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Original Research

Core Ideas

- The texture of the top layer controlled infiltration more than that of the sublayer.
- Finger flow was more uniform in soils with gravel but irregular in layered water-repellent soils.
- Changes in cumulative infiltration and finger length were well correlated with wetting area.

Finger Flow Development in Layered Water-Repellent Soils

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Finger flow in water-repellent (WR) soils significantly influences the transport of water and solutes in the soil, but the mechanics of finger flow occurrence in layered WR soils is not clear. Soil chamber infiltration experiments with a total of 20 treatments, including five different WR levels with four layer combinations, i.e., clay or sandy loam overlying sand or heavy gravel, were conducted to reveal the mechanics of finger flow occurrence in layered WR soils. The variations of the finger flow dynamics and infiltration parameters were investigated. The results showed: (i) the temporal variations of cumulative infiltration (CI) decreased with the increase of the WR level so that CI was generally larger when the top layer was sandy loam rather than clay loam and therefore the top layer soil texture controlled CI more than the sublayer; (ii) for the wettable treatments, finger flow was clearly and uniformly generated in layered soils with a sublayer of heavy gravel rather than sand, but for WR layered treatments, fingers developed irregularly with the WR levels and finger length, width, and velocity varied with the WR levels; (iii) there were good power function or linear correlations between CI and cumulative wetting area, and between CI and finger length; and (iv) water content in the top layer was higher than in the sublayer and generally decreased with the increase of WR level. Finger flow development in layered WR soils was generally irregular and showed a large degree of complexity.

Abbreviations: BD, bulk density; CI, cumulative infiltration; CWA, cumulative wetting area; DCDMS, dichlorodimethylsilane; DI, distributing index; SI, shape index; WDPT, water droplet penetration time; WR, water-repellent.

Preferential flow is a common phenomenon, with water and solutes moving along certain pathways while bypassing a major fraction of the soil porous matrix (Hendrickx and Flury, 2001). Four general types of preferential flow have been classified (Allaire et al., 2009): crack flow, burrow flow, finger flow, and lateral flow. Of these, finger flow has been studied extensively by hydrologists, geophysicists, and environmental scientists (Šimůnek et al., 2003). When finger flow develops, the water breaks into the subjacent layer through fingers rather than uniformly through the entire layer (Rezanezhad et al., 2006). Finger flow affects infiltration and soil water distribution (Jamison, 1946; Bond, 1964). It accelerates the transport of water and solutes through the unsaturated soil zone and raises the risk of groundwater contamination. Finger flow may be caused by the following factors: (i) soil textural contrasts in a layered structure (Dobrovolskaya et al., 2014) or (ii) soil water repellency (Hendrickx et al., 1993; Bauters et al., 1998; Wang et al., 1998). Different soil layers may have contrasting soil hydraulic conductivity, resulting in capillary barriers or hydraulic barriers depending on the underlying textural contrast. When a coarser layer underlies a finer layer (Starr et al., 1978), the upper layer with a lower hydraulic conductivity restricts water movement to the lower soil and fingers can develop. This is considered a capillary barrier. Capillary barriers have been shown to cause finger flow. Many researchers have explained its mechanics from experimental as well as theoretical respects. Hill and Parlange (1972) found that fingers in layered soils had a saturated inner core percolating downward surrounded by an unsaturated outer layer. Hillel and Baker (1988) gave a descriptive theory of fingering in layered soils, which was possibly due to the restriction of the water supply from the top layer. According to Baker and Hillel (1990), the finger flow velocity increased across the interlayer plane when the sublayer conductivity was greater

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than the transmission rate from the top layer. Dobrovolskaya et al. (2014) concluded that wettable unlayered and fine-over-coarse layered structures were not prone to finger flow if the textural contrast of the layers was slight.

Soil water repellency is an influencing factor for finger flow. It is caused by the low solid-surface free energy of the soil particles resulting in a weak attraction between solid and liquid phases (Roy and McGill, 2002). It has been commonly found in many regions of the world (DeBano, 1981) and is often referred to as "the norm rather than the exception" (Dekker and Jungerius, 1990). This property could enhance the water ponding time at the soil surface and can cause preferential flow in soils (Ritsema and Dekker, 1994). The unsaturated water movement mechanism of finger flow in water-repellent (WR) soils is relatively complicated, from the finger flow occurrence conditions to the detailed properties of the fingers, and related research has been performed since the early 1950s (DeRoo, 1952; Raats, 1973). Finger flow was present in different degrees of WR sands (Bauters et al., 1998) and in low-level sandy subsoil (Ganz et al., 2013). Except water repellency, many factors including soil structure, different infiltration ways, etc., affect finger flow occurrence. Ritsema and Dekker (1994) found that fingers preferred to form in the places where the top layer had the lowest degree of potential water repellency. Wallach and Jortzick (2008) observed finger-like wetting fronts during point-source infiltration in wettable and WR sands. Further, researchers began to change some conditions or compare the results from different treatments. Wang et al. (2000) showed that the infiltration rate increased with time during one-dimensional infiltration in layered WR soils, which was contrary to wettable homogeneous soils. Carrillo et al. (2000) conducted laboratory infiltration experiments with different water entry pressures and ponded water depths at the top layer. They found that with an increase in the water droplet penetration time (WDPT) (DeBano, 1981), the tendency for finger formation also increased. Although finger flow development has been investigated in previous research (Bauters et al., 1998; Wang et al., 1998), there is limited research about finger flow development mechanics in WR layered soils.

Our objectives were to analyze the variations of infiltration behavior in layered soils with surface layer hydrophobicity. The finger flow and infiltration parameters included cumulative infiltration (CI), finger length (F_L), width of half finger length (FW_h), wetting front velocity (F_v), finger bottom velocity (B_v), and soil water content (θ_v). Previous results showed that coarse overlying fine soil systems led to preferential flow (Li et al., 2017), so infiltration experiments were conducted for four different groups of layered soils (i.e., clay loam overlying sand, clay loam overlying heavy gravel, sandy loam overlying sand, and sandy loam overlying heavy gravel) and five WR levels for the top layer of each group. This research aimed to reveal the mechanics of finger flow development in WR layered soils. The findings will improve our understanding of water movement, especially the finger flow phenomenon in WR soils, and will also potentially contribute to improved management practices for WR layered soils.

