M. MINÁRIK
REEVALUATION OF METHODS FOR ESTIMATING THE PERMEABILITY OF SELECTED SLOVAK DAMS

ABSTRACT

This paper deals with estimating the permeability of a rock mass from the results of the Lugeon test. It concentrates on the effect of testing different lengths of sections during the execution of this test. In the phase of decision-making concerning the necessity of grouting, this phenomena is not applied (in the grouting criteria). On the other hand, this factor is an input to the empirical formulas for computing permeability. The numerical modelling as well as the statistical data processing of the results of the actual pressure tests shows the importance of considering this factor.

KEY WORDS

• Lugeon pressure test,
• grouting curtain,
• permeability,
• rock mass

INTRODUCTION

In Slovak conditions, reducing the permeability of a dam foundation is usually resolved by designing of a grout curtain. The design of this seepage remedy is a consequence of the failure of water pressure test criteria as the most reliable test for estimating the permeability of a rock mass. The purpose of this test is to isolate a borehole section and pump water to the rock mass under pressure until the water loss is stable. At that time the loss of water is measured during a gauged time. After the measured loss is matched with the critical water loss, it is necessary to make a decision as to whether the design of a seepage treatment is needed. When the quality of the dam foundation is worse than these criteria, the foundation around the tested borehole has to be grouted.

The rock mass’s permeability is tested over the whole length of a dam’s profile. In practice the boreholes are usually located between the tested and grouted holes, so that the density of the tightened rock foundation rises. This procedure is stopped after the target is realized – the criteria are fulfilled. Many times the increasing concentration of the grouted holes does not lead to the desired goal- the criteria are not fulfilled. Due to the high technological, time and financial requirements of grouting, the question of the necessity of additional grouting is significant. Because of the objective reality that there have been no failures or abnormalities observed on many dams with unfulfilled criteria, there is an opinion that the criteria established in the past and still used are too strict. The mentioned criteria are more or less based on the empirical knowledge of authors from the beginning or middle of the last century (Lugeon, Jähde, etc.), which was derived without the current understanding of groundwater flow principles. Based on knowledge subsequently acquired the criteria were later modified (Verfel 1992, Kutzner 1985, Houlsby 1990, etc.). Nevertheless, some important parameters that can significantly affect pressure test results, such as the length of the testing section by pressure test, the geological conditions or pressure test technology have not been equally applied. This paper concentrates on analyzing the effect of different lengths of the testing section on pressure test results using the finite element method (FEM), but
mainly by processing pressure test results obtained from selected Slovak dams. Using the empirical formulas (tab. 1) of various authors it is possible to calculate the permeability of rock foundation \( k_f \) (from the water losses measured during the pressure test). In calculating permeability, the approach of every author in factoring the “length of the testing section” is different, but all the formulas consider it. The problem is that if we enter the same value of water loss in these formulas, we will calculate a different permeability of the rock mass for every choice, or it is impossible to determine which result is accurate. Through the medium of the numerical modelling of the pressure test, it is possible to verify the reliability of these formulas.

<table>
<thead>
<tr>
<th>Author</th>
<th>Dupuit</th>
<th>Altovský</th>
<th>Møye</th>
<th>Hoek - Bray</th>
<th>MV Japonsko</th>
<th>Verigin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formula</td>
<td>( k = \frac{Q \ln \frac{R}{r_0}}{2 \pi L P} )</td>
<td>( k = 0.525 Q \log \frac{0.66 L}{r} )</td>
<td>( k = \frac{Q c}{L p} )</td>
<td>( k = \frac{Q \ln (\frac{2 L \sqrt{L}}{d})}{2 \pi L} )</td>
<td>( k = \frac{L \mu}{120000 \ln (\frac{L}{r})} )</td>
<td>( k = \frac{Q \ln (\frac{147 L}{\bar{z} r})}{2 \pi L P} )</td>
</tr>
<tr>
<td>where</td>
<td>( \frac{R}{r_0} = 40 )</td>
<td></td>
<td></td>
<td>( c = \frac{1}{2 \pi} \ln \frac{L}{2 r} )</td>
<td>( \lambda = \frac{k_f}{k_p} )</td>
<td></td>
</tr>
<tr>
<td>Symbols and units</td>
<td>( Q ) - water loss ( [m^3 \cdot s^{-1}] )</td>
<td>( L ) - length of section ( [m] )</td>
<td>( P ) - pressure ( [m] )</td>
<td>( d ) - length of section ( [m] )</td>
<td>( r ) - borehole radius ( [m] )</td>
<td>( \bar{z} ) - anisotropy</td>
</tr>
<tr>
<td>O - water loss ( [m^3 \cdot s^{-1}] )</td>
<td>L - length of section ( [m] )</td>
<td>P - pressure ( [m] )</td>
<td>r - borehole radius ( [m] )</td>
<td>O - water loss ( [m^3 \cdot s^{-1}] )</td>
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</tr>
</tbody>
</table>

