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A new and simple water retention model for root-permeated soils

C. W. W. NG, J. J. NI, A. K. LEUNG* and Z. J. WANG

C. W. W. NG

Char Professor, Department of Civil and Environmental Engineering, the Hong Kong University of Science and Technology, Hong Kong SAR

J. J. NI

Research student, Department of Civil and Environmental Engineering, the Hong Kong University of Science and Technology, Hong Kong SAR

A. K. LEUNG*

Lecturer, School of Science and Engineering, University of Dundee, Dundee, Scotland, UK
Contact address: Fulton Building, School of Science and Engineering, University of Dundee, Nethergate, Dundee, Scotland, UK, DD1 4HN
*Corresponding author (e-mail: a.leung@dundee.ac.uk)

Z. J. WANG

Department of Civil and Environmental Engineering, the Hong Kong University of Science and Technology, Hong Kong SAR

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ABSTRACT

Vegetation affects the soil hydrology through not only evapotranspiration (ET) but also changes in soil water retention curve (SWRC). There are only limited models which are able to predict root-induced change in SWRC. These models often contain many empirical parameters that are not easy to be obtained and calibrated. This letter proposes a new and simple model with only one root parameter, namely root volume ratio R_v, needed for predicting SWRC of a root-permeated soil. The new model considers void ratio change through the volume reduction of air void of soil due to the presence of roots. The modified void ratio of a root-permeated soil is then fed into a void ratio-dependent SWRC model to predict any resulted change in SWRC. The performance of this new model is validated against three case studies. Good agreement between measurements and predictions is obtained, with discrepancies of degree of saturation less than 13% for a given suction.

KEY WORDS: Partial saturation; Suction; Vegetation

INTRODUCTION

The presence of vegetation is known to affect the hydrology and, hence, stability of some major civil infrastructure such as man-made slopes/embankments (Osman and Barakbah, 2011; Scanlon *et al*., 2011; Smethurst *et al*., 2015; Ng *et al.,* in press). Past studies have been carried out to investigate the effects of plant evapotranspiration (ET) on the changes in soil moisture content or soil suction through field monitoring (Lim *et al*., 1996; Simon & Collison, 2002; Pollen-Bankhead and Simon, 2010; Leung & Ng, 2013; Leung *et al*., 2015a), laboratory studies (Fan and Su, 2009; Ng *et al*., 2013, 2014; Garg *et al*., 2015; Leung *et al*., 2015b; Veylon *et al*., 2015) and numerical or/and analytical modelling (Indraratna *et al*., 2006; Zhu & Zhang, 2014; Ng *et al*., 2015).

In addition to plant ET, some existing studies suggest that the presence of plant roots in soil could directly affect soil hydraulic properties. Field and laboratory tests (Gabr *et al*., 1995; Huat *et al*., 2006; Aravena *et al*., 2011; Ng *et al*., 2014; Leung *et al*., 2015b) have evidently showed that vegetated soil has lower water infiltration rate and enhanced water retention capacity than bare soil. The root-induced change in soil hydraulic properties is arguably attributed to the alteration of soil structures, predominantly due to occupancy of roots in soil pore space (Scanlan & Hinz, 2010; Scholl *et al*., 2014; Leung *et al.* 2015b), which consequently leads to changes in soil pore size and, hence, soil water retention curve (SWRC; Romero *et al*., 1999; Ng & Pang, 2000; Ng & Leung, 2012). However, it should be noted that such soil-root-water interaction might be different in fine-grained soils. Veylon *et al.* (2015) revealed that root growth in clayey soils influences the frequency and magnitude of drying-wetting cycles and consequently the formation of soil aggregates.

