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A new method for measuring long-term infiltration rate with 0.4 sec-microgravity generated by a 2 m high drop tower

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Abstract: Understanding water behavior in porous media in microgravity conditions is essential for growing soil-cultivated crops in outer space. A drop tower is a cost-effective method to generate microgravity environments. Still, it provides only a few seconds or less microgravity, which is insufficient for observing time-consuming phenomena such as infiltration in soil. In this study, we proposed a new infiltration procedure, where infiltration occurred repeatedly for 0.4 s μG conditions generated by a 2 m high drop tower. The infiltration for the next 0.4 s μG proceeded after a new wetting front location was initiated by manually advancing the wetting front. Repeating this procedure, referred to the intermittent infiltration procedure hereafter, enabled us to observe long-term infiltration under microgravity condition. We measured infiltration rates in glass beads of 0.4 mm and 2 mm diameter using the intermittent infiltration procedure. The infiltration rate for 0.4 mm glass beads agreed with that observed in the continuous infiltration experiment, although that for 2 mm glass beads was underestimated. We anticipated that this limitation could be overcome by utilizing higher drop towers capable of generating several seconds of microgravity. The intermittent infiltration procedure opened affordable measurements of soil physical parameters under microgravity to address challenges associated with repetitive experiments. Numerical simulations were also conducted to evaluate the intermittent infiltration, assuming porous media as a bundle of capillaries, by comparing infiltration rates between continuous infiltration over an extended period and intermittent infiltration by integrating 0.4-second infiltration. For capillaries with a 0.3 mm inner diameter, the infiltration rates for intermittent and continuous infiltration remained consistent. However, the inertial regime must be considered for capillaries with an inner diameter greater than 1.5 mm, leading to underestimating infiltration rates.

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1. Introduction

The International Space Exploration Coordination Group (ISECG), which comprises 27 space agencies, including the Japan Aerospace Exploration Agency (JAXA), aims to achieve a manned lunar mission in the 2020s and a manned Mars mission after 2030 (ISECG, 2024). As these missions are expected to be long-term, transporting food and other supplies solely from Earth is technically and economically unfeasible (Kitaya, 2016). Therefore, realizing space agriculture onboard spacecraft is required for crop production.

However, crop production in porous media under microgravity (μG) faces significant challenges in controlling water supply, such as poor water absorption (Massa et al., 2017; Bingham et al., 2000). Since soil physical properties observed under Earth's gravity (1 G) may not be linearly interpolated under μG (Mohamed et al., 2002), measurements under μG conditions are essential.

Several methods generate μG environments, lasting months to years for space stations, minutes for sounding rockets, tens of seconds for parabolic flights, and less than a few seconds for drop towers (Kogure, 2007). Although space stations and parabolic flights offer longer μG environments to allow onboard manual operation of experimental equipment, using these facilities is limited due to the cost. Despite these limitations, they have been utilized to study infiltration phenomena in porous media, e.g., Yendler et al. (1996) and Mohamed et al. (2002). Yendler et al. (1996) reported reduced infiltration rates in 1.5-mm glass beads under μG in the Mir space station compared to 1 G. Similarly, Mohamed et al. (2002) observed decreased infiltration rates in mixed silica sand and kaolinite samples during parabolic flights. Conversely, Sato et al. (2024) found no reduction in infiltration rates for 0.2 – 0.6

mm glass beads, meaning consistent results with those under 1 G, under μG generated by parabolic flights. These contradictory findings highlight the complexity of understanding gravity's impact on infiltration in porous media and the need for further investigation. Limited experimental opportunities raise concerns about statistical reliability, highlighting the challenges associated with μG studies (Yendler et al., 1996).

Sato et al. (2019) explored using a three-dimensional clinostat, which simulated μG by randomly rotating samples, to address the difficulty of repeatedly conducting μG experiments. The clinostat failed to eliminate gravity-driven infiltration in high permeable porous media such as Toyoura sand, proving unsuitable for simulating infiltration under actual μG conditions.

Among the available methods, drop towers are the most cost-effective for repeated experiments. However, their extremely brief μG duration (less than a few seconds) limits their application to phenomena that reach equilibrium quickly, such as droplet contact angle measurements (Naganuma et al., 2020). There have been no reports of drop towers being used to study time-consuming processes such as infiltration in porous media, although they have been long required.

In this study, we developed a novel procedure to conduct experiments for long-term infiltration by repeatedly observing small amounts of infiltration during brief μG intervals using a 2 m high drop tower applying step-wise initial infiltration distances. We evaluated whether our proposed procedure could accurately replicate continuous infiltration phenomena, thereby expanding drop tower application for μG research.

