NTNU

Norwegian University of Science and Technology

An Experimental Investigation on Porosity in Gravel Beds

Christy Ushanth Navaratnam, Jochen Aberle & Jana Daxnerová

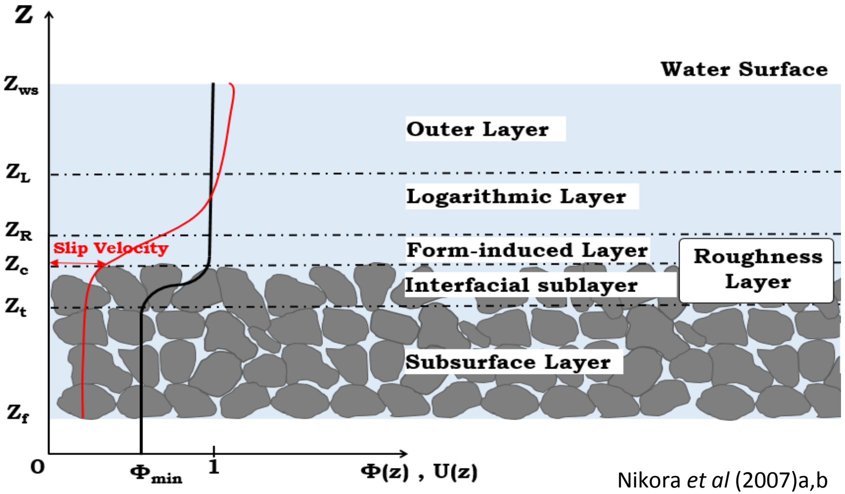
Department of Civil and Environmental Engineering,
Norwegian University of Science and Technology (NTNU),
Trondheim, Norway.

Outline

- Introduction
- Experimental set-up
  - Large scale tests
  - Small scale tests
- Results
- Summary

Introduction

- Flows over gravel beds are
  - hydraulically rough bed flows with low relative submergence
  - spatially heterogeneous
- Spatial flow heterogeneity may be described using the double-averaged (time and space) momentum equations.



Nikora *et al* (2007)a,b

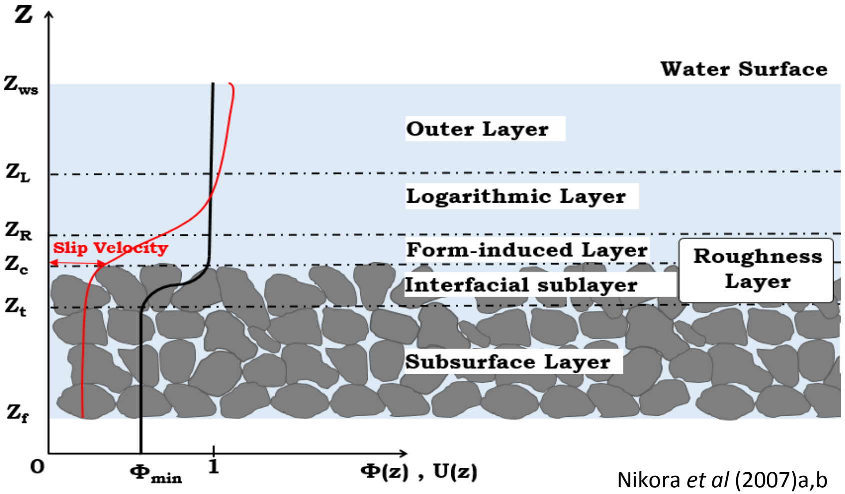
Introduction

- The flow in the interfacial sublayer and the subsurface layer is affected by the roughness which can be described by the roughness geometry function (ϕ)

$$\phi = V_f / V_0$$

'Porosity'

