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On the application of single-board computers and physical computing for the investigation of the water retention curve of unsaturated granular soils

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ABSTRACT: In this conference contribution we present an overview of our recent studies regarding the hysteretic nature of the water retention curve (WRC). We compare the WRC of a coarse-grained granular model soil called "Hamburg Sand" to mono- and polydisperse packings of glass beads. Laboratory tests are executed using an automated measurement technique based on a setup driven by a Raspberry Pi single-board computer, a self-built tensiometer and a 3D-printed syringe pump. Following the example of the measurement of the WRC, we explain the basic concept of physical computing using a single-board computer, which is perfectly suitable to get students in touch with programming and scientific experiments. Furthermore, we outline, how such experimental setups can be used for in situ experiments with parallel computed tomography (CT) 3D-imaging to investigate capillary effects on the pore level and their impact on the macroscopic soil behaviour.

Keywords: granular soils, water retention behaviour, single-board computer, unsaturated soil mechanics, computed tomography

1 INTRODUCTION

As soil begins to desaturate, air infiltrates its pores and matric suction s evolves acting as an additional internal stress component influencing the soil's (hydro-) mechanical behaviour. To describe this behaviour, it is key to gain knowledge about the water retention curve (WRC) of a soil, describing the dependency of matric suction on water content during drainage and imbibition of the soil. This dependency is individual to every type of soil and furthermore highly dependent on flow direction and flow rate leading to the hysteretic nature of the WRC (Bear, 1979).

2 MEASUREMENT SETUP

The used measurement setup to determine the WRC is referred to as the UNSAT-*Pi* 2. A detailed description can be found in Milatz (2020). Since its first appearance many minor or major improvements regarding the measurement precision and overall usability were made, but the basic design has remained the same. The technical concept is summarized here in brief.

2.1 Raspberry Pi

The heart of the presented test setup (see Fig. 1) consists of a Raspberry Pi 4B single-board computer. This model is built with a 4-core-processor with 1.5 GHz clock speed and up to 8 GB of RAM. Furthermore, the board is built with several different physical connectors, the most important ones being the general-purpose input/output (GPIO) pins, which are the key feature to enable physical computing. Additionally, support for wireless connections via Bluetooth and Wi-Fi is provided. Physical computing describes interactive systems which can make use of sensors and are therefore able to react to conditions in the surrounding environment.

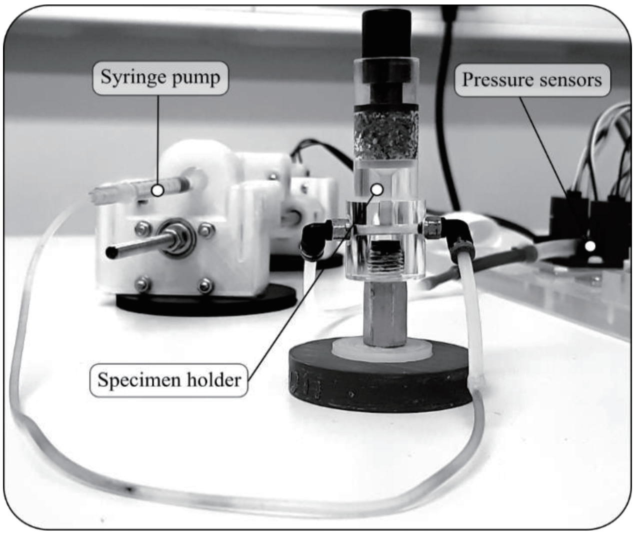

Fig. 1. Measurement setup showing the syringe, the specimen holder, including a specimen made of Hamburg Sand, and the pressure sensors as well as the connected water-filled tubes.

By using the preconfigured operating system Raspberry Pi OS, which already comes with the easy-to-learn Python programming language, the GPIO pins can directly be utilized for setting up the presented experiments. The Raspberry Pi is therefore – amongst other more specialized platforms – one of the most successful single-board computers and enjoys great popularity in the maker scene as well as in teaching and research. In previous applications, students had to use actuators to respond to sensor readings or used special setups to measure hydro-mechanical properties of unsaturated soils, such as uniaxial compressive strength (Milatz, 2019) or the WRC, being the focus of this paper.

2.2 The UNSAT-*Pi* 2

The UNSAT-*Pi* 2 represents a setup for the measurement of the WRC consisting of the described Raspberry Pi and further components such as pressure sensors and a stepper motor-driven syringe pump which is used to apply pore water flow. The frame of the pump is 3D-printed and was originally developed by Wijnen et al. (2014) and published under an open source license to support developing countries with affordable yet precise and high-quality medical instrumentation.