Quantifying root-induced modification in soil hydraulic properties, including SWRC, are vital to more correctly predict the hydrology and, hence, assess the stability of the civil infrastructure subjected to rainfall. Such root-induced modification is especially prominent for the case under high relative humidity (RH; i.e., low vapour pressure deficit) and cloudy condition (i.e., minimal supply of radiation), during which any suction induced by plant ET and root osmotic action are practically negligible (Sidle *et al.*, 1985; Snyder *et al.*, 2003). To date, there are only a few models, which may capture root-induced change in SWRC. Scanlan (2009) and Scanlan & Hinz (2010) proposed a conceptual model to capture the reduction in soil pore size by idealising soil pore throats as a bundle of cylindrical tubes containing plant roots. Their model considers that the presence of a root reduces the effective diameter of a pore throat and this, in turn, increases the height of capillary water and enhances matric suction. This model requires 13 parameters, some of which are empirically-based and cannot be easily obtained in a test. Scholl *et al*. (2014) determined a set of pore size parameters to deduce root-induced change in SWRC through inverse analyses of column tests, where changes in soil moisture and suction of vegetated soil were monitored. Physical meaning of the back-analysed SWRC parameters is not clear, because these parameters can be heavily affected by the subjective choices of their initial values and the parameter searching algorithm of the inverse analysis.

This letter proposes a new and simple model of SWRC for root-permeated soils. This model was then validated by three case studies.

NEW WATER RETENTION MODEL FOR ROOT-PERMEATED SOIL

The new model considers that plant roots occupy some soil pore space and, hence, reduce soil pore size. Considering the mass-volume relationship and phase diagram of an unsaturated soil where part of its air void is occupied by plant roots (Fig.1), the void ratio of a root-permeated soil may be expressed by the following equation:

$$e = \frac{e_0 - R_v(1+e_0)}{1+R_v(1+e_0)} \tag{1}$$

where e_0 is the void ratio of bare soil [-], R_v is the root volume ratio [$\mathrm{mm^3/mm^3}$], which is defined as the total volume of roots per unit volume of soil. $R_v = 0$ means that there are no plant roots in the soil (i.e., bare soil). R_v is less than $e_0/(1+e_0)$, as total root volume cannot be larger than the total soil pore size. Depending on the plant type, R_v is a function of depth within root zone. It should be noted that it is not the intention of this study to model any effects of root decay, and the associated formation of macro-pores (Ghestem et al., 2011), on the change in soil void ratio. Furthermore, for simplicity, the proposed model does not consider any change of soil microstructure (i.e., micro-cracks development and aggregates formation) during drying-wetting cycles. The proposed model is thus more suitable for low plasticity soils such as sands and/or silts.

In order to model the effects of the presence of roots on the change in water retention ability of a soil, the void ratio-dependent SWRC equation proposed by Gallipoli *et al.* (2003) may be adopted:

$$S_r = \left[1+\left(\frac{se^{m_4}}{m_3}\right)^{m_2}\right]^{-m_1} \tag{2}$$

where S_r is the degree of saturation of soil; s is the matric suction; and m_1 [-], m_2 [-], m_3 [kPa], m_4 [-] are the model parameters. m_1 and m_2 control the shape of a SWRC (van Genuchten, 1980), while m_3 and m_4 are related to the air-entry value (AEV) of the parent soil. Considering that the void ratio has negligible effects on SWRC at high suction range, the product, $m_1 m_2 m_4$, can be set to 1 (Gallipoli *et al.*, 2003). Therefore, by knowing the SWRC of the parent soil and the root parameter, R_v, SWRC of root-permeated soil can be predicted.

VALIDATION OF THE NEW MODEL

In order to validate the new SWRC model, field and laboratory tests are conducted to obtain all necessary parameters. In addition, the laboratory test data reported by Leung *et al.* (2015b) is also selected for validation. Although there are some limited case studies that also show the SWRCs of both bare and root-permeated soil (Rahardjo *et al.*, 2014; Yan & Zhang, 2015), the root parameter, R_v, is not reported. These case histories thus cannot be used for validation of this study.

