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TDR CENTRIFUGE PERMEAMETER MODELLING FOR HYDRAULIC CHARACTERISTICS MEASUREMENT OF UNSATURATED SOIL

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Landslides from heavy rainfall in hilly areas threaten lives and infrastructure. This study examines the Soil Water Characteristic Curve (SWCC) and hydraulic parameters of unsaturated soils utilizing an innovative TDR Centrifuge Permeameter conceptual model combined with the NCU Beam-Geotechnical Centrifuge (BGC). TDR, Electric Tensiometers, LVDT, and LDT sensors measures volumetric water content, matric suction, deformation, and surface topography in the model. Infiltration rates and soil-water behavior driven by density, rainfall intensity, and hysteresis were increased under 1G and 20G gravitational forces. SWCC models optimized using Nelder-Mead (NM) and Differential Evolution (DE) algorithms had great accuracy (R2>0.95), with Van Genuchten and Kosugi models fitting best. Electrical conductivity also closely associated with water content, supporting Archie's Law. The study found that the TDR Centrifuge Permeameter is a powerful instrument for unsaturated soil behavior analysis, outperforming standard approaches. Future study should refine SWCC hysteresis models and expand applications to different soil types.

Keywords: Mass Movements, Soil Water Characteristic Curve (SWCC), TDR Centrifuge Permeameter, Unsaturated Soil Hydraulic Properties, Electric Conductivity in Soils, Centrifuge Technology for Soil Analysis.

1 INTRODUCTION

Landslides have become a natural disaster that continues to increase over time which are frequently initiated by rainfall which can caused destruction to infrastructure and loss of life (Li et al., 2022). Apart from external factors may be a problem, some landslides are also influenced by lack of knowledge in understanding soil behavior and phenomena, therefore to reduce the risk of landslides requires a thorough understanding of the soil behaviour especialliy in water infiltration and how it affects soil stability. SWCC is an important instrument for understanding the hydraulic properties of unsaturated soils. It offering key insights into how the soil behaves under varying moisture conditions (Rahardjo et al., 2019). However, conventional methods to obtain the SWCC, are slow and sample destructive (McCartney & Zornberg, 2010). These shortcomings provide the basis for conducting this research. The solution to overcome the limitations of traditional methods that had been obtained by the use of centrifuge permeameters (JG.Zornberg & McCartney, 2010). The devices apply centrifugal force to accelerate the infiltration process in soil samples, reducing the time required to obtain hydraulic properties of the samples (Rahardjo et al., 2019). The development of centrifuge permeameters has provided a breakthrough in this field, researchers have gained insights into soil behavior that can be scaled up to predict real-world conditions. Several successful studies have demonstrated the efficacy of centrifuge permeameters in obtaining SWCC parameters and hydraulic conductivity tests under field-realistic conditions. Recent work even explored using centrifuge permeameters in testing chalk samples Al-Jaf et al. (2022). Despite these advancements, several limitations rising, one major limitation is the experiment require adequate materials and expertise, which can be tedious. Additionally, the theoretical models used represent small subset of the numerous models available. Furthermore, TDR can measure not only volumetric water content (VWC-θ) but also electrical conductivity (EC-σ), a critical hydraulic characteristic of soil that has not been extensively discussed. This study addresses the limitations identified in previous research on centrifuge permeameters. The innovation lies in reducing the complexity of modeling and development by utilizing readily available materials and requiring less tedious expertise. Furthermore, the scope of previous research will be expanded to include essential aspects of soil behavior including soil deformation and electrical conductivity. This innovative opens up new opportunities for flexible and affordable research, paving the way for future advancements in centrifuge permeameter research.