The syringe itself is attached via a tube to the specimen holder, an acrylic cylinder that enables the experimentalist to visually inspect the insides of the specimen for compaction control. The tube is mounted onto a T-shaped channel that connects the water to the specimen above and another tube which leads to a pressure sensor (see Fig. 1). The second sensor keeps track of variations of the ambient air pressure and besides that may also be utilized to reduce noise in the measured analog signal by reading the differential pressure of both sensors. As the soil specimen is separated from the water channels with a porous sintered glass disk, on which a microporous filter membrane is placed, this system operates as a tensiometer to measure matric suction. Of great importance for the measurement of matric suction is, that the whole system must be filled with de-aired water without any air entrapments.

2.3 Tested materials and specimen preparation

The examined granular materials can be divided into two groups being (quasi-)mono- and polydisperse materials as shown in Table 1. Hamburg Sand is a coarse-grained model sand frequently used at our institute. “Hamburg Glass” is a packing of glass beads consisting of four glass bead mixtures, approximating the grain size distribution of Hamburg Sand (Milatz, 2020). All other glass bead packings are assumed to be monodisperse with a given variation in the mean diameter and were produced by the German company Sigmund Lindner GmbH. The used glass beads are part of the SiLibeads Type S series and are made of soda-lime glass. All specimens for WRC testing are prepared by pluviating the particles into the already water-filled specimen holder. In between filling layers, the packing is carefully compacted by tapping. The specimen itself has a target height and diameter of 12 mm aiming for a target void ratio of e = 0.61. These small dimensions have been selected in agreement with the requirements for full-field CT imaging of the specimens.

Table 1. Tested materials. Given are the grain density ρ_s and the minimum and maximum void ratios e_min and e_max representing the boundaries of the achievable packing densities.

Group/Name	ρ_s $\left(\frac{\mathrm{g}}{\mathrm{cm}^3}\right)$	e_min $(-)$	e_max $(-)$
Polydisperse			
Hamburg Sand	2.64	0.520	0.805
Hamburg Glass	2.50	0.550	0.672
Quasi-Monodisperse			
Glass beads d = 1.000±0.050 mm	2.50	0.574	0.648
Glass beads d = 0.655±0.055 mm	2.50	0.571	0.677
Glass beads d = 0.550±0.050 mm	2.50	0.545	0.681

2.4 Testing procedure

After an initial 30 min logging phase for the equilibration of initial matric suction, four cycles of drainage and imbibition are executed, varying the macroscopic specimen degree of saturation S_r as shown in Fig. 2 (top). The constant flow rate by means of change in volume per time dV/dt is selected to be $7.77\mathrm{x}10^{-4}$ m^3/s or dS_r/dt = $1.508 \mathrm{~x~} 10^{-4}$ 1/s (change in degree of saturation per time), respectively.

3 RESULTS

3.1 Hysteresis of the water retention curve

The combination of recorded S_r and s reveals the hysteretic nature of the WRC. In Fig. 3 the WRC for

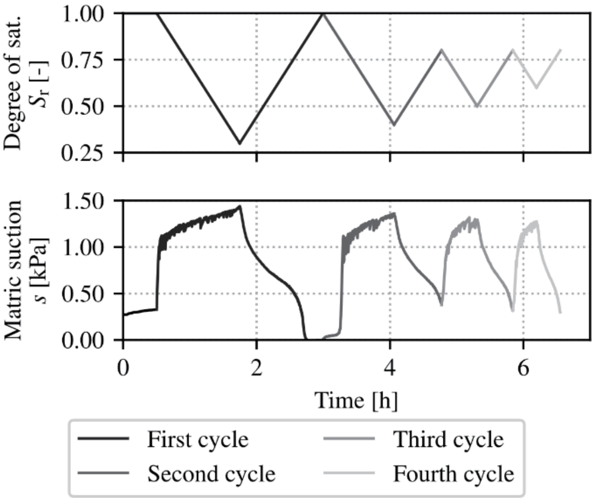

Fig. 2. Test procedure. Variation of the degree of saturation over time (top) and response of matric suction for glass beads with a diameter of d = 0.550±0.050 mm over time (bottom).

glass beads with a diameter of $d = 0.550 \pm 0.050$ mm is shown. Starting with an initially saturated sample corresponding to a degree of saturation of 1.0, drainage takes place leading to a rapid increase in matric suction. Beyond the air entry point of around 1.2 kPa the suction increases only slightly. At a degree of saturation of 0.3 the flow direction is reversed and drained water gets reimbibed. The evolving matric suction now follows a different path. As imbibition continues, matric suction reaches 0 kPa with degree of saturation still being smaller than 1.0. This can be explained by entrapped air that prevents some of the pores to be filled with water again. The inclination of the curve in negative suction areas can be interpreted as hydrostatic pressure as a result of a water column forming above the sample due to entrapped air and the same amount of reimbibed water which was pumped out for drainage in the first place.