Test plan and procedures

The field tests were double-ring infiltration tests conducted at a site called Eco-Park in Hong Kong (Fig. 2(a)). A flat soil bed was constructed by compacting a 2 m-thick layer of completely decomposed granite (CDG; silty sand), until a relative compaction of 95% (i.e., dry density of 1777 kg/m^3) was reached. Two rings with diameters of 0.6 and 0.3 m were inserted into the ground by 150 and 75 mm depth, respectively. Any gapping between the ground and the two rings was sealed with cement paste. Inside both rings, 19 seedlings of *Schefflera heptaphylla* were transplanted to the soil bed in the uniform pattern and were irrigated every two days for four months for root establishment prior testing (Wang *et al.*, 2007). The leaf area index, which is a dimensionless index indicating the total area of leaves over the projected planar area of plant canopy, of this species was 1.8 ± 0.2. Three pairs of moisture probes and tensiometers were installed at 100, 250 and 400 mm depths at the middle of the rings for monitoring the responses of soil moisture content and suction, respectively. When plant roots were established, a constant ponding head of 100 mm was applied inside both rings. Changes in soil moisture and suction were monitored continuously until the steady state was reached. The vegetated soil bed was then allowed for natural evapotranspiration, during which the changes in soil water content and suction at 100 mm (i.e., within the root zone) were measured to determine the

SWRC of root-permeated soil. After testing, the plant roots were excavated to obtain R_v using an image-based analysis (Himmelbauer *et al.*, 2004). The root zone was divided into several horizontal layers along root depth. An average R_v value was determined for each layer. In order to account for any plant variability, three repeated tests (i.e., 57 seedlings in total) were conducted. The above test procedures were repeated for soil bed without vegetation, for determining SWRC of bare soil.

The laboratory tests were carried out at a temperature- and humidity-controlled plant room. The same type of CDG was compacted in a steel drum in 15 layers (600 mm in diameter; see Fig. 2(b)), until a relative compaction of 95% (i.e., dry density of 1777 kg/m^3) was reached. In total, 13 seedlings of *S. heptaphylla* were transplanted to the compacted CDG uniformly. The method of root establishment, instrumentation and the test procedures to obtain SWRCs were identical with the field tests described above. Three test replications for bare and vegetated soils were examined (i.e., 39 seedlings in total).

Leung *et al*. (2015b) conducted a similar laboratory test to those carried out in this study, using the identical soil type and plant type. The tests were performed in the same plant room. The only differences were that in Leung *et al.* (2015b), (i) the tests were for one single tree, and (ii) the relative compaction of the soil adopted was 80%. Similarly, three test replications were performed.

Observed root characteristics

Overview of the root systems of some typical tree seedlings tested in the field and laboratory studies is shown in Fig. 3. It can be generally seen that the roots growing from the bottom of tree stem are predominantly fresh roots, which is displayed as whitish colour (MaCrady & Comerford, 1998). No observable decayed roots are found. These root characteristics satisfy the conditions and assumptions stated in the proposed SWRC model and, hence, can be used for validation.

Fig. 4 shows the measured distribution of R_v of the *S. heptaphylla* obtained from the three cases. Note that the vertical axis is the depth normalised with the maximum root depth in each corresponding case. It can be seen that the R_v for both the field and laboratory tests conducted in this study distributes non-linearly along depth, exhibiting a parabolic shape. A peak value of R_v of about 0.032 and 0.034 mm^3/mm^3 is identified near the mid-depth of the root zone. On the contrary, the distribution of R_v obtained from Leung *et al.* (2015b) is rather different and it is approximately linear, with a peak value of about 0.065 mm^3/mm^3 near the soil surface. The SWRC of root-permeated soil in each case is evaluated at the depth, where the instruments were installed. The depth of evaluation and the corresponding value of R_v in each case are summarised in Table 1.

