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A 3D-printed physical model of a 2D granular packing for experimental qualitative validation of multifluid LBM Simulations

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ABSTRACT: A miniature physical model of a two-dimensional granular packing was 3D-printed to experimentally investigate pore emptying during drainage and to support the validation of multifluid numerical simulations using the lattice Boltzmann method (LBM). The printed geometry directly replicates the grain configuration employed in the simulations, enabling a direct comparison between simulated and observed drainage behavior. The device is 40 by 24 millimeters. The grains are represented by disks attached to a back plate, and the device allows the insertion of a transparent plate in front of it, so that its drainage is visible and can be recorded. Printing lasted around 10 minutes. Water mixed with blue food dye was employed, and drainage was caused by gravity and by suction provided by a paper towel placed under the model. The top of the model was in contact with ambient atmospheric pressure. The observed pore emptying sequence and fluid distribution show good qualitative agreement with numerical predictions. Limitations of the physical model are primarily associated with 3D printer resolution and sample size. The results demonstrate that rapid 3D-printed physical models provide an effective and low-cost platform for validating pore-scale multiphase flow simulations in granular media.

1 INTRODUCTION

Numerical simulations are generally a powerful tool for investigating phenomena in soil. When addressing specifically fluid related mechanisms, such as the multiphase aspect of unsaturated soils or its coupled hydromechanical behavior, the lattice Boltzmann method (LBM) is frequently raised as the principal option, given its simpler equations and higher parallelizability (Huang *et al.*,2015). Hosseini *et al.* (2024) and Hosseini and Kumar (2025) are examples of the applications of this method for investigations of specific behaviors of unsaturated soil, respectively drainage-imbibition hysteresis of the soil water retention curve and parameter χ in the modelling of effective stresses.

These numerical results need to be validated[1] by experimental results. The usual methodology in this context is computed tomography, as performed by Wang *et al.* (2023) in their comparative studies. Although their work shows how powerful the tool is, this method is expensive and time consuming. For that, 3D printed physical models present themselves as a simpler and less time and resource consuming alternative. Although not many, other authors have resorted to 3D printing for validation of numerical simulations, such as Kitao *et al.* (2021) and Tong *et al.* (2017).

Additive manufacturing, commonly known as 3D printing, emerged in the late 1980s with the development of stereolithography and has since evolved into a versatile fabrication technology used in research, industry, and prototyping. Among the

[1] Validation, in contrast to verification, means checking the physical meaningfulness of the model, in a way to be able to affirm how close to reality it is. Verification, on its turn, means checking if the equations were implemented and are being solved correctly, which was done during the development of the code.

various materials available, polylactic acid (PLA) has become one of the most widely used thermoplastics, particularly in fused deposition modeling (FDM). PLA is derived from renewable resources such as corn starch and sugarcane, offering good printability, low warping, and minimal odor during processing. These properties make PLA especially suitable for rapid prototyping, educational use, and the production of geometrically complex components with moderate mechanical requirements.

In this context, this paper's objective is to present a 3D printed physical model developed to validate the multifluid LBM simulation results and conclusions presented in Toffoli *et al.* (2026). There, the numerical simulations are performed with three different multifluid methods with the objective of comparing their capabilities in the unsaturated soil context and elect the most suitable one. To support the conclusion obtained purely from the numerical results, the pore emptying order obtained there is compared to the pore emptying order from the physical model presented here.

The paper is structured as follows: Section 2 presents the methodology employed for designing and printing the piece, while Section 3 presents the obtained results and how they compare to the numerical results.

2 METHODOLOGY

The methodology is divided between the numerical part of the study and the experimental one. Since the focus here lies on the second part, the one about the numerical methods and their details is brief and general.

2.1 Numerical part: lattice Boltzmann method

The lattice Boltzmann method (LBM) is a computational fluid dynamics strategy able to model fluid and its interaction with complex geometries. The reader is referred to Krüger *et al.* (2017) and to Huang *et al.* (2015) for the detailed equations of the LBM in general and for the ones of each employed multifluid method.