V_f – volume occupied by the fluid
V_0 – total averaging volume



Nikora *et al* (2007)a,b

Introduction

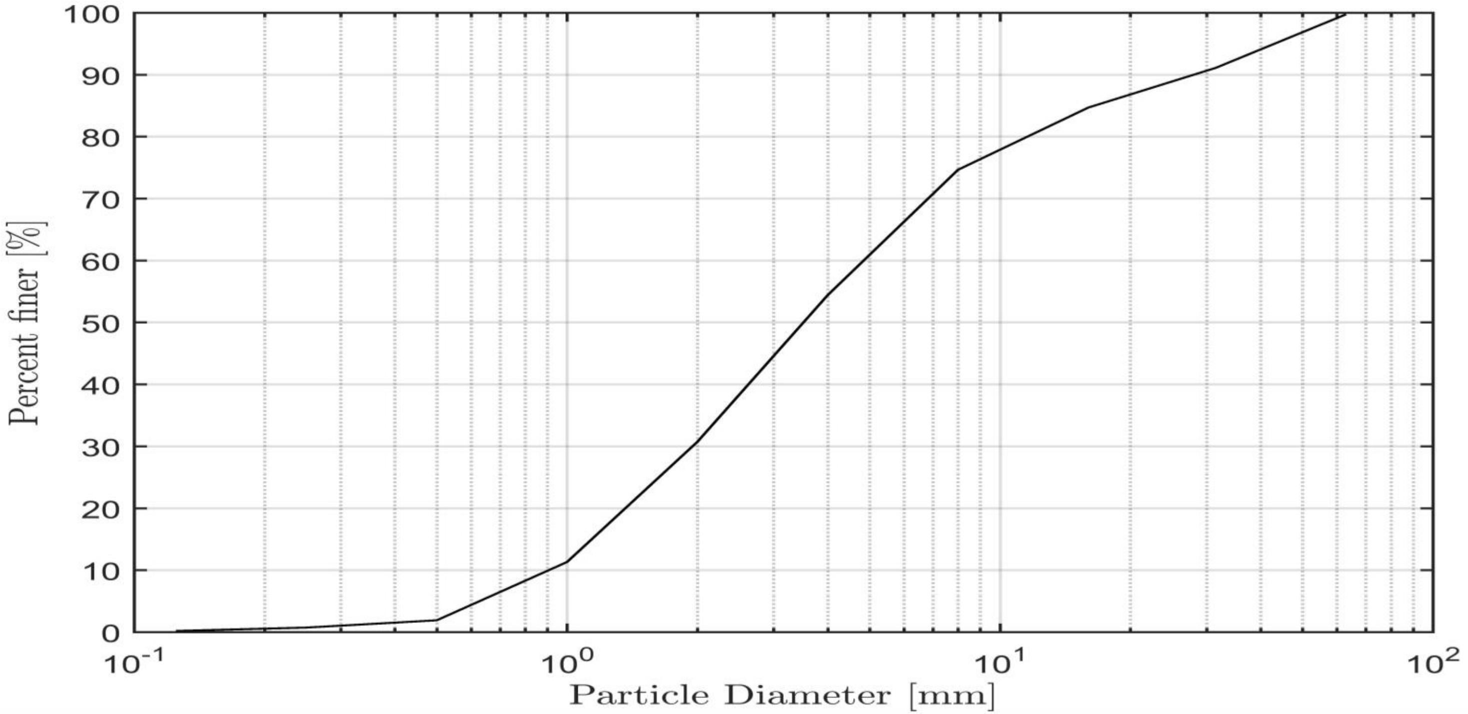
- Measurement of porosity,
  - Empirical predictors
    - Median grain size d_{50} (e.g., Carling and Reader, 1982)
    - Sorting coefficient (e.g., Wooster et al., 2008)
    - Grain size characteristics (e.g., Frings et al., 2011)
    - Combination of all above and other factors (grain shape & depositional environment) (e.g., Liang et al., 2015)
  - Direct or indirect porosity mesurements

    Direct
    - Water displacement method (e.g., Aberle, 2007, Dey and Das, 2012)
    - Gas expansion/adsorption method (e.g., Anovitz and Cole, 2015)
    - X-ray computed tomography (e.g., Slotwinski et al., 2014)
    - Ultrasonic techniques (e.g., Slotwinski et al., 2014)

    Indirect
    - Topographic data (DEMs) (e.g., Aberle, 2007)

