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MEASURING THE PERMEABILITY OF OPEN-FRAMEWORK GRAVEL

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science

By

James Thomas Ferreira Jr.
B.S., Bridgewater State College, 2007

2009
Wright State University

WRIGHT STATE UNIVERSITY
SCHOOL OF GRADUATE STUDIES

June 11, 2009

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY James Thomas Ferreira Jr. ENTITLED Measuring The Permeability of Open-Framework Gravel. BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science.

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ABSTRACT

James Thomas Ferreira Jr. M.S., Department of Earth and Environmental Sciences,
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Open-framework gravel has permeability, k , above the measurement range of most conventional constant-head permeameters used in laboratories. Here I addressed the challenge of measuring such high k by using a permeameter long enough that the differences in head across it were on the order of 10^{-3} m and therefore measurable. I collected data over the range from linear-laminar flow to non-linear, non-Darcian flow. In doing so, I verified that k was measured under Darcian flow. I measured k between 4,000 and 100,000 Darcies among experiments using different sediments.

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1.0 Introduction

Open-framework gravel has permeability, k , above the measurement range of most conventional constant-head permeameters used in laboratories. This study addresses the challenge of measuring k , in open-framework gravel in the laboratory.

Gravely fluvial deposits are often dominated by sandy gravels and gravely sands. Within these gravely sediments are open-framework gravel strata, which may be connected to form preferential flow pathways (e.g. Klingbeil et al., 1999; Lunt and Bridge, 2004). Lunt et al. (2004) noted that such pathways act as “thief zones” during enhanced recovery in hydrocarbon reservoirs, or create rapid and localized dispersion of contaminants in aquifers.

Open-framework gravel strata form preferential flow pathways because their k is much greater than the surrounding sandy gravels and gravely sands. As shown by Conrad et al. (2008), k varies non-linearly in sediment mixtures as a function of the volume fraction of the finer component. A typical-grain size distribution found in open-framework gravel is given in Figure 1. Open-framework gravel typically has a sand fraction of 10% or less, and the k is greater than 1×10^4 Darcies. Gravely sand and sandy gravel typically have more than 30% sand and consequently have a k close to that of sand, typically 1×10^2 Darcies or less (Morris and Johnson, 1967; Klingbeil et al., 1998).

Open-framework gravel presents a challenge for quantifying k because, under typical laboratory flow conditions, the hydraulic gradient, $\frac{\Delta h}{\Delta l}$, is so small that it is hard to measure.

For example, under typical flow rates through open-framework gravel the difference in head, Δh , might be much less than 1.0 mm over a length, Δl , of 3.0 meters.

Figure 1.1: Representative grain size distribution for open-framework gravel from Lunt et al. (2004).

Kleineidam (1998) quantified k in open-framework gravel using a laboratory permeameter with a length of 0.4 m and internal diameter of 0.1 m. The challenge of measuring a small head difference was addressed by using electronic pressure transducers. Although this approach is innovative, Kleineidam (1998) did not report important details such as the head difference between manometer ports, the Reynolds numbers under which the data were recorded, and confirmation that the measured flows were in the linear-laminar Darcian regime.

In this study, I addressed the challenge of measuring k for sediments with very high permeability by using a very long permeameter. The “megapermeameter” has a distance of 2.91 m between manometer ports and is mechanical so the difference in head can be directly

observed. I also collected data over the range from linear-laminar flow to non-linear, non-Darcian flow. In doing so, I was able to both verify that permeabilities were measured under Darcian regime, and to document the Reynolds numbers at which the transition to non-Darcian regime takes place.

Here I do not address the issue of packing or preserving the in-situ granular arrangement of the sediment. The longer term goal is to examine, in a general way, the variation in k in sediment mixtures, as a function of the volume fraction of finer-grained sediment. To do so requires mixing sediment with a systematic variation in the volume fraction of fines, and measuring k of these samples. Thus, here I am addressing the specific challenge of measuring k in prepared mixtures of gravels with a low fraction of sand, which are models for open-framework gravel.

