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Seepage and well hydraulic study of pumping test with laboratory and field measurements

Ph.D. thesis booklet

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PRELIMINARIES, MOTIVATION

For planning underground structures or construction dewatering it is essential to know the area's soil physical properties, such as hydraulic conductivity, which can be determined by field or laboratory measurements. Laboratory experiments on soil samples (oedometer, triaxial, or grain distribution tests) are simple and cost-effective. Still, the point sampling method's disadvantage is that we gain relevant information only from a minor part of the area.

The field measurement's advantage is that soil's physical parameters can be examined in situ. Hence, they provide more accurate results, but their implementation is more time-, equipment- and cost-intensive. The pumping test is one of the most widely used field test by hydrogeologists and civil engineers. Pumping tests provide valuable information about both the aquifer and the well.

Various hydrodynamic phenomena can be observed in laboratory conditions by using scale models. Both domestic (Öllős 1956) and international (Klotz 1971, Williams 1985, Wendling et al. 1997, Klauder et al. 2009) researches have focused on seepage and well hydraulics based on scale models.

In 2011 a pumping test related study began in the laboratory of the Department of Hydraulic and Water Resources Engineering of the Budapest University of Technology and Economics. In 2015, I joined this study, and it has been the basis of my doctoral research. The creation of the scale sample model was driven by the experience of several field measurements (Hajnal 2003, Hajnal et al. 2009). One of the conclusions of the field measurements was that there is an enormous need for guidelines for engineers that could help plan and carry out the pumping tests, especially when there is only a small amount of initial data considering the area's geology. In ideal circumstances these guidelines are based on field measurements, but scale models can provide an efficient option to complement field data to examine various types of aquifers and well designs. In addition, scale model measurements are relatively cheap and easy to perform. Based on the laboratory measurement's experience, a database or complex guidelines can be created to support engineers' work. The main goal of my doctoral research was to develop a scale model which is capable of examining seepage and well hydraulics by simulating pumping test. Furthermore, to provide a methodology about how laboratory-scale results can be extended to real size.

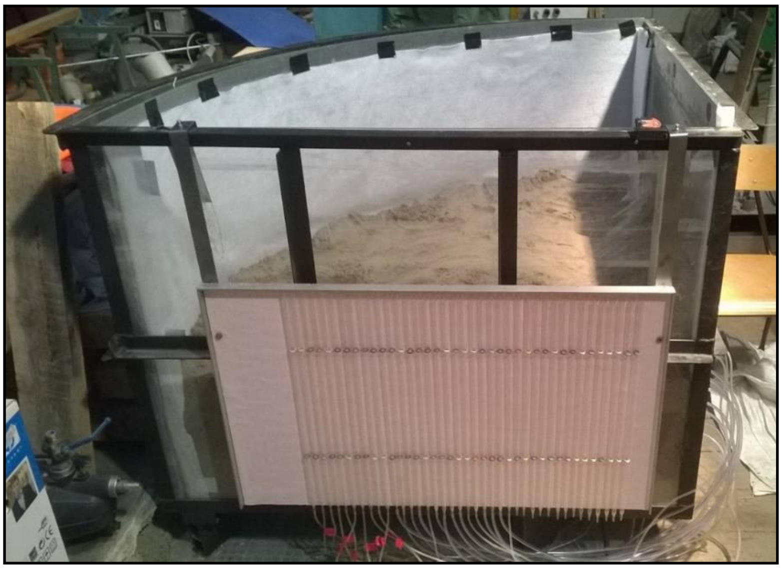
OBJECTIVES

Based on a review of available standards, technical reports and scientific studies I formulated the research goals, including laboratory measurements, data processing, and numerical modeling. The objectives of the doctoral research were described accordingly:

- Design steady state and transient laboratory measurements with the scale model to determine hydraulic conductivity. Compare the laboratory results using theoretical methods relating to the grain distribution curve. Set up a ranking of these methods according to their reliability.
- Carry out well hydraulic measurements with several wells with different perforations. Determine the well screen loss value depending on the diameter of the well screen slot and the drawdown in the well.
- Carry out laboratory measurements to gain additional knowledge about the flow conditions and the possibility of forming non-linear flow in the aquifer. Determine important parameters for well design such as critical entrance velocity (v_{crit}) and critical Reynolds number (Re_{crit}).
- Simulate the laboratory measurements employing numerical models to verify of drawdown, discharge, and hydraulic conductivity obtained by the scale model to assess its applicability for real cases. Determine the limitations of the usage of the scale model.
- Transform laboratory-scale measurement results to the real size and verify them with field pumping tests.

