Root growth impact on soil hydraulic conductivity during wetting and drying circles

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Abstract

Saturated hydraulic conductivity (K_{sat}) plays a crucial role in the hydrological cycle by influencing water absorption and availability for assessing slope stability, erosion control and developing more resilient agricultural practices. On the other hand, vegetation and climate would play a significant role in influencing the variations in soil infiltration. This study aims to comprehensively explore the dynamic interplay between plant root formation, desiccation crack and seasonal changes on K_{sat}. The research employs the double ring infiltrometer test to estimate K_{sat} during wetting and drying circles. Prior to the double ring test, root growth patterns were observed using a minirhizotron and then was analysed as Root Area Ratio (RAR). The study reveals that Vetiver roots reduced crack intensity factor (CIF) compared to bare soil. Additionally, roots are pivotal in creating preferential flow pathways which results in higher K_{sat} compared to that in bare area. Dry periods significantly increased K_{sat}, with a 16-fold rise in vegetated areas due to root growth.

Keywords: Desiccation crack; double ring infiltration tests; root growth; saturated hydraulic conductivity; seasonal climate

1. Introduction

Soil hydraulic conductivity (K_{sat}) plays a key role both in many aspects, such as assessing water availability and runoff in agriculture, as well as modelling soil slope stability in geotechnical engineering [1]. Utilizing vegetation as a natural material for erosion control and slope stabilization is becoming more common in nature-based solutions [2,3] because vegetation could provide mechanical soil reinforcement through the root systems [4,5]. Beside this the root growth across would also impact on the soil hydraulic conductivity. For instance, Rahardjo et al. [6] found that the existences of plant would decrease K_{sat} as compared to bare soil. Moreover, Nguyen et al. [7] found that as the increase of plant age as well as increase in root biomass, it would make the K_{sat} decrease. In vice versa, Leung, et al. [8] found that the existence of the root would increase of the K_{sat} while Rajamanthri et al. [9] observed that the root biomass would increase the K_{sat} in three difference ages. Recently, Cui [10] found that Grass roots enhance the K_{sat}. As planting density increases, the roots create more preferential flow pathways in the soil, resulting in a higher saturated hydraulic conductivity.

Furthermore, studies indicate that vegetation significantly alters soil structure and promotes cracking, which in turn influences K_{sat}. Yu et al. [11] found that dense vegetation led to distinct linear crack patterns due to root permeation. Gadi et al. [12] further supported this by observing that the cracks in vegetated soil were relatively higher than in bare soil throughout the test period. However, Gao et al. [13] demonstrated that vegetation effectively reduces desiccation cracking in red clay slopes during dry periods. They found that plants, particularly those with deep roots, stabilize the soil by limiting the formation of cracks, which are known to increase erosion and slope instability.

In addition, K_{sat} exhibit significant variability due to various environmental factors, particularly rainfall and drought patterns [14]. Cerda [15] highlighted the substantial impact of seasonal changes on soil hydrology. Cheng [16] found that the development and spread of cracks in soil are strongly influenced by drying-wetting cycles. Specifically, under consistent environmental conditions, the extent of cracking increases as the soil dries and with each additional drying-wetting cycle. Gao et al. [17] investigated that the repeated drying and wetting cycles