Materials and Methods

Soils

Four soil types, including clay loam, sandy loam, sand, and heavy gravel, were prepared for the laboratory soil chamber experiments. The clay and sandy loams were collected from the fields and Wei River banks, respectively, in Yangling, Shaanxi, China. After removal of ground impurities, the clay loam and sandy loam were passed through a 2-mm-diameter sieve and air dried. The sand and heavy gravel were purchased (Company of Qingcheng Water Purification Materials). The sand and heavy gravel particle sizes ranged from 1 to 2 and 2 to 4 mm, respectively. The particle contents of the clay and sandy loams were measured using laser diffractometry with a Longbench Mastersizer 2000 (Malvern Instruments). Soil textures were classified by the International Classification System (Table 1).

Because the WDPT test is an easy procedure for measuring soil water repellency persistence (Dekker and Jungerius, 1990), it was used to assess the initial WDPT ($WDPT_i$) of the four wettable soils. Soil with a WDPT <5 s is considered wettable (DeBano, 1981). The scale used to classify WDPT values ranges from 6 to 59 s for slightly WR, 60 to 599 s for strongly WR, 600 to 3600 s for severely WR, and greater than 3600 s for extremely WR (Bisdom et al., 1993). The average WDPT values of eight replications were used to determine the $WDPT_i$ values for the four weather-dried soils (Table 1).

Dichlorodimethylsilane (DCDMS) is a transparent, oil-like liquid that can encapsulate soil particles, producing a relatively

Table 1. Particle contents, hydraulic properties of weather-dried soil water content (θ_r), saturated soil water content (θ_s), saturated hydraulic conductivity (K_s), and bulk density (BD), and the initial water droplet penetration time ($WDPT_i$) of the tested wettable soils. The range of particle diameters for clay, silt, sand, and heavy gravel (HG) are <0.002, 0.002 to 0.02, 0.02 to 2, and >2 mm, respectively, following the International Classification System.

Soil texture	Clay	Silt	Sand	HG	θ_r	θ_s	K_s	BD	$WDPT_i$
	%				cm^3/cm^3		cm/min	g/cm^3	s
Clay loam	19	42	40	0	0.025	0.46	6×10^{-4}	1.4	1.2 ± 0.8
Sandy loam	6.5	23	71	0	0.003	0.36	0.054	1.7	0.7 ± 1.3
Sand	0	0	100	0	0.004	0.51	0.179	1.3	0.4 ± 1.7
Heavy gravel	0	0	0	100	0.003	0.55	0.216	1.2	0.3 ± 2.1

stable hydrophobic layer outside the particles. It can react with water and produce polydimethylsiloxane and HCl (Goebel et al., 2007). This is a common and effective method to create stable WR soils (Bachmann and van der Ploeg, 2002). The chemically treated soil has more static and more stable water repellency. After gradually adding DCDMS to the wettable soils (only to the clay and sandy loams of the four soil types), saturating the soils and mixing the DCDMS and soils uniformly, the soils were completely air dried. To achieve a complete reaction with DCDMS, the treated soils were left in the laboratory for several weeks. During this period, the soils were mixed regularly and tested for persistence every 4 d until the WDPT did not change. Table 2 presents the DCDMS application masses to obtain different WR levels, the WDPT values ($WDPT_p$) (DeBano, 1981), the contact angles (ω) (ω values were measured following the sessile drop technique proposed by Bachmann and van der Ploeg [2002], using average values of six replications) for the prepared WR soils, and the standard errors are given.

Table 2. The tested properties of water-repellant (WR) soils prepared with dichlorodimethylsilane (DCDMS), including the water droplet penetration time of prepared soils ($WDPT_p$) and the contact angle (ω).

DCDMS application	$WDPT_p$	WR	WR level	ω
g/kg	s			°
		Clay loam		
0	0.55 ± 0.16	wettable	L1	0
16.2	38.2 ± 16.4	slightly WR	L2	105 ± 2.5
24.3	72.0 ± 22.7	strongly WR	L3	116 ± 9.1
48.6	1625 ± 285	severely WR	L4	129 ± 8.3
64.8	4530 ± 765	extremely WR	L5	138 ± 10.2
		Sandy loam		
0	0.25 ± 0.08	wettable	L1	0
24.3	21.4 ± 5.80	slightly WR	L2	97 ± 3.8
32.4	338 ± 102	strongly WR	L3	112 ± 8.5
64.8	1025 ± 187	severely WR	L4	118 ± 13.6
72.9	4140 ± 149	extremely WR	L5	120 ± 11.8

Soil Layer and Water Repellency Treatments

The air-dried soils were packed into a 5- by 5-cm chamber with a 10-cm-depth hydrophobic top layer overlying a 45-cm-depth wettable sublayer. The packing densities were designed by packing process before hand and the specific values of the four kinds of soils are shown in Table 1. After packing, they were left for 24 h to settle. Four soil layer groups—A, B, C, and D—were constructed. The ordering of the groups moves from a finer textured top layer (Group A) to a coarser top layer (Group D). The texture in the sublayer was always coarser than the top layer. For Group A, different WR levels of clay loam were packed in the top layer and wettable sands were packed for the sublayer, denoted as clay loam–sand. Groups B, C, and D had clay or sandy loams at different WR levels as the top layers and sand or heavy gravels as the sublayers, denoted as clay loam–heavy gravel, sandy loam–sand, and sandy loam–heavy gravel, respectively. In each group, there were five WR levels of the same soils for the top layer; for convenience they are denoted as L1, L2, L3, L4, and L5, in order of increasing repellency level, but the sublayers were the same. A total of 20 treatments were designed (Table 3). The treatments were named $GiLj$, where i = A, B, C, or D and j = 1, 2, 3, 4, or 5, to produce different groups of soil textures and WR levels. These treatments simulate two representative and common types of field layered soils in the Loess Plateau, which have sand overlying loam soil and loam soil overlying sand, respectively (Zhang, 2004; Cheng et al., 2013). Three replicates were conducted for each treatment.

Infiltration Equipment and Observation Methods

The soil chamber was constructed for observing wetting front dynamics during infiltration. It was comprised of transparent Plexiglas with a wall thickness of 1.0 cm and a volume of 60 by 50 by 5 cm (Fig. 1). The dimensions of the soil chamber were determined by the soil particle sizes. Because the larger particle size soil (sand with 1–2 mm, heavy gravel with 2–4 mm) was used, the thickness of the chamber was designed to be 5 cm. This design was to avoid larger pores occurring between the chamber internal surface and soil block. To avoid water leakage, Vaseline lubricating jelly was put on the edges of the soil chamber. Ponded infiltration experiments were conducted for the designed 20 treatments. A Mariotte bottle was used to maintain a constant head (2 cm) of distilled water on the soil surface. The surface of the soil was padded with thin filter papers to prevent water scouring and soil splashing.

