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DOI

[10.1139/cgj-2016-0629](https://doi.org/10.1139/cgj-2016-0629)

Publication date

2017

Document Version

Accepted author manuscript

Published in

Canadian Geotechnical Journal

Citation (APA)

Shao, W., Ni, J., Leung, A. K., Su, Y., & Ng, C. W. W. (2017). Analysis of plant root-induced preferential flow and pore-water pressure variation by a dual-permeability model. *Canadian Geotechnical Journal*, 54(11), 1537-1552. <https://doi.org/10.1139/cgj-2016-0629>

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Journal:	<i>Canadian Geotechnical Journal</i>
Manuscript ID	cgj-2016-0629
Manuscript Type:	Article
Date Submitted by the Author:	19-Nov-2016
Complete List of Authors:	Shao, Wei; Technische Universiteit Delft Ni, Junjun; The Hong Kong University of Science and Technology, Department of Civil and Environmental Engineering Leung, Anthony; University of Dundee, Division of Civil Engineering Su, Ye; Charles University in Prague Ng, Charles Wang Wai; Hong Kong University of Science and Technology
Keyword:	planting density, suction, preferential flow, dual-permeability model, slope stability

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Analysis of plant root-induced preferential flow and pore water pressure variation by a dual-permeability model

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16 **Abstract**

17 Vegetation can affect slope hydrology and stability via plant transpiration and its induced
18 matric suction. Previous work suggested that the presence of plant roots would induce
19 preferential flow, and its effects may be more significant when the planting density is high.
20 However, there is a lack of numerical study on how planting density affects soil pore water
21 pressure and shear strength during heavy rainfall. This study aims to investigate the impact of
22 plant root-induced preferential flow on hydro-mechanical processes of vegetated soils under
23 different planting densities. Two modelling approaches, namely single- and dual-permeability
24 models, were integrated with an infinite slope stability approach to simulate pore water
25 pressure dynamics and slope stability. Laboratory tests on soils with two different planting
26 densities for a plant species, *Schefflera heptaphylla*, were conducted for numerical
27 simulations. Decayed roots were found to be more evident in the high planting density soil.
28 The single-permeability model overestimated the pore water pressure in shallow soil and
29 underestimated the infiltration depth. The dual-permeability model, which is able to model the
30 effects of preferential flow, can better capture the observations of rapid increase of pore water
31 pressure and deeper pressure response in the vegetated soil. However, caution should be taken
32 on the choice of pore water pressure when using the dual-permeability model to assess the
33 factor of safety. The dual-permeability model using the pore water pressure in the preferential
34 flow domain and that in the matrix domain would result in lower and higher factor of safety,
35 respectively.

36

37 **Keywords:** planting density; suction; preferential flow; dual-permeability model; slope
38 stability

39

40 1. Introduction

41 Vegetation has been recognised as an environmentally friendly restoration technique for slope
42 stabilization. On one hand, due to the mechanical reinforcement of plant root system, the
43 tensile strength provided by roots at the potential slip surface of a slope increases soil shear
44 strength, which may be used to stabilize the landslide-prone areas (Cohen et al. 2009). On the
45 other hand, plant transpiration and root water uptake can induce soil matric suction (equal to
46 negative pore water pressure in unsaturated soils), resulting in an increase in soil shear
47 strength (Ng and Menzies 2007) and a decrease in soil hydraulic conductivity (Leung et al.
48 2016; Ng and Leung 2012).

49 Slope restoration is affected by growing and decaying of roots, which would consequently
50 cause changes in both soil hydraulic and mechanical properties (Lehmann and Or 2012). Due
51 to plant life cycle and competition among plants, growing and decaying of roots may lead to
52 changes in tensile strength for the root reinforcement (Cohen et al. 2009). Besides, root
53 occupation and biodegradation has been shown to significantly affect the soil hydraulic
54 properties such as soil water retention curve and saturated hydraulic conductivity (Li and
55 Ghodrati 1994; Scholl et al. 2014; Leung et al. 2015a, b; Vergani and Graf 2015; Ng et al.
56 2016a). The pattern of infiltration and associated soil moisture and pore water pressure
57 dynamics would therefore be affected by root physiological processes (Snyder et al. 2003).

58 Planting density is an important factor influencing the physiological processes of root in terms
59 of growing and decaying, and therefore altering the effectiveness of slope restoration. Low
60 planting density leads to low root biomass production, resulting in a reduction of root
61 reinforcement and root water uptake (Ng et al. 2016b). In contrast, high planting density
62 induces higher transpiration during an intermittent period between rainfall events, causing a
63 greater increase in matric suction in root zone. In addition, high planting density may lead to
64 the competition for water, nutrients, and light among neighbouring plants, which could
65 consequently hamper root biomass production, resulting in root decaying (Azam – Ali et al.
66 1984; Darawsheh et al. 2009; Benomar et al. 2012; Ng et al. 2016b).

67 Recent studies reported by Ng et al. (2016a, b) found that the growth of plant was
68 accompanied with root biomass production, affecting the root occupancy of soil pore space.
69 As a result, for the case of low planting density, vegetated soil may have relatively lower soil
70 hydraulic conductivity and higher water retention ability than bare soil (Scanlan and Hinz

71 2010; Scholl et al. 2014; Leung et al. 2015b; Ng et al. 2016b). In contrast, for the case of high
72 planting density, the presence of decayed roots would increase the saturated hydraulic
73 conductivity and reduce the water retention ability (Ng et al. 2016b).

74 Decayed root channels can compose a self-organized macropores network, in which the
75 preferential flow may be triggered under high-intensity rainfall or wet soil moisture condition
76 (Sidle et al.2001; Jarvis 2007; Ghestem et al. 2011; Nimmo 2012). The rainfall may infiltrate
77 through the interconnected root channels, resulting in rapid water movement and pore water
78 pressure response in deep soil (Beven and Germann 2013). Even in an individual macropore,
79 which is not directly connected to surface infiltration or ponded water, the hydraulic
80 connection can be achieved by pressure propagation and water exchange between macropores
81 and matrix (Nimmo 2007; Nieber and Sidle 2010). Preferential flow can affect tracer transport
82 in terms of reducing travel time, increasing infiltration depth, and affecting concentrations in
83 drainage flow (Jarvis 2007; Beven and Germann 2013). Particularly, under heavy rainfall or
84 snow-melting conditions, the occurrence of preferential flow in a potentially unstable slope
85 could cause rapid infiltration and percolation (Uchida 2004; Shao et al. 2015). Consequently,
86 preferential flow induces fast pore water pressure change at the potential slip surface, and this
87 could play an important role in triggering slope failure (Van Asch et al. 1999; Hencher 2010;
88 Sidle and Bogaard 2016).

89 The commonly-used numerical models for coupling seepage and slope stability analysis are
90 single-permeability models, which employ the Darcy-Richards equation or its various
91 simplification (e.g., the linear diffusion equation, Boussinesq equations) in an assumed single-
92 continuum soil(Iverson 2000; Talebi et al. 2008; Lu et al. 2012). A single-permeability model
93 often neglects the effects of preferential flow, so it could underestimate the amount of
94 infiltration, percolation, and drainage in slopes during heavy rainfall (Beven and Germann
95 2013). Existing numerical studies indicate that the single-permeability model is unable to
96 correctly simulate rapid water and tracer movement in macropore soils (Jarvis 2007; Köhne et
97 al. 2009). Recent studies also suggested that even though the equivalent parameter sets were
98 used by the single-permeability model, it is still not possible to simulate fast pressure response
99 and the associated effects on slope stability (Shao et al. 2015, 2016).

100 It is a remaining challenge on how to deterministically quantify the impact of preferential
101 flow on slope hydrology and stability (Uchida 2004; Hencher 2010; Bogaard and Greco 2016).
102 Many preferential flow models have been developed such as a pore-network model, dual- or

103 multi-continuum conceptualization of soil porous medium (see review by Köhne et al. (2009)).
104 Specifically, the dual-permeability model uses two coupled Darcy-Richard equations (Gerke
105 and Köhne 2004; Köhne et al. 2009) to quantify the dual-effect of the matrix and preferential
106 flow on infiltration, pressure propagation, and their effects on slope stability (Shao et al. 2015,
107 2016). Application of such dual-permeability model for an ecological system may be
108 necessary to simulate the hydrological and mechanical responses of soils with widespread
109 decayed roots that potentially form a macropore network.

110 This study aims to quantify the impact of planting density on soil hydrology, including the
111 response in pressure propagation and their effects on soil mechanical responses and slope
112 stability. Numerical modelling and analyses were conducted to simulate and back-analyse the
113 recent experiments reported by Ng et al. (2016b). In the experiments, a tree species,
114 *Schefflera heptaphylla*, with ornamental and ecological value for slope rehabilitation and
115 reforestation was tested. The species were planted in big drums with different planting
116 densities. Root area index was measured to quantify the effects of planting density on root
117 growth and decay. The measured variation of soil pore water pressure during a rainfall event
118 was simulated using both the single- and dual-permeability models. Subsequently, the role of
119 planting density on slope stability was analysed.

120 **2. Laboratory test**

121 **2.1 Test plan, test setup and instrumentation**

122 Two different planting densities of 36 (test D36), and 320 (test D320) seedlings/m²,
123 corresponding to the plant spacing of 0.18 m and 0.06 m were investigated (Ng et al. 2016b).
124 Each planting density was tested with three replicates. There were six drums in total for
125 testing vegetated soils, each of which has a diameter of 0.6 m and a height of 0.5 m. An
126 additional drum was compacted with bare soil for measuring soil water retention curve and
127 saturated hydraulic conductivity. Multiple-holes were made in the bottom of each drum for
128 creating a free drainage boundary. The targeted plant species, *Schefflera heptaphylla*, is small-
129 sized, and semi-deciduous. Plant individuals were transplanted to the test drums with a
130 uniform spacing at the targeted plant densities (Figure 1).