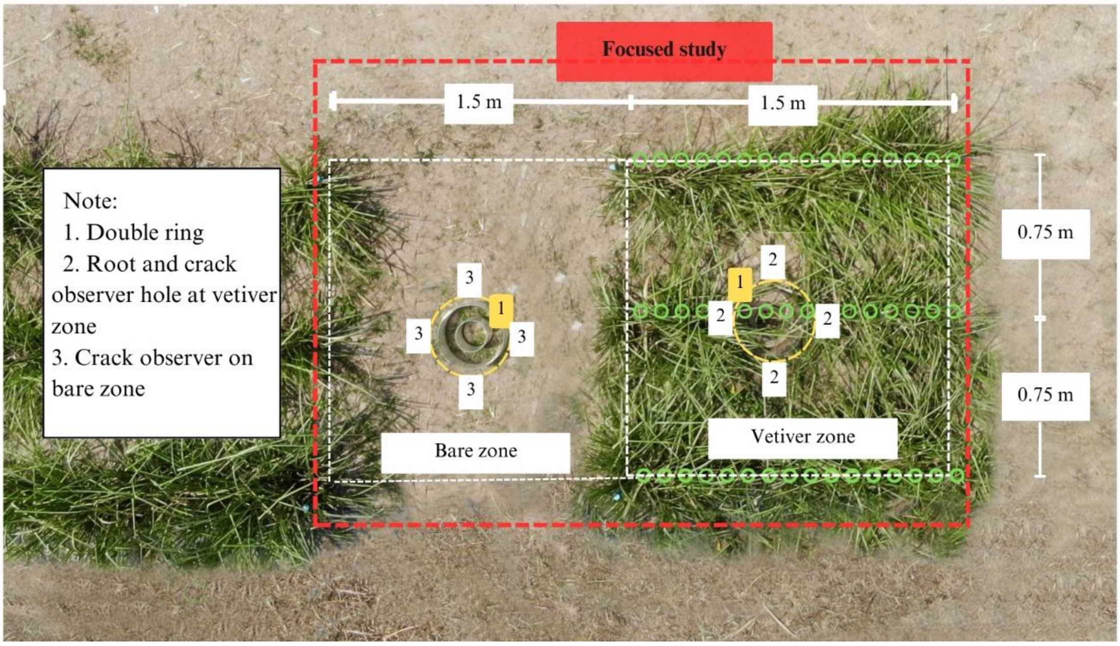

Fig. 1 *Overview of field set up*

alter the soil's internal structure, specifically the connections between soil aggregates. The soil's response to these cycles leads to a more porous structure that facilitates water movement, hence influence on K_{sat}. However, a significant limitation in understanding K_{sat} in vegetated soils stems from the scarcity of systematic field observations that track seasonal variations in root and crack dynamics.

This research aims to investigate the interaction between plant roots and desiccation cracks, as well as the combined effect with seasonal variations on K_{sat}. Root growth and decay patterns in the field are observed in both vegetated and bare areas. Besides this, the root growth was also using a Minirhizotron and analysed through the Root Area Ratio (RAR). Simultaneously, crack formation is monitored using the same method and interpreted CIF. Continuously, the test was conducted for three seasons of observation for evaluating the root growth effect and seasonal change.

2. Methodology

2.1 Field setup

A field observation was conducted on a flat, square plot, divided into two 1.5m x 1.5m zones as shown in Figure 1. The vegetated zone was planted with vetiver grass (*Vetiveria zizanioides sp.*), while another zone was left bare to serve as a control. Vetiver grass was chosen due to its established effectiveness in soil and water conservation, erosion control, and slope stabilization [18], as well as its ability to thrive in various climates and soil conditions, including waterlogged environments [19]. The vetiver tillers initially be cultivated until robust root systems established to ensure the plants were adequately developed and prepared for field transplantation. Following this, the tillers the strong roots were transferred to the field. Vetiver tillers were planted in rows, with 10 cm spacing between plants within each row and 75 cm spacing between rows, adhering to established guidelines for optimal root growth and minimal plant competition [19,20]. Soil samples were analysed to determine the site's soil properties, revealing that the soil is classified as high plasticity clay according to the Unified Soil Classification System (Table 1).