RESEARCH METHODS

As the first step, I designed, constructed and set up a physical scale model. With the physical model, I simulated steady and transient seepage hydraulic conditions. From the measurements results, I calculated the soil hydraulic conductivity by Dupuit and Theis methods. Furthermore, I used fourteen different theoretical methods relating to the grain distribution curve (for example, USBR, Slichter, Barr, etc.) to determine hydraulic conductivity. To evaluate my own measurement data sets from the point of view of well hydraulics, I used the methodology presented by Öllős (1958) and Williams (1985). Small-scale verification of data measured under laboratory conditions is described in finite element software, called FEFLOW 7.0. I converted the scale model results to real size using the Mosonyi-Kovács model law, and I compared them with pumping tests under field conditions.



Picture 1. The scale modell filled with soil

NEW SCIENTIFIC RESULTS

In this doctoral research, seepage and well hydraulic investigations were performed by a physical scale model, a numerical model, and field tests. The new general scientific results are given in the form of thesis statements.

Thesis 1: I established a ranking of different theoretical methods relating to the grain distribution curve for determine hydraulic conductivity.

I calculated hydraulic conductivity from the steady state scale model measurements with the Dupuit method. I verified the results employing validated numerical models. The difference between the numerical and laboratory models did not exceed 9%. Besides the steady state measurements, the transient pumping tests were evaluated with Theis method, and the difference was given between the average hydraulic conductivities at 36%. The differentiation between the hydraulic conductivity quantified by theoretical methods relating to the grain distribution curve and the Dupuit method ranged from 2% to 540%, however, the upper limit of the interval represented an excessively high value. Based on their deviations from the reference value, I classified fourteen theoretical methods into five different groups according to their reliability (Table 2).

Table 1. Hydraulic conductivity values by various methods

Type of measurement	Methods	Hydraulic conductivity [m/s]	Difference from Dupuit (2018-2019) [%]
Grain distribution curve	USBR	2.30E-04	2
	Slichter	2.73E-04	21
	Barr	3.25E-04	44
	Alyamani and Sen	4.13E-04	84
	Krumbein and Monk	4.14E-04	84
	Beyer	5.14E-04	128
	Seelheim	5.16E-04	129
	Hagen	5.20E-04	131
	Krőber	5.92E-04	163
	Sauerbrei	6.37E-04	183
	Chapius	7.25E-04	222
	USCRO	7.43E-04	230
	Hazen	7.97E-04	254
	Jáky	1.44E-03	540
Scale model	Theis (2018-2019)	1.43E-04	36
	Dupuit (2018-2019)	2.25E-04	-
	Dupuit (2015)	2.93E-04	30
Numerical model	„FA” modell	2.34E-04	4
	„FB” modell	2.46E-04	9

Table 2. Reliability of theoretical methods relating to the grain distribution curve

Difference from the reference	Methods	Reliability
0-50%	USBR, Slichter, Barr	Reliable
50-100%	Alyamani and Sen, Krumbein and Monk	Acceptable
100-200%	Beyer, Seelheim, Hagen, Krőber, Sauerbrei	Good estimation
200-300%	Chapius, USCRO, Hazen	Poor estimation
300%-	Jáky	Questionable

References: Hajnal and Farkas (2011), Vig et al (2016), Farkas et al. (2019a), Farkas et al. (2019b)

Thesis 2: Based on laboratory experiments, I demonstrated that the well screen perforation affects the value of well screen loss and the shape of the drawdown curve.

2.1. The function between the well screen loss and the screen slot diameters (besides the same 5% open area on the well screen) was derived from PVC material wells. (Fig. 1). Most of the evaluation methods of pumping tests, like Dupuit method, neglects the well screen loss. With laboratory measurements, I established that the larger slot diameters cause a more significant well screen loss value. The quotient of the water table in the well and the saturated aquifer thickness (h_i/H) was extended when the drawdown value increased in every case of well screen design, but the differential was not the same (Fig 3.). I compared my results with a dataset measured by a porous concrete well, and I determined that the less significant well screen loss related to the PVC well.