Performance of the new model

Figs 5(a) to (c) show the measured SWRC of bare soil tested in each case. Each SWRC is fitted with Eq. (2) to calibrate the coefficients, m_1, m_2, m_3 and m_4 (see Table 1). Based on these coefficients and the root parameter R_v, SWRC of root-permeated soil is predicted and compared with the respective measurements (including all replicates). Good agreement between the measurement and prediction can be generally seen in all three cases. At any given suction, the maximum discrepancy of S_r is less than 13%. It can be consistently seen that in all three cases, the presence of roots caused an increase in air-entry value (AEV), while the desorption rate does not show significant change. The AEV increased from 1 to 3 kPa for both the field and laboratory tests conducted in this study. Similarly, Leung et al. (2015*b*) also reported an increase in AEV by 4 kPa in their laboratory study. The similar SWRC change due to the presence of roots is also found in the test data presented by Rahardjo *et al.*

(2014) and Yan & Zhang (2015), who report an increase in AEV by 4 kPa in silty soils and 3 kPa in sandy soils, respectively. The observed increase in AEV, from both the measurements and prediction, is an indication of the increase in water retention capacity due to the presence of roots in soil pore space. This is in line with the experimental observation made by Romero *et al.* (1999) and Ng & Pang (2000), who also show that a decrease in void ratio of bare soil (i.e., denser soil) would possess a higher AEV.

CONCLUSIONS

A new and simple SWRC model was developed for root-permeated, low plasticity soils such as sands and silts, which do not show significant soil microstructural changes during drying-wetting cycles. This model can capture the reduction of soil void ratio due to the presence of roots in the air void of soil. Totally the model requires five parameters: four for describing the SWRC of the parent soil (without any vegetation) and one for characterising a root property, namely root volume ratio. The performance of this new model is verified by a laboratory test reported in literature and two new additional field and laboratory studies. The model illustrates its capability of predicting SWRC of silty sand vegetated with a tree species, *S. heptaphylla,* reasonably well. Moreover, it is able to capture a substantial increase in soil air-entry value (AEV) due to the presence of roots. The maximum discrepancy of degree of saturation is less than 13%, for a given suction.

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LIST OF NOTATIONS

AEV	Air entry value
CDG	Completely Decomposed Granite
ET	Evapotranspiration
SWRC	Soil Water Retention Curve
R_v	Root volume ratio
S_r	Degree of saturation
e	Void ratio
e_0	Void ratio of bare soil
m_1	Fitting parameter in Gallipoli’s equation (Gallipoli *et al.*, 2003)
m_2	Fitting parameter in Gallipoli’s equation (Gallipoli *et al.*, 2003)
m_3	Fitting parameter in Gallipoli’s equation (Gallipoli *et al.*, 2003)
m_4	Fitting parameter in Gallipoli’s equation (Gallipoli *et al.*, 2003)
s	Suction
θ	Volumetric water content

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A LIST OF FIGURES

Table 1. Summary of parameters for the new water retention model

Test	Parameters for Eq. (2)					Depth	R_v
	m_1 [-]	m_2 [-]	m_3 [kPa]	m_4 [-]	e_0 [-]	[mm]	[mm^3/mm^3]
This study (Field)	0.11	2.5	0.30	3.64	0.52	100	0.032
This study (Laboratory)	0.15	1.9	0.18	3.51	0.50	100	0.034
Leung *et al*. (2015b)	0.04	8.6	0.70	2.98	0.72	50	0.043