2. Theory

Under conditions where gravitational effects on infiltration are negligible, such as horizontal infiltration or under μG, the infiltration distance L is proportional to the square root of the elapsed time t (Washburn, 1921):

$$L = \lambda\sqrt{t} \tag{1}$$

Similarly, the cumulative infiltration I is proportional to the square root of t (Miyazaki et al., 2005):

$$I = S\sqrt{t} \tag{2}$$

Here, the proportionality coefficients λ and S are called the degree of infiltration and sorptivity, respectively, and are indicators of the ease with which water infiltrates porous media. To determine λ and S based on these equations, the relationship between t and L or I needs to be known, which typically requires continuous and prolonged observation of infiltration.

We squared both sides of Eq. (1):

$$L^2 = \lambda^2 t \tag{3}$$

Differentiating Eq. (3) with respect to t yields:

$$\frac{d}{dt}L^2 = \lambda^2 \tag{4}$$

Multiplying both sides of Eq. (4) by dL/dL, we obtain:

$$\frac{d}{dL}L^2 \cdot \frac{dL}{dt} = \lambda^2 \tag{5}$$

Equation (5) simplifies to:

$$2L \cdot \frac{dL}{dt} = \lambda^2 \tag{6}$$

By dividing both sides of Eq. (6) by $2L$ ($L \neq 0$), the relationship between the infiltration rate dL/dt and the infiltration distance L is expressed as:

$$\frac{dL}{dt} = \frac{\lambda^2}{2L} \qquad (L \neq 0) \tag{7}$$

From Eq. (7), λ can be determined from the relationship between the infiltration distances L and the infiltration rate dL/dt. Even under discontinuous and short-time μG conditions, it is possible to measure dL/dt for a specified infiltration distance L by allowing the wetting front to advance to a new location (referred to the initial infiltration distance hereafter) under 1 G before the next μG experiment and observing the subsequent infiltration distance under μG. By adjusting the initial infiltration distance and repeatedly measuring dL/dt under μG, λ can eventually be evaluated under those conditions.

Similarly, transforming Eq. (2) yields:

$$\frac{dI}{dt} = \frac{S^2}{2I} \qquad (I \neq 0) \tag{8}$$

This allows S to be evaluated without the need for prolonged continuous infiltration observations, similar to λ.

This approach, hereafter called the intermittent infiltration procedure, enables estimating infiltration properties under conditions where continuous observations are impractical. In this study, we investigated its applicability to evaluate infiltration under short-duration μG conditions.

3. Materials and Methods

3.1 Numerical simulations

The intermittent infiltration procedure was investigated using numerical simulations. By assuming the porous me-

dia as a bundle of capillaries (Dullien, 1979), the infiltration phenomenon in capillaries under μG can be described as:

$$\frac{d(m\bar{v})}{dt} = f_{\mathrm{cap}} + f_{\eta} \tag{9}$$

where m is the mass of the infiltrating fluid, $\bar{v}$ is the infiltration rate, t is time, f_{cap} is the capillary force, and f_{η} is the viscous force (Amara and Nasrallah, 2011). These forces are expressed as:

$$f_{\mathrm{cap}} = 2\pi R\sigma\cos\theta \tag{10}$$

$$f_{\eta} = -8\pi\eta z\frac{dz}{dt} \tag{11}$$

where R is the capillary radius, σ is the surface tension, θ is the contact angle, η is the viscosity, and z is the infiltration distance. The mass m is further expressed using the density of water ρ :

$$m = \rho\pi R^2 z \tag{12}$$

Equation (9) was solved using the Runge-Kutta method to obtain the numerical solution for the infiltration rate. Infiltration rates from long, continuous infiltration processes in capillaries with inner diameters of 0.3 mm, 1.5 mm and 3.0 mm were compared with those from intermittent infiltration experiments involving repeated progression and cessation of infiltration. In the long continuous infiltration processes, the initial infiltration distance was set to 0.0001 m, and infiltration was simulated for 20 s to determine the relationship between L and dL/dt. In the intermittent infiltration experiments, the initial infiltration distance was varied from 0.0001 m to 0.4 m in increments of 0.01 m, and infiltration was simulated for 0.4 s at each initial infiltration distance to obtain the corresponding infiltration rate. The physical properties of water were used as simulation parameters: $\sigma = 0.0072$ N m^{-1}, $\eta = 0.001$ Pa s, $\rho = 1000$ kg m^{-3}, and $\theta = 0^{\circ}$. For the intermittent infiltration experiments, infiltration durations of 0.4 seconds (representing a 2-meter high drop tower) and 2.4 seconds (representing a 50-meter high drop tower) were used.

