Soil & Tillage Research 182 (2018) 130–143

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

# Effects of straw incorporation on desiccation cracking patterns and horizontal flow in cracked clay loam

Ce Wang[a,b], Zhan-yu Zhang[a,b,*], Shi-min Fan[b], Richwell Mwiya[b], Mei-xiang Xie[b]

[a] *Key Laboratory of Efficient Irrigation-Drainage and Agricultural Soil-Water Environment in Southern China, Ministry of Education, College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 210098, China*
[b] *College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 210098, China*

## ARTICLE INFO

*Keywords:*
Desiccation crack
Straw incorporation
Horizontal infiltration
Wetting-Drying cycles
Soil swelling
Wetting front

## ABSTRACT

Shrink-swell soil cracks upon dehydration, providing potentially preferential pathways for gravity-driven flow and contaminants transport. The process of crack-preferential flow is swelling-dependent, due to the dynamical changes in porous structure (cracks) in response to moisture variation. Incorporating straw into soils modifies the behavior of soil cracking, soil deformation characteristics and hydraulic properties, which has a possibility of inhibiting propagation of crack-preferential flow. The objectives of this study were to investigate the effects of straw incorporation on the crack patterns and preferential flow and to reveal how the swelling dynamics of cracked soils intervene the crack-preferential flow process. The soils were treated with three densities of straw incorporation. We investigated the horizontal infiltration in uncracked and cracked soils amended with straw and exposed to wetting-drying cycles. Horizontal flow patterns and the dynamics of crack closure were recorded with a digital camera mounted above the specimen. The propagation characteristics of the wetting front (WF) were quantified using digital image processing and morphological algorithms. The results showed that straw incorporation markedly inhibited the cracking degree and rendered the crack patterns more fragmented. Significant fluctuations in the infiltration rate were observed in cracked soils in the early stages of the infiltration process, and the straw incorporation attenuated the fluctuations of the infiltration rate. Normal crack apertures (perpendicular to the infiltration direction) blocked the continuous capillary-driven flow as air barriers and decelerated the infiltration rate in comparison to uncracked soils. The longitudinal cracks (along the infiltration direction) served as preferential pathways and facilitated the early-stage infiltration, but the duration of crack-preferential flow was dominated by the swelling rate of the aggregated soil clods. The tortuosity of the WF revealed that the flow regime transitioned from crack-preferential flow to matrix flow as the infiltration process progressed. Our results suggest that the crack-preferential flow becomes less pronounced as the cracks become progressively narrower, resulting from the swelling dynamics of the soil matrix. The fluctuations in the infiltration rate and the developing extent of crack flow can be attenuated by straw incorporation through restricting crack ratio and modifying crack morphology. Rice straw at a threshold density (experimentally determined) could be incorporated into soils to restrict the flow regime transition point (from crack preferential flow to matrix flow) to the depths of root zones, thus effectively precluding deep percolation induced by the cracks in shrink-swell soils.

## 1. Introduction

Soil desiccation cracks are macroscopic behaviors of soil deformation and pore system shrinkage, resulting from tensile stresses induced by sustained evaporative water loss (Tang et al., 2011b). Desiccation cracking detrimentally modifies soil hydraulic and mechanical properties. Cracks act as preferential pathways for water flow and solute transport which bypass the soil matrix and directly move downwards, preventing the water and nutrients from being completely absorbed into the soil matrix (Allaire et al., 2009). The presence of desiccation cracks typically causes a decrease in irrigation efficiency (Tuong et al., 1996), exacerbates groundwater contamination (Oostindie and Bronswijk, 1995) and induces soil erosion. Desiccation cracks significantly facilitate soil hydraulic conductivity, and create bypass flows and deep percolation after irrigation events (Cabangon and Tuong, 2000; Inoue, 1993; Liu et al., 2004, 2003; Tuong et al., 1996). Since desiccation cracking is detrimental to groundwater quality, water use efficiency in agriculture and soil-water conservation, measures should

---

[*] Corresponding author at: College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 210098, China.
*E-mail address:* zhanyu@hhu.edu.cn (Z.-y. Zhang).

https://doi.org/10.1016/j.still.2018.04.006
Received 18 May 2017; Received in revised form 29 March 2018; Accepted 7 April 2018

be taken to impede crack formation or modify surface soil conditions. Such measures include straw mulching, straw incorporation, shallow surface tillage, sprinkling irrigation (Tuong et al., 1996).

Methods for increasing soil strength, inhibiting crack formation and delaying crack initiation have been tested, e.g. straw mulching and incorporation of additives (straw fiber, vegetation roots, and polypropylene fiber) (Li et al., 2016; Tang et al., 2012; Xue et al., 2014). Straw mulching is an effective means to conserve moisture and restrain crack width during the fallow period, but it does not necessarily reduce cracking depth and deep percolation during land preparation for rice cultivation (Cabangon and Tuong, 2000). A strong resistance of clay to cracking was detected with straw-fiber incorporation. Clay soil containing straw fibers has a lower infiltration capacity than those without straw fiber addition (Xue et al., 2014). Incorporating straw residues into heavy clay soil helps to return and conserve nutrients in the long term and also decreases soil cracking and water losses from bypass flow (Dobermann and Fairhurst, 2002). Furthermore, straw incorporation increases the organic carbon content, regenerate soil structure and improves soil physical and hydraulic properties, which is important for sustaining production in rice–wheat cropping systems (Singh et al., 2010). Mousavi et al. (2012) proposed that, adding 4% rice straw in silty clay soil and 6–7% of rice straw in silty clay loam favors delaying crack formation and thus conserving water (Mousavi et al., 2012). However, information is lacking regarding the impacts of straw incorporation on crack morphology and flow processes in unsaturated, cracked soils.

