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To cite this article: L. Perez-Jaimes *et al* 2025 *IOP Conf. Ser.: Earth Environ. Sci.* **1480** 012014

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MINIATURE TESTING DEVICE TO STUDY THE EFFECT OF EXTERNAL LOAD, AND IRRIGATION RATE AND DIRECTION ON THE CAPILLARY COLLAPSE OF UNSATURATED SOIL

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Abstract: The capillary collapse is an irreversible volumetric deformation of partially saturated soils induced by an increase in the water content. While extensively studied by several authors, there remain factors yet to be explored. Based on preliminary laboratory tests, this paper proposes an experimental device to study how changes in irrigation rate, direction, and total stress on the soil specimen affect collapse behavior. This device will be used in future collapse tests during with parallel X-ray computed tomography (CT) imaging to understand the phenomenon from a microscopic approach.

1. Introduction

Capillary collapse in soil refers to an irreversible volumetric change resulting from an increase in the sample's saturation degree under constant vertical stress. This occurs in partially saturated soils with a loose, metastable structure where increased water content dissolves capillary bridges and induces heterogeneous changes at the particle level, leading to volumetric deformation [1, 2, 3]. This phenomenon has been studied by various authors [1, 2, 4] at macro and micro scales using techniques like oedometer testing and X-ray CT. While these studies provide valuable insights, capillary collapse remains highly complex, with certain influential components yet to be explored.

This paper proposes a device to study the effect of changes in irrigation rate and direction, and initial total vertical stress state. The rate and direction of water entry are factors that must be studied because both factors control the change in effective stress in the soil and the distribution of capillary forces between soil particles, crucial for understanding soil skeleton behavior during collapse. Another important aspect to consider is the possibility of different initial total vertical stress states, as these generate a considerable change in the forces involved in the collapse phenomenon. The device design allows for future studies using parallel CT imaging, a widely used non-destructive technique for understanding soil structure changes at the grain level during the wetting process. This facilitates microscopic analysis of the collapse phenomenon.

2. Methodology and results

This paper utilizes three soil models: two coarse-grained sands, denoted as Hamburg Sand I and Hamburg Sand II, with one being more angular than the other, and a third model comprising a polydisperse pack of glass beads, all with a similar particle size distribution. The collapse potential and subsequent settlement estimation were characterized using the Single Specimen Collapse test proposed by [1]. This method involves placing the soil sample at a specified water content and initial density, subjecting it to a predetermined loading procedure, and then flooding it with distilled deionized water to induce collapse [5]. The results suggest that the collapse potential of the analyzed soils



is moderate.

Additionally, a collapse test, following the methodology proposed by [2], was performed on loose sand sample, evaluating three irrigation rates. Settlements were measured using three LVDTs sensors (Linear Variable Differential Transformers) connected to an Arduino UNO via MATLAB code, ensuring measurement reliability and error reduction. To prevent the sensors from affecting the sample integrity and as a reference for deformation measurements, a red disc with a mass of 102 grams was placed on top of the sample. Water increments were applied using a manually controlled GDS Standard Pressure/Volume Controller. Tests consisted of 10 steps of 4.12 mL water volume increments at three different irrigation rates (100 mLs^{-1} , 200 mLs^{-1} , 500 mLs^{-1}), five test replicates each. Figure 1 illustrates a test conducted with an irrigation rate of 100 mLs^{-1} , an initial porosity $n = 0.61$, and an initial saturation degree $S_r = 0.12$.



Figure 1. Collapse test on Hamburg Sand II sample.

The test series with different flow rates did not show a clear influence of the irrigation rate on soil deformation, as suggested by [2]. Apparently, in Figure 2, it is seen that higher rates led to increased deformation at each wetting step; however, more tests need to be evaluated to define a trend. Additionally, the test uncovered two distinct behaviors during the wetting process. The first corresponds to the anticipated collapse process, characterized by deformations accompanying each increase in water content. The second occurs after the sixth water increment, where deformations tend to stop or not being significant compared to earlier steps. This behavior aligns with the hypothesis of three collapse phases proposed by [4]. The collapse and post-collapse phases observed in the test correspond to rapid suction loss destabilizing the soil structure in the collapse phase, resulting in significant deformations, while the post-collapse phase sees the sample nearing saturation with minimal suction values, leading to no further deformations with increased water. The pre-collapse phase cannot be appreciated due to the initial saturation degree of the samples. However, a more detailed particlelevel analysis is necessary to comprehend the underlying changes driving this behavior. The maximum observed deformation corresponds to 26.5% of the initial sample height, a value considered during equipment sizing.