The wetting processes during infiltration were traced by adding Brilliant Blue FCF with a concentration of 20 g/m^3 into

Table 3. The experimental water-repellent (WR) levels L1 (wettable) to L5 (extremely WR) and layer texture combination group treatments for finger flow. The depth ranges for the top and sublayers were 0 to 10 and 11 to 55 cm, respectively.

	Top layer					Sublayer
Texture group	L1	L2	L3	L4	L5	L1
A	clay loam	clay loam	clay loam	clay loam	clay loam	sand
B	clay loam	clay loam	clay loam	clay loam	clay loam	heavy gravel
C	sandy loam	sandy loam	sandy loam	sandy loam	sandy loam	sand
D	sandy loam	sandy loam	sandy loam	sandy loam	sandy loam	heavy gravel

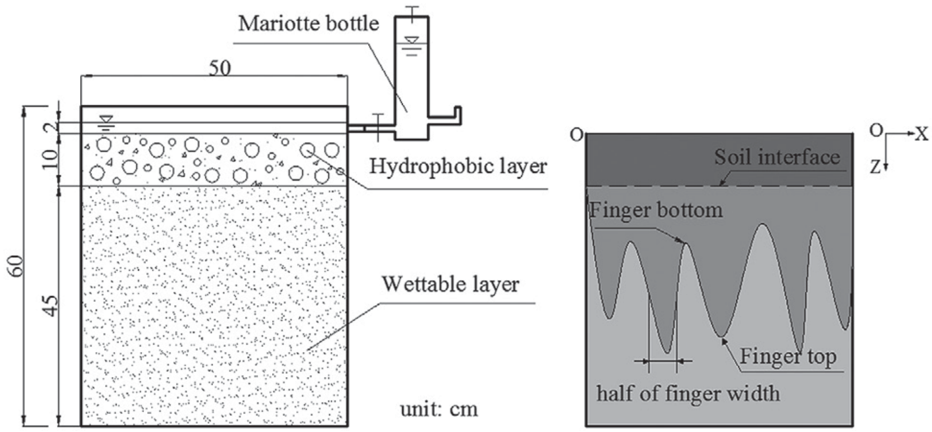

Fig. 1. The experimental equipment system and sketch of finger flow.

the distilled water. At this stain concentration, soil water movement would not be affected much and wetting fronts could be observed clearly. Variations in CI were measured by the changes in the Mariotte bottle contents vs. infiltration time. When the infiltration was terminated, soil samples from the wetted zone were taken to measure θ_v using the gravimetric method. Because the infiltration process was relatively quick, the advances of the wetting front with Brilliant Blue were obvious enough to be marked on the container walls for different infiltration stages. To avoid the influence of the lower boundary, the experiments were stopped when the wetting front reached 45 cm.

Data Analysis

Based on the measurements, different infiltration behavior properties for finger flow were analyzed (Zhang, 2004), including CI, wetting front, cumulative wetting area (CWA), finger length F_L (i.e., the length from finger bottom to finger top, cm), width of half finger length FW_h, cm), finger front velocity F_v (i.e., finger top movement distance with time, cm/s), and finger bottom velocity B_v (i.e., finger bottom movement distance with time, cm/s). The shape index SI and distributing index DI were also calculated using the observed F_L and FW_h:

$$SI = \frac{F_L}{FW_h} \quad [1]$$

$$DI = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(F_{L,k} - \bar{F}_L\right)} \quad [2]$$

where N is total number of fingers and $F_{L,k}$ is the F_L for the kth finger, $k = 1, 2, ..., N$.

The variability of SI and DI was quantified with the coefficient of variation (CV), calculated as (Nielsen and Bouma, 1985)

$$CV = \frac{SD}{x_{avg}} \quad [3]$$

where SD and x_{avg} are the standard deviation and the mean value of the data series x, respectively. Variability levels were classified by $CV \leq 0.1$, $0.1 < CV < 1.0$, and $CV \geq 1.0$, as weak, moderate, and strong, respectively.

Results and Discussion

Cumulative Infiltration and Wetting Front Variations

Variations in CI for the 20 treatments are illustrated in Fig. 2.

1. In Groups A, B, C, and D, the CI curves of the wettable treatment (L1) were not all higher than the WR treatments (L2, L3, L4, and L5). For the WR treatments of Groups A, B, C and D, the CI curves generally decreased as the WR levels of the top layer increased, meaning that it needed a longer time for the treatments with higher WR levels to reach the same CI. Wang et al. (2000) found gradually increased infiltration

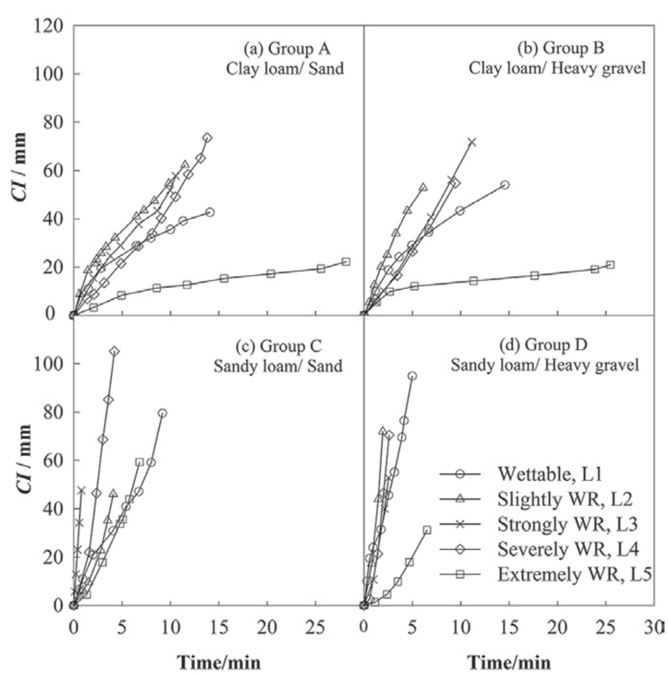

Fig. 2. Temporal variations of cumulative infiltration (CI) for the 20 treatments including four layer texture combination groups and five water repellency (WR) levels.

rates in soil chamber infiltration experiments of WR soils. This agrees with our results for increased CI as the infiltration proceeded, especially for the top layer of the sandy loam treatments. The reason that there was generally a shorter time for the increased infiltration rate was that infiltration in all the treatments of the four groups and finger flow development were both fast.