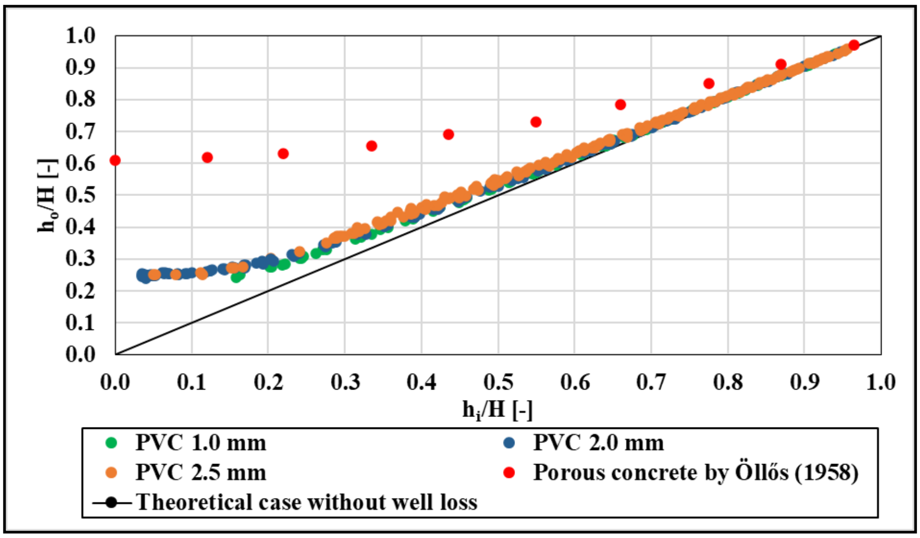


Figure 1. Well screen loss demonstrated by the dimensionless form of the value of water level inside the well (h_i/H) as a function of the water level outside the well's screen (h_o/H) (Farkas et al. 2021)

Table 3. Deviation of the dimensionless form of the value of water level inside the well (h_i/H) from the theoretical case without well loss

Slot diameter [mm]	Deviation of h_i/H from the theoretical case without well loss				
	1%	5%	10%	25%	50%
1.0	0.80	0.51	0.38	0.25	0.16
2.0	0.80	0.55	0.42	0.28	0.19
2.5	0.80	0.60	0.47	0.32	0.21

2.2. I explored the functional relationship between the well screen loss and the drawdown related to the well screen slot diameters. I quantified how many percentages of the drawdown formed directly in the near-well area to each of the screen slot types. In the case of the smallest drawdown, the well screen loss is given ~5% of the total drawdown at each kind of screen slots. In the case of the maximum drawdown, this ratio was increased to 14% with 1,0 mm slot diameter, 17% with 2,0 mm slot diameter, 18% with 2,5 mm slot diameter (Fig 2-4.). As a result of the analysis, I established polynomial equations to be able to estimate well screen losses for any drawdown and different type of perforations (Fig 5.).

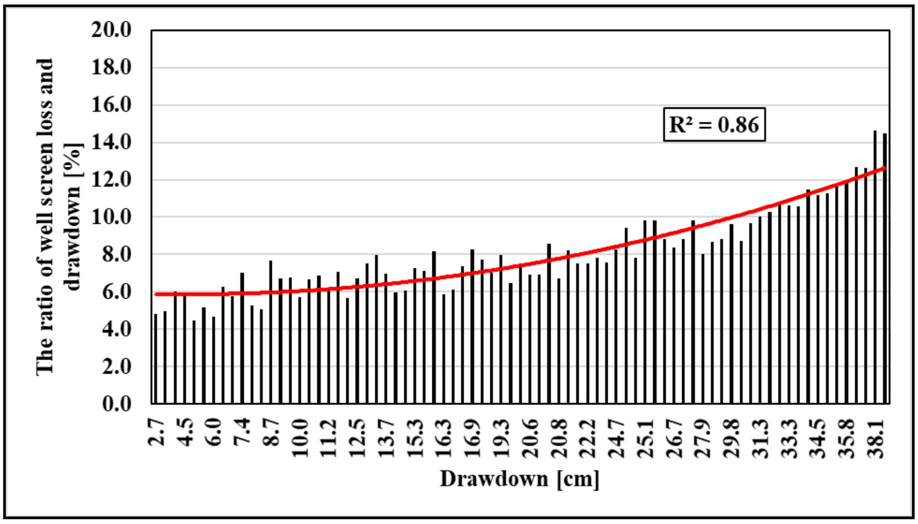


Figure 2. Functional relationship between well screen loss and drawdown at the 1.0 mm slotted pumping well (normalized to 10 °C) (Hegedűs et al. 2019)