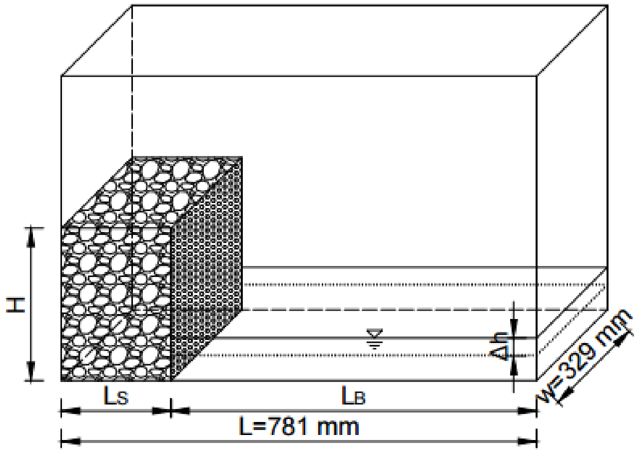
Experimental set-up

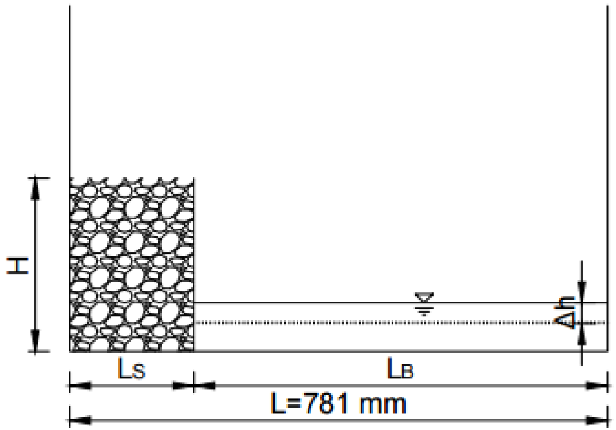
- Large scale test



Experimental set-up

- Small scale tests





Tested materials

- Gravel mixture
- Uniform gravel
- Uniform fine sand
- Golf balls

$$\emptyset = \frac{V_f}{V_0} = \frac{V_{st} - V_B}{w\, L_S\, \Delta h} = \frac{V_{st} - w\, L_B\, \Delta h}{w\, L_S\, \Delta h}$$

V_{st} – volume of water added in a step
V_B – volume of water in the basin
Δh – water level increment

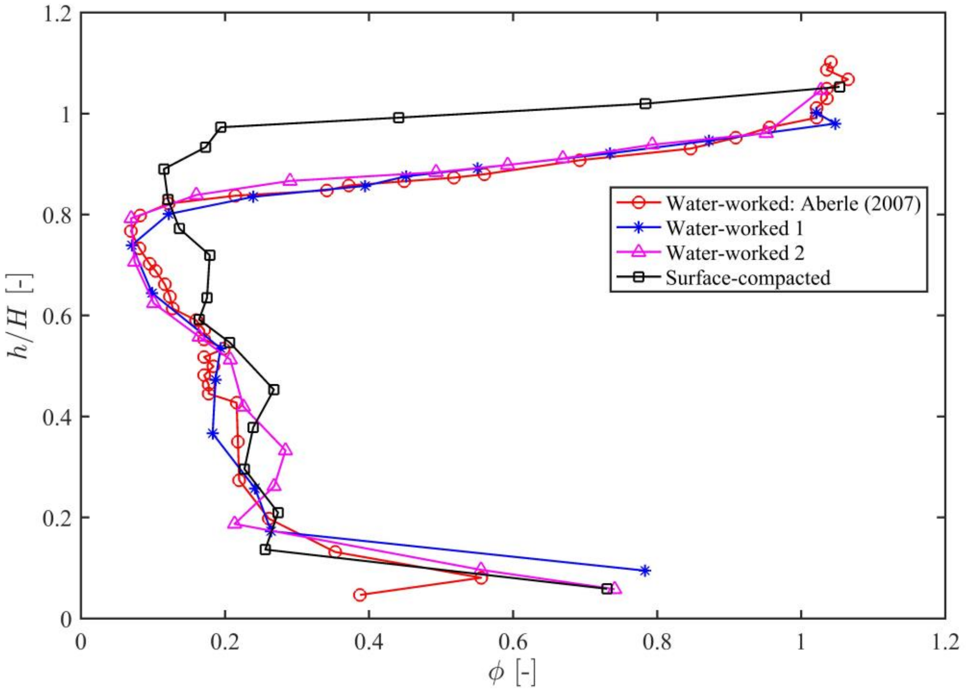
Experimental set-up

- Summary of test cases

Test Case	Grain Size (mm)	Bed height (mm)	Bulk Porosity	Minimum Porosity
Flume tests				
Surface-compacted gravel (screeded)	0.64 - 64	200	0.26	0.115
Water-worked gravel	0.64 - 64	200	0.31	0.071
Small scale tests				
Surface-compacted gravel (screeded)	0.64 - 64	154	0.29	0.059
Layer-compacted gravel	0.64 - 64	184	0.25	0.055
Uncompacted gravel	0.64 - 64	200	0.37	0.124
Manually-shaken gravel	0.64 - 64	196	0.29	0.110
Uniform gravel-Run 1	8	215	0.48	0.391
Uniform gravel-Run 2	8	210	0.51	0.406
Uniform fine sand	0.33		0.37	0.001
Golf balls	42 (diameter)	232	0.51	0.249