2. The CI curves in Groups A and B were generally lower than in Groups C and D within the same infiltration time, indicating that the infiltration processes differed when the soil texture of the top layer was different even at the same WR level of the top soil layer. This emphasizes the control of the texture of the top layer of soil on infiltration. In Groups C and D, the top layer of sandy loam had a much higher saturated hydraulic conductivity (K_s, 5.4×10^{-3} cm/min) than clay loam (6×10^{-4} cm/min), which permitted more water to infiltrate into the soil in the same time.

3. In Groups A and B, when WR levels for the top layer were the same, the sublayer treatments of clay loam over heavy gravel had general larger CI values than clay loam over sand. However, in Groups C and D, infiltration in the sandy loam over heavy gravel treatments was not always larger than the sandy loam over sand treatments. This may be caused by unstable flow, which is analyzed in detail below.

4. There were more increases in CI at the longer infiltration time for Groups C and D than for Groups A and B (called a *rising tail* here), especially in the treatments of GAL5, GBL4, GCL4, GDL3, and GDL5. This phenomenon has been commonly observed in WR soils whether the soils were layered or not

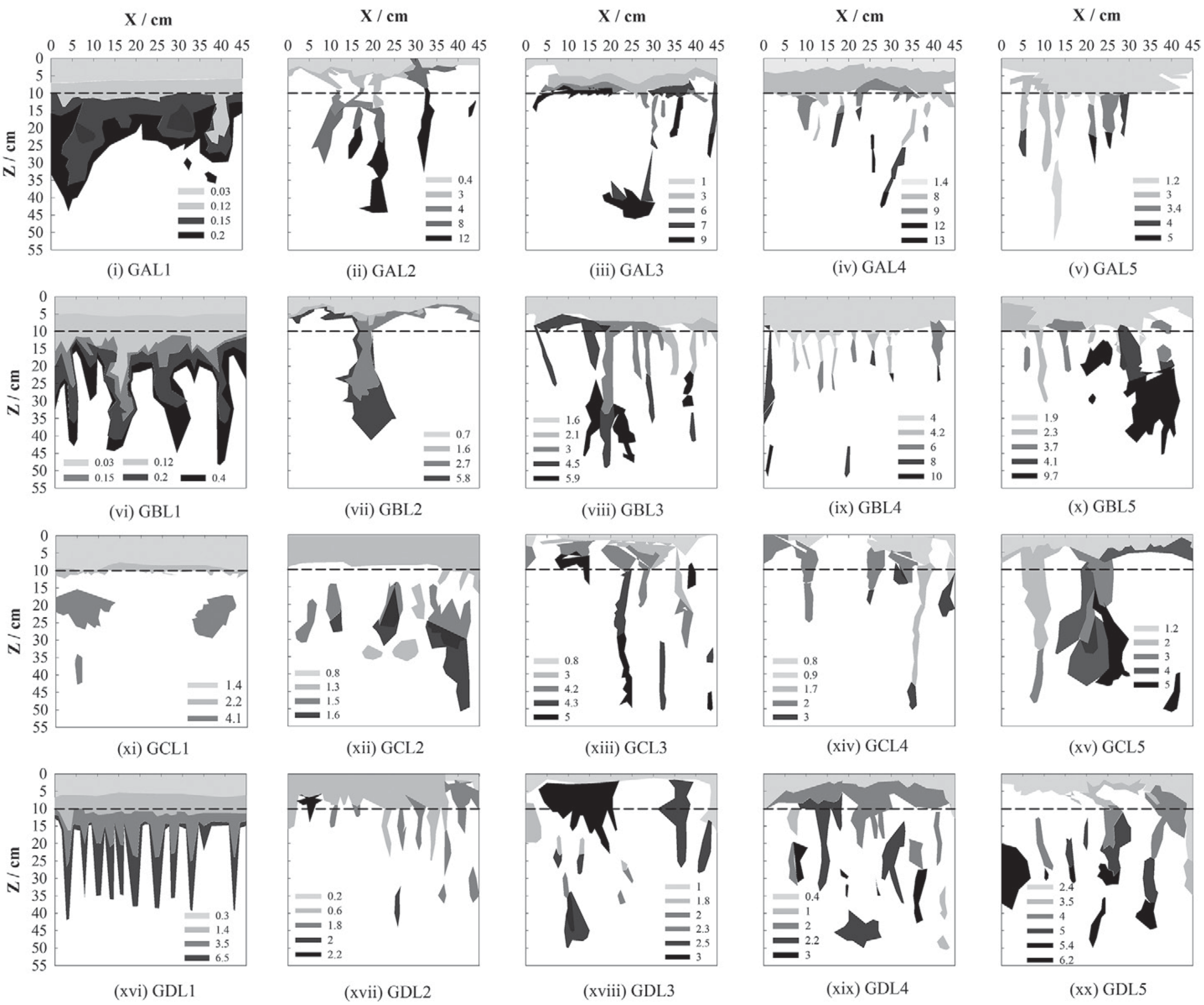

Fig. 3. Wetting front movement for the 20 different G*i*L*j* soil treatments, where *i* is the layer texture combination (*i* = A, B, C, D, see Fig. 2) and *j* is the water repellency (*j* = 1 [wettable] to 5 [extremely water repellent]). Gray shades indicate infiltration times in minutes.

(Wang et al., 2000) and indicates a gradual breakthrough of soil water repellency and an accelerated infiltration rate compared with the initial infiltration stages.

Although it has been theoretically and practically understood that infiltration in wettable soils is faster than in WR soils (DeBano, 1981), Fig. 2 disagrees with this. Finger flow occurred because of the irregular water movement and unstable flow resulting from the unexpected fast water movement in some unknown paths.

Finger flow development processes for all 20 treatments are illustrated in Fig. 3.

1. In the wettable treatments, four out of the total of 20 treatments, wetting fronts in the top 10-cm layer were generally regular and uniform. In the WR top layer treatments, however, wetting fronts became irregular. In some treatments, finger flow occurred in the top 10-cm layer.
2. In Group A, unstable flow in the wettable soil treatment GAL1 was very weak and developed later than in the other four WR treatments. For the four WR treatments of GAL2, GAL3, GAL4 and GAL5, as the WR levels increased, the FW_h decreased, but the formation time of fingers in the various treatments didn't follow any order of WR level.
3. In Group B, although fingers occurred in all five treatments, the patterns were obviously different and fingers became narrower and narrower as the WR levels of the top layer increased. In the GBL5 treatment, two fingers out of six converged at depths of 25 to 40 cm. The treatment GBL2 had only a single wide finger, which is different from the other 19 treatments.
4. In Group C, the wettable treatment GCL1 did not have any fingers because the soil textural contrast (sandy loam over sand) was low. Fingers of the other four WR treatments were all nonuniform and irregular.
5. In Group D, the formed fingers were mostly uniform for the wettable treatment GDL1 but nonuniform for the WR top layer soils.
6. The fingers were less regular and similar for Groups A and C (the sublayer was sand) than for Groups B and D (the sublayer was heavy gravel). For the wettable treatments, finger flow clearly generated in layered soils a with sublayer of heavy gravel, while for layered soils with a sublayer of sand, fingers were not clearly generated. This shows finger flow generated under different combinations of fine and coarse soils, and the fingers occurred with time lags, which was different than the stable flow.
7. Different WR levels tended to enhance the irregularity of finger shapes, but no obvious trend was observed related to different WR levels. In general, the differences in finger shapes between wettable and WR treatments were obvious. This shows that the irregularity of fingers was influenced by both the soil texture of the different layers and the WR level.