Table 1 Soil Properties

Soil Properties	Unit	Value
Field dry density	kN/m^3	13.56
Specific gravity		2.57
Liquid limit	%	53.61
Plastic limit	%	14.5
Plasticity index	%	39.11

2.2 Double ring test

Figure 2 illustrates the double-ring infiltrometer setup used in the field observations, specifically within the vegetated zone (V1). This setup was consistently applied to the other two zones, V2 and the bare (B) zone, as shown in Figure 1. The infiltrometers consisted of two concentric acrylic tubes: an inner ring with a 15 cm diameter and an outer ring with a 30 cm diameter. These rings were inserted into the soil to depths of 10 cm and 20 cm, respectively. the double rings were installed one week after planting. The size of the double ring may slightly influence the initial lateral expansion of the vetiver root system within the confined area under the ring. However, the overall impact on root development is likely minimal. Vetiver roots are deep and adaptable, meaning they will likely grow around the ring and penetrate deeper soil layers, where the roots have more room to spread. The ring may alter soil moisture dynamics in a localized area, but this effect is unlikely to cause long-term limitations on root growth. Additionally, transparent acrylic was chosen to allow sunlight penetration, minimizing disruption to natural evapotranspiration and plant growth. To reduce soil disturbance throughout the experiment, all double ring infiltrometers were installed permanently in each of the three zones.

The double ring tests were performed according to the falling-head standard test. The double ring test procedures was specified in the ASTM D 3385 [21]. The falling head method was a commonly employed technique for studying field water infiltration, specifically in accordance with the double ring test [22]. To monitor water level changes within the inner ring during the infiltration tests, HC-SR04 ultrasonic distance sensors were installed on top of the ring, as depicted in Figure 2. These sensors, capable of measuring distances from 2 cm to 400 cm with a 0.3 cm accuracy, were used to track the fluctuating water levels. The sensors were connected to a datalogger, which recorded this water level changes at one-second intervals.

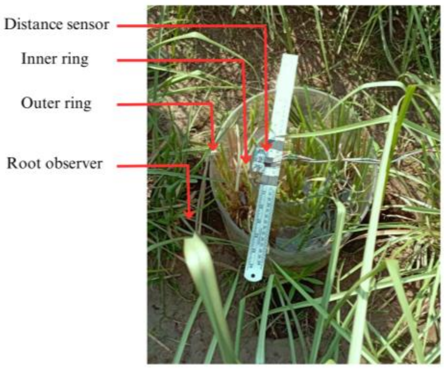

***Fig. 2** Detail of double ring*

Furthermore, K_{sat} (m/s) was calculated using the Elrick model [23]. This model provides an empirical approach to estimate K_{sat} from initial infiltration data under falling-head conditions. It is especially useful for soils with low permeability, where the influence of gravity on early infiltration is minimal. The Elrick's method describes infiltration as follow:

$$\mathrm{I(t)} = S.t^{\frac{1}{2}} \tag{1}$$

where I(t) is the cumulative infiltration, S is the soil sorptivity at the ponded head (m/s), and t refers to the time (s). White and Sully [24] proposed an approximate analytical relationship among S, K_{sat}, and ϕ_m, which is expressed as follows:

$$S = \left\{2(\Delta\theta)K_{sat}H + \left[\frac{(\Delta\theta)\phi_m}{b}\right]\right\}^{\frac{1}{2}} \tag{2}$$

where $\Delta\theta$ is the difference between saturated and initial water contents (m3/ m3), H is the ponded head (m), ϕ_m is the matrix potential (m2 s−1), and b is a constant value of 0.55.

The substitution of equation 2 into equation 1 can be written as:

$$\mathrm{I(t)} = t^{\frac{1}{2}}\left\{2(\Delta\theta)K_{sat}H + \left[\frac{(\Delta\theta)\phi_m}{b}\right]\right\}^{\frac{1}{2}} \tag{3}$$

Under the falling-head condition, the cumulative infiltration is a function of H as follows:

$$\mathrm{I(t)} = \left(\frac{c}{A}\right)(H_0 - H_t) \tag{4}$$

Where c and A are the cross-sectional areas of the falling-head tube and the soil sample, respectively. By substituting Equations 2 and 4 into Equation 1, it can be written as follows:

$$\mathrm{t}^{\frac{1}{2}} = \frac{c}{A}\frac{(H_0 - H_t)}{\left\{2(\Delta\theta)K_sH + \left[\frac{(\Delta\theta)\phi_m}{b}\right]\right\}^{\frac{1}{2}}} \tag{5}$$

K_{sat} can be determined using simplified Equation 5, which is fitted with measured early falling head data through an iterative process involving the parameters $\Delta\theta$ and ϕm. This process continues until the value of K_{sat} converges to a stable result, ensuring an accurate calculation of the saturated hydraulic conductivity.