131 The tested soil was completely decomposed granite (CDG) that can be classified as silty sand
132 according to the Unified Soil Classification System (USCS; ASTM, 2010). The CDG was
133 compacted at a dry density of 1780 kg/m³ for all the test drums. Two vertical arrays of

134 miniature-tip tensiometers were installed at the depth of 0.05, 0.10, 0.15, 0.25, and 0.35 m to
135 measure the negative pore water pressure. An array of tensiometers (denoted by R) was
136 located in the middle of the drum that is beneath a tree individual. Another array (denoted by
137 M) was installed next to the array R with a distance of half-spacing. The volumetric water
138 content at depth of 0.05 m and 0.10 m was measured by two soil moisture probes (SM300,
139 Delta-T Device Ltd).

140 All test drums were placed in a plant room with well-controlled environmental condition. The
141 air temperature and relative humidity were maintained at $25\pm 1^\circ\text{C}$ and $60\pm 5\%$, respectively.
142 The radiation energy was provided by the cool white fluorescent lamp with irradiance of 5.0
143 $\text{MJ}/\text{m}^2/\text{day}$, and the wave band was within the range of 400-700 nm to promote the plant
144 growth (Ng et al. 2014). Irrigations were applied frequently to maintain the average soil
145 moisture that was close to the field capacity, which is commonly considered to be sufficient
146 for root growth (Wang et al. 2007).

147 **2.2 Test procedures**

148 A two-stage test was conducted after a 4-month growing period. The first stage was to
149 saturate the drums with a constant ponding head until the soil in each drum was fully-
150 saturated. Afterward, the ponding water was removed and all the drums were exposed to a 4-
151 day drying period under the same atmospheric condition. The second stage was commenced
152 immediately after the drying test. Artificial rainfall was applied with a controlled intensity of
153 $73 \text{ mm}/\text{h}$ and duration of 2 h, corresponding to a 10-year return period in Hong Kong (Lam
154 and Leung 1995). All the drums were inclined at a small angle of 2° to ensure that any water
155 ponded on the soil surface during rainfall could turn into infiltration-excess overland flow.
156 The distributions of pore water pressure in all drums were recorded at a 10-min interval
157 during the second stage infiltration tests.

158 After the infiltration test was completed, all plants were carefully removed from each drum.
159 The roots were cleaned to investigate the geometry of root system. The detailed procedures
160 can refer to Ng et al. (2016b). The rooting depth is defined as the deepest soil depth, beyond
161 which no root can be found. Root area index (RAI) is defined as the ratio of the total root
162 surface area to the cross-section area of soil for a given depth. The ImageJ software was used
163 to reconstruct the root system with high-resolution images (i.e., 12 pixels per unit mm of

164 length). The root surface area of each cross-section was calculated by converting the pixel
165 number into surface area of roots in mm².

166 The measured RAI distribution with soil depth and typical root systems obtained at different
167 planting densities are shown in Figure 2. All the root systems were in parabolic shape along
168 depth. The root system from the test D36 was more dispersed. The average rooting depth in
169 test D36 was 0.16 m, which was 30% longer than that in test D320 (i.e., 0.125 m). However,
170 the largest RAI values of test D320 (i.e., 0.7) was 40% larger than test D36 (i.e., 0.5).
171 Interestingly, in all the repeated tests, the decayed roots were commonly found in soil of test
172 D320, while the roots in test D36 were mainly fresh and less decayed roots were observed.

173

174 3. Mathematical models

175 The models described herein aim to capture and simulate the transient infiltration processes
176 and pore water pressure dynamics in a one-dimensional (1D) profile of vegetated soil. For
177 modelling simplicity, the roots in each tested drum are considered to be homogeneously
178 distributed within the root zone. As it has been shown by Ng et al. (2016b) that any plant
179 transpiration during the short 2 h rainfall event in the drum tests was minimal, it is reasonable
180 to ignore the plant transpiration as well as soil evaporation in the calculation (Sidle et al.1985;
181 Snyder et al.2003). In this study, the effects of roots on infiltration are represented by the
182 parameterisation of the soil hydraulic parameters, including soil water retention curve and
183 saturated hydraulic conductivity (Leung et al. 2015a, b; Ng et al. 2014, 2016a, b).

184 3.1 Single-permeability model

185 The single-permeability model uses one Darcy-Richards equation to simulate the transient
186 response of pore water pressure to rain-pulses:

$$187 \quad C \frac{\partial h}{\partial t} = \frac{\partial}{\partial z} \left[K \left(\frac{\partial h}{\partial z} + 1 \right) \right] - \Gamma \quad (1)$$

188 where t (T) is time, θ (L³L⁻³) is the water content, C ($d\theta/dh$) (L⁻¹) is the differential water
189 capacity, h (L) is the pressure head, K (LT⁻¹) is the unsaturated hydraulic conductivity, and Γ
190 (T⁻¹) is the source or sink term that may be used to calculate root water uptake (Feddes 1976;
191 Leung et al. 2015a, b) and soil evaporation (if a longer term of soil moisture dry-down and

192 pressure recession was to be modelled). In this study, the term Γ is set to be zero, considering
 193 that the plant transpiration during the short period of rainfall (2 h) is negligible (Snyder et al.
 194 2003).

195 The Mualem-van Genuchten model is used to describe the hydraulic properties of vegetated
 196 soils (Van Genuchten 1980):

$$197 \quad \Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \begin{cases} [1 + |\alpha h|^n]^{-m}, & h < 0 \\ 1, & h \geq 0 \end{cases} \quad (2)$$

$$198 \quad C(\Theta) = \begin{cases} mn\alpha(\theta_s - \theta_r)\Theta^{1/m}(1 - \Theta^{1/m})^m, & h < 0 \\ S_s, & h \geq 0 \end{cases} \quad (3)$$

$$199 \quad K(\Theta) = K_s \Theta^{0.5} \left[1 - (1 - \Theta^{1/m})^m \right]^2 \quad (4)$$

200 where Θ (-) is the effective saturation, θ (L^3L^{-3}) is the volumetric water content, subscript r
 201 and s denote residual and saturated state, S_s (L^{-1}) is the specific storage in saturated soil, and α
 202 (L^{-1}), n (-), and m (-) are the fitting parameters.

203 The boundary condition of the single-permeability model can be specified as the flux of
 204 rainfall intensity or pressure head for ponding condition. The switch between the two
 205 boundary conditions are achieved by theories and formula referring to van Dam and Feddes
 206 (2000).

207 3.2 Dual-permeability model

208 The dual-permeability model uses two Darcy-Richards equations to simultaneously simulate
 209 the non-equilibrium phenomenon that is caused by the different pore water flow velocities in
 210 preferential flow paths and in soil matrix (Gerke and van Genuchten 1993):

$$211 \quad C_f \frac{\partial h_f}{\partial t} = \frac{\partial}{\partial z} \left[K_f \left(\frac{\partial h_f}{\partial z} + 1 \right) \right] - \frac{\Gamma_w}{w_f} \quad (5)$$

$$212 \quad C_m \frac{\partial h_m}{\partial t} = \frac{\partial}{\partial z} \left[K_m \left(\frac{\partial h_m}{\partial z} + 1 \right) \right] + \frac{\Gamma_w}{w_m} \quad (6)$$

213 where the subscript f indicates the preferential flow domain, the subscript m indicates the
 214 matrix domain, w (-) is the volume fraction of the preferential flow domain or the matrix
 215 domain, and Γ_w (T^{-1}) is the water exchange term (Gerke and van Genuchten 1993):

$$216 \quad \Gamma_w = \alpha_w \frac{K_m(h_f) + K_m(h_m)}{2} (h_f - h_m) \quad (7)$$

217 where α_w (L^{-2}) is the water exchange coefficient.

218 The soil hydraulic characteristics of both matrix and preferential flow domain are described
 219 by the Mualem-van Genuchten model (Van Genuchten 1980). The total effect adopts the
 220 Durner's formula (Durner 1994). The volumetric ratio of the preferential flow and matrix
 221 flow sums up to one:

$$222 \quad w_f + w_m = 1 \quad (8)$$

223 The total volumetric water content of the soil is the weighted average of volumetric water
 224 contents in two domains:

$$225 \quad \theta = w_f \theta_f + w_m \theta_m \quad (9)$$

226 The same holds for the total saturated hydraulic conductivity of the soil:

$$227 \quad K_S = w_f K_{Sf} + w_m K_{Sm} \quad (10)$$

228 The boundary conditions of the Darcy-Richards equation could be specified as pressure head,
 229 flux, or mixed. The specified infiltration flux i (LT^{-1}) on the dual-permeability soil surface can
 230 be divided into two constituting domains (Dusek et al. 2008):

$$231 \quad i = w_f i_f + w_m i_m \quad (11)$$

232 where i_f and i_m are specified boundary fluxes on the surface of matrix domain and preferential
 233 flow domain.

234

235 The preferential flow may not to be triggered at the beginning of a rainfall event;
 236 consequently, and the infiltration only starts in the matrix domain (Shao et al. 2016),
 237 expressing as:

$$238 \quad R = i = w_m i_m \quad (12)$$

239 If the specified flow at the matrix surface exceeds its infiltration capacity, the boundary
 240 condition of the matrix domain would change to a specified pressure head. Hereafter, the

241 infiltration-excess water at that time-step would be reallocated to the surface boundary of the
242 preferential flow domain:

$$243 \quad i_f = \frac{R - w_m i_m}{w_f} \quad (13)$$

244 If the specified flux for the preferential flow domain is larger than its infiltration capacity, the
245 boundary conditions of both domains would switch to a specified pressure head that
246 corresponds to the depth of ponding water on soil surface.

