reduce the measured value.

We cannot say what the coefficient of permeability of the soil is, we can only state the value we received by performing a certain type of measurement. And even if we do that, we need to take into account the disturbance of the soil sample, the errors of our method, etc. One must examine the method used to produce the result as well as the distribution of the result and the error lodged in the examination.

Presenting the above measured values helps us orientate ourselves among the mysteries of the coefficient of permeability. The poorest conclusion one can draw is that the value of the coefficient of permeability is uncertain and therefore there is no need to determine it. One should not follow that road: on the contrary, one should underpin soil mechanics opinions by sound measurements.

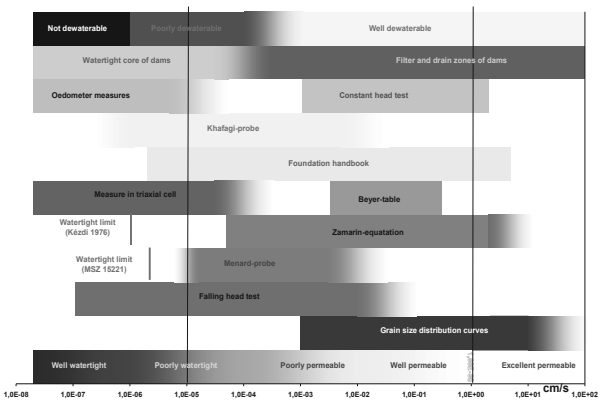

Figure 3. Soil permeability characteristics and the ranges of determining the coefficient of permeability

6 REFERENCES

Casagrande A. 1938. Seepage through dams, J.N. Engl. Water Works Association, L1(2), pp 131 -172.

Darcy H. 1856. *Les fontaines publiques de la ville de Dijon*. Dalmont, Paris.

Galli L. 1968. Planning of dikes, (in Hungarian), VIZITERV tervezési segédletek, 11. kötet, Vízügyi Tervező Vállalat.

Hazen A. 1895. The filtration of public water-supplies, New York.

Kézdi, Á. 1976. Soil mechanics, (in Hungarian), Tankönyvkiadó, Budapest

Kovács Gy. 1972. Seepage hydraulics, (in Hungarian), Akadémiai Kiadó, Budapest

Lumb P. 1966. The variability of natural soils. Canadian Geotechnical Journal Nr 3.

Mlynarek, Z. 2010. Quality of in situ and laboratory tests contribution to risk management.

Nagy L. 200. Geotechnical questions of flood dikes, (in Hungarian). Vízügyi Közlemények, (2000), LXXXII. évf., Vol. 1., pp. 121-146.

Nagy L. 2007. Flood defence against dike slope slide, (in Hungarian). Innova-Print Kft. nyomda, ISBN 978-963-87073-9-0.

Nagy L. 2008. A comparative study of the permeability (in Hungarian), Kézdi memorial conference, (2008), pp. 97-106, Budapest, ISBN 978-963-06-5725-9.

Rózsa L. (editor) 1977. Foundation engineering handbook (in Hungarian), Műszaki kiadó.

Uzielli M. 2008 Statistical analysis of geotechnical data. Proceedings of Geotechnical and Geophysical Site Characterization Conference, Balkema, Taiwan, Taylor, Frances 2008.