Furthermore, Root density was directly assessed in a 10 cm x 10 cm hole, 10 cm deep, located next to the outer ring of the infiltrometer, as detailed in Figure 2. Before each infiltration test, a digital camera was used to take pictures of the roots within this hole. The root content was then quantified using the root area ratio (RAR) and crack intensity was quantified as crack intensity factor (CIF). Preceding the quantitative analysis, a series of digital image processing methods were undertaken, encompassing steps such as grayscale conversion, binarization, denoising, skeletonization, and crack identification. Subsequently, the analysis of the RAR and CIF was carried out using Python software. The RAR was calculated by dividing the number of root pixels (A_r) by the total number of pixels (A) in Equation 6.

$$RAR = \sum_{i=1}^{n}\frac{A_r}{A}x\ 100\% \tag{6}$$

Furthermore, CIF was assessed by dividing soil crack pixels (ac) by total number of pixels (A), as shown in the following equation:

$$CIF = \sum_{i=1}^{n} \frac{a_c}{A} x\, 100\% \tag{7}$$

3. Results and Discussion

3.1 Crack and root observations

Figure 3 provide the crack and root observation over three seasons in Thailand. Based on Meteorological Department of Thailand [25], Thailand has three different season which defines as the rainy season which occurred from May to October; the dry winter took time from November to January; and the dry summer which happen during February to April. The Monochrome images illustrate the binarized crack patterns which was analysed by on the observation photo taken before each water infiltration test. The crack intensity factor (CIF) represents the crack density in each image, while the average CIF (avgCIF) reflects the overall crack density across all observation holes. Initial observations in October 2021, at the end of the rainy season, showed limited crack formation, with a crack diameter (CD) of 1.1 mm and a CIF of 0.9%. The cracks were small and sparse, reflecting the high soil moisture from the previous months of rainfall. This increased soil moisture was attributed to the significant rainfall during this period. The cracks were short and discontinuous, marked by a red-dotted oval. The average CIF was 0.8%, indicating a low overall crack density. By January 2022, drier conditions resulted in increased cracking, with CD reaching 2.7 mm and CIF 3.2% (avgCIF 3.0%). Cracks became longer, more connected, and more complex, reflecting reduced soil moisture and increased evaporation. Cracks continued to expand and interconnect, indicating progressive soil desiccation. In April 2022, the dry summer season, CD peaked at 3.5 mm, CIF at 4.4%, and avgCIF at 5.2%, likely due to increased evaporation. Evaporation increases cracks in soil by reducing moisture content, causing the soil to shrink. As the soil loses water, it contracts and creates tension, which leads to the formation of cracks, especially in clay-rich soils that are more prone to shrinkage. These cracks can widen and deepen over time as evaporation continues.