2.0 Methodology

Two sediment models were created for this study. One represents uniform pebbles. The other represents open-framework gravel.

The first model was chosen to test the methodology using uniform spheres with a single grain-size, d . I used commercially available marbles with d nearly uniform at 10 mm. These are the same pebble-sized spheres used by Kamann et al. (2007) and Conrad et al. (2008) in studying k and porosity in pebbly sand mixtures. I will refer to this as the uniform pebble model.

The open-framework gravel model was chosen to represent the distribution of grain-sizes reported by Lunt et al. (2004) for open-framework gravel deposited in the Sagavanirktok River, Alaska. To create this sediment model natural sediment were collected from a gravel bar in the Mad River in Dayton, Ohio, and sieved into grain-size categories given in Table 2.1. They were then remixed according to the weight percentages shown in the table.

To measure k , a premixed sample was loaded into a transparent PVC cylinder with an inner diameter of 0.1 m and length of 2.91 m between manometer ports as shown in Figure 2.1.

Premixed material entered through the top of the cylinder and a mixing rod was used to stir the mixture to prevent layering. The sediment was saturated with water through the base of the permeameter to allow air between individual grains to escape. The volume of

water required to saturate the pores was recorded in each experiment so that the porosity, ϕ , of each sediment model could be calculated.

Table 2.1: Grain-size distribution of open-framework gravel.

Wentworth Size Scale	Size of Upper and Lower Sieve Mesh (mm)	Size of Upper and Lower Sieve Mesh (phi)	Weight Percentages Used
Pebble	32.00 to 22.63	- 5.0 to - 4.5	2.50
	22.63 to 16.00	- 4.5 to - 4.0	8.33
	16.00 to 11.31	- 4.0 to - 3.5	15.00
	11.31 to 8.00	- 3.5 to - 3.0	20.83
	8.00 to 5.66	- 3.0 to - 2.5	21.28
	5.66 to 4.00	- 2.5 to - 2.0	13.75
Granule	4.00 to 2.83	- 2.0 to - 1.5	8.33
	2.83 to 2.00	- 1.5 to - 1.0	3.75
Very Coarse Sand	2.00 to 1.41	- 1.0 to - 0.5	2.08
	1.41 to 1.00	- 0.5 to 0.0	1.25
Coarse Sand	1.00 to 0.71	0.0 to 0.5	0.63
	0.71 to 0.50	0.5 to 1.0	0.42
Medium Sand	0.50 to 0.35	1.0 to 1.5	0.21
	0.35 to 0.25	1.5 to 2.0	0.42
Fine Sand	0.25 to 0.18	2.0 to 2.5	0.21

Figure 2.1: Schematic drawing of the constant-head permeameter in the vertical position showing the important components.

Experiments were then run with different gradients. For each experiment a flow rate, Q , was measured by recording the time required to fill a 1000 ml graduated cylinder. Importantly, the manometer tubes are adjacent, allowing the small difference in head between the manometers, Δh , to be measured. The Δh was measured using a digital micrometer which measured to the hundredth of a millimeter. Temperature was measured using a digital thermometer. The temperature was used to determine the density, ρ , and the viscosity, μ , of the fluid as tabulated in deMarsily (1986).

To determine that steady state had been established, normalized flow rate, $Q\mu/\rho gA$, was plotted against time as shown in Figure 2.2. In the uniform pebble model, the time needed to stabilize the flow rates ranged from about three hours under higher flow rates to

three days under lower flow rates. In the open-framework gravel model, the time to stabilize ranged from about three hours under higher flow rates to five hours under lower flow rates.

Figure 2.2: Plot showing time required for flow to stabilize after a change to the gradient for a typical experiment with open-framework gravel model sediment.