The hydraulic paths measured in the following drainage and imbibition cycles (*scanning paths*) lie between the first cycle curves describing the envelope curves (also called *Primary drainage path* and *main imbibition path*) which is in good agreement with the literature (Pham, 2005, Fredlund and Xing, 1994).

The equilibrium state of the measured WRC, i.e., its flow rate independence, can be confirmed by comparing the data with an independent equilibrium WRC measurement technique based on Peters and Durner (2008). Here a Hyprop evaporation test (Meter Group AG) is used, which shows a very good agreement for the developing matric suction on the primary drainage path. Only slight overshooting can be observed for a degree of saturation between 0.9 and 0.5.

It's worth mentioning that the maximum measured matric suction is around 1.4 kPa which is comparatively small when compared for example to cohesive soils which can develop suctions in the order of magnitude of megapascals. In addition to that no filtering/smoothing has been applied to the shown data underlining the measurement precision of the presented test setup. The resolution of the used analog-digital-converter was determined to be 8×10^{-5} kPa.

3.2 Comparison of the WRC of different materials

When comparing the WRC of different materials (see Fig. 4), a shift to higher suctions with reducing particle diameter can be observed. This observation is valid for the increased air entry value as well as for the maximum suction values at the returning point of $S_r = 0.3$ on the primary drainage path.

The measured increase of suction at the air entry point with decreasing grain size is in agreement with theory of capillarity, which states an increase in capillary rise, equivalent to higher matric suction, in smaller pore geometries, which are present in packings with smaller particles. Also, for monodisperse glass beads it can be observed that the amount of entrapped air is reduced when increasing the particle diameter. For the polydisperse materials no significant difference in the amount of entrapment air can be observed.

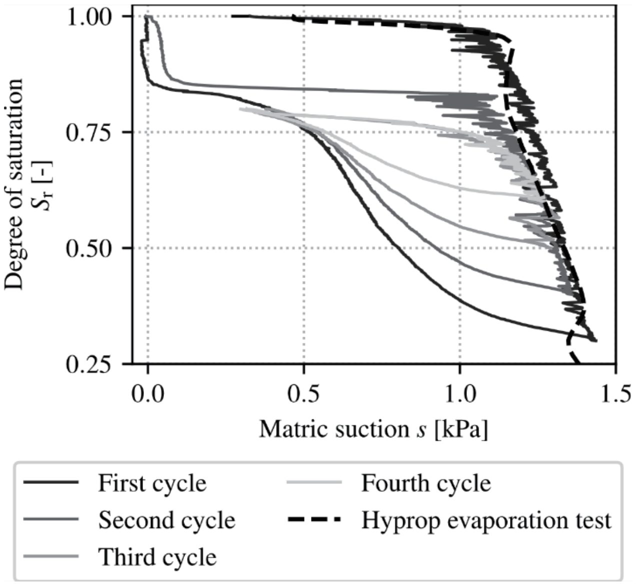

Fig. 3. Resulting WRC for glass beads with a diameter of $d = 0.550 \pm 0.050$ mm showing the dependency of matric suction s on the degree of saturation S_r.

The matric suctions in polydisperse materials exceed the ones in monodisperse materials. Except for the monodisperse material with $d = 0.550 \pm 0.050$ mm, being close to the polydisperse materials. This observation might be explained by polydisperse packings generally evolving more complex pore structures with smaller particles being able to fill larger pores which leads to higher suction values. For the monodisperse material the high suction values might evolve from pore sizes representing the mean pore diameter of the polydisperse materials leading to a similar water retention behavior.

Finally, the inclination of the saturation drop on the primary drainage path is not as steep as for the monodisperse materials resulting in a smoother transition from higher to lower degrees of saturation. This might be explained by the variety of different pore sizes present in polydisperse materials.