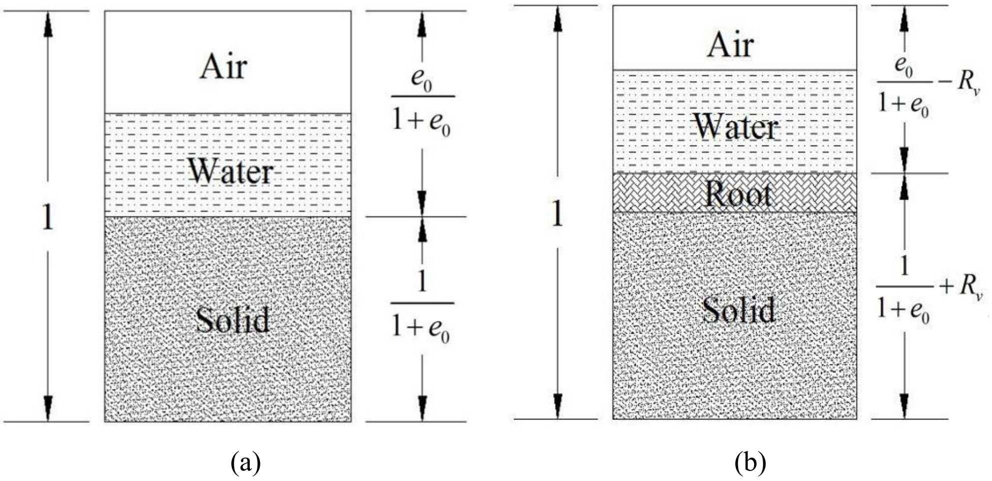

Fig. 1. Volumetric phase diagram of (a) a bare soil and (b) a root-permeated soil