247 3.3 Infinite slope stability calculation

248 In order to investigate the effects of planting density on the slope stability, an infinite slope
249 stability calculation is carried out, considering that the slope is vegetated with *Schefflera*
250 *heptaphylla* under the two planting densities in the drum tests. The hydrological processes in
251 the infinite slope are assumed to be the same as what the soils experienced in the drum tests.
252 The factor of safety F_s is expressed as the ratio of resisting force to gravitationally driving
253 force with three terms (Lu and Godt 2008):

$$254 \quad F_s(z_H) = \underbrace{\frac{\tan \phi'}{\tan \alpha}}_{\text{friction angle term}} + \underbrace{\frac{c'}{G \sin \alpha \cos \alpha}}_{\text{cohesion term}} - \underbrace{\frac{\sigma^s \tan \phi'}{G \sin \alpha \cos \alpha}}_{\text{suction stress term}} \quad (14)$$

255 where z_H (L) is the depth below the slope surface considered for slope stability calculation,
256 c' ($\text{ML}^{-1}\text{T}^{-2}$) is the effective soil cohesion, ϕ' (deg) is the friction angle, α (deg) is the slope
257 angle, and G ($\text{ML}^{-1}\text{T}^{-2}$) is weight of soil:

$$258 \quad G = \int_{z_H}^H [\gamma_s + \gamma_w \theta] dz \quad (15)$$

259 where γ_s and γ_w ($\text{ML}^{-2}\text{T}^{-2}$) are the specific weight of dry soil and water.

260 The suction stress σ^s ($\text{ML}^{-1}\text{T}^{-2}$) is given as:

$$261 \quad \sigma^s = \chi p_w = \chi \gamma_w h \quad (16)$$

262 where p_w ($\text{ML}^{-1}\text{T}^{-2}$) is the pore water pressure, and χ (-) is the matrix suction coefficient,
263 which may be approximated by the effective saturation (Lu et al. 2010).

264 The hydrological results were sequentially coupled with the soil mechanical calculations in
265 the following ways. The unit self-weight of soil was related to the soil moisture distribution
266 (Eq. (15)). The suction stress and shear strength were influenced by pore water pressure and
267 effective saturation. In the dual-permeability model, the pore water pressure head obtained
268 from either preferential flow domain, or matrix domain, or their weighting may be used as an
269 “effective pressure” (p_{eff}) for the slope stability analysis. Shao et al. (2015, 2016) selected the
270 pressure of the preferential flow model for stability calculation. This method considered that
271 the infiltration and pressure build-up in preferential flow paths reached a given depth of slope
272 failure plane, hence giving a relatively conservative estimation of slope stability. The
273 simulation conducted in the present study investigated the sensitivity of the choice of p_{eff} to
274 the F_s calculation, using (i) pressure from the preferential flow domain (p_f); (ii) pressure from
275 the matrix domain (p_m); and (iii) the arithmetic mean of the pressure between the two domains
276 (i.e., $0.5*(p_f + p_m)$). It should be noted that as far as the authors are aware, there is no
277 theoretical model available to determine the exact weighting of pressure between the two
278 domains that would affect soil shear strength. The scenario (iii) aims to explore how the
279 combined effects of the two domains would affect the assessment of slope stability.

280 4. Model implementation and parameterization

281 4.1 Numerical models and parameterization strategies

282 The mathematical models were numerically solved by an author-developed script under
283 Python 2.7 programming environment (Shao et al. 2016). The Darcy-Richards equation of
284 single- and dual- permeability models was solved by an implicit finite difference method (van
285 Dam and Feddes 2000; Simunek et al. 2005). The Picard iteration technique was used for each
286 time step. For ensuring numerical accuracy and computational efficiency during the
287 computation, the tolerable errors of water content were specified with 0.0001, and the time
288 step was adapted in a range of 0.02~5 min.

289 A uniform computational grid of 0.01 m was used to discretize the soil of 0.45 m depth. Both
290 the single- and dual- permeability models were used to simulate the infiltration tests. In both
291 models, the initial pressure head distribution before the infiltration tests was obtained by the

292 interpolation of the measured pore water pressure head right after the 4-day drying period.
293 Rainfall pulse with the intensity of 73 mm/h was set as the upper boundary condition, while
294 the boundaries may switch to the pressure head boundary with a ponding depth of 0.1 mm
295 under such high-intensity rainfall.

296 The soil hydraulic parameters were manually calibrated for two layers. The first layer was
297 from the soil surface to the rooting depth (i.e., root zone), in which the soil hydraulic
298 properties were affected by the presence of living and decayed roots. Below the root zone
299 where the soil was less affected by vegetation, the soil hydraulic parameters may be specified
300 to be the same as the bare soil. For numerical simulations, the following calibration strategies
301 were sequentially used to parameterize the models: (1) the soil water retention curves were
302 estimated according to the measurements of soil moisture and pore water pressure; (2) the
303 saturated hydraulic conductivities were estimated according to the measured infiltration rate;
304 and (3) for the dual-permeability model, the water exchange coefficients were estimated
305 according to the measured pore water pressure response. The hydraulic parameters for soils in
306 different experiment cases are listed in Table 1.

307 **4.2 Water retention curve**

308 The soil water retention curves (SWRCs) for single- and dual- permeability model were
309 determined according to water content and pore water pressure as shown in Figure 3. The data
310 points of water content and pressure head can be classified into two categories - drying series
311 and wetting series, depending on whether the data was from the first-stage drying period or
312 the second-stage infiltration period. In the bare soil, the difference between drying and
313 wetting curves is indiscernible. On the contrary, more significant hydraulic hysteresis was
314 found in the vegetated soils (regardless of the planting density). For pore water pressure
315 ranged from 0 to -10 kPa, the changes of water content during the wetting process is generally
316 smaller than that during the drying process, probably because of the presence of macropores.

317 For the single-permeability model, bare soil and vegetated soils (test D320 and D36) have the
318 same values of θ_r (0.1) and θ_s (0.3). Both parameters, α and n , controlling the shape of
319 SWRC, were fitted by the nonlinear least-squares algorithms using the sqcurvefit function in
320 Matlab. The fitted SWRC for bare soil and vegetated soils from single-permeability model are
321 shown in Figures 3 a, b, d, respectively, with all the fitting parameters shown in Table 1. Both

322 the n and α for the case of high planting density (D320) are relatively larger, which tend to
323 behave like a coarser soil.

324 The composite SWRC determined by the dual-permeability function is shown in Figures 3 c,
325 e. The composite SWRC has two groups of parameters to describe the different hydraulic
326 characteristics of the matrix and preferential flow domains. The parameters (θ and w) for the
327 volumetric ratio ($w(\theta_s - \theta_r)$) of the matrix and preferential flow domains were predefined,
328 according to the measured root volume. The θ_s for the preferential flow domain was thus set
329 to be 0.39 considering the occupancy of decayed roots in soil pore space (Ng et al. 2016b),
330 while the θ_s for the matrix domain is calculated according to Eq. 9. The volumetric ratio of
331 the preferential flow domain w_f commonly ranges from 0.025 to 0.2. Note that different
332 choices of w_f may result in equifinal parameter sets of SWRCs. This means that different
333 parameter sets of the dual-permeability model could result in the same composite SWRC of
334 the total domain for the dual-permeability model (Köhne et al. 2002). In this study, predefined
335 values of w_f were set to be 0.1 and 0.2 for the low and high planting density soils,
336 respectively. This means that the volumetric ratio of soil pores, $w_f(\theta_{sf} - \theta_{rf})$ belonging to the
337 preferential flow domains for the low and high planting density soil is about 3% and 6%,
338 respectively. A relatively higher value of w_f was specified for the high planting density soil
339 for taking into account the effects of decayed roots (Figure 2). The validity of the use of a
340 higher volumetric ratio w_f is discussed in the infiltration analysis later (Section 5.1).

341 For the dual-permeability model, the parameters, α and n , of the two domains are optimized
342 by the sqcurvefit function. These two parameters sets of the SWRC fitted for the matrix
343 domain of the dual-permeability model can be used to describe the measured water retention
344 behavior of the total domain, given the reasonably good agreement shown in Figures 3c, e.
345 The parameter n in the preferential flow domain was calibrated to be 1.5 for both D36 and
346 D320 soils according to the shapes of SWRC. On the other hand, α is related to the air entry
347 pressure, and the specified value for D36 and D320 is 6 and 10 m^{-1} , respectively. For the
348 deeper soil layer beyond the root zone, the soil hydraulic properties may not be affected by
349 root growth and decaying, and the parameters of α and n of both the matrix and preferential
350 flow domains thus followed the same parameters of bare soil.

351 4.3 Saturated hydraulic conductivity and water exchange coefficient

352 The values of K_s were calibrated based on the results obtained from the infiltration test. The
353 calibrated K_s of the bare soil is found to be 0.075 m/day when using the single-permeability
354 model. For the vegetated soils, the calibrated K_s for the high planting density soil (D320;
355 0.175 m/day) is higher than that for the low planting density soil (D36; 0.06 m/day). This is
356 consistent with the experimental observation in Figure 2 that the high planting density soil
357 contained more decayed roots. The decayed roots can affect the soil hydraulic behavior via
358 the changes in the shape of SWRC (Figure 3) and also lead to an increase in K_s (Table 1).

359 When using the dual-permeability model, the saturated hydraulic conductivity of the
360 preferential flow domain K_{sf} was set to be 4.5 m/day, which is 300 and 60 times larger than
361 K_{sm} for the case of low and high planting density, respectively. For the soil within the root
362 zone, the values of K_{sm} (0.018 m/day in D36, and 0.075 m/day in D320 soils) are in the same
363 magnitude as those for the bare soil (0.075 m/day). The K_{sm} for the low planting density soil
364 (0.018 m/day in D36) is lower than the K_s (0.075 m/day) of the bare soil, and this may be
365 related to the occupations of the live roots (Ng et al. 2016a).

366 In the dual-permeability model, the hydraulic interaction between the matrix and preferential
367 flow domains is governed by the water exchange term Γ_w in Eq. (7). The water exchange rate
368 between these two domains depends on the parameterization of α_w . For a larger α_w , an
369 equilibrium of pore water pressure between the matrix and preferential flow domains required
370 would reach more quickly. In this study, moderate values of α_w of 25 and 15 m⁻² are used for
371 the low and high planting density soils, respectively. The use of a lower α_w for the high
372 planting density soil may be related to the coating effects in biopores (Leue et al. 2010). The
373 hydraulic interaction between root channel and soil matrix may be hampered by the non-
374 wetting effects of soil organic matters (Jarvis 2007). Detailed calibration procedures of α_w for
375 a given set of infiltration data through different parameterisation strategies are provided in
376 Shao et al. (2015, 2016).