Table 4. The statistical properties of finger flow length (F_L) and width (FW_h) in water-repellant layered soils. Data for the treatment GCL1 is not shown because no obvious fingers developed but only unstable flow.

Treatment†	Fingers	F_L			FW_h		
		Min.	Avg.	Max.	Min.	Avg.	Max.
	no.	cm					
GAL1	3	4.2	10.8	14.9	7.8	7.3	10.1
GAL2	4	7	18.5	34.8	3	3.22	3.5
GAL3	4	9.1	15.9	30.5	0.9	1.44	2.2
GAL4	5	4.7	14.5	25.3	1.1	1.49	2
GAL5	6	2.5	13.4	19.5	1.8	1.98	2.2
GBL1	5	9.88	16.3	22.9	3.89	4.01	4.6
GBL2	1	17.2	24.5	33.8	2.3	3.87	6.3
GBL3	5	5.5	19.6	37.2	1.3	1.67	2.3
GBL4	6	2.93	9.35	15.6	0.6	1.02	1.55
GBL5	3	4	9.33	19.9	1.3	1.6	2.2
GCL2	3	7.2	11.1	16.1	1.85	3.17	4.1
GCL3	4	3.35	11.4	18.6	2.1	2.28	2.5
GCL4	4	2	15.7	42.2	1.5	2.75	4.3
GCL5	3	2.65	22.1	42.8	5.3	4.06	3.45
GDL1	10	4.96	12	22.2	1.7	1.81	1.96
GDL2	5	1.8	8.76	22.2	1	2.02	2.77
GDL3	3	9.65	9.81	16.5	1.2	1.46	1.7
GDL4	4	1.25	12.4	24.2	3	2.63	2.25
GDL5	4	8.7	17.7	31.1	2	2.95	5.7

† GiLj, where i is the layer texture combination (i = A, B, C, D, see Table 3) and j is the water repellency (j = 1 [wettable] to 5 [extremely water repellent]).

Parameters of Fingers

The minimum, average, and maximum properties for the parameters of number of fingers, F_L, and FW_h are given in Table 4.

1. In Group A, the finger number increased a little with the increase in WR levels. There were large differences for the

Table 5. The finger flow shape index, distributing index (DI), and CV values of the fingers with calculated from Eq. [1], [2], and [3] for the different treatments of layer texture combination Groups A to D (see Table 3) and water-repellant levels L1 (wettable) to L5 (extremely water repellant).

Group	L1	L2	L3	L4	L5	CV
			Shape index			
A	1.42	5.52	13.98	8.28	5.74	0.66
B	4.62	6.79	11.18	7.30	5.30	0.36
C	–	3.72	4.41	5.74	4.15	0.19
D	6.73	4.04	5.90	4.39	5.66	0.21
			Distributing index			
A	6.01	6.26	11.05	6.8	3.29	0.42
B	6.97	6.56	8.82	6.24	4.74	0.22
C	–	2.24	9.84	7.31	16.85	0.67
D	2.98	5.99	3.74	7.57	3.90	0.39

minimum, average, and maximum values of F_L and FW_h when comparing the five WR levels. The average F_L and FW_h ranged from 10.8 to 18.5 and 1.44 to 7.3 cm, respectively, but didn't change consistently with the increase in WR levels. The CV values for number of fingers, average F_L, and FW_h were 0.26, 0.2, and 0.8 for Group A and 0.50, 0.42, and 0.57 for Group B, respectively, indicating moderate variability. The parameters of number of fingers, average F_L, and FW_h for Group B ranged differently than for Group A.

2. The number of fingers varied little for the four WR treatments of L2, L3, L4, and L5 for both Groups C and D but was much smaller (<5) than the treatment GDL1 (at 10). The average F_L increased with increasing top layer WR levels for both groups but the average FW_h did not. The CV values of number of fingers, average F_L, and FW_h were 0.17, 0.34, and 0.25 for Group C and 0.53, 0.29, and 0.28 for Group D, respectively, all indicating moderate variability.

Values for the finger flow distributing index DI and shape index SI of the 20 treatments are presented in Table 5. The higher the SI values, the narrower and longer the fingers were, and the lower the DI values, the more uniformly the finger flow was distributed. For SI values, L3 at the strongly WR level had the largest SI values in three out of the four groups. However, the DI values varied greatly for the different treatments, although they were generally in accordance with Fig. 3. The CV values for SI and DI in each group were <1.0, showing moderate variability. In general, an increase in the WR level didn't cause consistent change in SI and DI, which indicates more complicated water movement processes in layered WR soils than in wettable soils.

Carrillo et al. (2000) found that, as the WDPT values increased, the tendency for finger formation also increased. In this research, the finger flow length F_L in Groups C and D increased also with the increase in WR level, which was consistent with the results of Carrillo et al. (2000) but inconsistent with Groups A and B. It seems that water movement in the WR clay loam had more irregularity than in the WR sandy loam. Rye and Smettem (2017) found that higher water repellency did not necessarily generate deeper flow pathways in tanks that were placed in a WR field. In our research, the maximum SI value did not appear in the extremely WR treatments, which means that higher water repellency had a key role in generating thinner and longer fingers. This result agrees with Rye and Smettem (2017).

The statistical values of the parameters finger top velocity F_v and finger bottom velocity B_v are given in Table 6. The F_v values reached as large as 2.73 cm/s and as small as 0.02 cm/s, showing the different developing velocities of fingers when WR levels and soil texture varied, although the variations in F_v didn't consistently follow a WR level order. The CV values for F_v were 0.45, 0.98, 0.2, and 0.68 for Groups A, B, C and D, respectively, all with moderate variability. The B_v values were generally small for all 20 treatments and ranged between 0 and 0.22 cm/s. The CV values for B_V were 1.49 and 1.08 for Groups A and C, respectively, which indicates strong variability. For Groups B and D, the CV values for B_V were both 0.75, indicating moderate variability. In general, the finger bottom stayed at the positions where the layer interface was located after water passed that depth, which was a common phenomenon during finger flow development. Moreover, fingers in most of the treatments preferred to develop in length rather in width. Fingers developed much faster in the vertical direction than in the horizontal one.