The objective of the numerical part of the study, described in detail in Toffoli *et al.* (2026), is to compare the results provided by three different multifluid LBM when modelling unsaturated soils. From the available alternatives for that, those three are the ones most frequently employed in LBM studies in this context, although there is no comparison between them indicating which one is most suitable for the task, meaning it has the ideal relation between accuracy and efficiency.

The difference between the three multifluid methods resides in the strategy they use to acknowledge and track the two or more different fluids. The multiphase methods will deploy an equation of state, that relates density to pressure and consequently the phase of the fluid. The first multiphase method employed is the Shan-Chen multiphase, the MPSC (Shan and Chen, 1994). Phase separation in this method is induced by the so-called Shan-Chen force, which is calculated from the pseudopotential observed between two different points. The second multiphase method is the He-Chen-Zhang, the HCZ (He *et al.*, 1999), applied recently in Younes et al. (2023), and its way of tracking phases is via a second probability density function (PDF) dedicated to this end, which is based on some phase-field equation like Allen-Cahn or Cahn-Hilliard. The third method is not multiphase anymore, but multicomponent, meaning two different components represented by two different PDFs. Its name is the multicomponent Shan-Chen, the MCSC (Martys and Chen, 1996).

Regarding the numerical model set up, the drainage of an initially liquid saturated 2D granular packing with 44 grains was simulated with these three different multifluid strategies described above. Figure 1 presents the packing and its boundary conditions. For inducing drainage in the simulation, mass was removed from the bottom, below the dashes representing the porous stone.

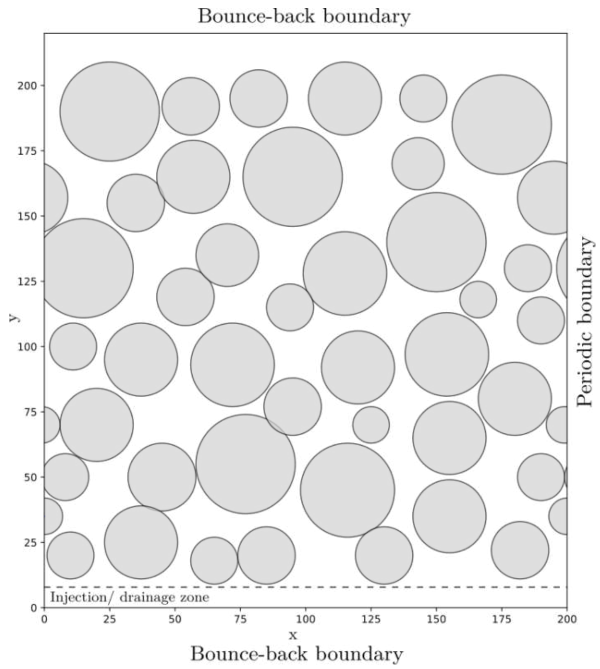


Figure 1. Simulated 2D granular packing.

2.2 Model design and 3D printing

The numerical simulations are two-dimensional, and thus the physical model consists of a back plate with disks attached to it, which emulate the grains. To represent the periodic boundaries on the sides, the domain was extended half its original size in each lateral direction. On the top, the model communicates with atmospheric pressure, and on the bottom the porous stone is emulated by dashes.

To close the front part of the model, a transparent sheet made of acrylic glass can be slid in tracks on the sides. This sheet is in direct contact with the disks representing the grains, and flow does not happen in this very narrow space.

The numerical simulations are run on a quasistatic regime, which means waiting for enough time steps between mass decrements for drainage. In this manner, the velocities of the fluids are very low and thus not important for the results. Fluid distribution and suction are the pursued values, and those results are the ones compared between the three numerical methods described above. Gravity is also absent in the simulation, so drainage is induced exclusively by this mass decrement under the porous stone, which is not possible to do in the physical model. This strategy makes the use of dimensionless numbers impossible, since the mechanism involved in the simulations is only capillarity. As a result, the similarity between the numerical and the physical models is mainly geometrical. Although this means that the model is rudimentary, it is still possible to compare liquid drainage paths between them and provide some physical counterpart for the comparison between the three numerical models.