2 METHODOLOGY

This study was performed through a sequence of tests utilizing an innovative centrifuge permeameter model developed with the NCU Beam-Geotechnical Centrifuge (BGC) as the core machine. Rotating the model increases the operational gravity level, lowering the time needed to acquire hydraulic properties from soil samples. An Acutronic 665 BGC with a 3 *m* arm radius could produce 200*G* of gravitational force and carry 550 *kg* (Hung & Liao, 2020). The soil sample model in Figure 1 includes five TDR1500 1.5 *GHz* 3-rod probes for θ & *EC* readings, five MPX6115VC6U silicon pressure sensors for matric suction (ψ), three high-sensitivity HSI-T002 LVDTs defflection(δ), and two Keyence IL high-accuracy lasers for surface topography ($T_{x,y,z}$) readings. The arrangement includes a three-open-nozzle artificial rainfall system closured in a lightweight yet sturdy and corrosion-resistant aluminum box carries a highly plastic clay soil sample composed of 80% kaolinite and 20% silica sand. Hi-gravity accelerates soil infiltration by up to 1/20 time required in the first experiment, enabled by the NCU Beam-Geotechnical Centrifuge Permeameter (CPBGC). This system allows flexible and rapid observation of soil-water interactions under varying conditions. Experiments were performed at 1*G* and 20*G* gravity levels with four different treatment conditions. Each experiment consisted of five phases, including reaching the target gravity level (except the first experiment), raining 1(R1), drying 1(D1), raining 2(R2), and drying 2(D2). The initial experiment was conducted at a gravity level of 1*G* as baseline (BL) with soil properties involving bulk density (γ_b) of 1.6 g/cm^3, initial water content (w_0) of 20.5%, raining duration (t_R) of 25 *mins*, drying duration (t_D) of 30 *mins*, both rainfall rates (R_1 & R_2) of 46 mm/h, and a target saturation ($S_{r,1}$) of 1.00. The experiment lasted 900 *mins* The identical soil characteristics as the first experiment were used in the second, however the gravity level was set at 20*G*. The treatment contained γ_b of 1.6 g/cm^3, w_0 of 20.5%, t_R of 25 minutes, t_D of 30 minutes, R_1 and R_2 at 46 mm/h, $S_{r,1}$ at 1.00, the overall duration of this experiment was reduced to 130 *mins* as a result of the higher gravity level applied by the BGC. The third experiment attempted to evaluate hysteresis and density variations with wider waveforms. The sample had γ_b of 1.3 g/cm^3, w_0 of 1.56%, t_R at 25 minutes, t_D at 60 *mins*, and R_1 and R_2 rates of 82 mm/h with $S_{r,1}$ at 0.75. The fourth experiment reverted density to the initial experiment to evaluate the impact of density variations while employing different rainfall rates at each stage to achieve prolonged quasi-equilibrium states (QES) needed for predicting hydraulic conductivity in samples with parameters γ_b at 1.6 g/cm^3 and w_0 at 3.88%, with varying rainfall rates. These four tests were intended to produce information that could be thoroughly examined to determine the hydraulic properties of the examined samples. Several SWCC models will be tested in the results of this experiment with model's fitting parameters were optimized using Nelder-Mead (NM) and Differential Evolution (DE) algorithms. These optimization methods solve nonlinear and multidimensional problems. NM uses simplex-based local optimization, whereas DE uses evolutionary algorithms for global optimization (Schild, 2022). This combination of techniques ensures robust parameter estimation, enabling accurate experimental SWCC modeling.

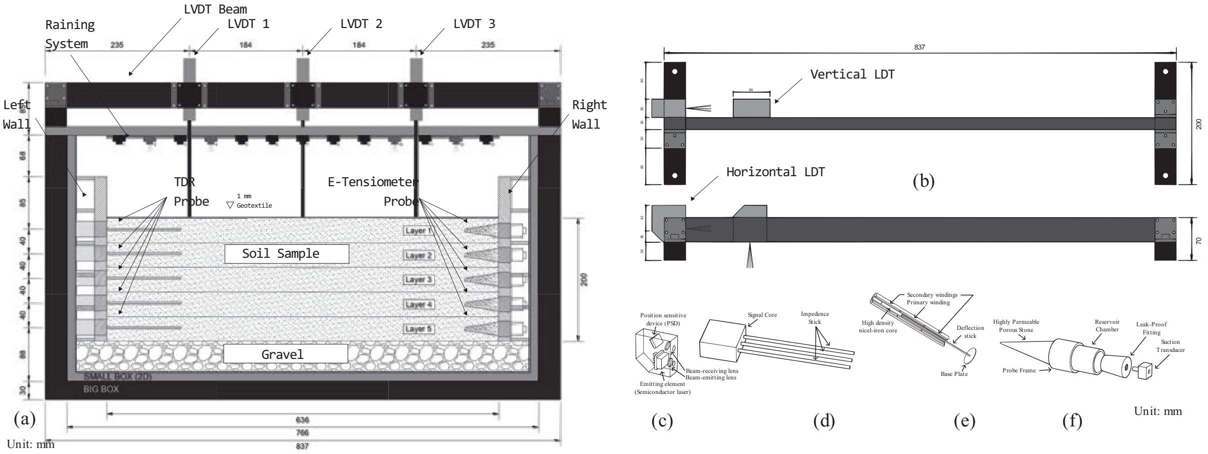

Figure 1 The centrifuge permeameter model: (a) main model, (b) Surface scanner. Probes: c) LDT, d) TDR, e) LVDT, f) ET.

