9th Global Energy and Water Exchanges Open Science Conference

July 7 – 12, 2024 | Sapporo, Japan

Evaluation of Pore Size Distribution and Soil-Water Characteristic Curve of Granite Residual Soil under multiple Drying-Wetting Cycles

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INTRODUCTION

This study aims to investigate the effects of multiple drying-wetting cycles on the pore size distribution (POSD) and soil-water characteristic curve (SWCC) of undisturbed granite residual soils using the nuclear magnetic resonance (NMR) spin-spin relaxation time (T_2) distribution measurement and the pressure plate test respectively.

Pore size distribution (POSD) is one of the important intrinsic property of soils which is associated with the porosity, void ratio and controls the physical, mechanical and hydraulic behaviors of soils. On the other hand, the soil–water characteristic curve (SWCC) is one of the important parameters required for the analysis of the problems related to unsaturated soils. The shape of the SWCC is dependent upon the POSD of the soil.

Granite residual soils are the weathering product of their parent materials. Due to formational environment, these soils are experienced by heavy rainfall, persistent drought and multiple drying-wetting cycles. This climatic variability, **namely drying-wetting cycle**, is considered to be one of the important factors that can significantly alter moisture distribution and hydro-mechanical behaviors of soils and may induce damage to infrastructures or foundations.

Theoretical background of NMR T_2

NMR relaxometry is become a promising method to evaluate the POSD in soil science as a fast and very simple alternative. The NMR signal is an exponential decay, characterized by initial signal amplitude (indication of pore volume) and distribution of relaxation times T_2 (related to pore size). According to *Coates et al. (1999)*, for a fluid saturated porous media (e.g. soil/rock), the NMR relaxation mechanisms are given by:

$$\frac{1}{T_2} = \frac{1}{T_{2B}} + \frac{1}{T_{2S}} + \frac{1}{T_{2D}}$$

Where, $\mathbf{T_2}$ is the transverse relaxation time of the pore fluid measured by Carr-Purcell-Meiboom-Gill **(CPMG)** sequence; $\mathbf{T_{2B}}$ is the transverse bulk fluid relaxation time; $\mathbf{T_{2S}}$ is the transverse surface relaxation time; $\mathbf{T_{2D}}$ is the diffusion relaxation time.

It is reported that Under Carr-Purcell-Meiboom-Gill (CPMG) sequence and at low field NMR, both T_{2B} and T_{2D} are negligible compared to T_{2S} (*Kleinberg, 2006*). Therefore, in the fast diffusion limit, the transverse relaxation time (T_2) depends on the transverse surface relaxation (T_{2S}) and the T_2 relaxation rate $1/T_2$ is proportional to the surface-to-volume (*S/V*) ratio of the pore (*Brownstein and Tarr, 1979*).

$$\frac{1}{T_2} = \frac{1}{T_{2B}} + \frac{1}{T_{2S}} + \frac{1}{T_{2D}} \rightarrow \frac{1}{T_2} = \frac{1}{T_{2S}} = \rho_2 \left(\frac{S}{V}\right)_{pore} \rightarrow \frac{1}{T_2} = \rho_2 \frac{4}{D}$$

Coates et al. (1999) — Brownstein and Tarr, 1979 — For cylindrical pores

ρ_2 is the surface relaxivity coefficient, which is a characteristics of magnetic interactions at the fluid-solid interface and $(S/V)_{pore}$ is the pore surface area-volume. and related to the pore diameter (D) i.e. i.e. $(S/V)_{pore}=F_s/D$ (*Tian et al., 2014*).

MATERIALS AND METHODS

The undisturbed granite residual soil samples collected at areas (5.0-7.0 m depth) around Jiangmen city (Kaiping), Gaungdong province, China, are used for this study.

Table 1. Basic material properties of the tested granite residual soils.