Carrillo et al. (2000) revealed that instability of flow had a relationship with velocity and depth, which would continue when the velocity increased with depth and tended to disappear when the velocity decreased with depth, and lateral flow below the WR layer diminished the fingering effects with depth in the medium WDPT (10-min) treatment. In this research, when the fingers reached a certain depth, its vertical movement disappeared and horizontal movement became more obvious; this was present for the treatments GBL5 and GCL5. There was agreement between this research and that of Carrillo et al. (2000) in the removal effects of lateral flow on fingers, but theirs happened for a WDPT of 10 min, which belongs to a strongly WR level; ours occurred in the two extremely WR treatments. However, we also investigated the influences of WR levels on finger flow. The

Table 6. The statistical results of finger flow front velocity (F_v) and bottom velocity (B_v) for the different treatments.

Treatment†	F_v			B_v		
	Min.	Avg.	Max.	Min.	Avg.	Max.
	cm/s					
GAL1	0.02	0.11	0.2	0.02	0.03	0.04
GAL2	0.05	0.15	0.1	0.05	0.08	0.1
GAL3	0.08	0.18	0.34	0	0.005	0.01
GAL4	0.04	0.06	0.2	0	0	0
GAL5	0.05	0.07	0.17	0	0	0
GBL1	0.1	0.11	0.11	0.01	0.015	0.02
GBL2	0.02	0.02	0.02	0	0	0
GBL3	0.03	0.09	0.26	0	0.005	0.01
GBL4	0.06	0.56	2.73	0.01	0.02	0.03
GBL5	0.25	0.46	0.61	0.01	0.015	0.02
GCL2	0.32	0.4	0.53	0	0.005	0.01
GCL3	0.22	0.26	0.29	0.01	0.04	0.07
GCL4	0.09	0.42	0.79	0.03	0.125	0.22
GCL5	0.07	0.35	0.62	0.02	0.025	0.03
GDL1	0.08	0.11	0.13	0.01	0.02	0.03
GDL2	0.06	0.24	0.67	0.01	0.05	0.16
GDL3	0.1	0.43	0.76	0	0.02	0.03
GDL4	0.3	0.62	0.93	0	0.08	0.175
GDL5	0.06	0.16	0.26	0.01	0.015	0.02

† G*iLj*, where *i* is the layer texture combination (*i* = A, B, C, D, see Table 3) and *j* is the water repellency (*j* = 1 [wettable] to 5 [extremely water repellent]).

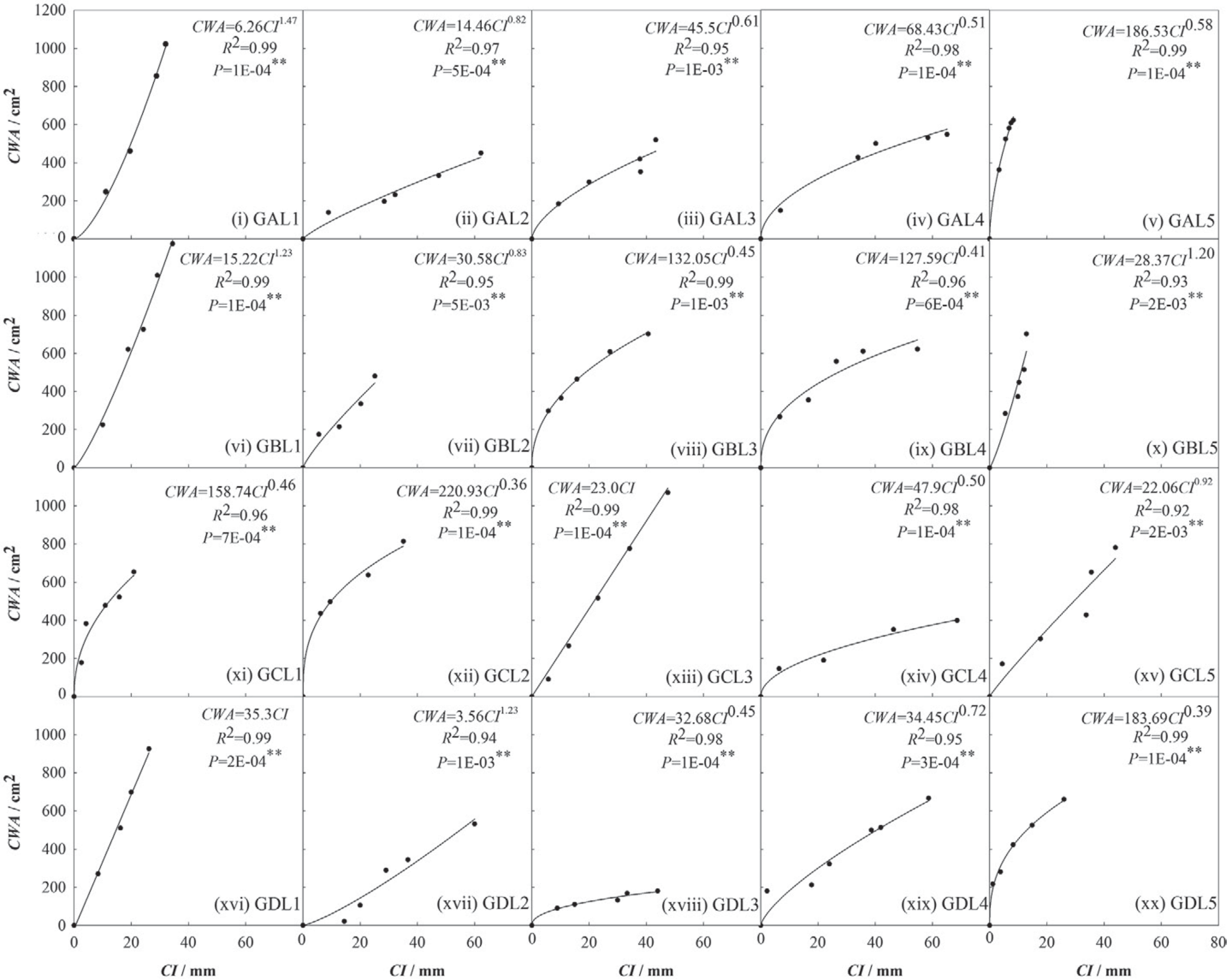

Fig. 4. The relationship between cumulative infiltration (CI) and cumulative wetting area (CWA) for the 20 different G*i*L*j* soil treatments, where *i* is the layer texture combination (*i* = A, B, C, D, see Fig. 2) and *j* is the water repellency (*j* = 1 [wettable] to 5 [extremely water repellent]).

uncertainty of finger flow development in WR soils increased finger development complexity.