3.2 Intermittent infiltration experiments with a drop tower

We designed the following experimental equipment to determine the infiltration rate of porous media under μG through intermittent infiltration experiments. A schematic diagram for the experimental apparatus is shown in Fig. 1. A transparent acrylic cylindrical column (inner diameter: 24 mm, length: 135 mm) filled with porous media was placed vertically and connected to a water reservoir at the lower end. A porous plate made of wire mesh (2 mm apart between wires) covered with cheesecloth was placed at the lower end of the column. The upper end of the column was sealed with a rubber stopper with a 5 mm diameter hole at the center, and a paper towel was positioned between the stopper and the porous media.

Glass beads with diameters of 0.4 mm (BZ-04, AS ONE corp.) and 2 mm (BZ-2, AS ONE corp.) were used as porous media. The glass beads were cleaned with neutral detergent, rinsed 10 times with distilled water following Lu et al. (1994), and then oven-dried at 110 °C for at least 24 hours. Before being used in experiments, the glass beads were cooled in a desiccator to room temperature. During filling the porous media into the column, the column was gently tapped to achieve uniform bulk density, resulting in dry bulk densities of 1.63 $\pm$ 0.01 Mg m^{-3} for the 0.4 mm beads and 1.54 $\pm$ 0.01 Mg m^{-3} for the 2 mm beads. Rubber gloves were consistently worn when handling glass beads, including cleaning, drying, and packing.

A transparent acrylic cylinder (inner diameter: 6 mm, length: 150 mm) was used as the water reservoir. Unlike horizontal infiltration experiments under 1 G, which often use a Mariotte bottle to eliminate hydraulic head pressure at the inlet (Sato and Noborio, 2018), such adjustments are unnecessary under μG due to minimal gravitational acceleration. However, the capillary force of the water source must be significantly smaller than that of the porous media since capillary forces dominate under μG (Maruo et al., 2019). The capillary force Δp was calculated using the Laplace equation (Jury and Horton, 2004):

$$\Delta p = \frac{2\sigma\cos\gamma}{r} \tag{13}$$

where σ is the surface tension of water (N m^{-1}), γ is the contact angle, and r is the pore radius (m). At 25 °C, the capillary force of the acrylic cylinder was 8.16 N m^{-2},

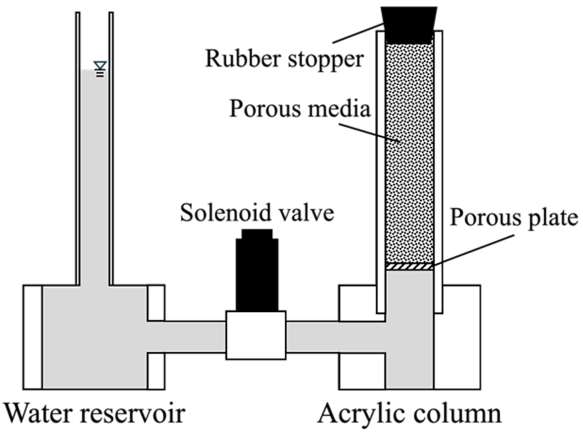


Fig. 1 Diagrammatic illustration of experimental apparatus.

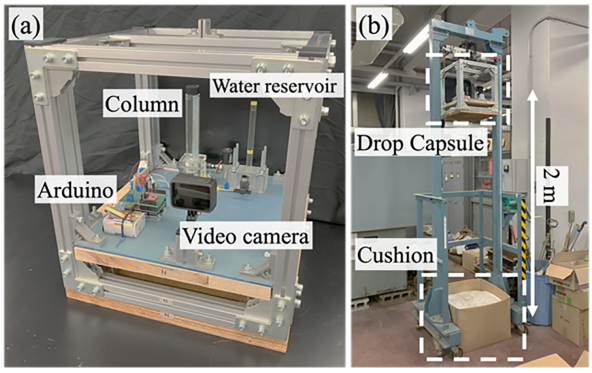


Fig. 2 Photographs of (a) a drop capsule and (b) a 2 m drop tower.

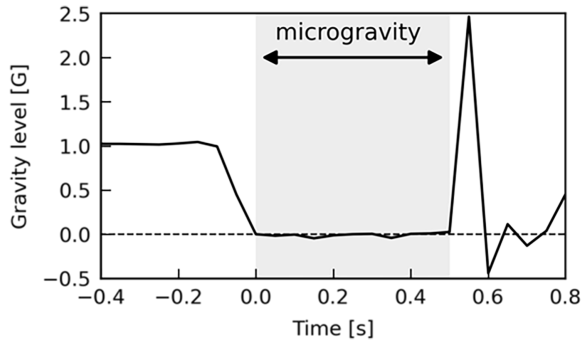


Fig. 3 Temporal gravity levels of 2 m drop tower.

which was significantly smaller than the capillary forces calculated from the equilibrium capillary rise height for the glass beads porous media (0.4 mm: 200.50 N m^{-2}, 2.0 mm: 88.03 N m^{-2}).