3 PRELIMINARY RESULTS

The sensor readings are detailed in Figure 2 revealed distinct patterns between the 1*G* and 20*G* experiments. The first experiment, showed θ values ranging from 0.05 to 0.45 m^3/m^3 gives Figure 3 as the distribution of TDR probe signals in the model, while *EC* ranged from 500-1000 $\mu S/cm$, establishing basic soil-water relationships. The second experiment accelerated water infiltration, with θ rising from 0.25 to 0.47 m^3/m^3 and *EC* peaking at 1800 $\mu S/cm$, enhanced hydraulic gradients under higher gravitational forces. The third experiment, which had the lowest initial water content (1.56%), revealed in Figure 5b significant hysteresis, especially in the upper soil layers, with higher hysteresis indices observed during the second drying phase. The fourth experiment, using varying rainfall intensities, showed how compaction levels and rainfall patterns affect soil behavior, with deformation readings between 0.0009-0.0013 *mm*.

The first, second, and fourth experiments exhibit complementary SWCCs, as shown in Figure 5a. This is because the use of the same density (1.3 g/cm^3) produces consistent trends even with different gravity level confirming the consistency of the readings. The SWCC processing demonstrated that the first, second, and fourth experiments had similar results because of identical initial sample densities, accompanied with high-initial water content in the first and second, and low-initial in the fourth. The third experiment, with low-initial and high-final water content, exhibited a hysteresis.

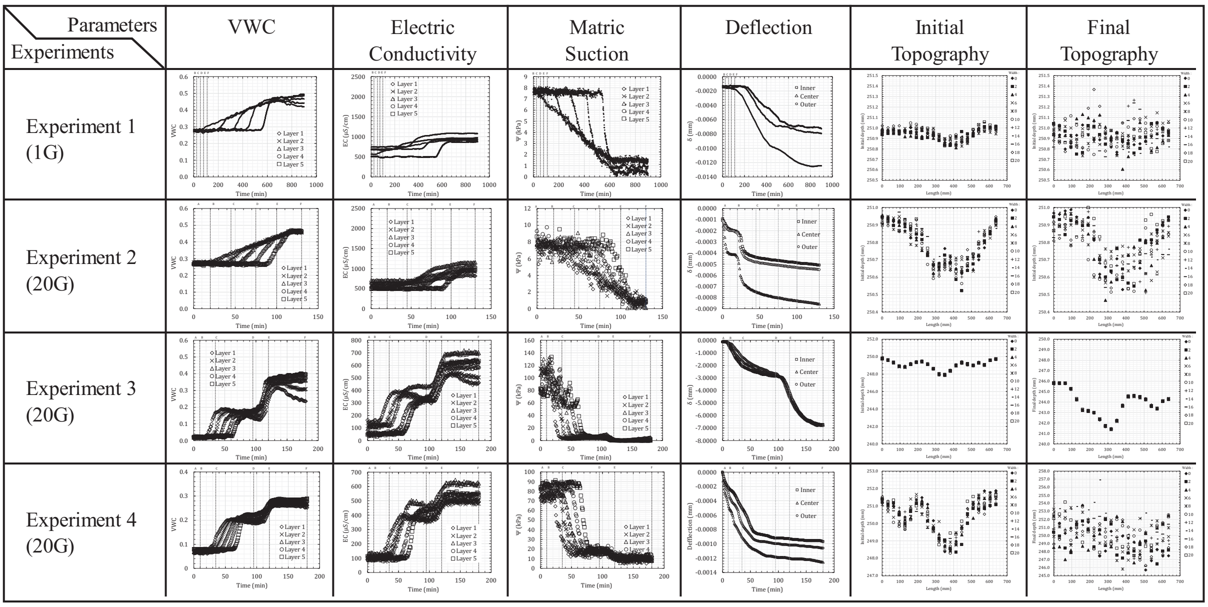

Figure 2 NCU CPBGC experiment reading.