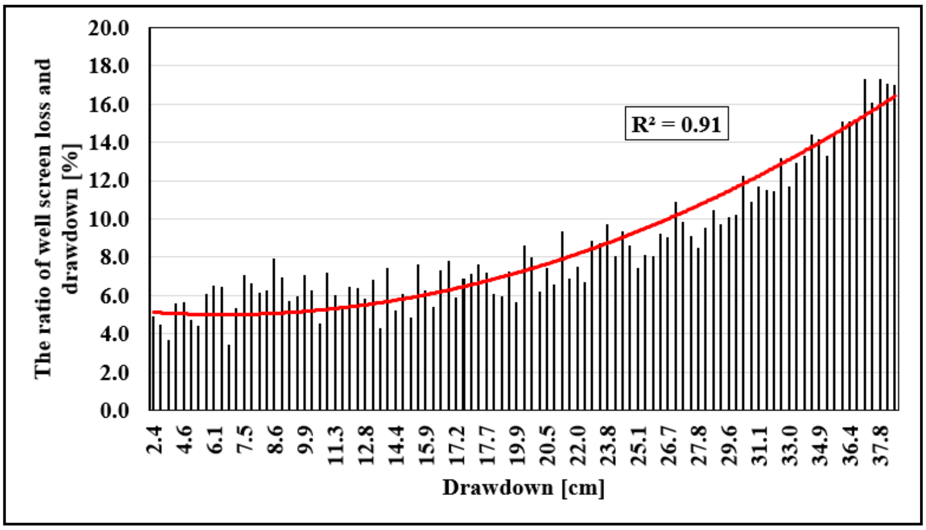


Figure 3. Functional relationship between well screen loss and drawdown at the 2.0 mm slotted pumping well (normalized to 10 °C) (Hegedűs et al. 2019)

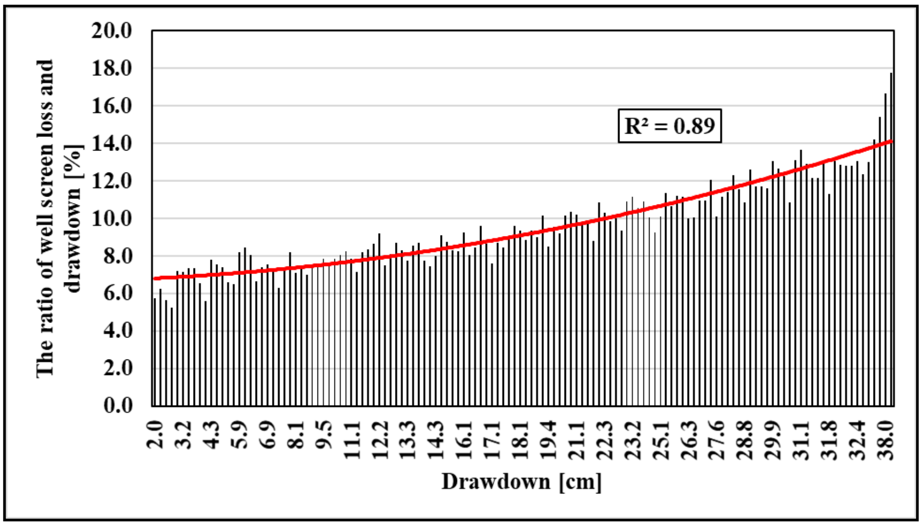


Figure 4. Functional relationship between well screen loss and drawdown at the 2.5 mm slotted pumping well (normalized to 10 °C) (Hegedűs et al. 2019)

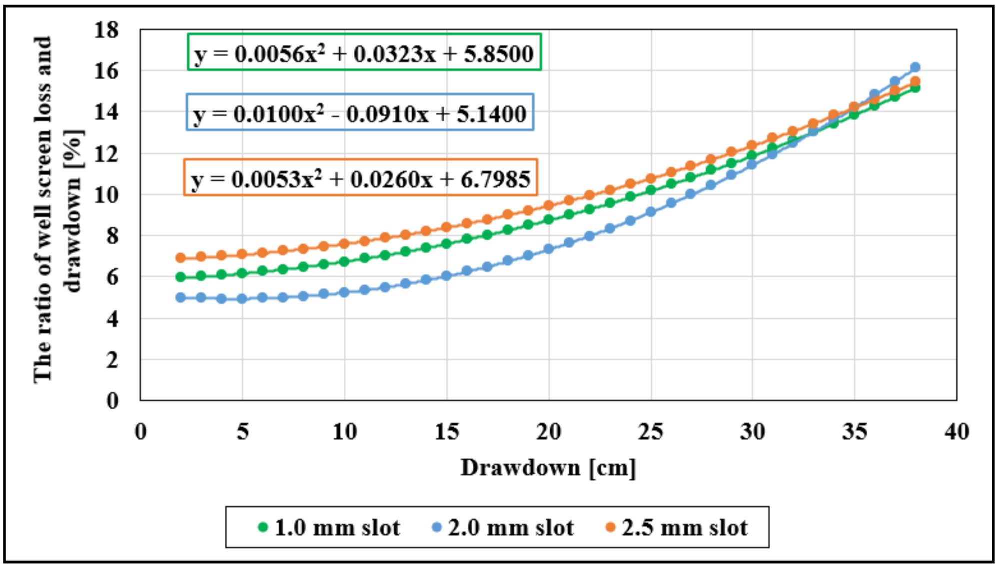


Figure 5. Well screen loss relationships as a function of drawdown

References: Hegedűs et al. (2019), Farkas et al. (2021)

Thesis 3: Based on laboratory experiments, I demonstrated that non-linear flow occurred during the pumping test in the scale model.