The porous column and water reservoir were connected via a solenoid valve controlled to open only under μG. The valve was managed by an Arduino UNO microcontroller (Arduino) and triggered for 0.4 seconds when gravitational acceleration along the Z-axis dropped below 0.25 G for at least 0.1 seconds, as detected by an acceleration sensor (MMA7361, Cixi Borui Technology Co., Ltd.). An LED status indicator that lights during the valve opening was fixed in front of the porous column to enable the valve operations to be grasped during image analysis. A video camera (GoPro Hero 9) was positioned 20 cm away from the column and recorded the temporal changes of the wetting front and water level of the water source in Full HD (1920 $\times$ 1080 pixels) at 60 fps. The resolution was 0.27 mm per pixel.

All experimental apparatus were fixed on a drop capsule made of an aluminum frame (40 $\times$ 40 $\times$ 45 cm). The experimental setup is shown in Fig. 2a. The drop capsule was dropped in a 2 m high drop tower (Fig. 2b) in the laboratory. Fig. 3 shows the temporal changes in gravitational acceleration. The μG environment lasted approximately 0.5 seconds. A cushion at the landing point mitigated landing impact forces. Initially, the apparatus was immediately lifted and re-dropped for repeated infiltration measurements. However, this method introduced errors due to the re-infiltration of previously wetted pores, as described in the results and discussions section. The procedure was refined by advancing the infiltration front 5 – 10 mm using a syringe before each subsequent drop. The drop experiment was conducted immediately after creating a new infiltration front to prevent evaporation, which could alter the contact angle if too much time elapsed before the next drop.

The modified procedure was conducted 30 times for the 0.4 mm glass beads and 33 times for the 2 mm glass beads. The infiltration rate dI/dt during the 0.4-second was calculated using the following equation,

$$\frac{dI}{dt} = \frac{dH \cdot A_\mathrm{w}}{A_\mathrm{c} \cdot dt} \tag{14}$$

where dH represents the changes in the water level in the water reservoir, A_w is the cross-sectional area of the water reservoir, A_c is the cross-sectional area of the porous column, and dt is the infiltration time. The changes in water level (dH) were analyzed using Python's OpenCV library (Open CV, https://opencv.org (accessed on December 12, 2024)).

3.3 Continuous infiltration experiment

A continuous infiltration experiment was conducted to investigate the differences in infiltration rates measured by the proposed intermittent infiltration experiment and the conventional continuous infiltration experiment (commonly referred to as the horizontal infiltration experiment in other studies). In this experiment, we observed continuous and prolonged infiltration in horizontally placed porous media under 1 G. Following the method described by Sato et al. (2024), a horizontally positioned porous media-filled column was connected to a Mariotte water reservoir. Infiltration was initiated by removing air between the water reservoir and the column using a syringe. During the experiment, the elapsed time after the start of infiltration, the infiltration distance, and the total infiltration volume were recorded. From the continuous infiltration experiment results, S was calculated using Eq. (2), and subsequently, the infiltration rate dI/dt was computed from Eq. (8). These values were then compared with the infiltration rates obtained from the intermittent infiltration experiments.

4. Results and Discussion

4.1 Numerical simulations

The results of numerical simulations for capillaries with

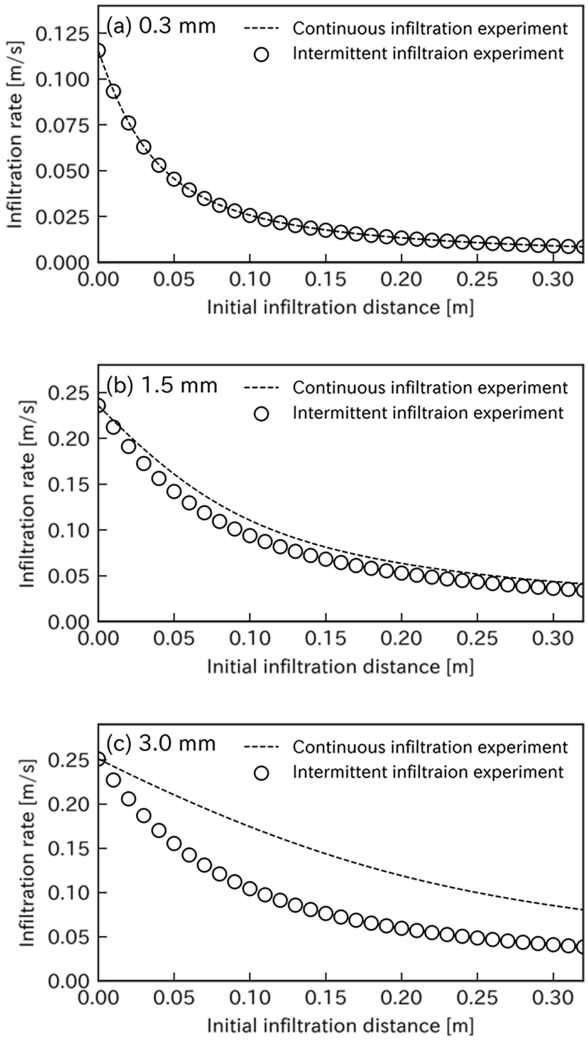


Fig. 4 Simulation results of infiltration rate in three capillaries: (a) 0.3 mm diameter, (b) 1.5 mm diameter and (c) 3.0 mm diameter.