Relationships between Cumulative Wetting Area and Cumulative Infiltration as Well as Finger Length

Figure 4 shows scatterplots of CI vs. CWA. In most of the 20 treatments, CWA values were nonlinearly correlated with CI values with quite high significance ($R^2 > 0.92$ at a 0.01 significance level), and the power function fitted the curve well. In the GCL3 and GDL1 treatments, linear regression fitted the curve better than a power function. The power function with a smaller power index and the linear regression relationship generally occurred in the treatments of unstable flow or continuous, wide fingers. In these treatments, the same water amount made the CWA increase significantly. However, in the treatments with tiny, broken fingers, the relationship between CI and CWA was a power function with a high power index. The CWA increased in degree less than the CI. This might be caused by water moving along the previous finger path and the wetting fingers to moving vertically downward rather than enlarging. Besides, the broken fingers with smaller CWA did not reflect the "true" CI value. The trend in the curve was generally determined by the match between fingers and infiltration development. The result consistently showed that more CI caused a larger CWA. However, the correlations didn't follow a WR level order for either clay loam or sandy loam.

Compared with the almost unchanged parameter FW_h, the parameter F_L is a more representative index to characterize finger flow shape. Therefore, it is necessary to compare the relationship between CWA and F_L. Figure 5 shows the correlations between CWA and F_L for each treatment. In each treatment, the values of CWA and F_L chosen were at the same time. In some treatments, fingers did not appear as infiltration began. Similar to Fig. 4, in nearly all the treatments F_L values

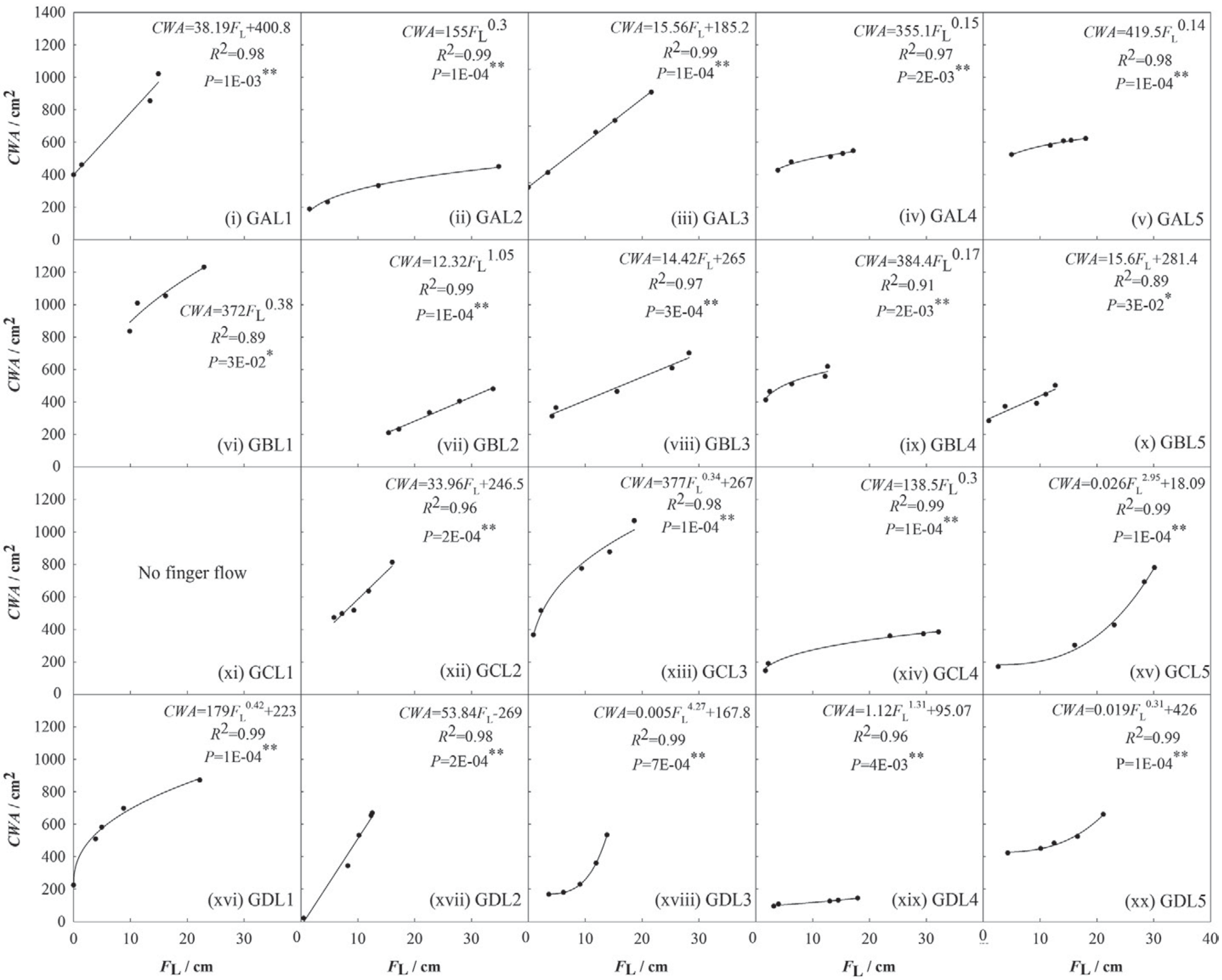

Fig. 5. The relationship between finger length (F_L) and cumulative wetting area (CWA) for the 20 different G*i*L*j* soil treatments, where *i* is the layer texture combination (*i* = A, B, C, D, see Fig. 2) and *j* is the water repellency (*j* = 1 [wettable] to 5 [extremely water repellent]).

were nonlinearly correlated with CWA values and the shape of the fingers had a large effect on the relationship between CWA and F_L. For example, in the GAL4 and GAL5 treatments, finger shape and distribution were similar. Fingers were quite tiny; even when F_L increased greatly, CWA did not increase much. However, fingers in GCL5 merged with each other during development, which led to CWA increasing substantially. Therefore, the curve shows an increasing trend in Fig. 5. In GAL1, GBL1, and GDL1, fingers with different widths caused different degrees of CWA increase, so the relationship of CWA and F_L shows different performance.