377 5 Results and Discussion

378 5.1 Infiltration rate and cumulative infiltration

379 The Infiltration rate and cumulative infiltration during the 2 h rainfall event are shown in
380 Figure 4. The measurement shows that infiltration rate and amount in D320 are higher than
381 those in D36. According to the study reported by Ng et al. (2016b), this is mainly attributed to
382 two reasons. For the case of high planting density (D320), the intense competition between
383 neighboring plants results in decayed roots (see Figure 2), hence creating preferential
384 channels that facilitate infiltration. On the other hand, the live root biomass in the case of low
385 planting density (D36) might have occupied the soil pore space, reducing the available pore
386 size and infiltration capacity (Ng et al. 2016a).

387 Both the single- and dual- permeability models can simulate the same cumulative infiltration
388 at the end of the rainfall event in both the cases (Figure 4), which is achieved by calibrating
389 the saturated hydraulic conductivities. As expected, the infiltration rate decreases from a high
390 value (close to the rainfall intensity) to a lower value (close to the saturated hydraulic
391 conductivity) during the 2 h rainfall period, due to the decreased pressure gradient at the soil
392 surface during the infiltration. Correspondingly, the cumulative infiltration is generally
393 approaching to a nearly constant increasing rate.

394 The single- and dual- permeability models could simulate infiltration rate well for the case of
395 low planting density (D36). On the contrary, much greater differences between two models
396 can be found when simulating infiltration rate and cumulative infiltration for the case of high
397 planting density (D320). Infiltration rate and cumulative infiltration in high planting density
398 soil is much higher than that in low planting density soil, and this can be modelled using a
399 high value of w_f to describe a higher soil moisture storage in preferential flow domain. At 50
400 min, for instance, the difference between the measured and simulated infiltration amount by
401 the dual-permeability model is less than 15%, but such difference is more than 50% using the
402 single-permeability model (Figure 4b). The dual-permeability model captures the infiltration
403 behavior better for both low and high planting density soils, while the occurrence of
404 preferential water flow may more significantly affect the infiltration rate and cumulative
405 infiltration for the case of high planting density.

406 5.2 Pore water pressure profile after rainfall

407 Figure 5 compares the measured and simulated pore water pressure before and after 1 and 2 h
408 of rainfall, respectively. Considering that the tensiometers used in the experiments were used
409 to record matric suction in the soil matrix, the pore water pressure in the matrix domain p_m

410 ($= \gamma_w h_m$) simulated by the dual-permeability model is used for comparison. The initial profile
411 of pore water pressure before rainfall is the result of the 4-day drying (i.e., end of the first
412 stage of the drum tests). Compared with the low planting density soil (D36), the pore water
413 pressure in high planting density soil (D320) is significantly lower both within and below the
414 root zone. This is attributed to the greater transpiration and plant root water uptake at high
415 planting density, causing a significant reduction of soil moisture and pore water pressure.

416 After 1h or 2h rainfall, the increased pore water pressure in shallower depth is much more
417 significantly than that in deeper depth, regardless of the planting density considered. After the
418 rainfall, the maximum depth of pressure response in D320 can be up to the depth of 0.35 m,
419 whereas that in D36 is shallower than 0.25 m depth. The observed pore water pressure
420 responses are consistent with the responses of infiltration rates (Figure 4). Higher infiltration
421 rate in D320 leads to a greater increase in pore water pressure, more cumulative infiltration,
422 higher infiltration rate, and hence deeper infiltration depth.

423 Simulated results from the single-permeability model show that, after 1 or 2 h rainfall, there
424 are clear wetting fronts within which the pore water pressure increases significantly. The pore
425 water pressure below remains unchanged. However, the single-permeability model
426 overestimates the pore water pressure within the wetting front, and underestimates the
427 infiltration depth for both cases of D36 and D320. The considerable changes of pore water
428 pressure in deeper depth during the rainfall tests cannot be simulated by the single-
429 permeability model. On the contrary, the dual-permeability model appears to give a better
430 match with the measurements of the pore water pressure profiles for the entire depth after 1
431 and 2 h of rainfall, despite of a slight overestimation of the pressure at 0.15 m in D320. The
432 deeper pore water pressure response observed in the experiments can be captured by the dual-
433 permeability model, especially for the high planting density soil where preferential flow may
434 be more significant.

435 **5.3 Hydrological processes simulated by single-permeability model**

436 The simulated vertical profiles of soil water content and pore water pressure during the 2 h
437 infiltration period by the single-permeability model is shown in Figure 6. The simulation
438 results show that by using the single-permeability model, a clear piston-shape wetting front
439 advancement can be identified from soil moisture and pore water pressure profiles in both the
440 low and high-planting density soils.

441 In low planting density soil (D36), the wetting fronts advance progressively downwards with
442 time. After 25 min of rainfall infiltration, the wetting front reaches the depth of 0.05 m, and
443 soil at the top 0.02 m becomes fully saturated. When rainfall continues from 25 to 120 min,
444 the wetting front advances nearly at a constant velocity. The maximum depth of water
445 infiltration after the rainfall is 0.11 m, and only the soil of the top 0.08 m is fully saturated.
446 There is no build-up of positive pore water pressure head, because the wetting front does not
447 reach the second soil layer (below the root zone) where the hydraulic conductivity is lower.

448 For the high planting density soil (D320), even though the values of initial soil water content
449 and pressure are lower than those in the low planting density soil, the variation of wetting
450 front with time is similar. The only difference is the velocity of the wetting front advancement.
451 In high planting density soil (D320), due to the higher infiltration rate (Figure 4), the rate of
452 wetting front advancement is relatively faster, extending the saturated zone to a deeper depth
453 of 0.14 m (compared to the depth of 0.09 m found in D36 soils). However, the pressure build-
454 up is still insignificant.

455 **5.4 Hydrological processes simulated by dual-permeability model**

456 Figure 7 shows the simulated water content and pressure in the matrix and preferential flow
457 domains, and the water exchanges between the two domains for the low planting density soil
458 (D36). Before rainfall, there is no water exchange between domains (Figure 7f), because the
459 initial pressure distributions in the matrix and preferential flow domains are the same. After 2
460 min rainfall, most of the rainwater infiltrates into the preferential flow domain, as the rainfall
461 intensity surpasses the infiltration capacity of the matrix domain. Consequently, the wetting
462 front in the preferential flow domain propagates with a relatively high velocity, as revealed by
463 the rapid increase of water content and pore water pressure in the deep soil (Figures 7a, d).
464 This implies that the preferential flow dominates the rainwater transport in soil. This
465 phenomenon becomes more significant after 5-min rainfall, indicating by the highest water
466 exchange at the depth of 0.05 m in Figure 7f.

467 Pressure build-up in the preferential flow domain starts when the wetting front propagates
468 beyond the rooting depth (at 0.16 m depth in D36). Below the root zone, the soil is less
469 permeable. After raining for 30 min, the advancement of the wetting front is relatively slower,
470 and the simulated pore water pressure in the preferential flow domain p_f shows a steady

471 distribution (close to a hydrostatic distribution) within the root zone. At the end of the rainfall,
472 the final infiltration depth of rainwater reaches 0.3 m.

473 Figure 8 shows the simulated distributions of soil water content and pore water pressure by
474 using the dual-permeability model for the high planting density soil (D320). The initial soil
475 water content and pore water pressure in this case are significantly lower than that in the case
476 of low planting density (D36), because of higher transpiration rate. At the beginning of
477 infiltration ($t = 2$ min), a significant fraction of rainwater infiltrates to the matrix domain
478 (Figures 8 a, b), while the water exchange rates along the soil profile are nearly zero. After 2
479 min of rainfall when infiltration capacity of the matrix domain has reached, rainwater starts to
480 infiltrate into the preferential flow domain. Afterwards, the preferential flow dominates the
481 pressure propagation. The difference in pore water pressure between the two domains results
482 in the water exchange from the preferential flow domain to the matrix domain.

483 The final infiltration depth after 2 h rainfall for the case of high planting density (D320) is
484 0.35 m, which is deeper than that in D36 (0.3 m). This is because the cumulative infiltration is
485 higher in the high planting density soil (Figure 4). The infiltrated rainwater may transport
486 through the preferential flow path and more predominantly affect the deeper soil pressure
487 response than the case in low planting density.

488 Overall, the dual-permeability model can capture the pressure response not only within, but
489 also below the root zone. Under the applied heavy rainfall (73 mm/h), the wetting front of the
490 preferential flow is deeper than that of the matrix flow, causing a fast and significant pressure
491 build-up for almost the entire soil profile that cannot be captured by the single-permeability
492 model. Interestingly, the soil in the matrix domain between the depths of 0.1 to 0.3 m remains
493 largely unsaturated – a hydrological process often called bypass flow. Although there are
494 substantial increases of water content and pore water pressure in deeper soil depths, the non-
495 equilibrium between the matrix and the preferential flow domains are revealed to be different
496 in low and high planting density soils. The simulations using the dual-permeability model
497 show that the preferential flow could lead to more significant responses of water content, and
498 the increase of pore water pressure in the high planting density soil is larger than those in the
499 low planting density soil.

500 **5.5 Preferential flow effects on slope stability**

501 The stability of infinite vegetated slopes with a gradient of 28° is analysed. The mechanical
502 properties of the CDG soils used in the drum tests were reported by Liu et al. (2015). The
503 effective cohesion of the CDG is 0 kPa, while the effective friction angle is 37.4° . The
504 effective cohesion contributed by mechanical root reinforcement was set to a relatively low
505 value of 2 kPa and is assumed to be constant and distributed uniformly within the root zone.
506 The values of factor of safety (F_s) of the vegetated slopes with two planting densities (i.e.,
507 D36 and D320) were calculated by combining the infinite slope stability modelling approach
508 (Eq. 14 – 16) with the single- or dual- permeability models.