3.0 Results and Discussion

The results of the experiments using the uniform pebble model are plotted in Figure 3.1. The $Q\mu/\rho gA$ is plotted versus the gradient. Darcy's law is valid over the range where this relationship is linear. The relationship is linear up to a gradient of 1.50×10^{-3} . The slope of the linear relationship is k . The slope of a fitted regression line over this range gives a k of $1.03 \times 10^{-7} \text{ m}^2$ (103,800 Darcies). The fitted regression line has an R^2 value of 99.81.

Figure 3.1: Normalized flow rate versus hydraulic gradient for the uniform pebble model.

The Reynolds numbers, R_e , for each experiment are also given as labels in Figure 3.1. It is clear that the transition from the linear-laminar Darcian regime to the nonlinear-laminar

regime occurs at R_e above 25. The Δh and R_e measured in Table 3.1 are measurements within the linear-laminar regime or where Darcian regime is valid only. The Δh were of the order of millimeters.

Table 3.1: Measured and computed parameters from experiments at different flow rates within the Darcian regime.

Uniform Pebble Model			Open-Frame Work Gravel Model		
$Q\mu/\rho g A \text{ (m}^2\text{)}$	$\Delta h \text{ (m)}$	R_e	$Q\mu/\rho g A \text{ (m}^2\text{)}$	$\Delta h \text{ (m)}$	R_e
3.34×10^{-11}	2.65×10^{-4}	5.40	1.66×10^{-11}	4.14×10^{-3}	2.67
4.24×10^{-11}	4.04×10^{-4}	8.92	2.06×10^{-11}	4.93×10^{-3}	3.31
6.41×10^{-11}	6.28×10^{-4}	10.80	2.43×10^{-11}	5.75×10^{-3}	3.90
6.78×10^{-11}	6.62×10^{-4}	11.17	2.80×10^{-11}	6.76×10^{-3}	4.50
7.26×10^{-11}	6.29×10^{-4}	11.29	3.15×10^{-11}	7.59×10^{-3}	5.06
7.15×10^{-11}	7.66×10^{-4}	11.71	3.60×10^{-11}	8.73×10^{-3}	5.78
9.58×10^{-11}	9.13×10^{-4}	15.07	3.95×10^{-11}	9.63×10^{-3}	6.51
1.12×10^{-10}	1.09×10^{-3}	17.99	4.58×10^{-11}	1.13×10^{-2}	7.36
1.26×10^{-10}	1.31×10^{-3}	20.24	5.04×10^{-11}	1.24×10^{-2}	8.10
1.36×10^{-10}	1.29×10^{-3}	21.54	5.82×10^{-11}	1.46×10^{-2}	9.34
1.39×10^{-10}	1.32×10^{-3}	22.06	6.04×10^{-11}	1.52×10^{-2}	9.72
1.59×10^{-10}	1.50×10^{-3}	24.82			

The ϕ measured in the uniform pebble model was 0.4034. Indeed, the ϕ in uniform spheres assembled randomly under friction when loading (e.g. stirred or poured) is known to be 0.4 (Yu and Standish, 1993; Kamann et al., 2007). The Kozeny-Carmen equation:

$$k = \frac{d}{180} \frac{\phi^3}{(1 - \phi)^2} \quad (1)$$

with the measured ϕ and with $d = 10 \text{ mm}$ gives a k of $1.0 \times 10^{-7} \text{ m}^2$ (99,752 Darcies). This estimated k is quite close to the measured value.

The results of the experiments using the open-framework gravel model are plotted in Figure 3.2. These results indicate that Darcy's law is valid up to a gradient of at least 1.5×10^{-2} . The slope of a fitted regression line over this range gives a k of $4.05 \times 10^{-9} \text{ m}^2$ (4,090 Darcies). The regression line has a R^2 value of 99.7.

Figure 3.2: Normalized flow rate versus hydraulic gradient for the open-framework gravel model.