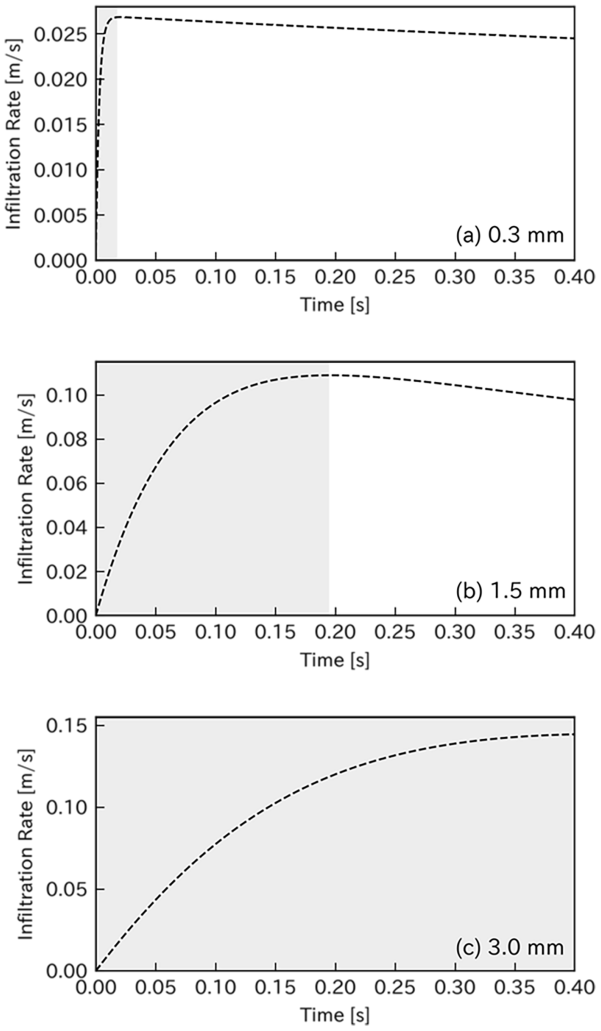


Fig. 5 The duration of the inertia regime(shaded): (a) 0.3 mm diameter, (b) 1.5 mm diameter, and (c) 3.0 mm diameter.

inner diameters of 0.3 mm, 1.5 mm, and 3.0 mm are shown in Fig. 4. For the 0.3 mm inner diameter, the infiltration rates observed in the continuous and intermittent infiltration experiments were identical (Fig. 4a). In contrast, for the 1.5 mm and 3.0 mm inner diameters, the infiltration rates measured in the intermittent infiltration experiments were lower than those in the continuous infiltration experiments (Figs. 4b and 4c).

Fig. 5 shows the temporal changes in the infiltration rate at an initial infiltration distance of 100 mm, i.e., the wetting front was located at 100 mm away from the column end, during the intermittent infiltration experiment. The infiltration rate initially increased due to the movement of the gas-liquid interface, which began infiltrating into the capillaries but subsequently decreased. The region where the infiltration rate increases is called the “inertial region”, where the inertial force acting on the liquid column dominates the infiltration rate (Quéré, 1997). Conversely, the subsequent decline corresponds to the “viscous region”, where viscous friction between the liquid column and the capillary wall becomes dominant.

The time for the liquid moving in the inertial region is short enough to be negligible when observing infiltration over long, continuous periods. Thus, infiltration rate measurements for porous media generally refer to the viscous region. In this experiment, the inertial region for the 0.3 mm inner diameter capillary (Fig. 5a) was approximately 0.018 s, which is negligible compared to the 0.4 s infiltration time. Consequently, the results of the intermittent and continuous infiltration experiments for the 0.3 mm inner diameter capillary were consistent.