EXAMINING THE EFFECT OF DIFFERENT LENGTHS OF A TESTING SECTION BY THE NUMERICAL MODELLING OF THE PRESSURE TEST

In order to analyse the mentioned problem, the ANSYS 6.1 finite element method software was applied. A solid numerical model was constructed, where a pressure test executed by using different lengths of testing sections (1, 3 and 5 meters) was simulated. The pressure tests were modelled for a cylindrically shaped environment, in the axis of which the tested borehole was situated. A unified permeability for every alternative length of the testing section - \( k_f = 1.10^{-6} \text{ m.s}^{-1} \) was modelled. Changes in the character of the equipotential lines and velocity vectors formed as a direct output from the FEM analysis (the results for the 1 and 5-meter-long sections are presented in fig. 1) were observed.

Attention should be paid to the fact that in the 1 m long section, water can flow radially and also vertically in all directions of the borehole’s surroundings; on the other hand, in the 5 m-long section it is possible to recognize two different parts: in the central part of the borehole is an extremely heavy radial flow, but near the section endings, the flow is realised to all the directions around the borehole as with the 1 m-long section. Because the designed model is three-
dimensional, it is possible to express the magnitude of water loss during the modelled pressure test. The water loss reduced to 1 meter of borehole length for each analysed alternative of the length of the testing section was expressed as:

\[ q_1 = 1.63 \times 10^{-4} \text{ m}^3 \text{.s}^{-1} \] - for a 1 m long section
\[ q_3 = 0.92 \times 10^{-4} \text{ m}^3 \text{.s}^{-1} \] - for a 3 m long section
\[ q_5 = 0.75 \times 10^{-4} \text{ m}^3 \text{.s}^{-1} \] - for a 5 m long section

The results acknowledge the hypotheses of the authors of the empirical formulas, i.e., that the factor of the length of the testing section by the pressure test should affect the permeability calculations. The reduced water losses calculated in the 1 m long testing section is under equivalently modelled geological conditions, more than two - times higher than the 5 m long testing section. Considering that the 5 meter long section is the standard length of a testing section, it seems that the loss measured by the shorter section length should be reduced before matching the critical loss by the reduction coefficient \( k_1 \), \( k_3 \), which conveys the effect of the different flow conditions in the case of testing sections shorter than 5 meters;

\[ k_1 = \frac{q_1}{q_5} = 2.17 \quad k_3 = \frac{q_3}{q_5} = 1.23 \]

Concerning the applicability of the empirical formulas presented for testing \( k_f \) calculations in terms of rendering the length of the testing section’s importance, the water losses calculated from the finite element method analysis were input to all the formulas (tab. 2). As the most accurate formula can be considered that formula, which will calculate the same permeability as was defined in the numerical model. The results of this analysis show:

- The most reliable formulas seem to be the formulas of Hoek-Bray and Verigin, which calculate almost the same permeability as was defined in the numerical model, for every length of testing section
- Dupuit’s formula is valid for 5 m length sections

Table 2 Estimating permeability from the water losses obtained by a FEM analysis (\( k_f [10^6 \text{ m}^3 \text{.s}^{-1}] \))

<table>
<thead>
<tr>
<th>Length</th>
<th>Dupuit</th>
<th>Altovský</th>
<th>Mowye</th>
<th>Hoek-Bray</th>
<th>MV Japonsko</th>
<th>Verigin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1m</td>
<td>1.92</td>
<td>2.34</td>
<td>4.11</td>
<td>1.20</td>
<td>6.27</td>
<td>1.04</td>
</tr>
<tr>
<td>3m</td>
<td>1.09</td>
<td>2.11</td>
<td>2.66</td>
<td>1.01</td>
<td>5.27</td>
<td>0.92</td>
</tr>
<tr>
<td>5m</td>
<td>0.89</td>
<td>2.01</td>
<td>2.29</td>
<td>0.94</td>
<td>4.94</td>
<td>0.87</td>
</tr>
</tbody>
</table>