4 CONCLUSIONS

The presented cyclic water retention experiments and measured WRCs show, that the application of single-board computers and physical computing opens the door to versatile user-defined experiments for the investigation of unsaturated soils. With the help of a suitable setup accurate measurements can be obtained in an automated and user-friendly way.

The control of hardware, such as motors, and the handling of measured data, both based on well-readable Python software, facilitates the application in research and also in undergraduate teaching. Based on our experience, students obtain an intuitive and illustrative

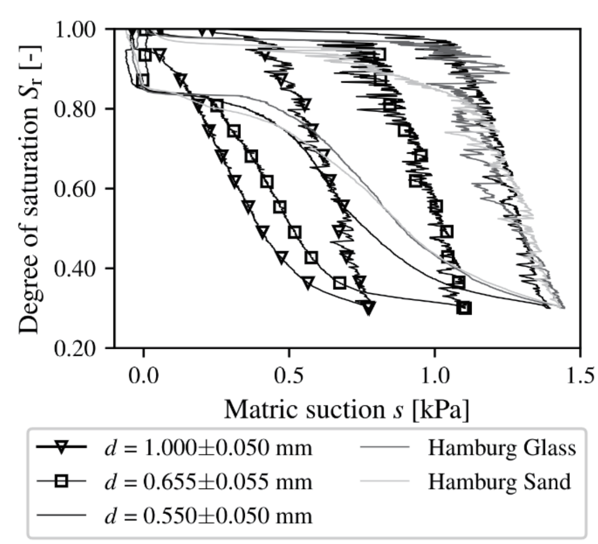

Fig. 4. Comparison of first cycle WRCs of different mono- and polydisperse materials. A shift of the measured matric suctions as well as different degrees of air entrapment can be observed.

access to programming, as they are in touch with a working experiment which can be directly controlled by application-oriented Python code.

To sum up, the presented setup allows to study the effect of different granular properties on the hydraulic behaviour of unsaturated soils. Dependencies of the WRC on the grain size distribution could be observed as well as varying air-entry values and slope inclinations. A good agreement of suction measurements with Hyprop evaporation tests could be shown to confirm, that the magnitude of matric suction is representative.

5 OUTLOOK

In future studies we aim for examining the dynamic water retention behaviour of all materials by varying the flow rate of drainage and imbibition. These non-equilibrium flow regimes of pore water at higher flow rates are known to lead to over- or undershooting of matric suction on drainage and imbibition paths respectively.

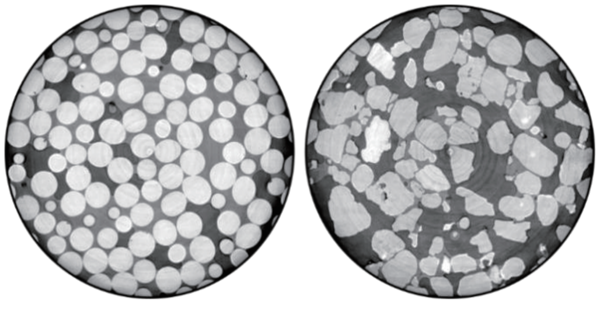

Fig. 5. Grey value images of synchrotron-based tomographies during cyclic water retention experiments showing a slice of glass beads (left) and a slice of Hamburg Sand (right). Lighter Areas show the particles, darker areas represent air-filled voids, intermediate grey values are the water phase.

As a further main application, the presented setup will be applied in in situ CT-experiments, i. e., in flow experiments with parallel CT image acquisition to capture the hydraulic behaviour on the microscopic pore scale in four dimensions (3D + time). Recent studies of the authors have already adapted the presented setup for experiments at the German Electron-Synchrotron "Deutsches Elektronen-Synchrotron" DESY. Cyclic drainage and imbibition during parallel CT imaging has been run to capture pore scale flow processes with high spatial and temporal resolutions. We were able to obtain a time series of images for all presented materials for a field of view of about 6 mm x 6 mm and a height of about 5 mm with a spatial resolution of 2.56 µm (see Fig. 5). The currently ongoing evaluation of experimental data focuses on the evolution of microscopic state variables, such as contact angles and interfacial areas, for a better understanding of the macroscopic soil behaviour, originating from microscopic properties and processes.

As a further outlook, the described hydraulic experiments with CT imaging will represent the basis for numerical simulations of unsaturated flow effects with the Multiphase Lattice Boltzmann Method (LBM).

ACKNOWLEDGEMENTS

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