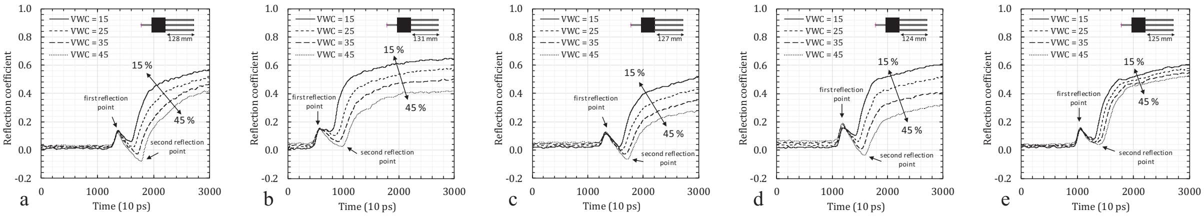

Figure 3 NCU CPBGC TDR probes waveforms: a) Probe 1, b) Probe 2, c) Probe 3, d) Probe 4, and e) Probe 5.

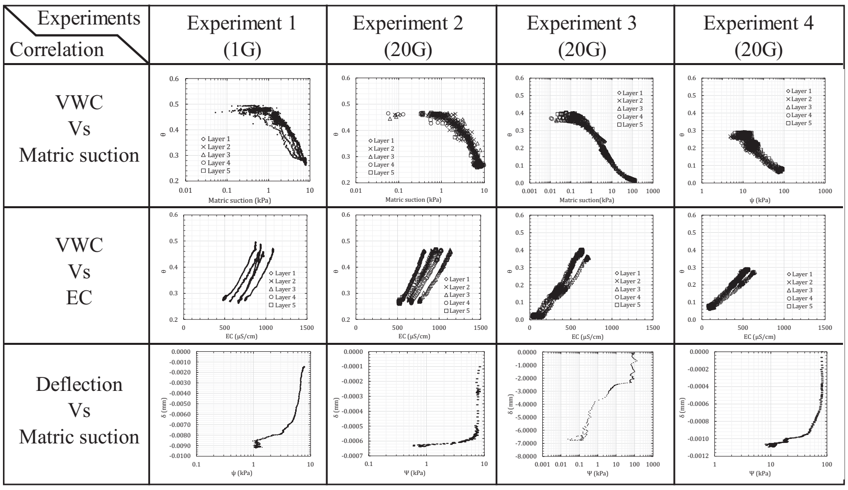

Figure 4 NCU CPBGC experiment results correlation.

The applicability of the SWCC models in Figure 6 showed that the Van Genuchten (VG) and Kosugi models fit the experimental data best, with $R^2 > 0.95$ and NRMSE < 0.02. These models were optimized using Nelder-Mead (NM) and Differential Evolution (DE) algorithms, addressing nonlinear, multidimensional problems by providing local and global optimization. Hysteresis analysis shown in Figure 5c from the third experiment showed higher indices in upper layers during the second drying phase, indicating increased water retention during drying. The study noted that all SWCC models struggled to fit the hysteresis form, particularly in regions with steep curvatures, suggesting an area for future model improvements. *EC* measurements shown in Figure 4 correlated strongly with θ, following Archie's law, with values ranging around 1130 $\mu S/cm$ at 0.4 m^3/m^3. The relationship is due to water in soil pores facilitating ion transport, leading to higher conductivity with increased water content, making *EC* a reliable proxy for θ. Figure 5d shown 1.3 g/cm^3 sample with low-start rainfall caused lower *EC* value, and smaller gradient. When subjected to higher rainfall rates, samples with densities both 1.3 g/cm^3 and 1.6 g/cm^3 showed wider gradients at both the beginning and end, indicating a gentler trend. Variations in gravity did not affect the readings which based on its transform equation primary caused the ion concentration and medium conductivity, which are directly determined by water content and the speed of electrical signals through the soil rather than gravitational changes. Differences in density were identified using δ analysis using LVDT and LDT readings. The differences between $T_{xyz,0}$ and $T_{xyz,1}$ showed unequal surface deformation, which provided complicated soil structure-hydraulic behavior interactions in the experiment arrangement. Due to the difficulties of achieving ideal soil particle matrix strength, especially during rains, high-precision LVDT output is used trough averaging for simplification. Hydraulic conductivity in Figure 5e is calculated using the Van Genuchten-Mualem (VGM) model using QES which occurred between 113 to 172 seconds during the third experiment, with relative hydraulic conductivity (Kr) values ranging from 2.41E-8 to 8.46E-8 and ψ values from 4.88 kPa to 20.63 kPa, represented by a hydraulic conductivity response line (HCRL).