Results

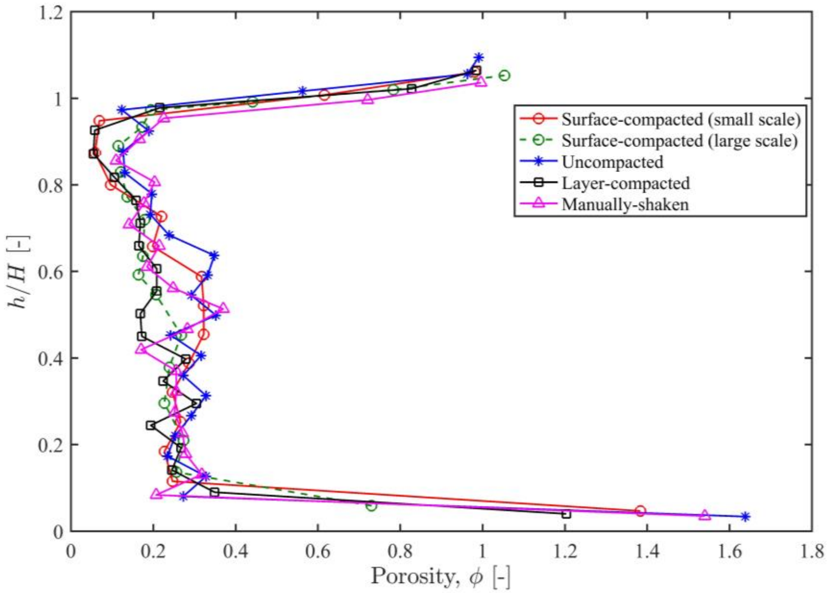
- Large scale test



- An absolute minimum of porosity obsereved at the level of roughness trough
- Validated the results of Aberle (2007)
- Larger porosity values at the flume bottom

Results

- Small scale test (gravel mixture)

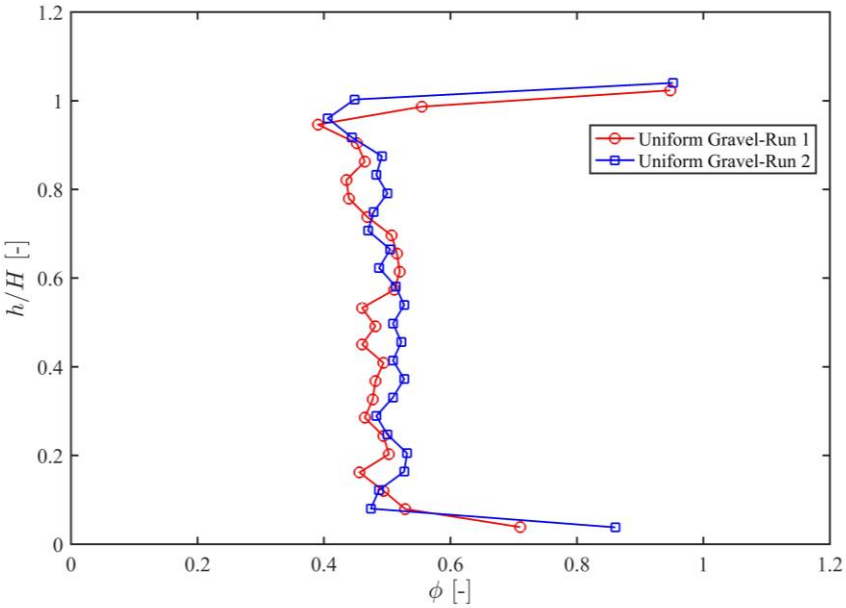


- An absolute minimum of porosity obsereved at the level of roughness trough
- Validated the results of Aberle (2007)
- Larger porosity values at the flume bottom ($\phi > 1$??)
- Absolute minimum of porosity is not solely due to the armoring process

$$\emptyset = \frac{V_f}{V_0} = \frac{V_{st} - V_B}{w\, L_S\, \Delta h} = \frac{V_{st} - w\, L_B\, \Delta h}{w\, L_S\, \Delta h}$$

Results

- Small scale test (uniform gravel)