I estimated Reynolds numbers by Equation 1 to describe the flow conditions near the pumping and the observation wells.

$$Re = \frac{v \cdot d_{50}}{\nu} \qquad [1]$$

Parameters: *Re* is Reynolds number [-], v is seepage velocity [m/s], d_{50} mean grain size [m], ν a kinematic viscosity [m^2/s].

3.1. I proved that a non-linear state does not occur between the first observation well and the potential (water intake) boundary condition of the scale model. During the most significant drawdown at the three pumping wells with different screen slots, the Reynolds numbers did not exceed 0.18 at any observation wells, so the flow condition in this part of the scale model can be considered laminar with high probability (Fig. 6).

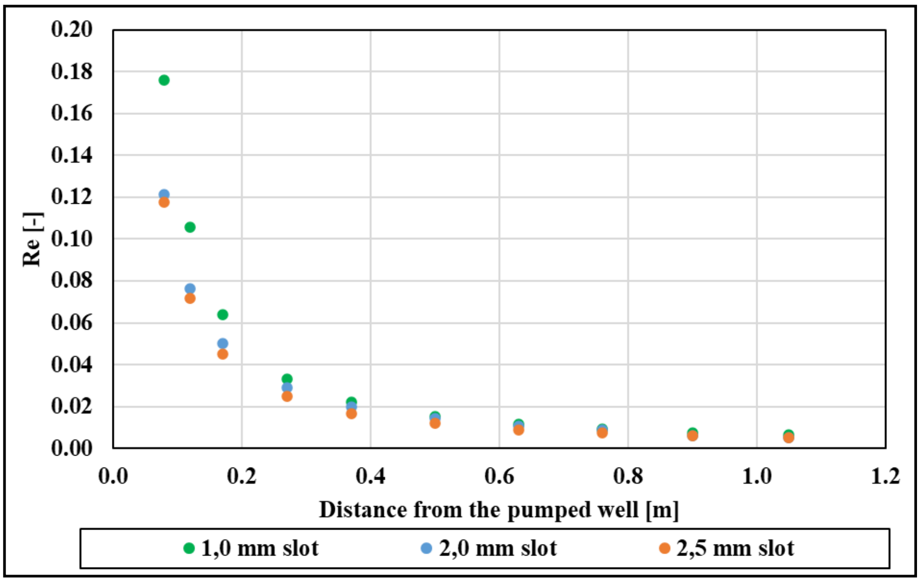


Figure 6. Reynolds numbers at the observation wells

3.2. I assigned a critical Reynolds number (Re_{crit}=16) based on the laboratory experiments where non-linear flow might develop on the well's screen. The measurement results in the near-well area showed that the range of the transition flow can occur between 16 and 23 Reynolds numbers (Fig. 7). I designated the value of the critical Reynolds number as the lower limit of transition flow. The obtained value of Re_{crit}=16 based on the scale model is in good accordance with previous studies' results which were derived from real size models.