Because the numerical modelling indicated the considerable effect of the length of the testing section on the measured values of the water losses by the pressure test, it was decided to confront the results determined with the results of the pressure tests executed in practice. Since almost all of the large dams in Slovakia are equipped with a grouting curtain, a huge amount of boreholes have been tested over time. The aim was to compare the results of the pressure tests executed under the same geological conditions (of the subsoil of a particular dam) by different lengths of testing sections. Concerning the large set of results gathered, only selected dams were used (Nosice, Palcmanska Masa, Vlcia Dolina and Ruzin 1.). The processing of the results of one of these dams – the Palcmanska Masa dam, is discussed below.

In the subsoil of the Palcmanska Masa dam, 946 borehole sections have been tested and subsequently grouted during treatment work on the grouting curtain. Of these, 151 were 1 m long; 150 were 3 m long; and 645 were tested using a 5 m long section. The goal was to observe the reduced water lost for particular lengths of the testing sections. In one pack (e.g., the 1 m section), the losses lie within a certain range of measured values. The characteristic that can highly render a set of random variables is the duration curve. Through its shape it is possible to deduce the properties of the random variable, i.e., if it consists of a set equal values or a set of unstable values. It is possible to determine if some extreme value does not affect the statistical parameters of the observed file too much. Therefore, the duration curves of the reduced water lost for the three processed choices are presented in figure 2.
The graph’s results indicate that under the same geological conditions, the magnitude of the measured water lost depends on the length of the testing section during the execution of the pressure test – it documents the position of the duration curves drawn. There is a high accordance with the numerical modelling results. Along with the by numerical modelling under the same geological conditions, the reduced water lost measured by the 1 m long section is much higher than that measured by the 5 m long section. The 3 meter long section gives the results between both boundary alternatives. These results acknowledge an assumption of the numerical modelling, i.e., that the expression of the reduction coefficients for reducing the water loss by a shorter length of testing sections than 5 meters is needed (before matching the measured and critical water losses). From the results offered it is possible to express the reduction coefficients with a concept similar to the FEM analysis. Therefore, it is necessary to characterize every set of values observed with one value of loss, since the duration curve covers all the measured values of the losses. The average value should be judged as the most reliable parameter representing the data file. The average values of the reduced water losses from the pressure test were observed to be the following three alternatives:

1 m long testing section \( q_1 = 2.351 \text{ l.min}^{-1}.\text{m}^{-1} \)
3 m long testing section \( q_3 = 1.371 \text{ l.min}^{-1}.\text{m}^{-1} \)
5 m long testing section \( q_5 = 1.151 \text{ l.min}^{-1}.\text{m}^{-1} \)

From these three values the reduction coefficients \( k_1 \), \( k_3 \) were formulated in the same way as in the numerical modelling of the pressure test:

\[ k_1 = \frac{q_1}{q_5} = 2.04 \quad k_3 = \frac{q_3}{q_5} = 1.19 \]

The same mechanism was applied by analysing the remaining three dams. The results as to the reduction coefficients are presented briefly in figure 3. The results are quite related for all the observed dams -Nosice, Palcmanská Masa, Vlcia Dolina and Ruzin I. Even if we compare these coefficients expressed through two independent methods (modelling, processing of stored reports), we can see the high concordance of the results.

CONCLUSIONS

It is important to mention that under Slovak conditions, the treatment of the grouting curtain was often designed based on exceeding the grouting criteria. The effect of this remediation was sometimes unsuccessful. The factor of the length of the testing section could be one of the reasons for this failure. Because determining the necessity of grouting the length of the testing section was not considered, the viewpoint on the rock mass’s permeability by using...
a shorter length of testing section was probably too pessimistic. Whereas, until now the approach used was on the side of safety, the following recommendation should be useful in practise from an economic point of view:

- If the pressure test is executed using a 1 meter long testing section, a higher (more than 2 times) reduced water loss than by a 5 meter long section should be accepted. To consider the factor of the length of the testing section, the losses gained by a 1 meter long section should be reduced by a coefficient of 2.0 ~ 2.5, or the grouting criteria should be modified by this coefficient.
- In the case of testing a 3 m long section, the water losses measured should be reduced by approximately 15 to 25 % .

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