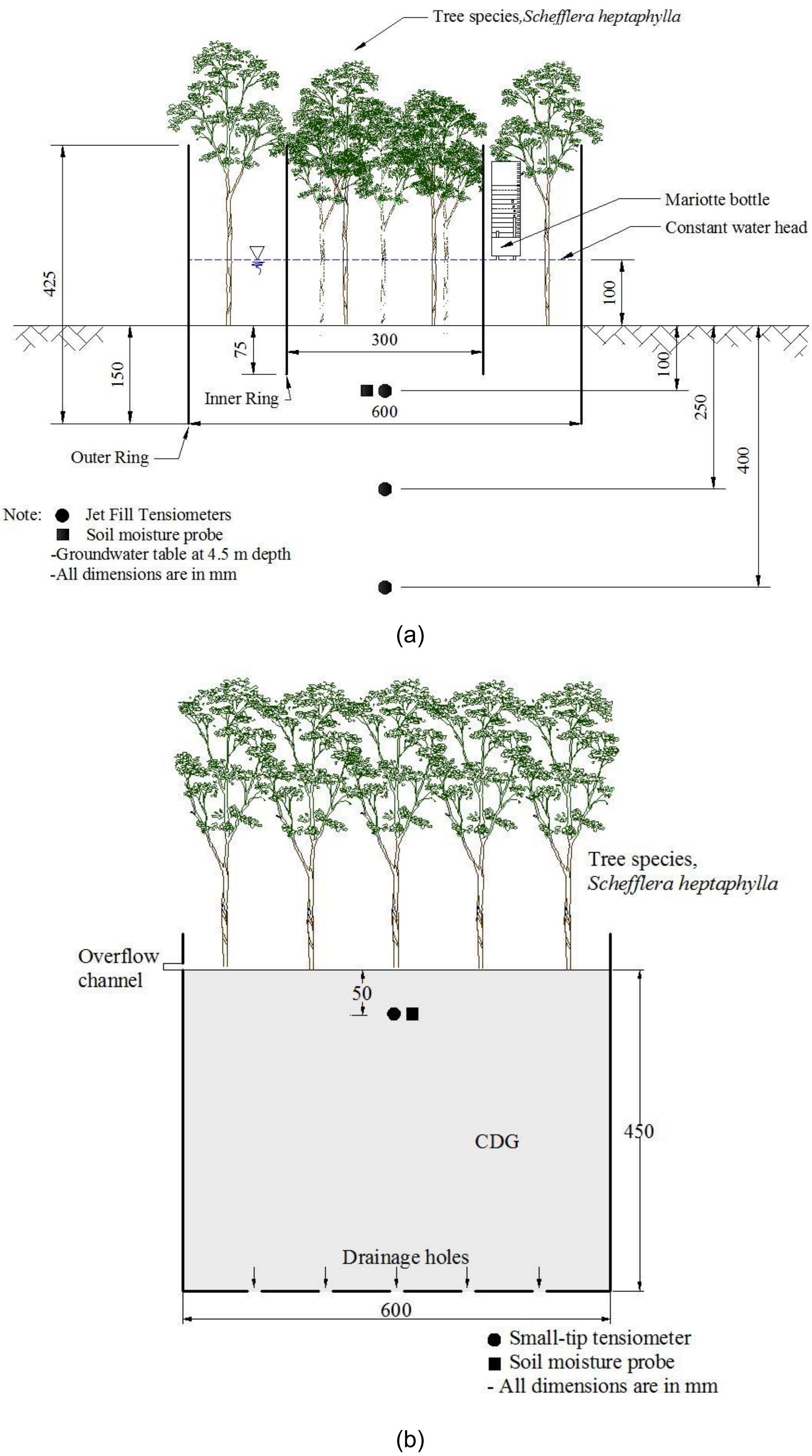

Fig. 2. Experimental setup and instrumentation for (a) the field study and (b) the laboratory study

Replicate 1 Replicate 2

(a)

Replicate 1 Replicate 2

(b)

Fig. 3. Overview of the root systems of some typical tree seedlings after testing of (a) the field study and (b) the laboratory study (each grid represents a 10 mm × 10 mm square)

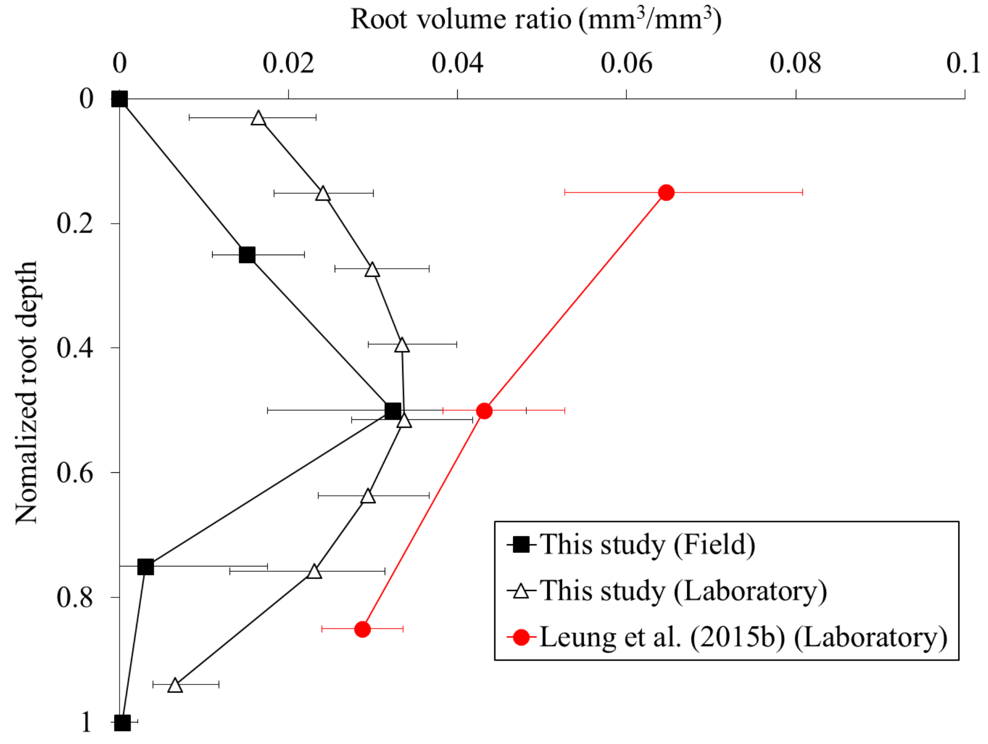

Fig. 4. Measured distributions of R_v with depth. Error bars represent standard error.