Figure 3.2 does not show exactly where the transition from the linear-laminar Darcian regime to the nonlinear-laminar regime occurs, but Darcy's law appears to hold up at least to R_e of 9. The Δh and R_e measured in the Darcian regime are given in Table 3.1. The Δh are of the order of centimeters. The ϕ measured in the open-framework gravel model was 0.2422. Independent measurement made on samples within a graduated cylinder gave an

average ϕ of 0.24. The average of ϕ measured in open-framework gravel sampled by Lunt et al. (2004) was 0.2.

The laboratory measurements of the k in open-framework gravels by Kleineidam (1998) were of the order of 1000 Darcies, and thus of the same order of magnitude as results presented here.

4.0 Conclusions

The megapermeameter used in these experiments worked well in determining the permeabilities of uniform pebble and open-framework gravel models. The methodology can be used to measure k at least as high as 1×10^6 Darcies. At that k , the differences in head between manometers are on the order of millimeters. At the lower end of the flow rates used (Figure 3.1) it was challenging to achieve a stabilized rate. Thus, the uniform pebble spheres are probably near the upper end of the range of k that can be measured with this permeameter.

In addition to measuring k , this methodology used in this study sheds light on the range of R_e over which the Darcy's law is valid. Importantly using this approach, k has been determined by flow rates and gradients that are indeed within the Darcian regime.

Measurements of the k of open-framework gravel models are in the range between 1×10^3 and 1×10^5 Darcies. The methodology using a 3.0 m long cylinder as a permeameter can be used to measure k within this range.

5.0 Appendix A

Uniform Pebble Model. Time Required for Flow to Stabilize After A Change to The Gradient.

Figure A.1: Uniform pebble model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 2.65×10^{-4} .

Figure A.2: Uniform pebble model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 4.04×10^{-4} .

Figure A.3: Uniform pebble model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 6.28×10^{-4} .

Figure A.4: Uniform pebble model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 6.62×10^{-4} .

Figure A.5: Uniform pebble model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 6.29×10^{-4} .

Figure A.6: Uniform pebble model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 7.66×10^{-4} .

Figure A.7: Uniform pebble model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 9.13×10^{-4} .

Figure A.8: Uniform pebble model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 1.09×10^{-3} .

Figure A.9: Uniform pebble model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 1.31×10^{-3} .

Figure A.10: Uniform pebble model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 1.29×10^{-3} .

Figure A.11: Uniform pebble model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 1.32×10^{-3} .

Figure A.12: Uniform pebble model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 1.50×10^{-3} .

6.0 Appendix B

Open-Framework Gravel Model. Time Required for Flow to Stabilize After A Change to The Gradient.

Figure B.1: Open-framework gravel model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 4.14×10^{-3} .

Figure B.2: Open-framework gravel model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 4.93×10^{-3} .

Figure B.3: Open-framework gravel model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 5.75×10^{-3} .

Figure B.4: Open-framework gravel model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 6.75×10^{-3} .

Figure B.5: Open-framework gravel model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 7.59×10^{-3} .

Figure B.6: Open-framework gravel model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 8.73×10^{-3} .

Figure B.7: Open-framework gravel model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 9.63×10^{-3} .

Figure B.8: Open-framework gravel model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 1.13×10^{-2} .

Figure B.9: Open-framework gravel model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 1.24×10^{-2} .

Figure B.10: Open-framework gravel model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 1.46×10^{-2} .

Figure B.11: Open-framework gravel model. Time required for flow to stabilize after a change to the gradient. The gradient used here was 1.52×10^{-2} .

7.0 Appendix C

Model Sediment

Figure C.1: Grain-size distribution used to create Pebble (Left) and Open-framework gravel (Right) models within the megapermeameter.

Two sediment models were created for this study as shown in Figure C.1. One represents uniform pebbles; the other represents open-framework gravel. Open-framework gravel was collected from a bar deposit within the Mad River at the intersection of North Findlay St. and East Monument Ave. in Dayton, Ohio.