For capillaries with 1.5 mm and 3.0 mm inner diameters, the inertial regions lasted 0.195 s and 0.428 s, respectively (Figs. 5b and 5c). These durations are significant relative to the 0.4 s infiltration time, leading to underestimating the infiltration rate in the intermittent infiltration experiment. This discrepancy arises because the contribution of the inertial region cannot be neglected within the limited infil-

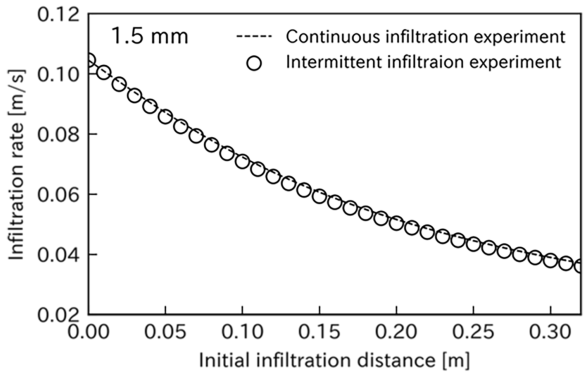


Fig. 6 Simulation results of infiltration rate in 1.5 mm diameter capillary with 2.4 sec intermittent infiltration experiment.

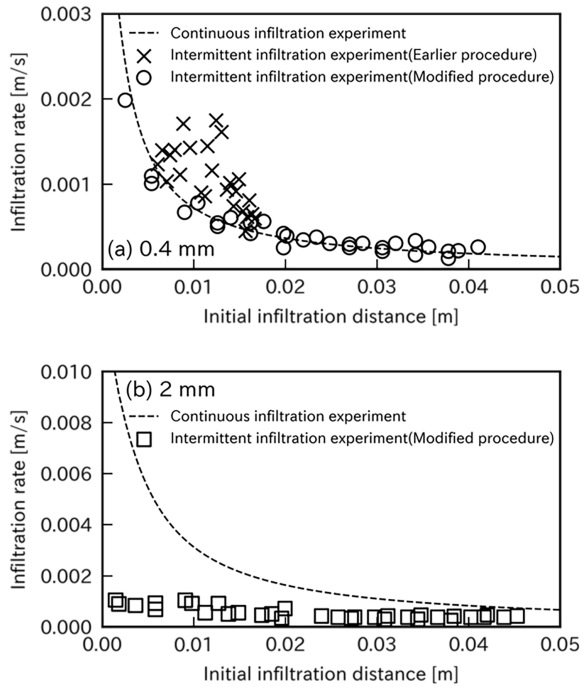


Fig. 7 Infiltration rates measured by intermittent infiltration experiment with 2 m drop tower: (a) 0.4 mm diameter glass beads and (b) 2 mm diameter glass beads.

tration time. Therefore, the intermittent infiltration experiment using a 2 m drop tower is unsuitable for capillaries with inner diameters larger than 1.5 mm.

However, longer μG durations could enable accurate infiltration rate measurements for capillaries with larger inner diameters. For instance, the 50 m high drop tower (COSMOTORRE, Hokkaido Space Science and Technology Creation Center) in Akabira, Hokkaido, provides a μG duration of 2.4 s (Maruo et al., 2022). Numerical results for the infiltration rate of a 1.5 mm inner diameter capillary measured with a 2.4 s intermittent infiltration experiment are shown in Fig. 6. The infiltration rates from the intermittent and continuous infiltration experiments were generally consistent, attributed to the diminished impact of the inertial region over the extended infiltration time.

4.2 Intermittent infiltration experiments with a 2 m high drop tower

Fig. 7a shows the infiltration rates of continuous infiltration experiments conducted under 1 G and intermittent infiltration experiments conducted under μG using 0.4 mm diameter glass beads. The crosses in Fig. 7a represent the results from an earlier procedure in which the experimental apparatus was immediately free-fallen again after landing. In these cases, the infiltration rates measured in the intermittent infiltration experiments were greater than those in the continuous infiltration experiments. This overestimate was attributed to the receding wetting front caused by the capsule's landing impact. The new wetting front reinfiltrated previously wetted pores, which were formed by the earlier receding wetting front, under the subsequent μG condition (Fig. 8a). Since previously wetted pores have a smaller contact angle, the capillary force acting on the liquid increases, resulting in an elevated infiltration rate.

To address this issue, the experimental procedure was modified. After the capsule landed, we advanced the wetting front by 5 – 10 mm before the capsule was dropped again (Fig. 8b). The circles in Fig. 7a show the infiltration rates measured after this modified procedure. They were consistent with the results of the continuous infiltration experiments. This result was consistent with previous experiments using 0.4 mm diameter glass beads under 1 G and 18-second μG conditions, simulated by parabolic flight (Sato et al., 2024). By preventing the wetting front recession resulting from landing impact, the infiltration rate could be accurately evaluated even under short μG durations.

In contrast, the infiltration rate measured for 2 mm diameter glass beads in the intermittent infiltration experiments was lower than in the continuous infiltration experiments. The pore diameter R was calculated using the equation proposed by Arya et al. (1999):

$$R = 0.816r\sqrt{(\rho_s - \rho_b)/\rho_b} \tag{15}$$

where r is the particle diameter (m), ρ_b is the bulk density (Mg m^{-3}), and ρ_s is the particle density (= 2.49 Mg m^{-3}). The pore diameters for 0.4 mm and 2 mm glass beads were calculated to be 0.24 mm and 1.28 mm, respectively.