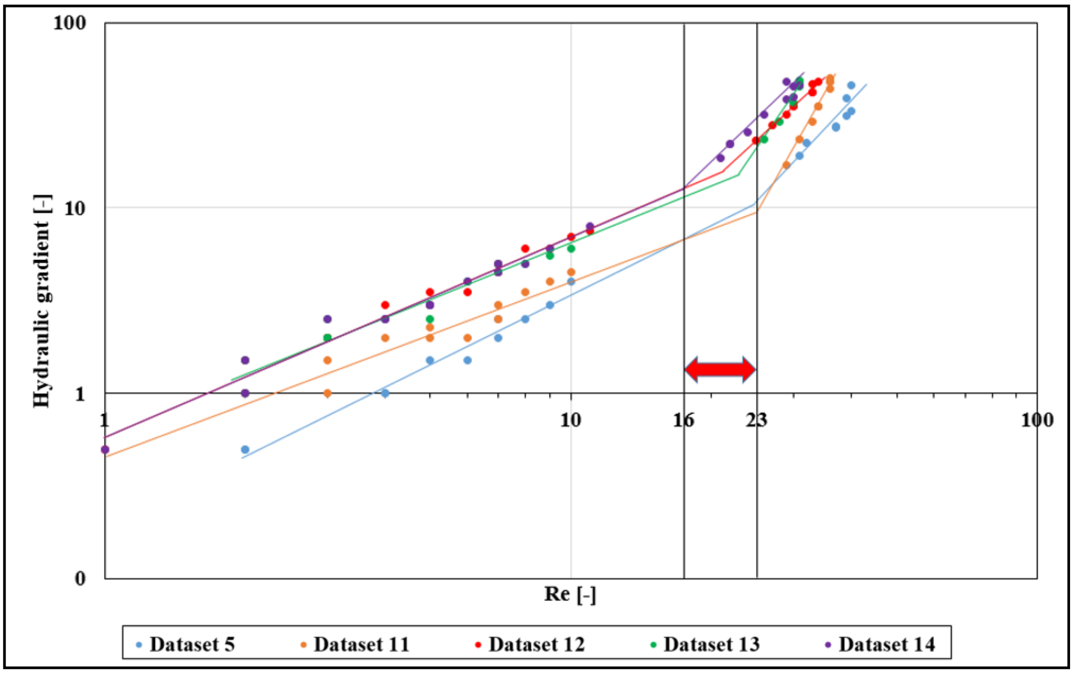


Figure 7. Hydraulic gradient as a function of Reynold number at the pumping wells screen

3.3. A I assigned a critical entrance velocity (v_{crit}=5.9 m/s) to the critical Reynolds number (Re_{crit}=16) where non-linear flow might develop on the well screen and when the friction loss is not negligible.

I selected Reynolds numbers to designate an interval of the transition flow (Thesis 3.2), and accordingly, I associated a critical entrance velocity interval between 5,9 m/s and 6,4 m/s (Fig. 8). Likewise, the critical Reynolds number, the critical entrance velocity, is the experienced interval's lower limit. Similarly to the Reynolds-number, the established value of v_{crit}=5,9 m/s is in accordance to previous studies' results.

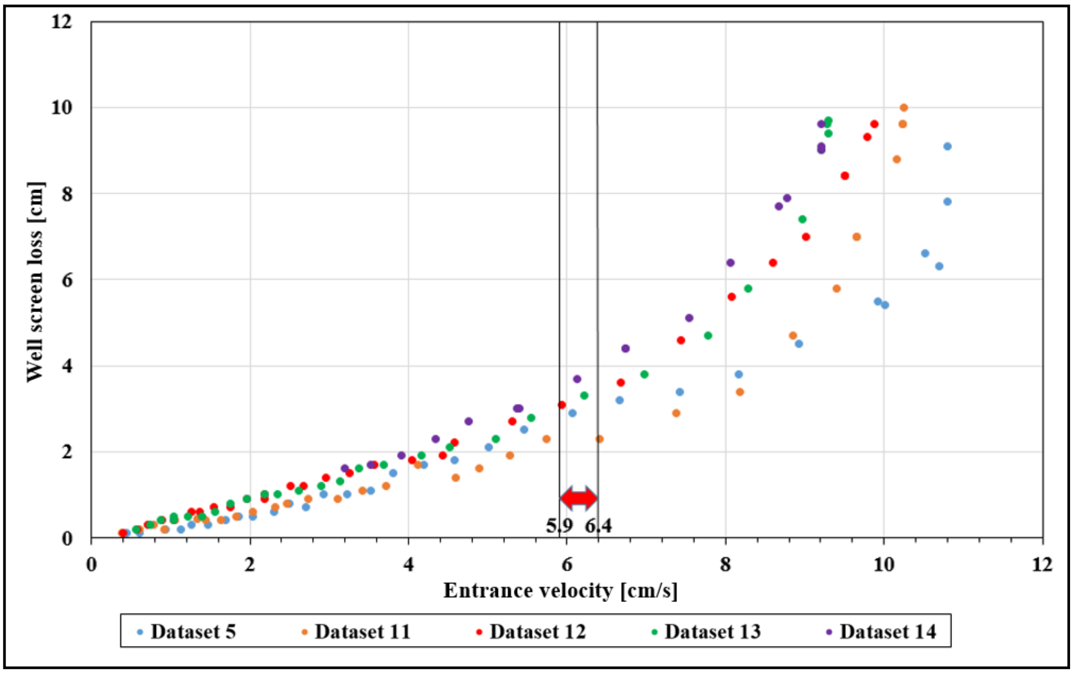


Figure 8. Well screen loss as a function of entrance velocity at the pumping wells screen

References: Farkas et al. (2021)

Thesis 4: By means of numerical modeling, I established a drawdown range and application limit when scale model results can be extended to real-size.

With the FEFLOW 7.0 numerical software, I successfully calibrated and validated the first model variants of the scale model, which could simulate laboratory results accurately. The numerical model validation was not accepted if the values of the piezometers error/drawdown quotient and discharge errors exceeded 5% (Table 4 and 5). Consequently, the numerical model simulations only restore the laboratory measurements results accurately if the drawdown is less than 50 mm.