The decisions regarding the size of the model were then based mostly on having a feasible physical model width for the printer, given its resolution restrictions. To have the smallest model possible then, 10 lattice units in the numerical model correspond to 1 millimeter in the physical one. The model was designed using the software Autodesk Inventor. Figure 2 presents its blueprints, namely top and side views. The measurements unit in them is millimeters.

Having decided on dimensions and designed the model with the appropriate software, it was printed by a 3D printer from Prusa, model MK4S, using PLA (polylactic acid) filament. The machine required around 5 minutes for printing the whole piece.

2.3 Drainage experiment

Blue food dye was mixed with water to improve contrast and visualization of the presence of the fluid in the pores. Drainage is induced by gravity and by the suction provided by a paper towel placed underneath the model and in contact with the fluid that is being drained.

The drainage experiment was performed with the physical model tilted, as presented in Figure 3, so that

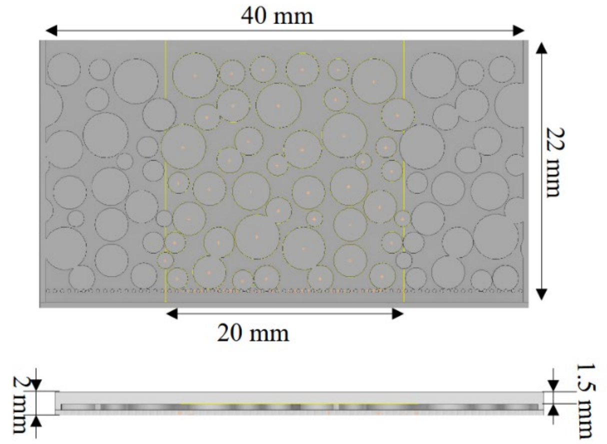


Figure 2. Front and top view of the physical model from software Autodesk Inventor. The simulation domain is that between the yellow lines.

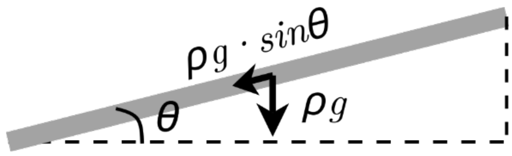


Figure 3. Lateral view of the tilted physical model.

the effect of gravity is severely reduced, since it is multiplied by the sin of the tilting angle (θ). The flow is thus slower and the pore emptying order is clearer. The angle used was around 10°, meaning the sample was almost horizontal.

Also, the Bond number can be calculated for the process: considering a density of water of 1000 kg/m³, a density of air of around 1 kg/m³, a surface tension between water and air at 25° C of 0.072 N/m and the average pore radius of 1 mm, the Bond number is around 0.14, which indicates a surface tension dominated process, confirming that gravity is not dominant.