Open-framework gravel grain d sorting were conducted by using nested sieves with openings of 32.0, 22.627, 16.0, 11.313, 8.0, 5.656, 4.0, 5.656, 4.0, 2.828, 2.0, 1.414, 1.0, 0.707, 0.50, 0.353, 0.25 mm and mechanically sieving by a Ro-tap vibrator. Weight percentage from the grain-size distribution reported by Lunt and Bridge (2004) was deposited into mixer and mixed for five minutes. Mixed sediment was deposited directly

into the cylinder, and stirring of sediment was conducted to prevent layering or bridging of grains.

8.0 Appendix D

Overview of Water-Based Constant-Head Permeameter

Figure D.1: Megapermeameter supported in the vertical position loaded with open-framework model. Upper and lower reservoirs are positioned on scaffolding.

The main body of the megapermeameter was constructed from a transparent PVC cylinder with a length of 3.05 m and an inner diameter of 0.1 m., as shown in Figures 2.1 and D.1. Manometer ports were drilled and tapped into the cylinder 0.07 m in from each end, so they are separated by 2.91 m. Each manometer tube has a diameter of 0.0017 m. At each end of the cylinder, threaded end caps were attached. Holes were drilled and tapped into the end caps; vinyl tubing with a diameter of 0.016 m was attached at each opening. Inside each end cap, a metal screen and wool packing were installed to prevent

sediment from exiting the cylinder. The carboy (18.93 L) is surrounded by the larger upper reservoir which collects over flow from the carboy (Figure D.2). The temperature of the fluid was also measured within the carboy using a digital thermometer. The lower reservoir was used to house the small submersible pump, which ran continually during experiments to provide the upper reservoir with a steady supply of fluid.

Figure D.2: Top view of upper reservoir with carboy.

The cylinder was supported in the vertical position during loading as shown in Figure D.1. A mixing rod was used to stir the sediment as it was being loaded to prevent layering. Once loaded and capped, the cylinder served as a constant-head permeameter for conducting water-based measurements. The sediment was saturated through the base of the permeameter to allow air between individual grains to escape. During permeability and porosity experiments the flow rate was measured by using a 1000 ml graduated cylinder. Changes in head were measured with a digital micrometer that was accurate to a hundred's of a millimeter.

9.0 REFERENCES

- Conrad, C.M., Ritzi, R.W., and Dominic, D.F., (2008), Air-based measurements of permeability in pebbly sands, *Ground Water*, 46, 103-112.
- de Marsily, G., (1986), *Quantitative Hydrogeology: Groundwater Hydrology for Engineers*, 564 p., Academic Press.
- Kamann, P.J., Ritzi, R.W., Dominic, D.F., and Conrad, C.M., (2007), Porosity and permeability in sediment mixtures, *Ground Water*, 45, 429-438.
- Lunt, A. and Bridge, J.S., (2004), Evolution and deposits of a gravelly braid bar, Sagavanirktok River, Alaska, *Sedimentology*, 51, 415-432.
- Morris, D.A., and Johnson, A.I., (1967), Summary of hydrologic and physical properties of rock and soil materials, as analyzed by the Hydrologic Laboratory of the U.S. Geological Survey 1948-60, *Geological Survey Water-Supply Paper 1839-D*.
- Kleineidam, S., (1998), Der einfluß von sedimentologie und sedimentpetrographie auf den transport gelöster organischer schadstoffe im grundwasser, Dissertation, Geowissenschaftliche Fakultät, Universität Tübingen, Germany.
- Klingbeil, R., (1998), Implications for groundwater flow and contaminant transport in heterogeneous glaciofluvial Quaternary deposits, Dissertation, Geowissenschaftliche Fakultät, Universität Tübingen, Germany.
- Klingbeil, R., Kleineidam, S., Asprion, U., Aigner, T., Teutsch, G., (1999), Relating lithofacies to hydrofacies: outcrop-based hydrogeological characterization of Quaternary gravel deposits, *Sedimentary Geology*, 129, 299-310.
- Yu, A.B., N. Standish, and A. McLean., (1993), Porosity calculation of binary mixtures of nonspherical particles, *Journal of American Ceramic Society*, 76, no. 11: 2813-2816.