DISCONTINUOUS PORE FLUID DISTRIBUTION UNDER MICROGRAVITY DUE TO PARTICLE REARRANGEMENT

Ming Xiao¹,*, Lakshmi N. Reddi², and Susan L. Steinberg³

¹ Department of Civil and Geomatics Engineering, M/S EE94. California State University, Fresno, CA 93740. USA
*e-mail: mxiao@csufresno.edu, web page: http://www.csufresno.edu
² Department of Civil and Environmental Engineering, University of Central Florida, Orlando, FL 32816, USA
³ Universities Space Research Association, Mail Code EC3, Building 29, Room 110, NASA Johnson Space Center, 2101 NASA Rd 1, Houston, TX 77058, USA

Summary. This paper reports (i) the experimental investigation conducted aboard the NASA’s KC-135 reduced-gravity flights to study possible particle separation and the distribution of discontinuous wetting fluid in porous media under microgravity, and (ii) numerical study of the effect of soil particle rearrangement on the water retention characteristics in zero gravity.

Keywords: microgravity, network model, particle rearrangement, pore fluid, porous media, water retention characteristics.

1 INTRODUCTION

The study reported in this paper is part of a long-term fundamental research investigation involving design of plant growth systems for crop production under microgravity. Spatial distribution of wetting fluid as well as size distribution of discontinuous pore fluid ganglia under microgravity may strongly impact plant growth conditions, such as water transport and intake by the root in the soil substrate. With gravity, excess water drains along a vertical gradient, and water recovery is easily accomplished; under microgravity, the distribution of water is less predictable and can easily lead to localized over-moistening or anoxia [1].

2 EXPERIMENTAL INVESTIGATION

2.1 Methodology

Parabolic flight of KC-135 aircraft offers researchers reduced gravity in the order of $10^{-2}$ g for up to 25 sec. The short microgravity period facilitates investigations on the role of gravity in fundamental physical processes. In this study, glass beads were used as porous media. Hexadecane, a petroleum compound immiscible with and lighter than water, was used as wetting fluid at residual saturation in glass beads. The higher freezing point of hexadecane (18°C) allowed the relatively quick onboard solidification of discontinuous pore fluid entrapped in glass beads, so that their size distribution could be measured using wet sieving after the flight. The experiments were conducted onboard NASA’s KC-135 flight in February 2004. Figure 1 depicts a representative flying profile of the KC-135 flight. The plane simulated varying gravity conditions by flying in parabolic profile, including a 25-sec 1.8g environment while gaining altitude at a
45-degree angle upward, a 25-sec microgravity environment at the top of the parabola, and another 25-sec 1.8g condition when the plane dives downwards. A nitrogen freezer (−150°C) was used to freeze the hexadecane pore fluids under 1g, 1.8g, and 10−2 g. Within the wall matrix of the freezer, liquid nitrogen was adsorbed and could spill out under microgravity. Three samples were put into the freezer prior to the 25s of microgravity — one before flight’s takeoff, one during the cruising of the flight (1g), and one when 1.8g was reached in the cabin. During the first 10 sec of the 25-sec microgravity, the glasses beads that encapsulated hexadecane pore fluid were free to rearrange, and then the capsule that contained the specimen was carefully put in the freezer that was able to freeze the hexadecane liquid in 15 sec and therefore preserve the changes that occurred in microgravity. Four KC-135 flights were conducted with one flight per day. The same procedure was repeated during the other 3 days of flights to test the reproducibility. After the flights, the measurements of the blob size distribution (BSD), which simulated the pore size distribution corresponding to residual saturation, were conducted in a constant-temperature room at 6°C. Then statistical analyses using the Kolmogorov-Smirnov test were conducted to verify whether the BSDs under the gravity conditions were significantly different from each other.