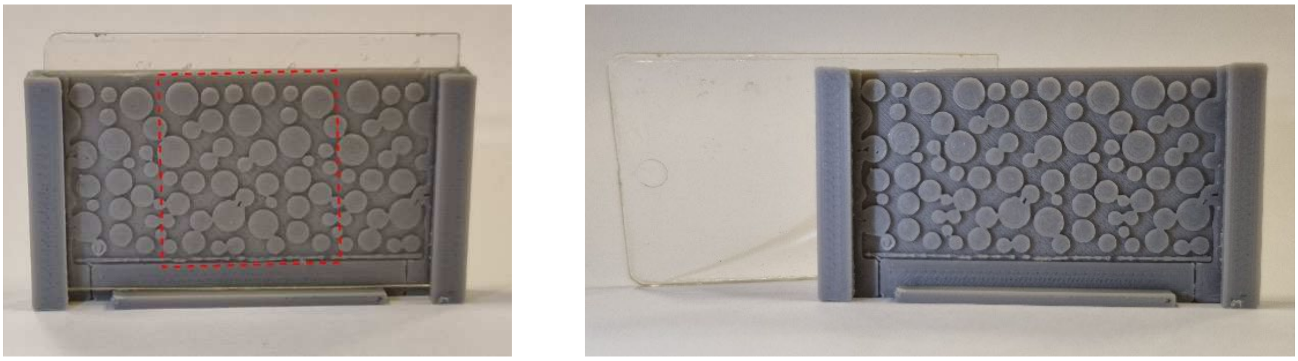
3 RESULTS

3.1 Numerical results

Since the focus of this paper is not on the numerical results, they are not going to be presented or discussed in detail. For more information on the comparison between the three numerical methods, refer to Toffoli *et al.* (2026).

3.2 Physical model manufacturing

Figure 4 presents the printed model and the region of interest for comparison with numerical simulation results.

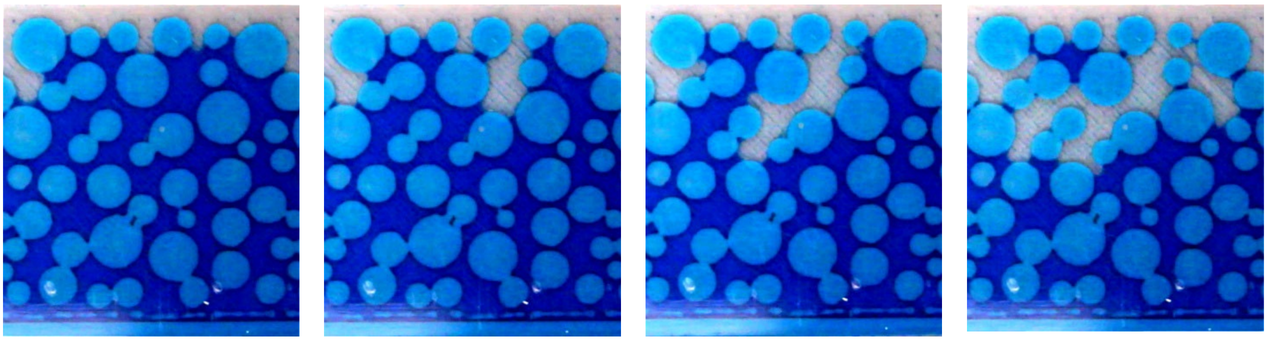


(a) Front piece slid in. *(b) Front piece not slid in.*

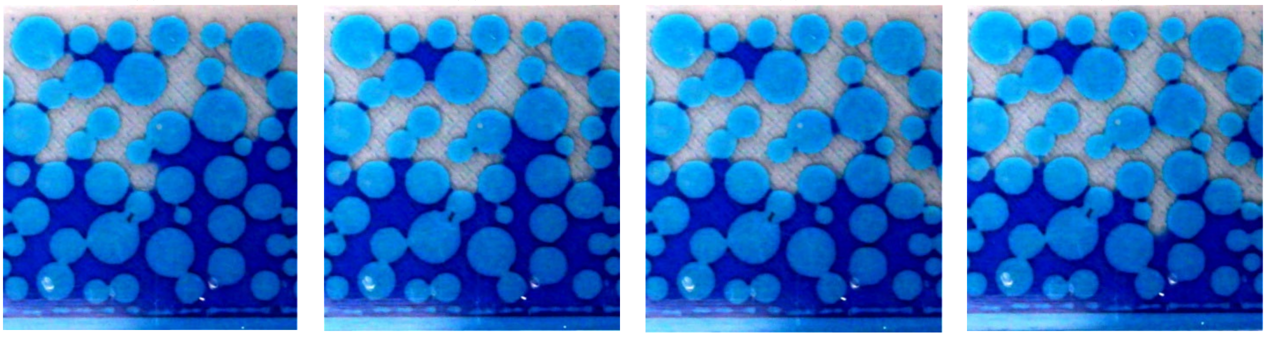
Figure 4. 3D printed physical model of the simulated media.