Distribution of Volumetric Water Content

Figure 6 illustrates the distribution of θ_v in the profiles for the 20 treatments.

For each group, the range of θ_v was narrower when the WR level increased. The θ_v values in the top 0 to 10 cm were larger than in the sublayer and decreased with the increase in WR level, which means that water repellency could increase the risk for runoff. The nonuniform distribution of θ_v was due to the occurrence of fingers. Ritsema and Dekker (1994) reported that the wettest zone of fingers was at the top in the field soils. In this research, θ_v was higher near the zone of the finger top, which agrees well with Ritsema and Dekker (1994). This indicates that finger flow did not have a strong water holding capacity and led to water transporting easily to deep soil. The contour shapes of fingers were in accordance with the description by Hill and Parlange (1972), although θ_v of the finger core was lower than the saturated water content, which was due to the WR top layer. Detailed θ_v distributions were also shown by Ritsema and Dekker (1994) but not specifically mentioned in that research because a total of 82 fingers were observed and maps were not shown for all. Wallach and Jortzick (2008) found that finger-like wetting fronts presented during point-source infiltration in the wettable

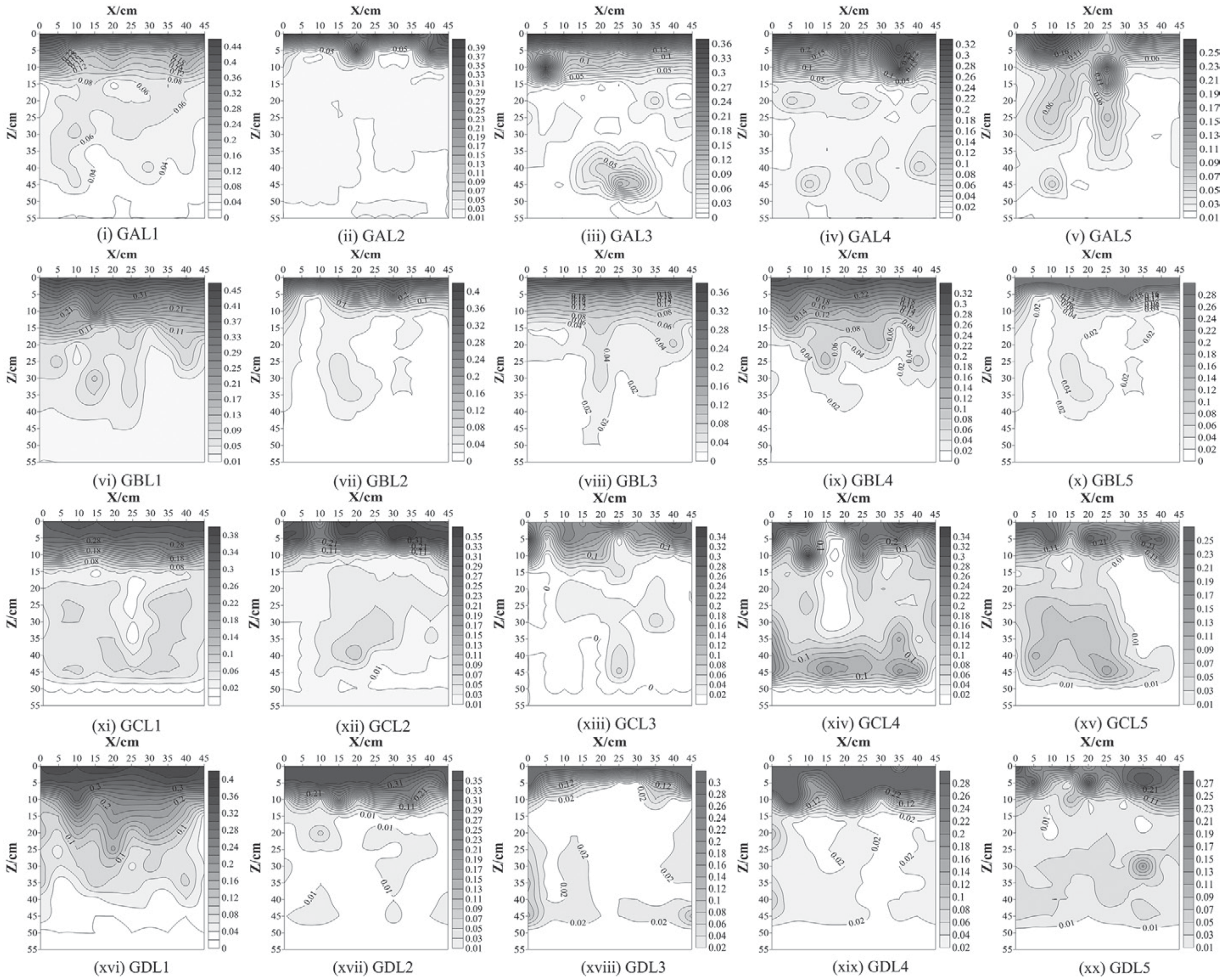

Fig. 6. Contour maps of soil water content (θ_v) for the 20 different G*i*L*j* soil treatments, where *i* is the layer texture combination (*i* = A, B, C, D, see Fig. 2) and *j* is the water repellency (*j* = 1 [wettable] to 5 [extremely water repellent]).

and WR sands, and soil moisture redistribution was mainly in the vertical direction, leaving a wet region at the location of the plume tip when redistribution started. Doerr et al. (2000) and Rye and Smettem (2017) also proposed that the presence of a wettable soil at depth will allow flow paths to spread laterally, drawing moisture rapidly down from the soil above.

Conclusions

Infiltration and finger development features in WR layered soils behaved differently than in wettable layered soils. The CI generally decreased as the WR level of the top layer increased and as the texture changed from sandy loam to clay loam. The top layer soil texture controlled wetting front movement and CI more than the sublayer. Both water repellency and a large soil texture contrast between layers contributed to the nonuniform wetting fronts and finger flow occurrence. The finger development indices (including F_L, FW_h, F_v, B_v, SI, and DI) varied when the WR level of the top layer soils changed. The variations of these finger-related parameters were generally random for different WR levels, but there were obvious differences between wettable and WR treatments. Power or linear functions fitted the relationship of CI to CWA and CI to F_L well. The θ_v in the top 10-cm layer generally decreased with the increase of WR level. Values of θ_v in the area near the finger top or the core of fingers were larger than in other parts of fingers. In general, this research reflects that stronger water repellency did not always cause more unstable infiltration or finger development. Layered soil structure and a large contrast in soil texture also contributed to the unstable water movement. Many factors contributed to the complexity of water movement affected by water repellency in a layered system.

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