As demonstrated by the numerical simulation, the proposed method could effectively evaluate infiltration rates for small pore diameters but underestimated the infiltration rates for larger pore diameters where the inertial region was effective. For glass beads with a particle size of 2

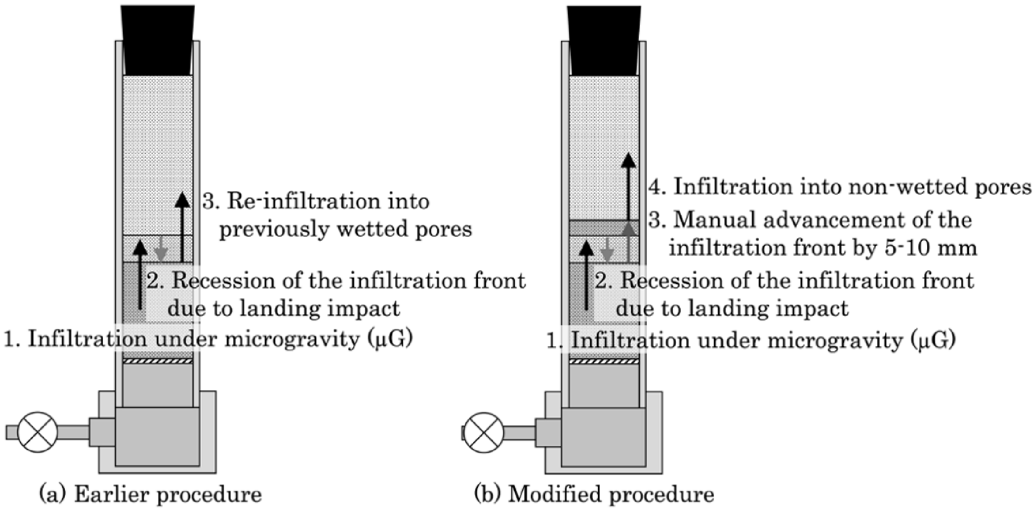


Fig. 8 Wetting fronts movement in porous media during the experiment: (a) Before the improved procedure, (b) Improved procedure.

mm, the calculated pore diameter was 1.28 mm, which was comparable to the capillary with an inner diameter of 1.5 mm in the numerical experiments (Fig. 4b). In this case, the infiltration rate was underestimated because the inertial region was significant relative to the short infiltration time available in the 2 m high drop tower. Therefore, extended microgravity durations, such as those provided by a 50-meter-high drop tower, are required to accurately evaluate infiltration rates in intermittent infiltration experiments using 2 mm or larger diameter glass beads.

5. Conclusion

This study proposed an intermittent infiltration experiment that simulated long-term μG infiltration by repeatedly observing small increments of infiltration using short-term μG conditions generated by a 2 m high drop tower, and the applicability of this procedure was evaluated. The infiltration rate for 0.4 mm diameter glass beads, having a small pore diameter, using the intermittent infiltration experiments was consistent with that observed in the continuous infiltration experiment. This consistency confirms the applicability of the proposed procedure for porous media with small pore diameters. However, for capillaries with inner diameters larger than 1.5 mm or glass beads with particle diameter larger than 2 mm, the infiltration rate was underestimated due to the significant influence of the inertial region.

This study demonstrated the intermittent infiltration experiments as a cost-effective and repeatable method for evaluating infiltration rates under μG conditions. This proposed procedure will provide a practical method to measure soil physical properties under μG, creating new opportunities to better understand the water behaviors that differ from those observed under 1 G conditions.

Acknowledgments

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References

Amara, M.E.A.B. and Nasrallah, S.B. (2011): Capillary rise in a non-uniform tube. Journal of Porous Media, 14(5): 411–422, doi:10.1615/JPorMedia.v14.i5.40.

Arya, L.M., Leij, F.J., van Genuchten, M.T. and Shouse, P.J. (1999): Scaling parameter to predict the soil water characteristic from particle-size distribution data. Soil Sci. Soc. Am. J. 63(3): 510–519. doi:10.2136/sssaj1999.03615995006300030013x.

Bingham, G.E., Jones, S.B., Or, D., Podolski, I.G., Levinskikh, M.A., Sytchov, V.N., Ivanova, T., Kostov, P., Sapunova, S., Dandolov, I., Bubenheim, D.B. and Jahns, G. (2000): Microgravity effects on water supply and substrate properties in porous matrix root support systems. Acta Astronaut. 47(11): 839–848. doi:10.1016/S0094-5765(00)00116-8.

Dullien, F.A.L. (1979): Porous Media: Fluid transport and pore structure, 2nd Ed, p. 42. Academic Press, San Diego.