3.3 Drainage experiment

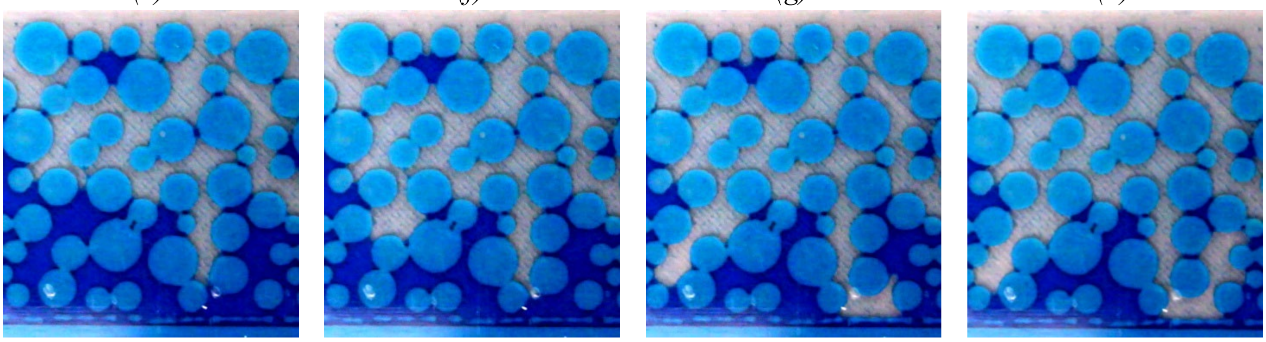
The drainage of the model was performed according to the conditions described in Subsection 2.3. Drainage took around 10 seconds.



(a) *(b)* *(c)* *(d)*



(e) *(f)* *(g)* *(h)*



(i) *(j)* *(k)* *(l)*

Figure 5. Physical model: fluid distribution at different points of drainage.

Snapshots of the fluid configurations during the drainage process are presented chronologically in Figure 5.

The results indicate that the physical model is a simple and unsophisticated but still efficient alternative for validating numerical models on fluid flow and multiphase behavior, especially for 2D configurations. Drainage happened as expected and capillarity had a significant effect during the process, given that the water level did not lower simultaneously and horizontally across the whole model. Also, between the front part of the disks representing the grains and the transparent front piece there was no flow, which is evidenced by the blue shade they keep until Figure 5(l). The limitations are mostly linked to the size of the model. Given the printer possibilities, it is not viable to obtain much smaller dimensions.

Although the numerical results are not the focus, a superficial comparison between the numerical simulations results and those in Figure 5 is still drawn. It is observed that all three methods capture the pore emptying order well at higher saturations, but the multiphase methods capture it better at lower saturations. For a detailed discussion, the reader is referred to Toffoli *et al.* (2026). To illustrate this, the fluid distribution resulting from the MPSC method simulations is presented for different points in time in Figure 6.

Since the model was drained almost horizontally, it is possible to affirm that drainage was induced mostly by the suction provided by the paper towel.