509 The calculated profiles of F_s before and after 2h rainfall are shown in Figure 9. When using
510 the single-permeability model, the simulated pore water pressure (Figures 6b, d) can be used
511 as an input to Eq. 14 for calculating its corresponding F_s . For the calculation of F_s using the
512 dual-permeability model (with $p_{eff} = p_f$), the simulated pore water pressure in the preferential
513 flow domain (Figures 7d, 8d) was substituted into Eq. 14 – 16. The pressure build-up and the
514 wetting front advancement by the preferential flow were much more significant than in the
515 matrix flow domain. Therefore, using p_f to calculate F_s could provide a more conservative
516 assessment of the slope stability.

517 Before rainfall, the F_s calculated by the two models are identical to each other. The F_s in the
518 high planting density slope (D320) is much higher than that of the low planting density slope
519 (D36) because of the reduction of pore water pressure by evapotranspiration. After 2 h of
520 rainfall, the F_s calculated by the single-permeability model is larger than 1.0 along the entire
521 soil profile, regardless of the planting density considered. This means that no slope failure
522 exists in both cases. It can be seen that the decrease of F_s happened mainly within the wetting
523 front, where the pore water pressure increases significantly (refer to Figure 6). The volume of
524 soil being affected is found to be greater in the slope with high planting density because of the
525 increased infiltration rate (refer to Figure 4). In contrast, F_s below the wetting front remains
526 unchanged. As has been revealed from the comparison shown in Figure 5, the use of the
527 single-permeability model may underestimate the pore water pressure in deep soil compared
528 with the measurement, due to its inability to capture preferential flow that might have taken
529 place in the vegetated soils. This highlights the importance of having the preferential flow to

530 be captured when assessing pore water pressure distributions in vegetated soil, in order to
531 prevent overestimation, hence less conservative, on slope stability calculation.

532 With the assumption of $p_{eff} = p_f$, the calculated F_s by the dual-permeability model is lower
533 than that calculated by the single-permeability model. The relatively high F_s in very shallow
534 depth is contributed by the mechanical root reinforcement, despite of the low effective
535 cohesion provided by roots of 2 kPa. Near and slightly below the interface between rooted
536 and bare soil, the dual-permeability model predicts F_s to be lower than 1.0, indicating a
537 potential slope failure. This is attributed to the relatively rapid pore water pressure build-up
538 due to the presence of preferential flow. Such preferential flow appears to exist in both the
539 low and high planting density soils, but it is comparatively more significant for the latter case
540 due to the much higher cumulative infiltration and infiltration rate (Figure 2 and 4). The more
541 decayed roots in the high planting density soil would result in more infiltration and larger
542 value of pressure build-up, which adversely affects the slope stability. However, it should be
543 noted that setting p_{eff} to be p_f represents a worst-case scenario that may lead to a rather
544 conservative calculation of factor of safety.

545 **5.6 Discussion about the choice of effective pressure for slope stability calculation**

546 In a heterogeneous soil where preferential flow could happen, it remains unknown about the
547 relative contribution of pore water pressure between the matrix domain and preferential flow
548 domains to the soil shear strength. Most of the existing hydro-mechanical models use single-
549 permeability model to calculate pore water pressure in soil matrix for slope stability analysis.
550 When coupling a dual-permeability model (which adopts a dual-continuum approach) with a
551 slope stability model, using the pore water pressure of p_f or p_m may lead to different results in
552 slope stability calculations. Instead of using p_f as p_{eff} to calculate F_s (as have been shown in
553 Figure 9), it may be necessary to investigate how different choices of p_{eff} would affect F_s .

554 Comparison of F_s calculated by using different p_{eff} (i.e., p_f , p_m , or their arithmetic mean
555 $(0.5*(p_f + p_m))$) is given in Figure 10. As expected, regardless of the planting density, the
556 calculated profile of F_s using p_m is much higher than that calculated one using p_f , because the
557 pore water pressure in the matrix domain is significant higher than that in the preferential
558 domain (see Figures 8d, e and 9d, e). This suggests that it is less conservation for the stability
559 calculation of vegetated soil to use p_m to completely ignore the effects of preferential flow.

560 In an attempt to examine the combined effects of p_f and p_m on p_{eff} and slope stability, the
561 calculated F_s using the arithmetic mean (i.e., $0.5*(p_f + p_m)$) is obtained for both the low and
562 high planting density soils in Figure 10. As expected, the calculated F_s in both cases falls
563 between the values obtained by either p_f or p_m , though the F_s tends to be closer to the latter
564 case. Note that the above calculation has made an assumption on the equal weighting on the
565 contribution of p_f and p_m to shear strength. As far as the authors are aware, the exact
566 weighting is not known and it is believed to be dependent on the geometry, location, and
567 distribution of the preferential flow channels and potential failure surface. More detailed
568 investigation to correlate preferential flow with soil shear strength is needed in the future.

569 6. Summary and concluding remarks

570 Effects of plant-induced preferential flow on soil hydrology and slope stability were explored
571 through experimental and numerical modelling approaches in this study. Rainfall infiltration
572 tests were conducted in compacted silty sand vegetated plots with a selected tree species,
573 *Schefflera heptaphylla*, with two different planting densities (i.e., high planting density 320
574 seedlings/m² and low planting density 36 seedlings/m²). Post-test reconstruction of the plant
575 root systems suggested that root decaying in the high planting density soils was much more
576 evident than that in the low planting density soils. In order to capture the effects of root
577 decaying on preferential flow, two numerical models were implemented to simulate the
578 infiltration tests: one is the single-permeability model (which uses one Darcy-Richards
579 equation to consider matrix flow-only), and another is the dual-permeability model (which
580 couples two modified Darcy-Richards equations to simulate both matrix and preferential
581 flow). The calibrated hydrological models were further used to evaluate the effects of plant-
582 induced preferential flow on the stability of infinite vegetated slopes.

583 The test results show that the planting density has significant effects on the shape of soil water
584 retention curve (SWRC). The presence of decayed roots caused a decrease in air-entry
585 pressure, while desorption and adsorption rates remain almost unchanged. The root-induced
586 changes in SWRC were able to be captured by both the single- and dual- permeability models.
587 The experiment also showed that the infiltration rate in high planting density soils was
588 significantly higher, and this may be caused by the preferential flow along macropores created
589 by decayed roots. The dual-permeability model, in which preferential flow could be modelled
590 by the dual-continuum approach, showed a closer match with the measurements than the

591 single-permeability model. The single-permeability model however significantly
592 underestimated the infiltration rate at the beginning of rainfall (0-20min) and then
593 overestimated during the last period (80-120 min).

594 Considering both preferential flow and matrix flow domains when using the dual-permeability
595 model showed that preferential water flow was likely to take place in both low and high
596 planting density. The preferential flow effects appeared to be more significant in the high
597 planting density soil because of the greater increase in pore water pressure and deeper depth
598 of infiltration. These hydrological processes were, however, not possible to be captured by the
599 single-permeability model due to its inability to simulate the preferential flow effect using the
600 matrix flow domain alone. Instead, the single-permeability model simulated the piston-shape
601 of wetting front advancement during rainfall, which resulted in significant under-prediction of
602 infiltration depth and overestimation of the pore water pressure within the root zone.

603 Because of the inability of the single-permeability model, a less conservative calculation of
604 slope stability is resulted. Regardless of the planting density considered, the single-
605 permeability model estimated significantly higher factor of safety than the dual-permeability
606 model, especially on the deeper soil depths below the root zone. In contrast, when the dual-
607 permeability model was used, a lower factor of safety is resulted. While the shallow stability
608 of the vegetated slopes (up to 0.1 m depth within the root zone) is mainly provided by the
609 mechanical root reinforcement, the factor of safety below the root zone is marginally closer to
610 1. Although the dual-permeability model is better captured the variations of pore water
611 pressure in vegetated soils, caution should be taken on the choice of effective pressure for this
612 model when assessing the factor of safety. Simulation using the pore water pressure in the
613 preferential flow domain and the matrix domain in the model would result in over- and under-
614 conservative assessment of the stability of vegetated slopes, respectively.

615

616 **Acknowledgements**

617 Research grants HKUST6/CRF/12R provided by the Research Grants Council of the
618 Government of the Hong Kong SAR is acknowledged. The first author is financially
619 supported by the scholarship (No. 2011671055) provided by the China Scholarship Council.
620 The third author would also like to acknowledge the EU Marie Curie Career Integration Grant

621 under the project 'BioEPIC slope' and research travel support from the Northern Research
622 Partnership (NRP).

623

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Table 1. Soil hydraulic parameters for the single-permeability model (Single), and the dual-permeability model (Dual) for the matrix and preferential flow (PF) domains

Model	Soil	Depth (m)	Domain	w (-)	θ_r (-)	θ_s (-)	K_s (m/day)	a (m ⁻¹)	n (-)	l (-)	a_w (m ⁻²)
Single	Bare	0-0.45	Total domain	-	0.1	0.3	0.075	5	1.25	0.5	-
	D36	0-0.16	Total domain	-	0.1	0.3	0.060	4	1.26	0.5	-
	D320	0-0.13	Total domain	-	0.1	0.3	0.175	6	1.37	0.5	-
Dual	D36	0-0.16	Matrix domain	0.9	0.1	0.29	0.018	5	1.25	0.5	25
			PF domain	0.1	0.1	0.39	4.5	6	1.50	0.5	
	0.16-0.45	Matrix domain	0.9	0.1	0.29	0.018	5	1.25	0.5	25	
		PF domain	0.1	0.1	0.39	0.018	5	1.25	0.5		
	D320	0-0.13	Matrix domain	0.8	0.1	0.27	0.075	5	1.30	0.5	15
			PF domain	0.2	0.1	0.39	4.5	10	1.50	0.5	
0.13-0.45		Matrix domain	0.8	0.1	0.27	0.075	5	1.25	0.5	15	
		PF domain	0.2	0.1	0.39	0.115	5	1.25	0.5		

Note: for the single-permeability model, the hydraulic parameters for the soil below the root zone are specified to be the same as those for the bare soil.