Table 4. Results of the calibrated and validated model variant A

Name of measure-ment	Draw-down [mm]	Boundary conditions [mm]		Mean absolute error from P1-P35 [mm]	Ratio piezometer deviation and drawdown [%]	Discharge [l/min]		Deviation of the discharges [%]
		Pumping well	Potential boundary			Calculated	Measu-red	
FA	81	379	460	1.4	1.7	0.21	0.21	0.0
FA-V1	181	299	480	3.8	2.1	0.42	0.40	5.2
FA-V2	162	318	480	3.2	2.0	0.39	0.37	4.1
FA-V3	142	338	480	2.9	2.0	0.35	0.34	1.9
FA-V4	138	322	460	3.1	2.2	0.32	0.31	4.3
FA-V5	124	356	480	2.9	2.4	0.31	0.30	3.3
FA-V6	123	337	460	2.5	2.0	0.29	0.28	4.5
FA-V7	104	376	480	2.6	2.5	0.27	0.26	5.2
FA-V8	79	381	460	1.8	2.3	0.20	0.20	2.6
FA-V9	67	413	480	3.0	4.4	0.19	0.19	1.2
FA-V10	59	401	460	2.4	4.0	0.16	0.15	4.6
FA-V11	46	434	480	3.3	7.1	0.13	0.15	12.4
FA-V12	38	422	460	2.7	7.2	0.11	0.12	13.0
FA-V13	25	455	480	2.8	11.3	0.07	0.10	28.3
FA-V14	14	446	460	2.4	17.0	0.04	0.07	58.8

Table 5. Results of the calibrated and validated model variant B

Name of measure-ment	Draw-down [mm]	Boundary conditions [mm]		Mean absolute error from P1-P35 [mm]	Ratio piezometer deviation and drawdown [%]	Discharge [l/min]		Deviation of the discharges [%]
		Pumping well	Potential boundary			Calculated	Measu-red	
FB	81	379	460	0.6	0.8	0.21	0.21	0.0
FB-V1	181	299	480	2.1	1.1	0.43	0.40	6.4
FB-V2	162	318	480	2.0	1.2	0.39	0.37	5.6
FB-V3	142	338	480	2.3	1.6	0.35	0.34	3.3
FB-V4	138	322	460	1.4	1.0	0.33	0.31	5.1
FB-V5	124	356	480	2.3	1.8	0.31	0.30	4.4
FB-V6	123	337	460	1.5	1.3	0.30	0.28	5.6
FB-V7	104	376	480	1.9	1.8	0.27	0.26	5.1
FB-V8	79	381	460	1.2	1.5	0.20	0.20	2.8
FB-V9	67	413	480	2.1	3.2	0.18	0.19	2.6
FB-V10	59	401	460	1.1	1.9	0.15	0.15	2.0
FB-V11	46	434	480	1.5	3.3	0.13	0.15	18.4
FB-V12	38	422	460	1.4	3.8	0.10	0.12	19.0
FB-V13	25	455	480	1.5	5.8	0.07	0.10	35.0
FB-V14	14	446	460	1.2	8.3	0.04	0.07	70.1

I used Mosonyi-Kovács model law to convert the data verified by numerical modeling to real-sized pumping tests. Based on the results, I concluded that the discharge value could be determined with the physical model in medium-coursed sand if the actual value of the drawdown remains between 0.5 and 1.7 m (Table 6).