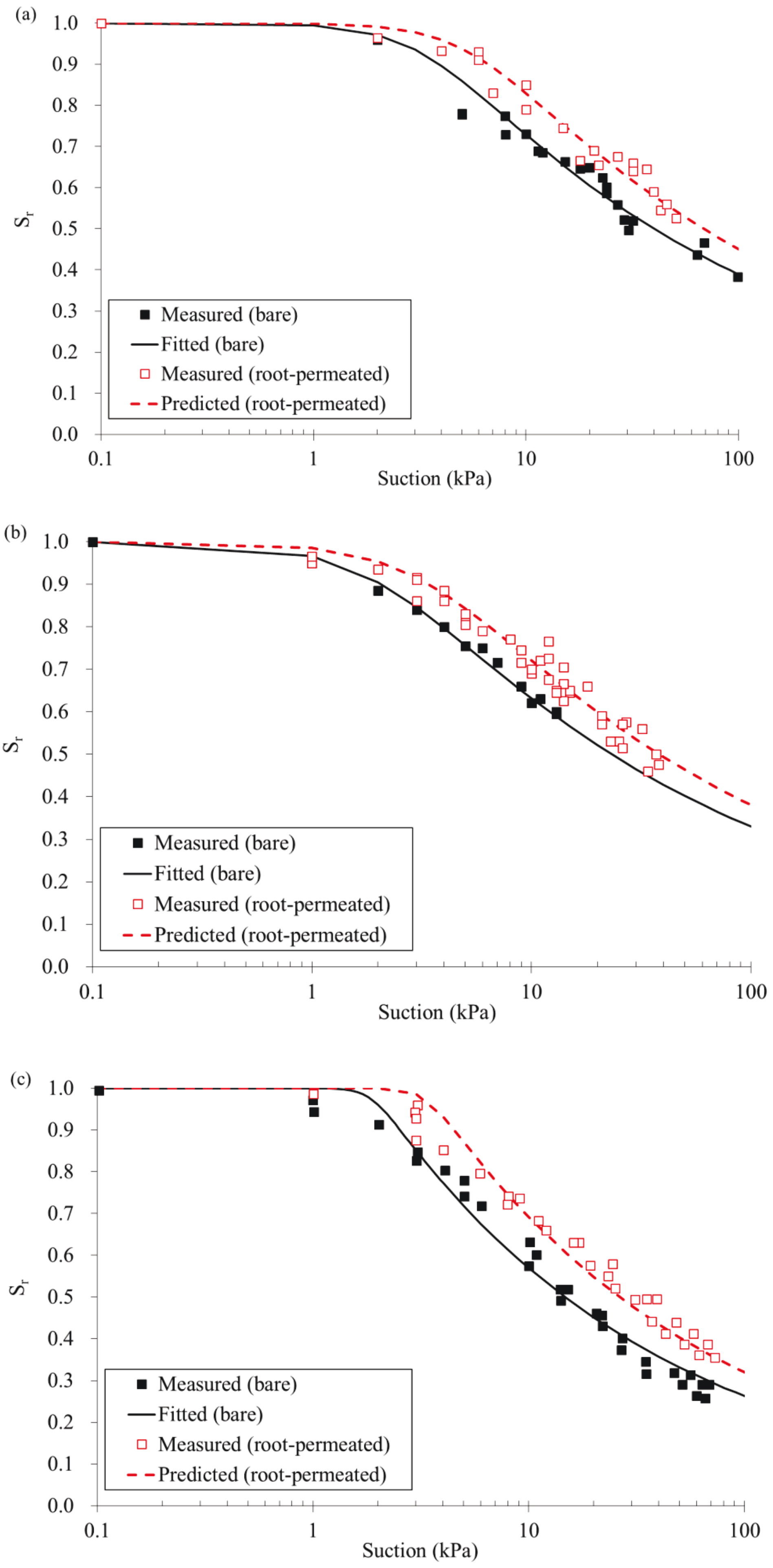

Fig. 5. Comparison of the measured and predicted SWRCs of bare and vegetated soil for (a) the field tests; (b) the laboratory tests; and (c) the laboratory tests reported by Leung *et al.* (2015b)