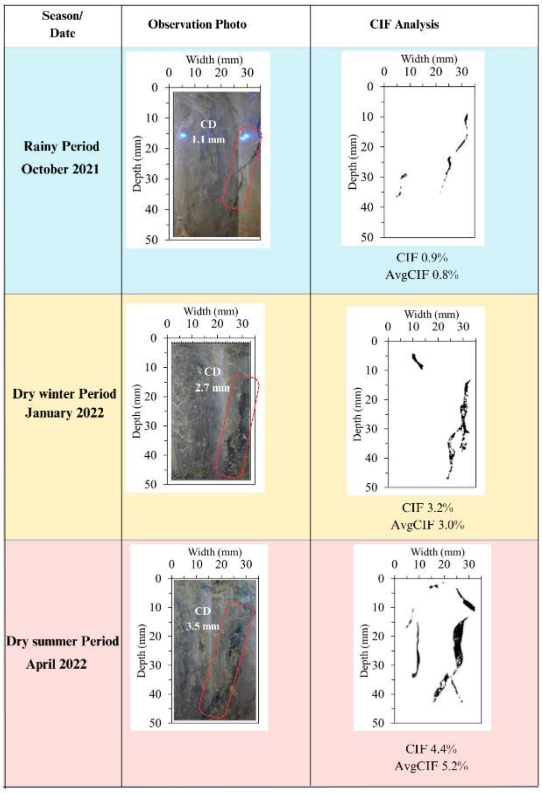

Fig. 3 *Crack observation in bare area*

Figure 4 displays a photo of vetiver zone taken from the observation hole within the planting row. Initial observations in the vetiver zone revealed only minor cracks. However, in January 2022, thin cracks approximately 15 mm long began to form, resulting in an avgCIF of 1.0%. During the drought period extending through April 2022, these cracks gradually expanded, reaching a maximum width of around 0.8 mm and a length of about 35 mm by February 2022. This expansion of cracks led to an increase in avgCIF to 2.9% by April 2022. During drought periods, soil moisture decreases due to a higher evapotranspiration in the drought period. As the soil shrinks, the roots may not be able to mitigate the forces causing the cracks to widen, compared to the earlier rainy period. It is also important to note that cracks in the vegetated soil were four times narrower than those observed in Zone B during the same period. This might be happened due to the plant roots could occupy a portion of the soil pores, limiting the drying-induced soil shrinkage leading to a reduction in the final degree cracking [26].

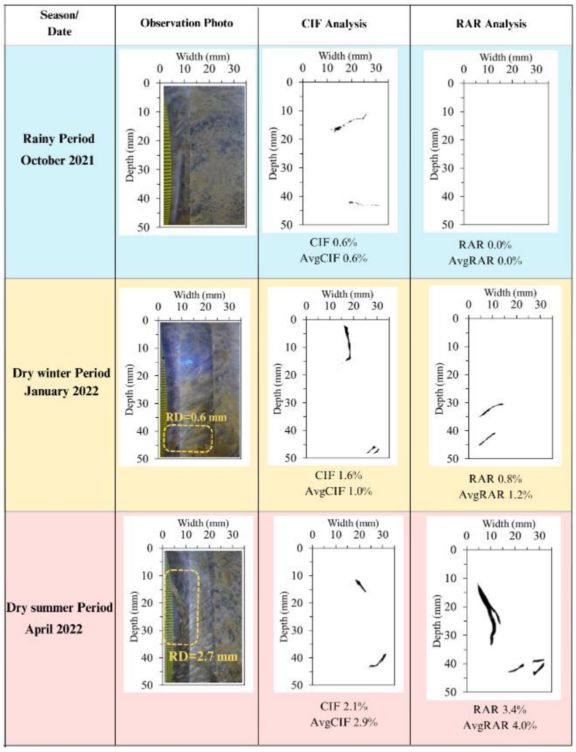

Fig. 4 Root and crack observation in vetiver area

In term of root observation, the RAR refers to the ratio of the root area to the total area in the image, while avgRAR represents the average RAR calculated from root observation images collected from all observation sites. During the first observation in October 2021, about one week after planting the grass, the roots were still in the early stages of establishment. This phase, typical in plant development, is marked by initial root spread within the soil, helping to stabilize the plant and facilitate the uptake of water and nutrients [27]. Three months after planting, in January 2022, the presence of fine roots in the image corresponds with the expected stages of root system development in plants. As the plant continues to grow, the root system expands, with the emergence of coarse roots, resulting in an increase in avgRAR to 1.2%. These roots play a vital role in providing structural support and reflect the plant's adaptive response to the physical and nutritional conditions of the soil [28]. The photographic evidence capturing the shift from fine to more substantial coarse roots demonstrate the typical adaptive response of plant root systems to environmental changes. Over the course of growth, the roots continued to extend, reaching a root diameter (RD) of 2.7 mm and an average root area ratio (avgRAR) of 4% by April 2022. This increase in root density and depth enhances the plant's ability to access water from a larger soil volume, which can contribute to higher evapotranspiration rates. During the summer drought period, while the roots were not clearly visible in the images, the average RAR gradually increased due to the emergence of finer roots in other areas. It is likely that the coarse roots grew deeper into the soil during this dry period to reach additional moisture from the lower layers [29].