Table 6. Conversion of the model tests results into real field quantities

<table>
<tr><th rowspan="3">Name of measure-ment</th><th colspan="2">Values measured in the physical model</th><th colspan="4">Numerically calculated values</th><th colspan="6">Values converted to real field quantities</th></tr>
<tr><th rowspan="2">Drawdown [mm]</th><th rowspan="2">Discharge [l/min]</th><th colspan="2">Deviation piezometer [mm]</th><th colspan="2">Deviation discharge [%]</th><th rowspan="2">Drawdown [mm]</th><th rowspan="2">Dis-charge [l/min]</th><th colspan="2">Accuracy water level [mm]</th><th colspan="2">Accuracy discharge [l/min]</th></tr>
<tr><th>FA</th><th>FB</th><th>FA</th><th>FB</th><th>FA</th><th>FB</th><th>FA</th><th>FB</th></tr>
<tr><td>FA</td><td>81</td><td>0.21</td><td>1.4</td><td>-</td><td>0.0</td><td>-</td><td>762</td><td>74</td><td>13.3</td><td>-</td><td>0.0</td><td>-</td></tr>
<tr><td>FB</td><td>81</td><td>0.21</td><td>-</td><td>0.6</td><td>-</td><td>0.0</td><td>762</td><td>74</td><td>-</td><td>6.1</td><td>-</td><td>0.0</td></tr>
<tr><td>V1</td><td>181</td><td>0.40</td><td>3.8</td><td>2.1</td><td>5.2</td><td>6.4</td><td>1703</td><td>142</td><td>36.0</td><td>19.3</td><td>7.4</td><td>9.1</td></tr>
<tr><td>V2</td><td>162</td><td>0.37</td><td>3.2</td><td>2.0</td><td>4.1</td><td>5.6</td><td>1524</td><td>131</td><td>30.0</td><td>18.6</td><td>5.4</td><td>7.3</td></tr>
<tr><td>V3</td><td>142</td><td>0.34</td><td>2.9</td><td>2.3</td><td>1.9</td><td>3.3</td><td>1336</td><td>120</td><td>27.3</td><td>21.4</td><td>2.3</td><td>4.0</td></tr>
<tr><td>V4</td><td>138</td><td>0.31</td><td>3.1</td><td>1.4</td><td>4.3</td><td>5.1</td><td>1299</td><td>110</td><td>28.9</td><td>13.3</td><td>4.7</td><td>5.6</td></tr>
<tr><td>V5</td><td>124</td><td>0.30</td><td>2.9</td><td>2.3</td><td>3.3</td><td>4.4</td><td>1167</td><td>106</td><td>27.6</td><td>21.3</td><td>3.5</td><td>4.7</td></tr>
<tr><td>V6</td><td>123</td><td>0.28</td><td>2.5</td><td>1.5</td><td>4.5</td><td>5.6</td><td>1157</td><td>99</td><td>23.2</td><td>14.6</td><td>4.5</td><td>5.6</td></tr>
<tr><td>V7</td><td>104</td><td>0.26</td><td>2.6</td><td>1.9</td><td>5.2</td><td>5.1</td><td>979</td><td>92</td><td>24.2</td><td>17.8</td><td>4.8</td><td>4.7</td></tr>
<tr><td>V8</td><td>79</td><td>0.20</td><td>1.8</td><td>1.2</td><td>2.6</td><td>2.8</td><td>743</td><td>71</td><td>17.4</td><td>11.0</td><td>1.8</td><td>2.0</td></tr>
<tr><td>V9</td><td>67</td><td>0.19</td><td>3.0</td><td>2.1</td><td>1.2</td><td>2.6</td><td>630</td><td>67</td><td>27.8</td><td>20.1</td><td>0.8</td><td>1.7</td></tr>
<tr><td>V10</td><td>59</td><td>0.15</td><td>2.4</td><td>1.1</td><td>4.6</td><td>2.0</td><td>555</td><td>53</td><td>22.4</td><td>10.4</td><td>2.4</td><td>1.1</td></tr>
</table>

References: Vig et al (2016), Farkas et al. (2019a)

Thesis 5: Based on field pumping test data, I proved that the pumping well's discharge and drawdown could be extended from laboratory-scale to real-size by the length reduction coefficient (C) if the geometrical and kinematical similarity is fulfilled between the laboratory and field experiments.

The length reduction coefficient was determined by the quotient of the diameter of the pumping wells used in the field and in the laboratory. I estimated in the case of the Mázsa Square to C=9.41, and C=9.71 for the Könyves Kálmán Boulevard. I extended the scale model results to a real-size pumping test by the Mosonyi-Kovács model law, and therefore the drawdown was multiplied with C and the discharge with C^2. Between the laboratory experiments and the pumping test of Mázsa Square, the geometrical and kinematical similarity were confirmed. Besides that, laboratory result was found where the difference was 2% between the scale model's and field test's drawdown and discharge values (Table 7).

Table 7. Drawdown and discharge results deviations between of the physical model and field test

Parameters	Values measured in the scale model	Values converted to real field quantities	Values of field test	Deviation [%]
Drawdown [m]	0.205	1.93	1.89	2
Discharge [l/min]	1.44	127.2	130.0	2

The kinematical similarity was not confirmed for Könyves Kálmán Boulevard's pumping test, hence, I attempted to determine the extended, real-size discharge from the laboratory experiments. For this purpose, Equation 2 was used,

$$Q_v = Q_m \cdot C_k \cdot C^2 \qquad [2]$$

where Q_v is the discharge in the scale model extended to real-size, Q_m is the scale model's discharge, C_k is the hydraulic conductivity reduction coefficient, and C is the length reduction coefficient.

The discrepancy was given 46% between the discharges of the field measurement and the extended laboratory result. Therefore, I demonstrated that only the geometrical similarity, not enough to create the convertibility between the results of the scale model and field measurements.

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