International Space Exploration Coordination Group (ISECG) (2024): The global exploration roadmap, p. 8. Available online: https://www.globalspaceexploration.org/wp-content/isecg/GER2024.pdf (accessed on January 6, 2024).

Jury, W.A. and Horton, R. (2004): Soil physics, p. 45. John Wiley & Sons, New Jersey.

Kitaya, Y. (2016): Relation between space exploration and agricultural sciences: Establishment of controlled ecological life support system. Trends in the Sciences, 21(2): 87–91, doi:10.5363/tits.21.2_87.

Kogure, K. (2007): Microgravity experiment facilities and application. J. Plasma Fusion Res, 83(2): 161–163.

Lu, T.X., Biggar, J.W. and Nielsen, D.R. (1994): Water movement in glass bead porous media: 1. Experiments of capillary rise and hysteresis. Water Resour. Res. 30(12): 3275–3281, doi:10.1029/94WR00997.

Maruo, Y., Sato, N. and Noborio, K. (2019): Capillary rise under microgravity in variously-shaped capillary glass tubes. Int. J. Microgravity Sci. Appl., 36(2): 360206. doi:10.15011//jasma.36.360206.

Maruo, Y., Sato, N., Nogawa, K., Aoki, S. and Noborio, K. (2022): Pore-scale wetting process of capillary-driven flow in unsaturated porous media under micro- and earth-gravities. Water. 14(13): 1995, doi:10.3390/w14131995.

Massa, G.D., Dufour, N.F., Carver, J.A., Hummerick, M.E., Wheeler, R.M., Morrow, R.C. and Smith, T.M. (2017): VEG-01: Veggie hardware validation testing on the international space station. Open Agriculture, 2: 33–41, doi:10.1515/opag-2017-0003.

Miyazaki, T., Hasegawa, S. and Kasubuchi, T. (2005): Soil Physics, p.48. Asakura Publishing, Tokyo.

Mohamed, A.M.O., Antia, H.E. and Gosine, R.G. (2002): Water flow in unsaturated soils in microgravity environment. J. Geotech. Geoenviron. Eng, 128(10): 814–823, doi:10.1061/(ASCE)1090-0241(2002)128:10(814).

Naganuma, N., Nogawa, K., Maruo, Y., Sato, N. and Noborio, K. (2020): Evaluation of gravity dependence of contact angle and surface tension for water. Bull. Faculty Agric. Meiji Univ., 69(2): 73–79.

Quéré, D. (1997): Inertial capillarity. Europhysics Letters, 39(5): 533–538, doi:10.1209/epl/i1997-00389-2.

Sato, N and Noborio, K. (2018): Dimensional analysis of horizontal infiltration affected by surface tension and viscosity of a liquid. Soil Science, 183(3): 83–88, doi:10.1097/SS.0000000000000237.

Sato, N., Maruo, Y. and Noborio, K. (2019): Applicability of clinostat for simulating water infiltration in porous media under microgravity. Bull. Faculty Agric. Meiji Univ., 69(1): 33–39.

Sato N., Maruo, Y., Naganuma, N., Nogawa, K., Aoki, S. and Noborio, K. (2024): Water infiltration rate in fine glass beads under micro- and partial gravities. Adv. Space Res., 74(8): 4189–4195, doi:10.1016/j.asr.2024.07.050.

Washburn, E.W. (1921): The dynamics of capillary flow. Phys. Rev., 17(3):273–283, doi:10.1103/PhysRev.17.273.

Yendler, B.S., Webbon, B., Podolski, I. and Bulla, R.J. (1996): Capillary movement of liquid in granular beds in microgravity. Adv. Space Res., 18(4):233–237, doi:10.1016/0273-1177(95)00882-F.

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要　　旨

宇宙空間における土耕栽培を実現するためには，微小重力下における多孔質体中の水分挙動を明らかにする必要がある．落下塔は安価に利用できる一方で，微小重力継続時間が数秒以下と短いため浸潤実験の実施が困難であった．本研究では落下塔による短時間微小重力下で起こるわずかな浸潤を繰り返し観察することにより多孔質体の浸潤速度を測定する断続浸潤実験法を提案し，その適用性を検討した．0.4 秒の微小重力環境でも間隙径が 0.3 mm より小さい多孔質体であれば，断続浸潤実験により浸潤速度を評価できた．一方，間隙径が 1.5 mm 以上の毛管や粒径 2 mm の多孔質体では慣性領域が無視できずに浸潤速度を過小評価するため，より長い微小重力環境が必要であることが明らかになった．断続浸潤実験は微小重力実験を安価に繰り返し行うことを可能とし，1 G 条件下とは異なる水の挙動をより深く理解するための新たな可能性を開くと期待される．

キーワード：浸潤速度，微小重力，落下塔，断続浸潤実験