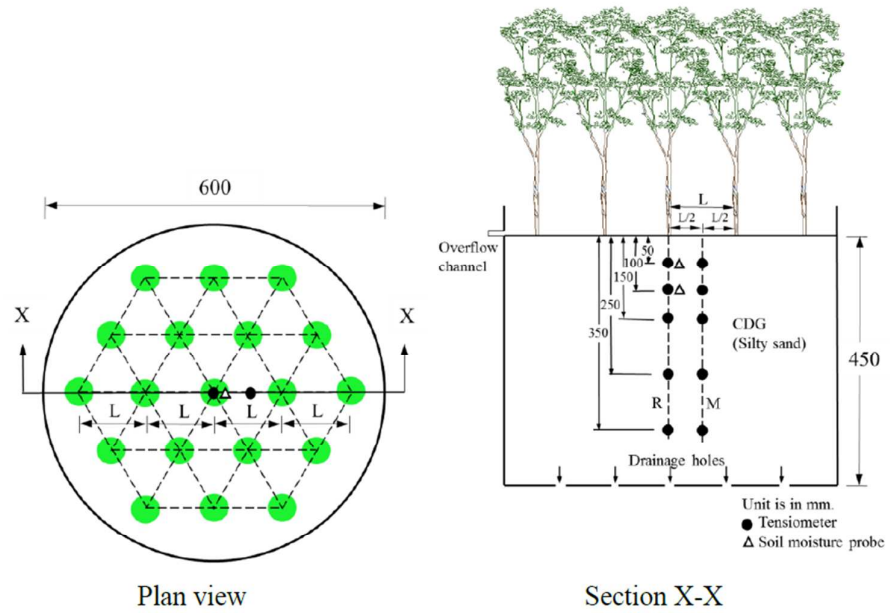


Figure 1. Schematic diagrams of a test drum and instrumentation (Ng et al., 2016b)

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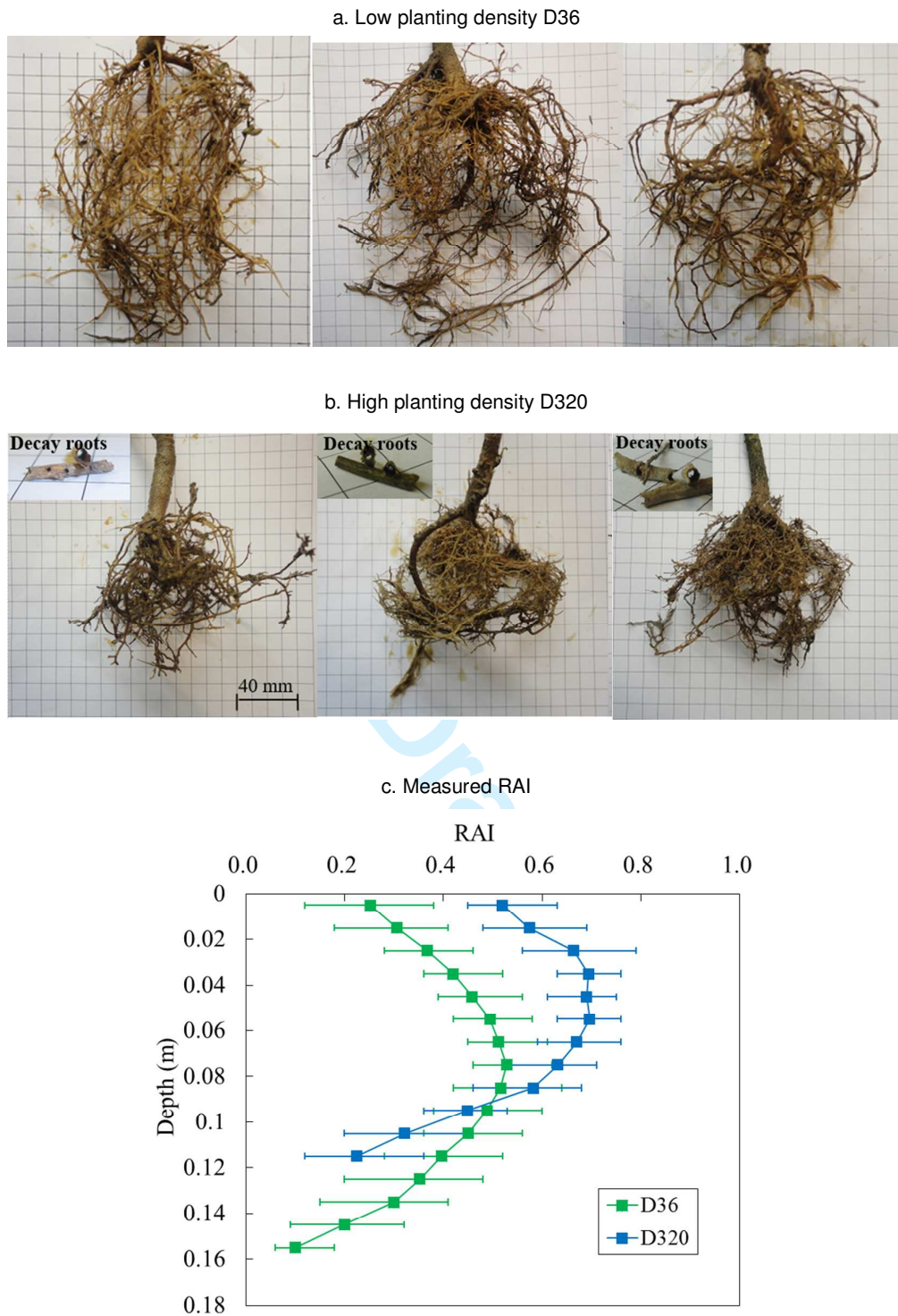


Figure 2. (a) Images of the root system for D36, (b) images of the root system for D320, (c) the measured RAI after a 4-month growing period (Ng et al., 2016b)

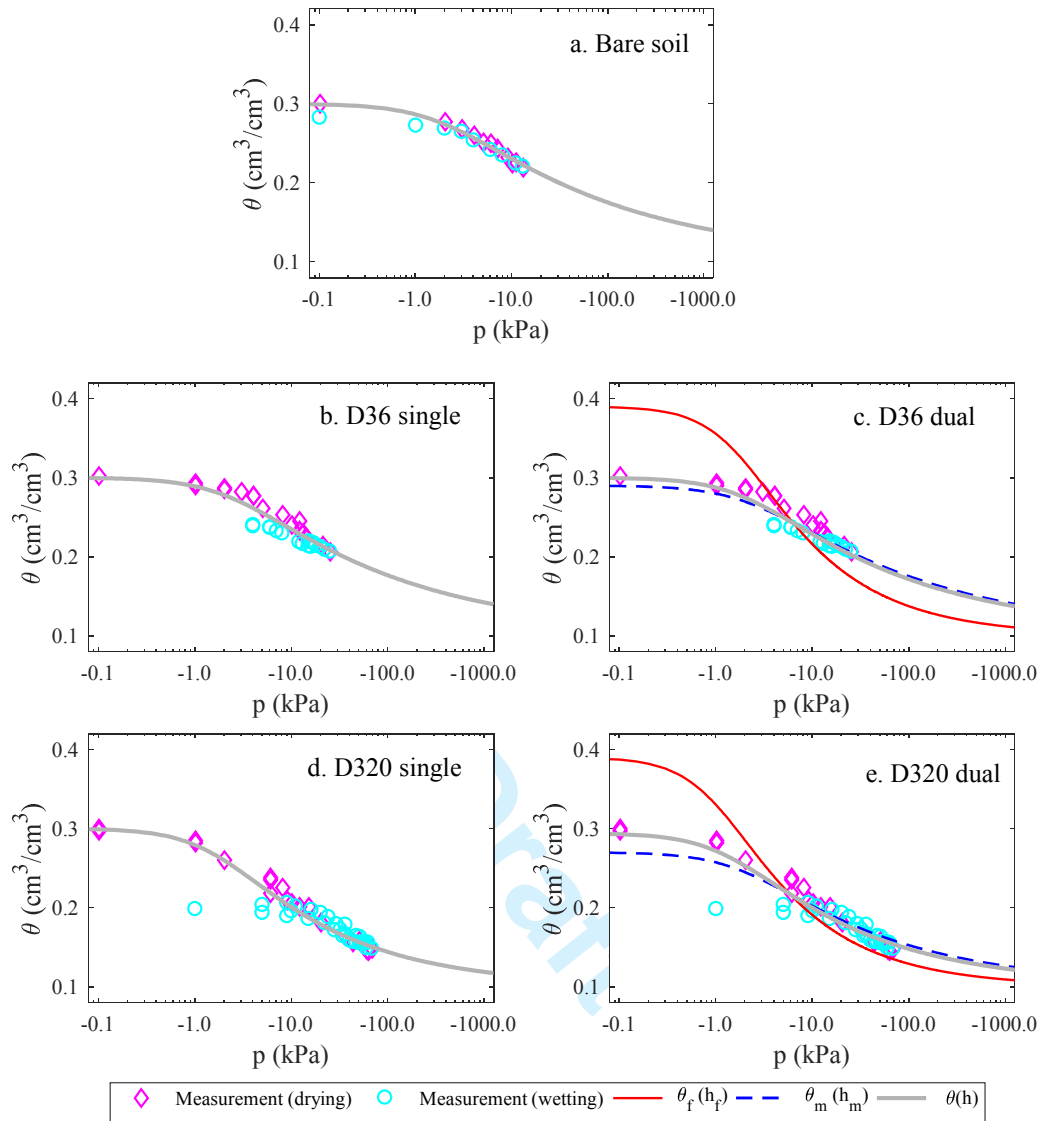


Figure 3. Soil water retention curve of (a) bare soil, (b) single- and (d) dual-permeability model in low planting density soil (D36), and (d) single- and (e) dual-permeability model in high planting density soil (D320)