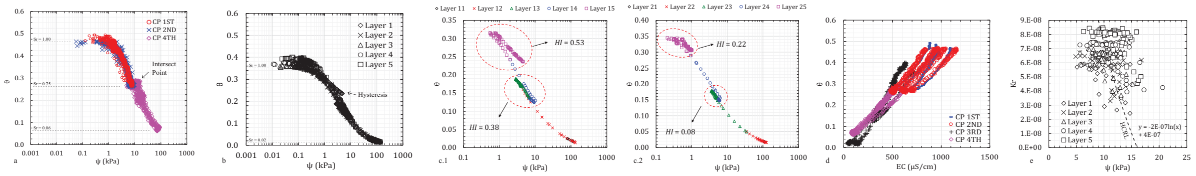

Figure 5 NCU CPBGC Comparison chart: a) SWCC 1ST, 2ND, and 4TH, b) SWCC 3TH, c.1) Hysterisis analysis L1, c.2) Hysterisis analysis L2, d) Combined EC-θ curves, e) Hydraulic characteristics.

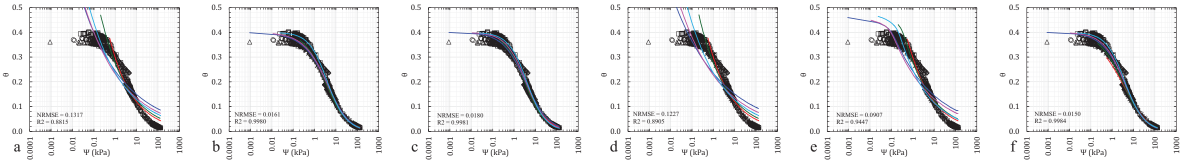

Figure 6 NCU CPBGC SWCC models applicability: a) Brooks-Corey (1966), b) Campell (1974), c) Van Genuchten (1980), d) Cosby-Hornberger-Clapp (1984), e) Fredlund-Xing (1994), f) Kosugi (1996).

4 CONCLUSION

The research concluded that the TDR Centrifuge Permeameter effectively measures the hydraulic characteristics of unsaturated soils. However, improvements are needed, particularly in fitting SWCC models to hysteresis phenomena and enhancing *EC* calibration methods for more reliable TDR signal-to-*EC* conversion. Prolonged QES were achieved but with limited length, suggesting the need for a larger built-in reservoir or additional water outlet flow to avoid water accumulation below the sample to achieve continuous-QES for broader HCRL. Further exploration of hysteresis and water-soil relationships, as well as testing broader soil types, will help extend understanding of soil responses under varying conditions.

REFERENCES

Al-Jaf, P., Smith, M., & Gunzel, F. (2022). Measurement of the hydraulic properties of chalk using centrifuge permeameter; the study of chalk hydraulic properties under accelerated gravitational force. *Quarterly Journal of Engineering*. https://doi.org/10.1144/qjegh2021-159

Hung, W.-Y., & Liao, T.-W. (2020). LEAP-UCD-2017 Centrifuge Tests at NCU. In B. L. Kutter, M. T. Manzari, & M. Zeghal, *Model Tests and Numerical Simulations of Liquefaction and Lateral Spreading* Cham.

JG.Zornberg, & McCartney, J. (2010). Centrifuge Permeameter for Unsaturated Soils. l: Theoretical Basis and Experimental Developments. *Journal of Geotechnical and Geoenvironmental Engineering, 136(8)*, 1051-1063.

Li, B., Liu, K., Wang, M., He, Q., Jiang, Z., Zhu, W., & Qiao, N. (2022). Global Dynamic Rainfall-Induced Landslide Susceptibility Mapping Using Machine Learning. *Remote Sensing*. https://doi.org/https://doi.org/10.3390/rs14225795

McCartney, J., & Zornberg, J. (2010). Centrifuge Permeameter for Unsaturated Soils II: Measurement of the Hydraulic Characteristics of an Unsaturated Clay. *Journal of Geotechnical & Geoenvironmental Engineering, 136*.

Rahardjo, H., Kim, Y., & Satyanaga, A. (2019, 2019/06/13). Role of unsaturated soil mechanics in geotechnical engineering. *International Journal of Geo-Engineering, 10*(1), 8. https://doi.org/10.1186/s40703-019-0104-8

Schild, P. (2022). Global Minimize [Improvment of solver algorithm]. Retrieved 1 January 2022, from https://github.com/SchildCode/GlobalMinimize