Depth (m)	ρ_d (g/cm³)	NMC %	Atterberg limits W_L %	W_P %	I_P %	(%)/Free swell	Grain size (%) Gravel	Sand	Silt	Clay
5.7~6.0	1.30	37.20	57.1	30.7	26.40	9.75	4.6	33.4	45.9	16.1

The samples (20 mm height & 45 mm dia) are dried up to moisture content 20% at constant temperature. Then the samples are saturated with distilled water after vacuum seeding about 2 hours and then submerged about 24h. This process is repeated until the desired numbers of **drying-wetting cycles (0, 1, 2, 4 and 8)** are completed.


Saturation device


15 bar Pressure Plate


23 MHz MiniMR NMR

A well accepted NMR-permeability equation, known as **Schlumberger-Doll Research (SDR) equation** developed by Kenyon et al. (1988), is used to obtain the surface relaxivity coefficient (ρ_2) which is:

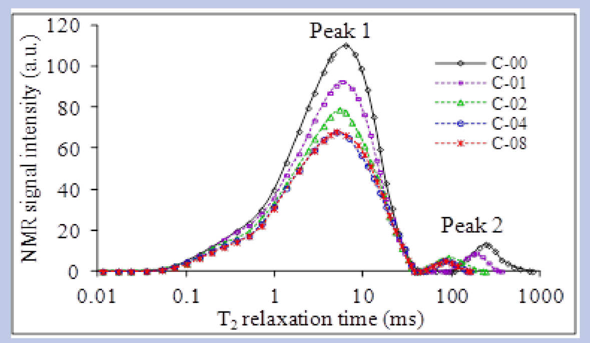
$$k_s = C\Phi^4 T_{2LM}^2 \rightarrow C = \rho_2^2 \rightarrow \rho_2 = \frac{\sqrt{k_s}}{\Phi^2 T_{2LM}}$$

Kenyon et al. (1988) — Kleinberg et al. (2003)

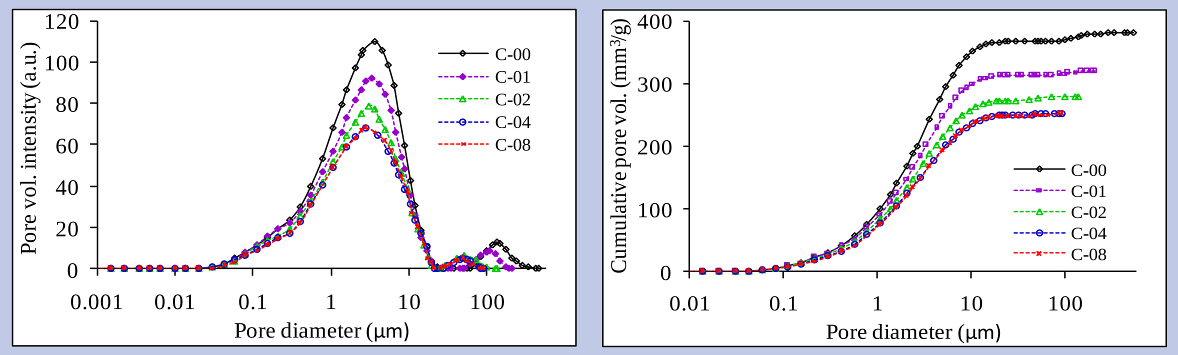
This the studied soils, the saturated permeability k_s is 9.91×10^{-16} m²; Φ is the saturated porosity of the NMR samples (Φ=0.5006); T_{2LM} is the geometric mean value of the T_2 distribution (T_{2LM}=0.86534 ms). **The obtained ρ_2 value is about 0.1452 μm/ms.**

RESULTS

NMR T_2 test results and POSD from NMR T_2



T_2 distribution curves with respect to D-W cycle



Variation of POSD distribution with respect to D-W cycle.