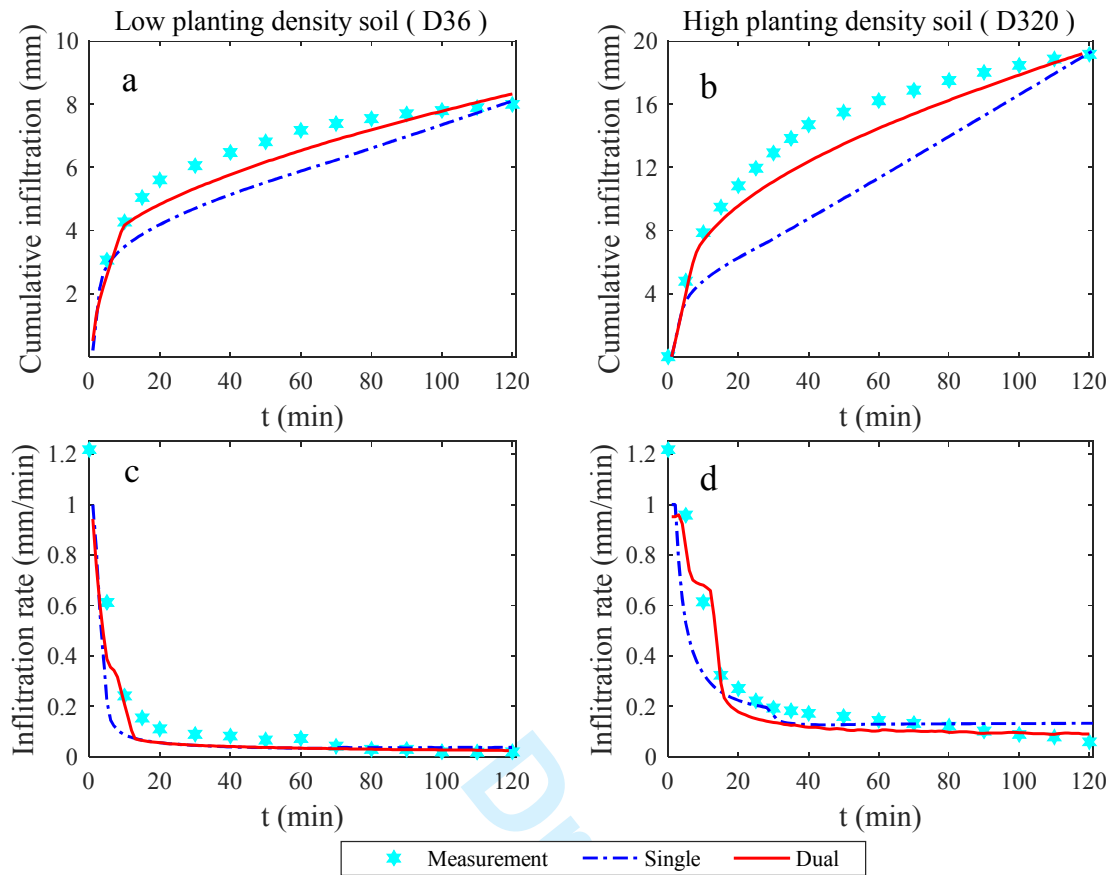


Figure 4. Comparison of the measurements (hexagram dots) and the simulations of cumulative infiltration and infiltration rate by the single- and dual- permeability models (lines) in low planting density soil D36 (left column) and high planting density soil D320 (right column)

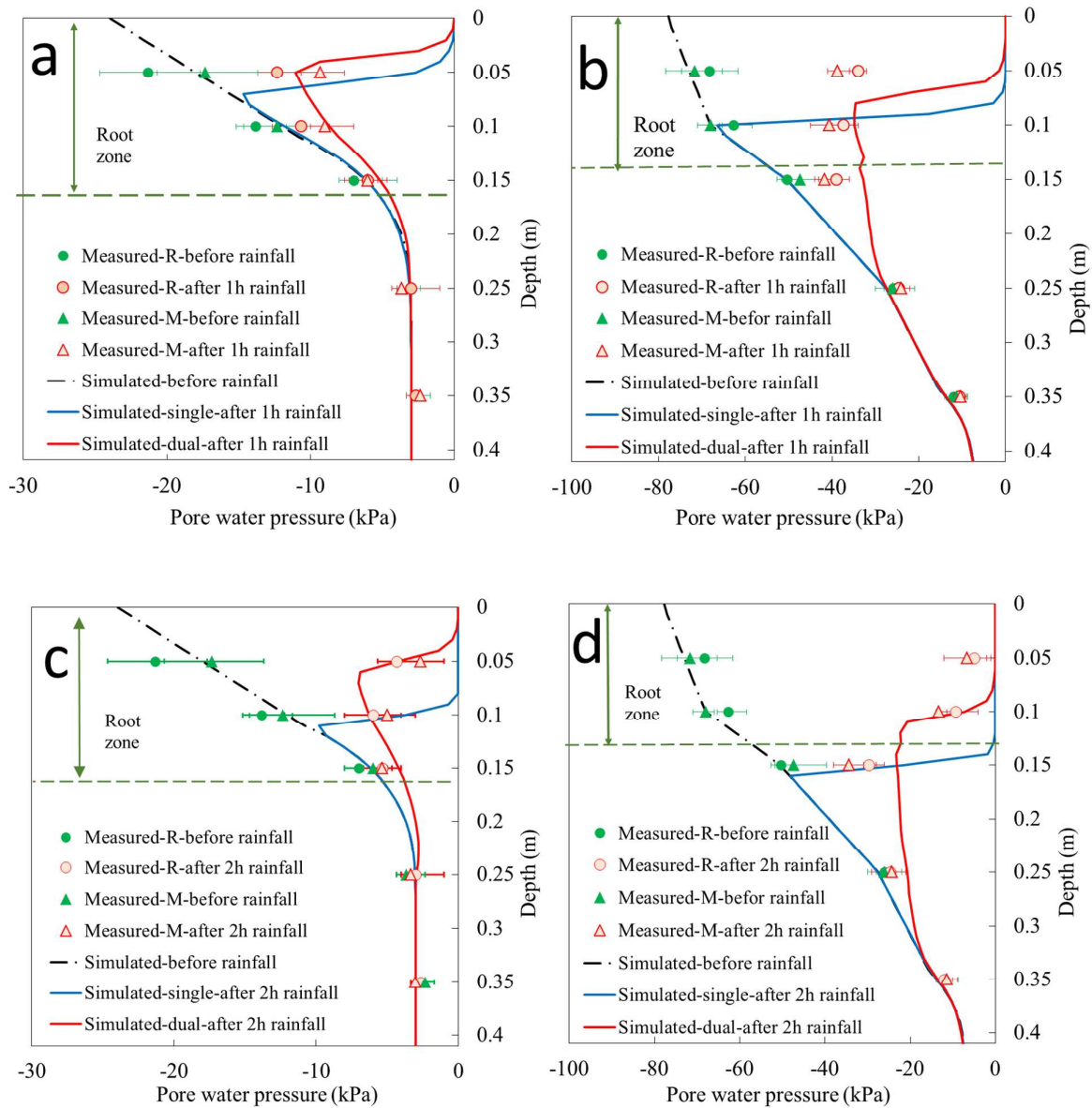


Figure 5. Comparison of the measured and simulated pore water pressure profiles by using the single- and dual- permeability models: (a) D36 and (b) D320 after 1 h rainfall, and (c) D36 and (d) D320 at 2 h rainfall

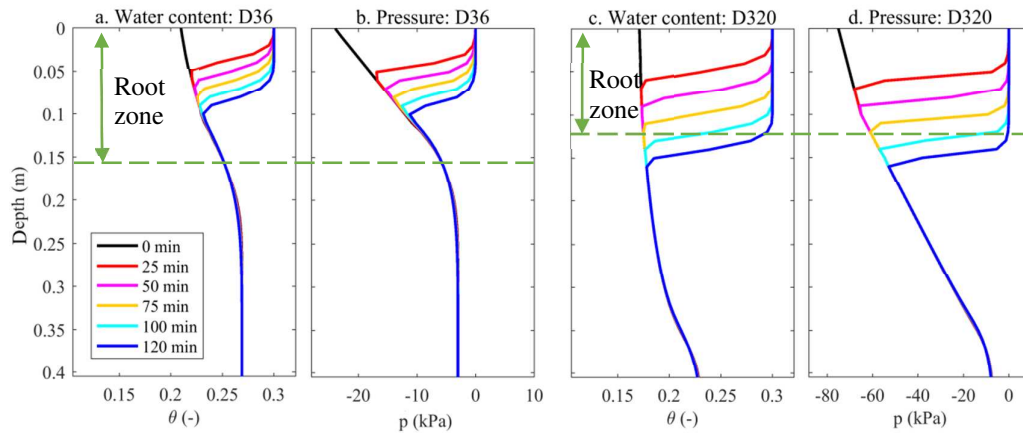


Figure 6. Simulated vertical profiles of soil water content (θ) and pore water pressure (p) in D36 and D320 soils by using the single-permeability model during the 2 hours of rainfall