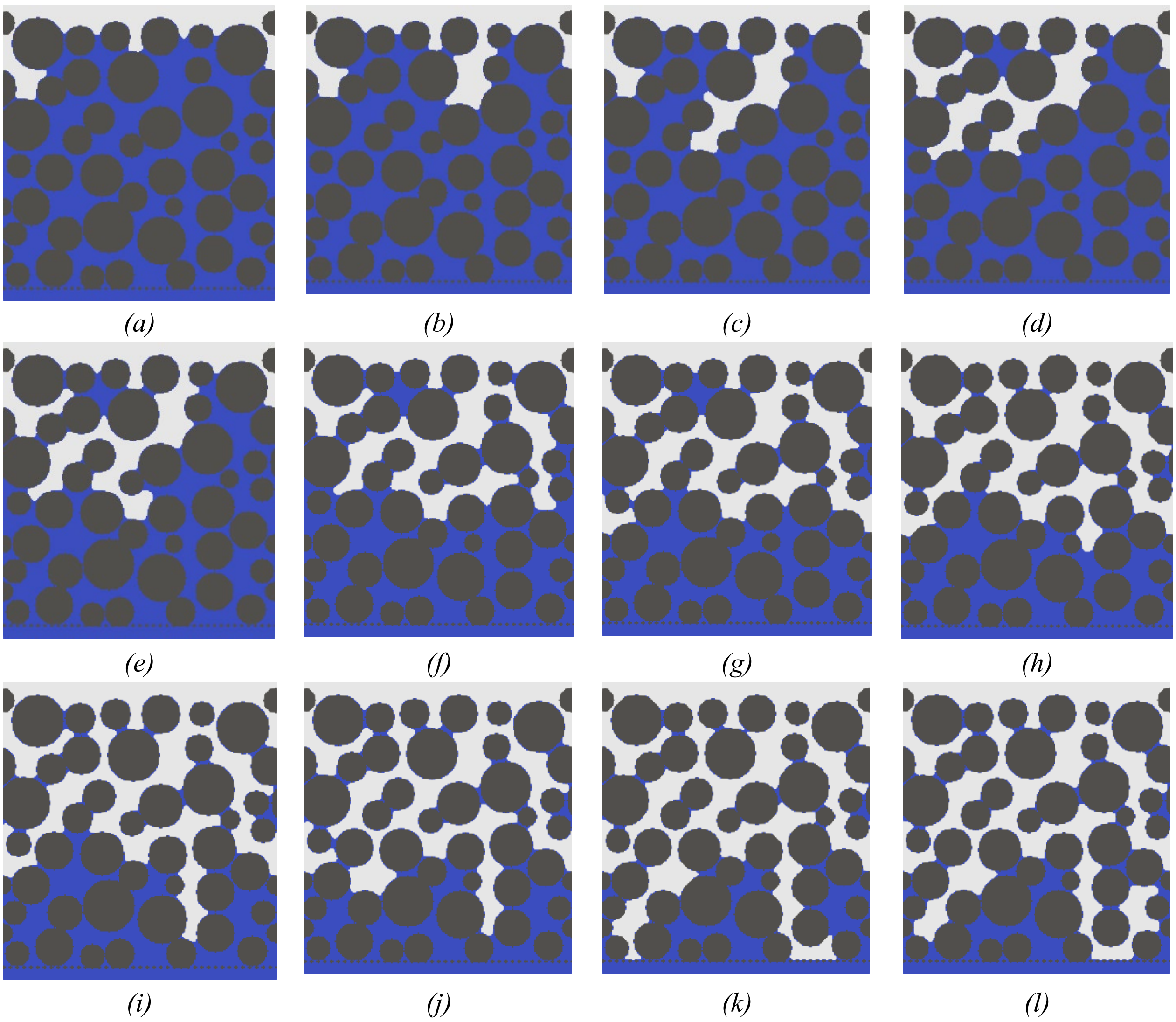


Figure 6. MPSC numerical model: fluid distribution at different points of drainage.

Gravity is then not an important difference between physical and numerical models, given that the numerical one does not consider gravity and drainage happens solely by a mass/volume removal on the bottom, below the porous stone.

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4 CONCLUSION

This paper proposes a 3D printed physical model as an experimental alternative to validation of numerical simulations. This use of physical models in literature is so far narrow, and even though the technique has its limitations, it can be a valuable alternative for fitting problems. The 3D printed model managed to reproduce the simulation configuration and a very close match was observed between the numerically and experimentally obtained pore emptying orders.

In the future, the physical model could be built in a more sophisticated manner by adding a pressure sensor to measure the liquid-phase pressure. This sensor would require some simple computer as well, like a RaspberryPi, to read and store the measurements. Apart from that, in another direction, 3D models could also be attempted, but a concept for the visualization of the fluid distribution inside the piece requires better elaboration.

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