Table 2. POSDs of drying-wetting cycle samples

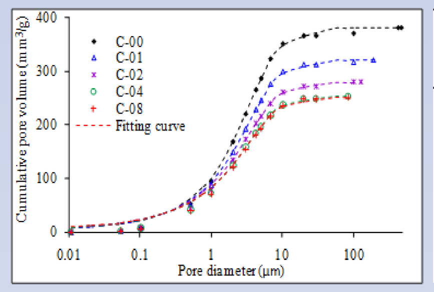
Wet-dry cycle no.	Total measurable pore vol. (mm³/g)	Pore vol. with different diameter (mm³/g) >10μm	10-5μm	5-1μm	1-0.1μm	<0.1μm
C-00	381.49	31.42	64.22	192.30	85.29	8.26
C-01	320.62	20.09	51.63	162.58	78.26	8.05
C-02	279.61	14.44	42.36	141.29	73.71	7.82
C-04	253.17	10.73	36.20	128.85	69.72	7.68
C-08	251.42	10.27	35.60	128.70	69.24	7.62

Both curve show **bimodal distributions.** NMR signal proportion and pore volume decrease with increasing D-W cycles. The reduction rate is more pronounced in the 1st cycle and decreases with subsequent cycles. the pore can be preliminarily divided into five different grades by the pore diameter: i) >10μm, ii) 10~5μm, iii) 5~1μm, iv) 1~0.1μm and v) <0.1μm). The pores ranging from **5~1μm** constitute (approx. 50.75%) the majority of the pore space. The effect of D-W cycles on larger pores (>1μm) is more obvious than smaller pores. The obtained POSD are fitted with the **V-G model in terms of the cumulative pore volume (mm³/g)** where the suction pressure is replaced by the pore diameter.

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1+(\alpha\psi)^n]^m} \rightarrow V_{Di} = V_r + \frac{V_s - V_r}{[1+(a/D_i)^b]^c} \rightarrow V_{Di} = \frac{V_s}{[1+(a/D_i)^b]^c}$$

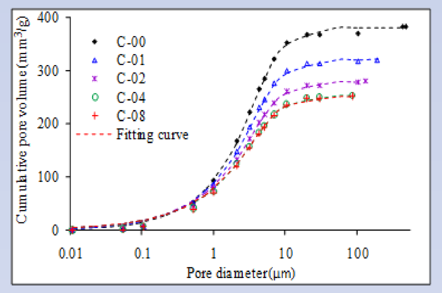
van Genuchten (1980) — Modified equation

Based on regression analysis, it is found that the correlation coefficient of the fitting curves increased much better if the residual pore volume is considered as 0. Therefore, a modified equation is proposed considering V_r equal to 0 and without changing the other fitting parameters.



Wet-dry Cycle no.	POSD fitting parameters V_s	V_r	a	b	c	R^2
0	380.93	1.88	6.7384	2.3201	0.2657	0.9513
1	320.62	1.74	6.9010	2.3277	0.2697	0.9689
2	279.42	1.65	6.9537	2.3322	0.2715	0.9725
4	253.09	1.60	7.0293	2.3506	0.2723	0.9603
8	252.16	1.59	7.0328	2.3520	0.2725	0.9682

POSD curve and fitting parameters of D-W cycle

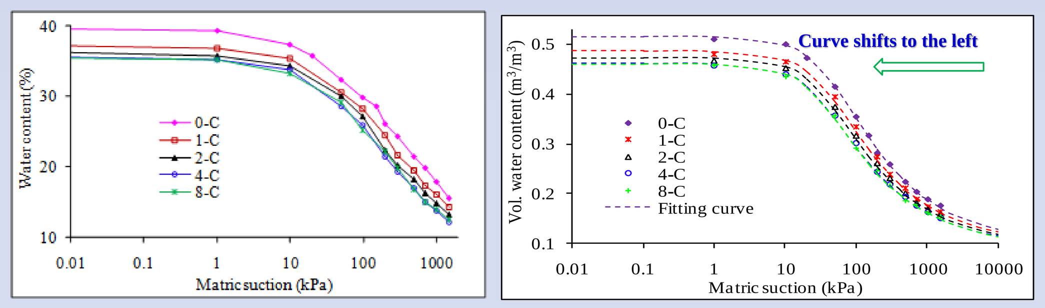


Wet-dry Cycle no.	Fitting parameters V_s	a	b	c	R^2
0	380.93	6.7384	2.3201	0.2657	0.9852
1	320.62	6.9010	2.3277	0.2697	0.9838
2	279.42	6.9537	2.3322	0.2715	0.9815
4	253.09	7.0293	2.3506	0.2723	0.9728
8	252.16	7.0328	2.3520	0.2725	0.9764

POSD curve and parameters of D-W cycle, considering V_r= 0).