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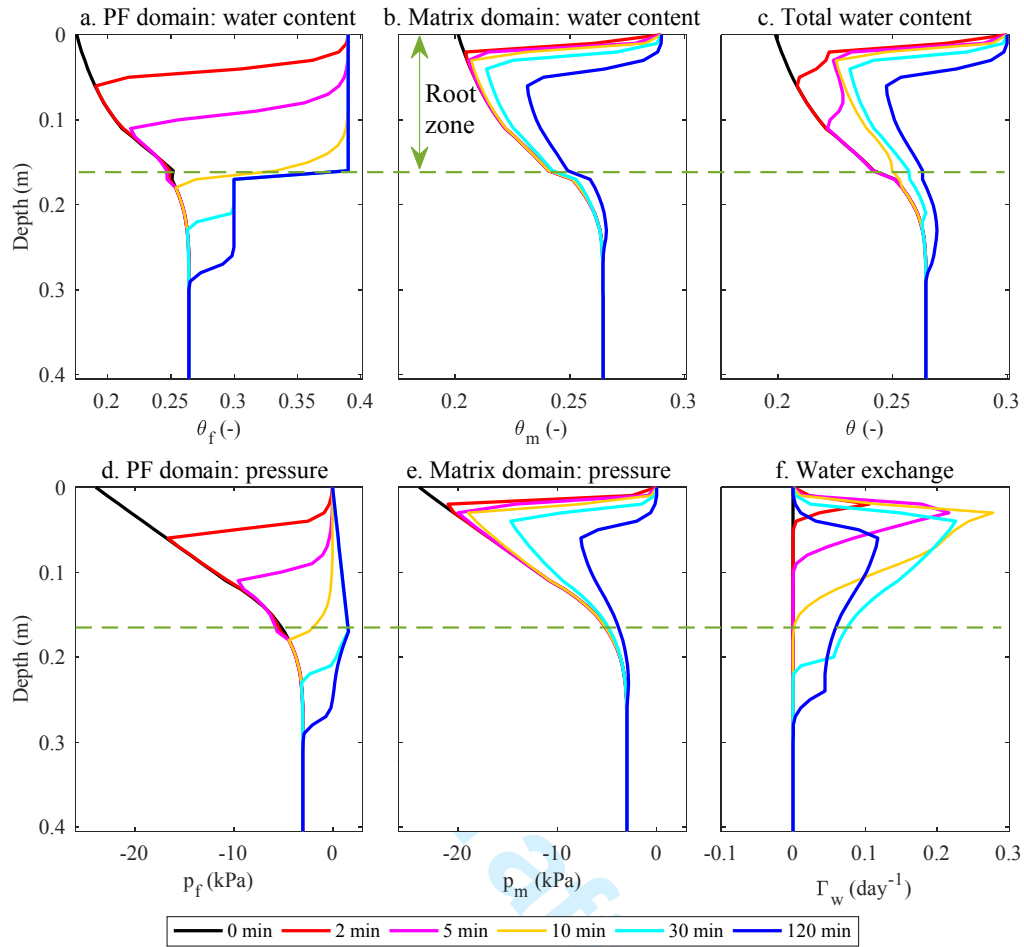


Figure 7. Simulated vertical profiles in D36 soil by the dual-permeability model during the 2 hours of rainfall: soil water content in (a) the matrix domain, (b) the preferential flow domain, and (c) the total domain; pore water pressure in (d) the matrix domain and (e) the preferential domain; and (f) the water exchange rate (positive denotes water exchange from the preferential flow domain to the matrix domain)

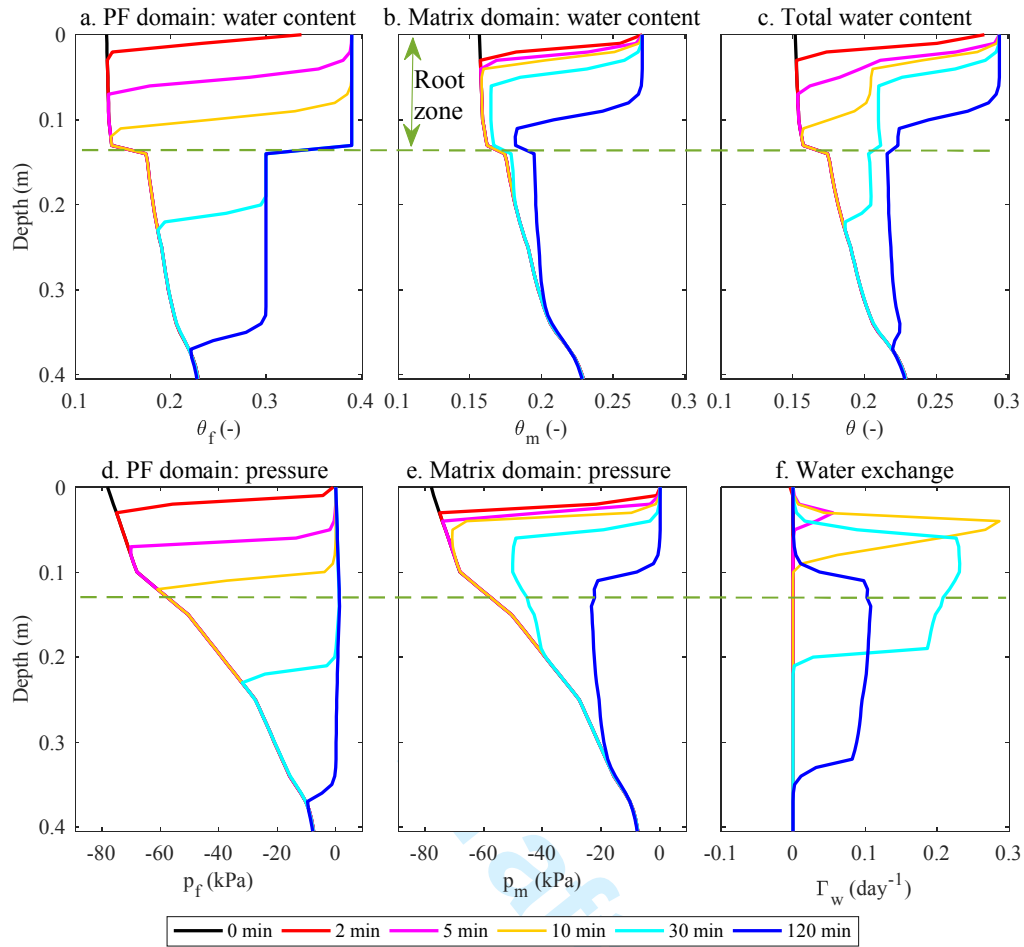


Figure 8. Simulated vertical profiles in D320 soil by the dual-permeability model during the 2 hours of rainfall: soil water content in (a) the matrix domain, (b) the preferential flow domain, and (c) the total domain; pore water pressure in (d) the matrix domain and (e) the preferential domain; and (f) the water exchange rate (positive denotes the water exchange from the preferential flow domain to the matrix domain)

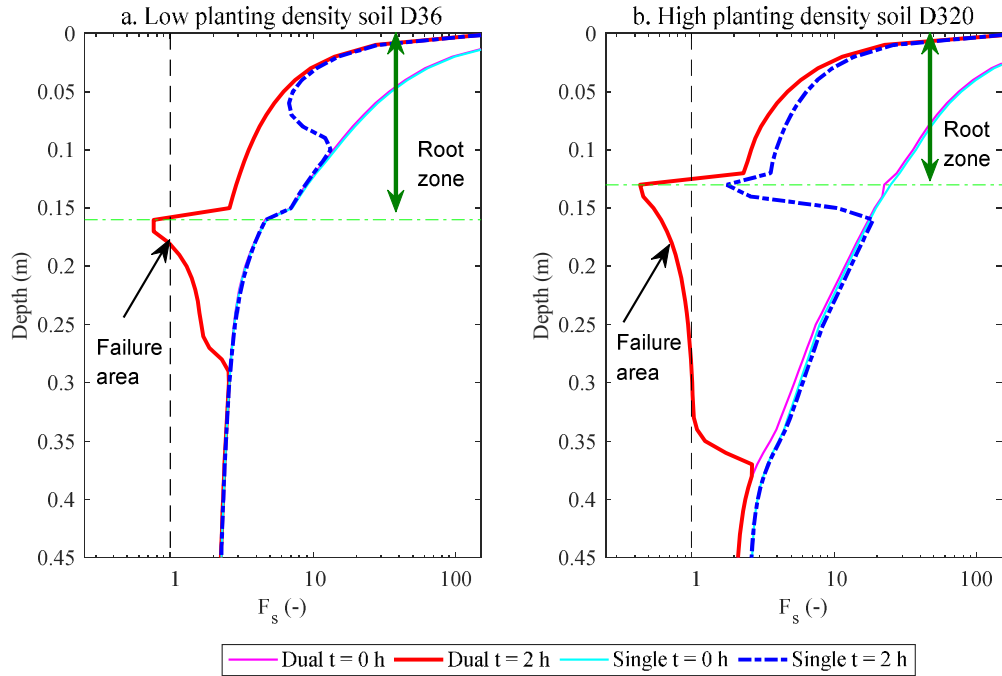


Figure 9. Effects of planting density on factor of safety (F_s) before and after the 2 h rainfall predicted by the single- and dual-permeability models (for $p_{eff} = p_f$)

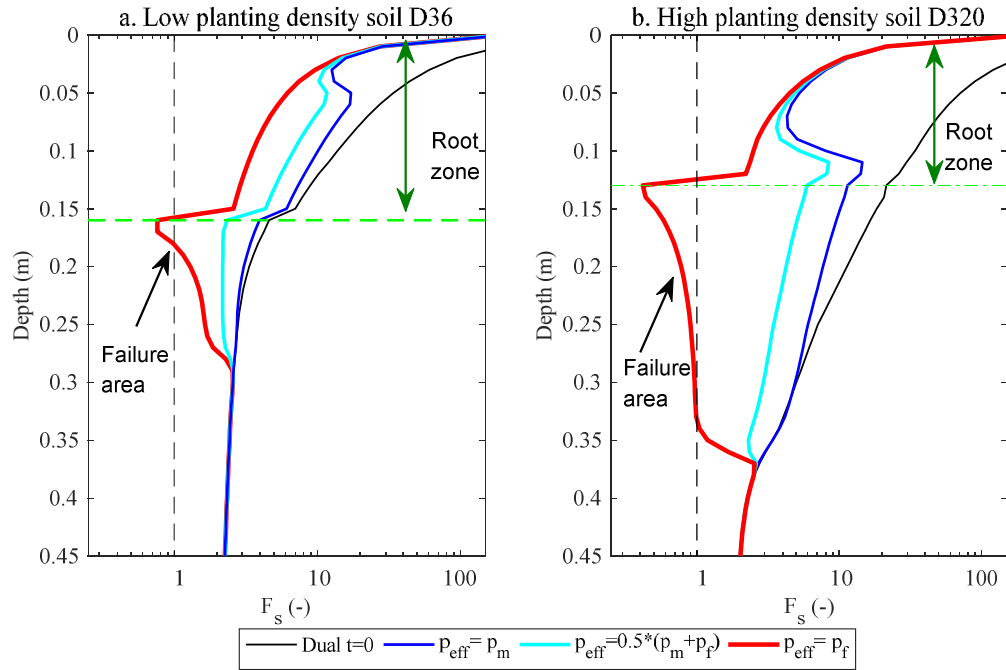


Figure 10. Effects of the choice of flow domain in the dual-permeability model on the slope stability