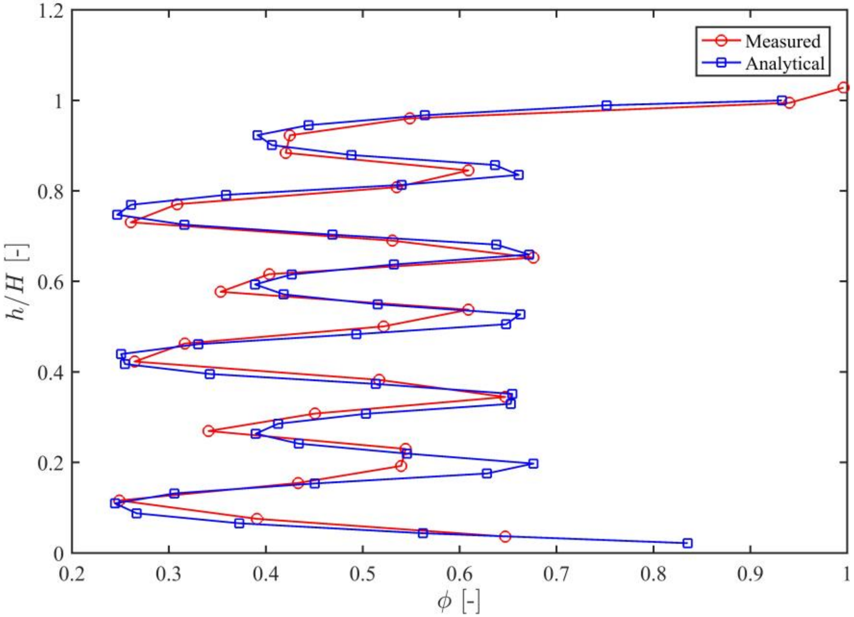


$$\emptyset = \frac{V_f}{V_0} = \frac{V_{st} - V_B}{w\ L_S\ \Delta h} = \frac{V_{st} - w\ L_B\ \Delta h}{w\ L_S\ \Delta h}$$

- Deviation of the absolute minimum from bulk porosity is less.
- Capillary action also causing porosity values smaller close to the surface and larger close to the tank bottom.

Results

- Small scale test (golf balls)



$$\emptyset = \frac{V_f}{V_0} = \frac{V_{st} - V_B}{w\ L_S\ \Delta h} = \frac{V_{st} - w\ L_B\ \Delta h}{w\ L_S\ \Delta h}$$

Summary

- An absolute minimum value of porosity observed at the level of roughness trough.
  - Validated the results from the literature
  - Not exclusively due to the static armoring
  - Partly due to the capillary action which under/over estimates the porosities close to the gravel surface and flume bottom respectively.
- Generally, the porosity in soils is determined as bulk porosities – capillary action would become ineffective.
- A correction factor for capillary action needs to be considered when the porosity profiles are measured using the water displacement method.

References

- Aberle, J. (2007). Measurements of armour layer roughness geometry function and porosity. *Acta Geophysica*, 55, 23-32.
- Anovitz, L. M. & Cole, D. R. (2015). Characterization and Analysis of Porosity and Pore Structures. *Reviews in Mineralogy and Geochemistry*, 80**,** 61-164.
- Carling, P. A. & Reader, N. A. (1982). Structure, composition and bulk properties of upland stream gravels. *Earth Surface Processes and Landforms*, 7**,** 349-365.
- Dey, S. & Das, R. (2012). Gravel-Bed Hydrodynamics: Double-Averaging Approach. *Journal of Hydraulic Engineering*, 138**,** 707-725.
- Frings, R. M., Schüttrumpf, H. & Vollmer, S. (2011). Verification of porosity predictors for fluvial sand-gravel deposits. *Water Resources Research*, 47**,** n/a-n/a.
- Liang, R., Schruff, T., Jia, X., Schüttrumpf, H. & Frings, R. M. (2015). Validation of a stochastic digital packing algorithm for porosity prediction in fluvial gravel deposits. *Sedimentary Geology*, 329**,** 18-27.
- Nikora, V., McEwan, I., McLean, S., Coleman, S., Pokrajac, D. & Walters, R. (2007a). Double-Averaging Concept for Rough-Bed Open-Channel and Overland Flows: Theoretical Background. *Journal of Hydraulic Engineering*, 133**,** 873-883.
- Nikora, V., McLean, S., Coleman, S., Pokrajac, D., McEwan, I., Campbell, L., Aberle, J., Clunie, D. & Koll, K. (2007b). Double-Averaging Concept for Rough-Bed Open-Channel and Overland Flows: Applications. *Journal of Hydraulic Engineering*, 133**,** 884-895.
- Slotwinski, J. A., Garboczi, E. J. & Hebenstreit, K. M. (2014). Porosity Measurements and Analysis for Metal Additive Manufacturing Process Control. *Journal of Research of the National Institute of Standards and Technology*, 119**,** 494-528.
- Wooster, J. K., Dusterhoff, S. R., Cui, Y., Sklar, L. S., Dietrich, W. E. & Malko, M. (2008). Sediment supply and relative size distribution effects on fine sediment infiltration into immobile gravels. *Water Resources Research*, 44**,** n/a-n/a.

Thank you