Upon wetting, the cracking degree and swelling properties of clay minerals greatly affect the propagation and duration of bypass flow through crack-preferential pathways. The solid skeleton of natural soils changes dynamically due to the shrink-swell properties of the clay mineral. Thus, during the infiltration process, the hydraulic conductivity of cracked soil may decline by several orders of magnitude (Leeds- Harrison et al., 1986). Dynamic behavior of soil swelling is of great importance to unsaturated flow in cracked soils. Evidence shows that bypass flow only lasts for hours before transforming into matrix flow (Favre et al., 1997; Greve et al., 2012). The issue of concern in crack flow is to experimentally ascertain how cracks contribute to preferential flow and the interaction mechanism between preferential flow processes and soil swelling behavior. Furthermore, the crack patterns and the swell-shrink behaviors are also prone to wetting-drying cycles (Kalkan, 2011; Tang et al., 2011a; Wang et al., 2017), which makes unsaturated transient flow in cracked soils more complicated to quantify. Effective irrigation management addressing crack preferential flow requires a comprehensive understanding of cracking degree, the duration of preferential pathways, the temporal variations in hydraulic properties, irrigation schemes and methods. Deep percolation and groundwater pollution could be effectively inhibited by controlling the cracking intensity and adjusting irrigation intensity and the timing of irrigation.

Incorporating shrink-swell dynamics of cracks and aggregates into classical flow and transport models in soils is still a considerable challenge confronted by soil physicists and hydrologists. Due to the swell-shrink dynamics of soils, the soil porous structure varies with changing moisture content; thus, water movement in unsaturated swelling soils can no longer be depicted by the Richards equation across the scale of cracks without accounting for the skeleton dynamics. Such modeling of unsaturated flow in soils with variable solid skeleton requires dynamic descriptions of both the crack morphology and soil hydraulic properties (Vogel et al., 2005). Crack quantification has been frequently addressed by researchers (Allaire et al., 2009; Tang et al., 2011b; Velde, 1999; Zhang et al., 2014a), evolving from in situ experiments to automatic recognition (Liu et al., 2013). When simulating unsaturated water flow in a deformed soil, the shrink-swell characteristics are usually incorporated into the Richards governing equation as a third soil-water function, in addition to the water retention curve and the unsaturated hydraulic conductivity curve (Bronswijk, 1988; Kim et al., 1999). The soil shrink-swell characteristic curve highlights the relations between specific volume and moisture content within a wetting-drying cycle (Chertkov, 2012), while the swelling potential varies depending on time, making it important to reveal the swelling mechanism with regard to both time and soil water conditions when incorporating swelling into crack-preferential flow modeling.

Our objectives of this study were: (i) to characterize the crack morphology in soils amended by straw incorporation, (ii) to reveal the horizontal infiltration characteristics in uncracked and cracked soils with incorporated straw under wetting-drying cycles, (iii) to investigate how the crack-preferential pathways and dynamic process of soil swelling upon wetting jointly interfere with the horizontal flow patterns, and (iv) to investigate the effects of straw incorporation on crack-preferential flow.

## 2. Materials and methods

### 2.1. Experimental set-up and treatments

The experiment was conducted indoors in the Key Laboratory of Efficient Irrigation-Drainage and Agricultural Soil-Water Environment in Southern China, Ministry of Education, Nanjing (31.9 °N, 118.8 °E). The tested soil is a clay loam classified as a Hapludalf (Alfisols) and was taken from an experimental field where rice and wheat have been alternatingly cultivated during the last 20 years. The soil is composed of 43% clay ($\leq 0.002$ mm), 32% silt (0.002 mm–0.02 mm) and 25% sand ($\geq 0.02$ mm) at the depth of 0–20 cm. Soil properties are presented in Table 1. The long-term annual mean precipitation and temperature in this area are respectively 1200 mm and 15.7 °C. The soil taken from the fields was sieved through a 3 mm aperture sieve to exclude impurities and then air dried and stored under dry and ventilated conditions for later use.

In this study, we intend to explore how rice straw addition influences the morphology of the desiccation cracks and how the unsaturated flow process is disturbed by both cracks and straw. The reclaimed straw was trimmed into 5 cm segments before being added into the soils. The experiments were laid out with three straw addition treatments: (1) no straw addition ($ST_0$), (2) straw addition with a density of 0.5 cm/cm$^3$ ($ST_{0.5}$), and (3) straw addition with a density of 1.0 cm/cm$^3$ ($ST_{1.0}$). The straw density here is defined as the length of straw per unit soil volume. Two identical specimens were prepared for each treatment. The rice straw segments were thoroughly and homogeneously mixed with the air-dried soils according to the three density treatments. Subsequently, soil samples (soil weight: 6400 g) with or without straw were filled into a square Plexiglas container with an average soil bulk density of 1.25 g/cm$^3$ in 10 mm height increments. The surface of each layer was roughly scrubbed before filling in the subsequent layer in order to eliminate unexpected soil discontinuity and to ensure the homogeneity of soil hydraulic properties between

**Table 1**
Physical properties of the tested soil.

| Soil properties | Values |
|---|---|
| Soil type | Clay loam |
| Classification | Hapludalf, Alfisols |
| Specific gravity | 2.62 |
| Sampling depth | 0–10 cm |
| Sand content ($\geq 0.02$ mm) | 25% |
| Silt content (0.002 mm–0.02 mm) | 32% |
| Clay content ($\leq 0.002$ mm) | 43% |
| Saturated moisture content | 55.80% in volumetric water content |
| Antecedent moisture content before infiltration experiments | 5.9% in gravimetric water content |
| Remolded dry bulk density | 1.18 g/cm$^3$ |
| Saturated hydraulic conductivity | $6.23 \times 10^{-2}$ cm/min |