2.1. Testing device

The device described in this paper builds upon methodologies and designs outlined in [2,6], previously used for studying capillary collapse at a micro level using X-ray CT. This device enables the study of collapse in a cylindrical specimen via wetting using a syringe pump. As proposed by [2], the phenomenon can be examined through stepwise collapses, enabling detailed analysis of small changes in soil microstructure due to water ingress. Moreover, based on laboratory collapse test results, the scripts allow for differentiated sampling. Initially, smaller water volumes will be injected,

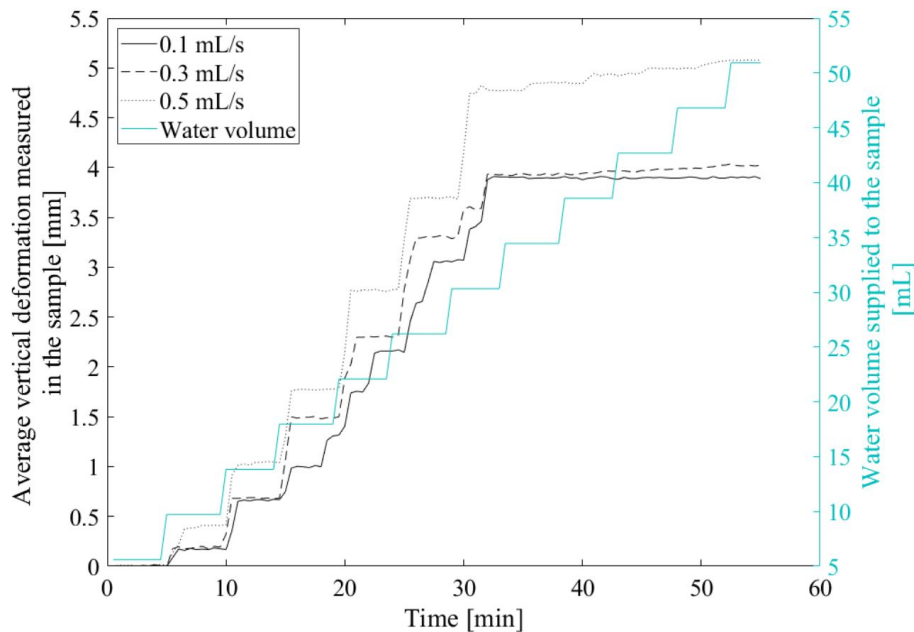


Figure 2. Average settlement of Hamburg Sand II soil samples for three irrigation rates, compared to the water volume in the sample over time.

with a greater number of scans during the collapse phase, while as the sample nears total saturation in the post-collapse phase, larger water volumes will be injected, and fewer scans will be taken. Based on the UNSAT-Pi 2 system developed by [6], the equipment incorporates a syringe pump controlled by a Raspberry Pi 4 model B, albeit with modifications to the Python scripts for regulating water volume and irrigation rate. In this instance, pore water sensors are omitted due to low water contents. The equipment has acrylic specimen holder for a soil sample of 14 millimeters in height and 12 millimeters in diameter, facilitating parallel X-ray CT imaging, and an air inlet point at the top to be maintain atmospheric pressure. There are two types of specimen holders (see Figure 3). Specimen holder type 1 allows bottom-zone irrigation, where water flows through a porous stone and filter paper to the sample. This model also incorporates an upper piece for applying initial external load, weighing 12 grams and enables load increments using dead weights. Guides maintain piston direction, preventing lateral movement during testing. Specimen holder type 2 enables top-zone irrigation through a 2.5 mm diameter hole, also safeguarded by filter paper. It integrates with the load increment piece, facilitating simultaneous tests with increased total vertical stress and top irrigation.

3. Conclusions

The study showed that irrigation rate could affect capillary collapse in unsaturated granular soils, but further research is required for validation. With the development of this testing equipment, it is expected to assess the influence of factors such as the rate and direction of irrigation, and the initial state of vertical total stresses from a microscopic perspective using techniques such as X-ray computed tomography.

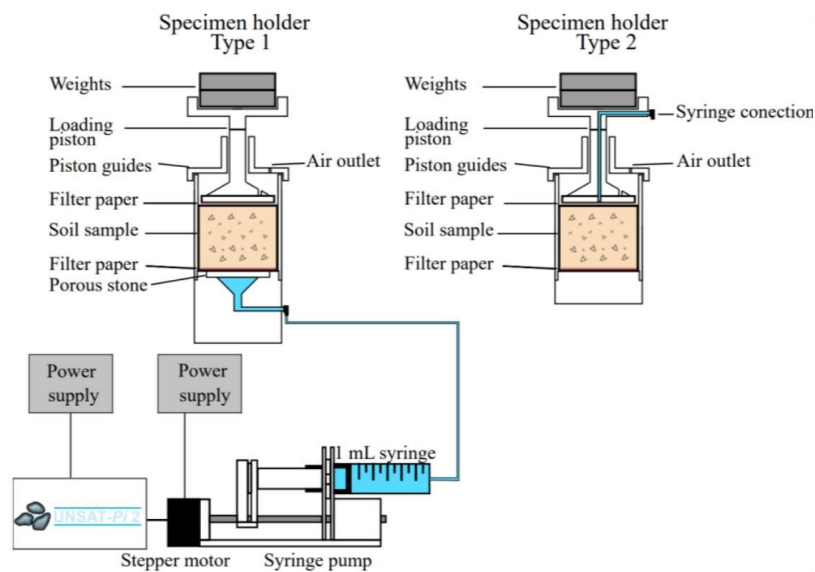


Figure 3. Schematic diagram of the proposed experimental setup design.

This work is funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) in the framework of the DFG project GR 1024/58-1 “Capillary collapse in unsaturated soils (KAKO).”

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