SWCC of D-W cycle (Pressure Plate Test)

To clarify the POSD results, the SWCC of multiple D-W cycle samples is examined and the results show that the initial saturated water content and residual water content decreases with increasing drying-wetting cycles i.e. the water-retention capacity decreases.



Wet-dry Cycle no.	Fitting parameters (using van Genuchten, 1980) θ_s	θ_r	α	n	m	R^2
0	0.5146	0.0898	0.0248	1.4502	0.3105	0.9924
1	0.4859	0.0880	0.0279	1.4610	0.3155	0.9885
2	0.4727	0.0870	0.0302	1.4649	0.3174	0.9934
4	0.4611	0.0865	0.0317	1.4668	0.3182	0.9907
8	0.4595	0.0864	0.0319	1.4671	0.3184	0.9925

SWCC curves and fitting parameters with respect to D-W cycles

DISCUSSIONS

The shape and changing tendency of SWCC and POSD curves are quite similar and the parameters are linearly proportional to each other. The cumulative pore volume of <0.1μm pore diameter is very close to the equivalent residual water content which might be the clay-bound water.

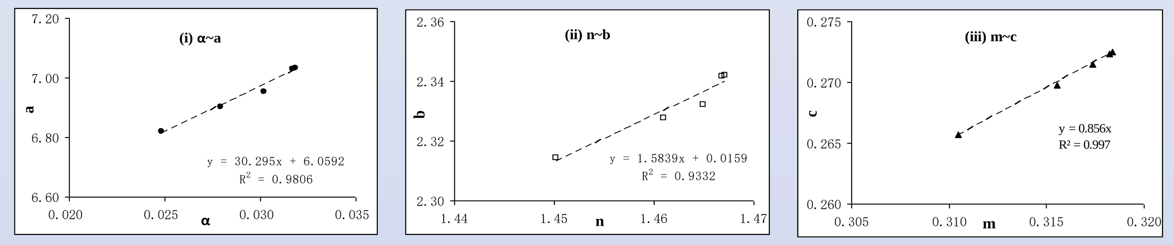


Fig. Relationship between the fitting parameters (i) α ~ a, (ii) n ~ b and (iii) m ~ c.

For comparison among the fitting parameters of POSD and SWCC, the relationship between a and α is taken as an example, where the parameter α has units of soil suction or the inverse of soil suction and inversely related to the air entry value and the parameter a has units of pore diameter. According to the Washburn (1921) equation, the equivalent pore diameters for the values of α are found to range from 7.1 to 9.1μm. For NMR test, the threshold pore diameters are range from 6.7 to 7.0μm. This finding shows that the pore diameter at the threshold level of NMR T_2 test and the air entry value of the SWCC are reasonably related. The variations among the fitting parameters may be caused by several reasons. Furthermore, the shrinkage cracks are expected during desiccation process in pressure plate test which may also be a reason for these variations.

CONCLUSION

The low field NMR technique is successfully used to analyze the POSD of multiple D-W cycle samples of the granite residual soil which appeared as an effective and quick method. The V-G model (1980) in terms of cumulative pore volume is used to describe the POSD of D-W cycle samples, which shows similarity and good linear relation to that of the SWCC curve and fitting parameters. Therefore, it can be said that NMR T_2 relaxometry might be employed as an alternative for assessing the micro-structural alteration of residual soils subjected to repeated D-W process, as the SWCC is highly reliant on the POSD of the soil.

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ACKNOWLEDGEMENT

The first author would like to acknowledge financial support from **Regional Hydroclimate Project *AsiaPEX*** to attending the conference. Thanks also to the organizing committee of the 9th GEWEX Open Science Conference. Special thanks to Prof. Dr. Toru Terao, Faculty of Education, Kagawa University.