2.2 Experimental Results and Analyses

The measured hexadecane BSDs of the 16 samples are presented in terms of cumulative distributions. Figure 2 shows representative four BSDs from the Day-4 experiments, in which the BSDs are the pore fluid distributions under 1g on ground (labeled as G-1g), 1g in the air (A-1g), 1.8g in the air (A-2g) and microgravity in the air (A-0g). The Kolmogorov-Smirnov analysis concluded that the pore fluid distributions did not change when the gravity condition changed from 1g on ground to 1g in the air, from 1g to 1.8g, and from 1.8g to 10−2g. Discontinuous pore fluid ganglia showed no noticeable breakup or coalescence during microgravity.

3 THEORETICAL INVESTIGATION

3.1 Model Formulation

In order to provide an understanding of the effect of particle rearrangement on water retention characteristics under microgravity, a three-dimensional pore network model is developed, based on a two-dimensional network model proposed by Payatakes et al. [2], Ng et al. [3], and Payatakes et al. [4]. In a porous medium, an
irregular pore can be idealized as a pore body with pore throats (Figure 3a). The pore body diameter, the pore length, and the volume of the unit cell can be calculated using the pore throat diameter. The formulae were presented by Payatakes et al. [4]. The pore network is made of three-dimensional elemental pores, i.e., conceptual elemental void space (CEVS). Each CEVS consists of six half-unit-cells in the three dimensions. The six half-unit-cells in a CEVS can have different sizes, and together they make up of one 3D conceptual pore. Figure 3b shows a 3D pore network with dimension of $2 \times 2 \times 2$ CEVSs. This study uses Ottawa sand whose particles are spheroid and have rough surface. The pore size distributions are represented using the pore throat distributions, which are derived from grain size distribution based on two extreme particle arrangements—the most compact rhombohedral and the most porous cubic packing. The model is then used to reveal the variation of water retention characteristics and the spatial distribution of pore fluid due to particle rearrangements.

![Fig. 3a. Unit cell simulating a pore](image1.png)  ![Fig. 3b. 3D pore network model (2×2×2 CEVS) (image2.png)]

### 3.2 Model Results

Particle rearrangement under zero gravity could happen *during* the drying or rewetting process, resulting in a “dynamic” pore size distribution and temporal change of water retention characteristics. This model studies the changes in water retention characteristics of Ottawa sand during the drying process due to particle rearrangement. The Ottawa sand is initially saturated under the cubic packing. At suction head of 10cm and volumetric water content of 0.46, the particle arrangement changes to rhombohedral packing. After that, the drying process continues under the new rhombohedral packing. Figure 4 shows that after the particle rearrangement the drying curve follows the drying curve of the original rhombohedral-packing. If the particle rearrangement (from cubic to rhombohedral packing) occurs at suction head of 14cm when the volumetric water content was close to the residual water content, the drying curve changes little and it continues to follow the water retention curve under the cubic packing. The simulations indicate that water retention characteristics are less affected by the particle rearrangement at low water content than at high water content. Figure 5 shows the predicted pore water spatial distributions in 3D pores ($10 \times 10 \times 5$ CEVS) during a drying process under 0g. Figure 5a shows the spatial distribution of pore water (represented in black) in the pore network in the cubic packing, in which 36 CEVSs are occupied by water; Figure 5b shows the pore water distribution after the
particles re-arrange from cubic to rhombohedral packing at a suction of 14 cm during the drying process and 52 CEVSs are occupied by water. Figure 5 suggests that the pore fluid is not uniformly distributed. The model results are in agreement with the study by Podolsky and Mashinsky [5] who observed local over-moistening in a substrate sample aboard the “Salyut-7” and “Mir” space stations.

4 CONCLUSIONS

The experimental research indicates microgravity has little effect on the size distribution of pore fluid blobs corresponding to residual saturation of wetting fluids in porous media. The blobs showed no noticeable breakup or coalescence during microgravity. The model simulations indicate increased hysteresis when particle arrangement changes from loose condition to compact condition. Particle rearrangement (from cubic to rhombohedral packing) significantly alters the water retention characteristics when the porous medium is nearly saturated. When the porous medium is close to residual saturation, water retention characteristics are almost unaffected by the particle rearrangement. Pore fluid spatial distribution in the porous media (Ottawa sands) is found to be non-uniform under zero gravity.

REFERENCES