3.2 K_{sat} along the seasons

Figure 5 presents a detailed overview of the temporal variations of K_{sat} across different seasons, comparing the differences between bare zone and vetiver zone. Initially, the K_{sat} value was about 2.9×10^{-7} m/s. Subsequently, K_{sat} rose almost five times in dry winter period compare than that in rainy period. on the other hand, the K_{sat} in vetiver zone increase about 6 times reaching to 1.99 $\times10^{-6}$ m/s in the end of dry winter period. furthermore, K_{sat} kept increasing during dry period reaching 4.46×10^{-6} m/s in the dry summer period which was 16 times compared to the K_{sat} in initial observation. The increase in K_{sat} in vetiver zone persisted throughout the dry conditions are consistent with previous research by Leung et al. [8], which found a positive correlation between below-ground traits such as root biomass and root length density with K_{sat}. In this study, the 16-fold increase in K_{sat} was associated with an average 4% rise in root biomass at six months of plant growth. This highlights the crucial role of root development during the establishment phase. As roots grow, they create additional micropores [30], enabling faster and more efficient water movement compared to the surrounding soil matrix. In contrast, the K_{sat} in Bare zone showed only a slight increase during the summer, much smaller compared to the increase observed in the vegetated zones. Notably, this relative stability in K_{sat} was maintained despite an increase in the CIF from 3.0 % to 5.2%, which was more than double the value seen in the vegetated zones. The rise in CIF within Zone B, mainly due to the expansion of pre-existing cracks (as shown in Figure 3), seemed to have little impact on the K_{sat} values. These findings suggest that root development in vegetated zones might help reduce the increase in CIF during the summer, leading to a decrease in K_{sat}. However, root growth also creates preferential flow paths, which appear to counteract the reduction in K_{sat} caused by fewer cracks, ultimately resulting in an overall increase in K_{sat}.

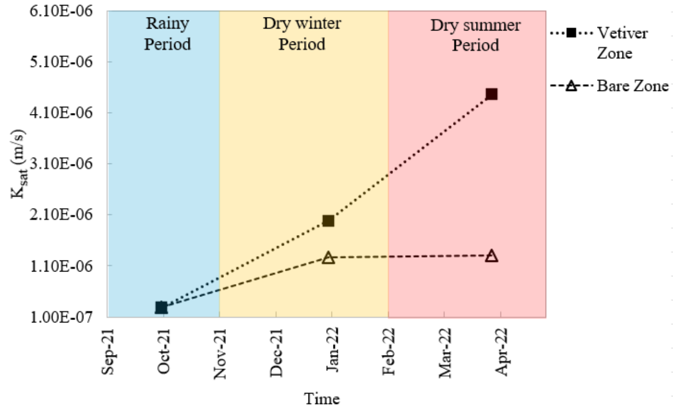

Fig. 5 K_{sat} variation along the seasons

4. Conclusion

Saturated hydraulic conductivity is vital for understanding water flow in the soil, affecting water absorption and availability. It's essential for evaluating slope stability, managing erosion, and improving agricultural resilience. This study explores how plant roots and desiccation cracks interact, and how seasonal changes influence K_{sat}. Root growth and decay were observed in vegetated and bare areas, with root area ratio (RAR) measured using a Minirhizotron. Crack formation was monitored and quantified using the crack intensity factor (CIF). The study involved three seasons to assess the combined effects of root growth and seasonal variation. The result show that Vetiver roots reduced visible cracking, leading to a more uneven crack distribution, a half decrease in CIF, and smaller average crack widths compared to bare soil. Additionally, K_{sat} significantly increased during dry periods. Root growth in vegetated areas resulted in a 16-fold K_{sat} increase, while bare areas only saw a 5-fold increase. This indicates that the presence of roots, in conjunction with cracking, had a much stronger influence on K_{sat} than cracks alone.

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