

EVALUATION OF HYDRAULIC CONDUCTIVITY VARIATIONS INDUCED BY SOIL CRACKING UTILIZING A MODIFIED SEEPAGE TESTING APPARATUS

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ABSTRACT: Landslides are a common hazard during the rainy season, particularly in hilly regions with hard, well-compacted soil layers. Due to the low seepage capacity of such soils, rainwater infiltrates slowly, leading to increased surface runoff. While this slow infiltration generally enhances slope stability by reducing pore water pressure, the presence of deep surface cracks can trigger landslides by facilitating rapid water seepage into the subsurface. The accelerated infiltration through cracks is governed by variations in the soil's seepage coefficient, yet research on this phenomenon remains limited. This study investigates the seepage coefficient of cracked soil using a newly developed modified seepage apparatus designed specifically for fractured soils. Experimental results demonstrate that the seepage coefficient in cracked soil ranges from 4.23×10^{-5} to 1.01×10^{-3} cm/s, indicating significantly higher permeability compared to intact soil. Furthermore, the seepage coefficient increases proportionally with crack width and depth, and the presence of sand infill material within soil cracks further modifies seepage behavior, highlighting the critical role of crack dimensions and composition in governing infiltration rates. These findings provide valuable insights into landslide initiation mechanisms, emphasizing how soil fracturing and infill materials exacerbate rainfall-induced slope failures. The study underscores the need to account for crack-induced seepage and infill effects in slope stability assessments, offering a foundation for improved landslide risk mitigation strategies in vulnerable regions.

Keywords: Landslide, Rainfall, Hydraulic Conductivity, Crack Soil, Modified Seepage Apparatus

1. INTRODUCTION

Soil cracking is a common phenomenon influenced by multiple factors, including surface shrinkage, past ground movement, and earthquake vibrations. The presence of layered sedimentary soils—particularly alternating thin sand and thicker silt-clay layers—as well as root-induced weathering, can further initiate and propagate cracks [1]. These cracks significantly alter hydrological and mechanical soil behaviour, particularly in slope stability contexts.

Pre-existing cracks act as preferential pathways for rainwater infiltration. During light rainfall, water entering cracks drains without accumulation, minimizing pore water pressure changes. However, under heavy rainfall, the infiltration volume exceeds the drainage capacity of cracks, leading to elevated pore water pressure (Figure 1). This pressure surge can trigger landslides, even on slopes with otherwise stable soil parameters [1, 2].

Cracks also disrupt rainwater seepage dynamics. During wet seasons, infiltrating water increases shear stress or reduces shear strength, while surface runoff and subsurface flow concentrate in cracked zones, exacerbating failure risks [3]. Deeper infiltration is particularly pronounced when water exploits pre-existing cracks [4]. Moreover,

propagating cracks weaken soil structure, further accelerating water ingress and weathering [5].

Landslide case studies underscore the role of cracks in slope failures. Deep-seated landslides often occur in cracked slopes with weak soil layers, amplified by rainfall [6–8]. For instance, Rogers and Selby [9] attributed landslides in New Zealand to pore pressure buildup in cracks post-rainfall. Rapid crack-driven infiltration generates localized pressure spikes, destabilizing slopes. Additionally, trapped water in cracks accelerates internal weathering, degrading shear strength parameters [10, 11].

Recent advances in dual-permeability modelling [12] and fractal-based soil-water characteristic curves (SWCCs) [13, 14] have quantified how crack networks alter infiltration and moisture retention. However, laboratory seepage tests often neglect crack effects, despite their field-observed impact on slope instability [15, 16]. Standard hydraulic conductivity tests (e.g., ASTM D5084-16a) focus on intact soils, failing to capture the enhanced permeability of cracked soils [17, 18].

This study addresses this gap by developing a modified seepage apparatus to measure hydraulic conductivity in cracked soils. This study investigates how crack dimensions, infill materials, and pressure variations influence seepage rates, linking these

findings to slope stability through coupled SEEP/W and SLOPE/W modelling. This study aims to refine landslide risk assessments by integrating crack-induced seepage dynamics.

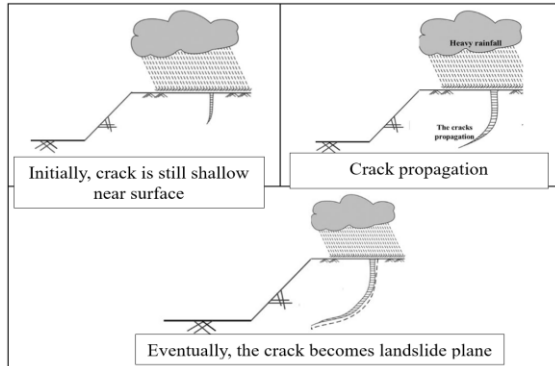


Fig 1. Crack propagation illustration.

2. RESEARCH SIGNIFICANCE

This study presents a novel investigation into the role of soil cracks in rainfall-induced landslides by quantifying seepage behavior using a newly developed modified apparatus tailored for fractured soils. Unlike conventional approaches that overlook subsurface discontinuities, this research systematically examines how crack width, depth, and sand infill affect the seepage coefficient. Experimental results demonstrate a significant increase in permeability due to fracturing, uncovering previously underexplored mechanisms. By integrating crack geometry and composition into seepage analysis, this work provides original insights into slope failure processes and establishes a robust experimental framework for improving landslide prediction and mitigation in vulnerable hilly terrains.

3. RESEARCH METHODOLOGY

The research was conducted with 2 main activities, including laboratory testing to obtain hydraulic conductivity on cracked soil. Other activities included numerical modeling to observe the effect of changes in hydraulic conductivity on cracked soil concerning the stability of a slope. The flow chart of the research implementation was shown in Figure 2.

4. LABORATORY TEST RESEARCH PROCESS

4.1 Test Preparation and Testing Process of Cracked Soil Samples

Laboratory test to determine the infiltration rate on cracked soil was conducted using a modified test tool with a concept for seepage test tool on cracked

soil as shown in Figure 3. The water discharge measurement system and hydraulic conductivity calculation of this tool were shown in Figure 4. Moreover, Figure 5 showed modified test tool that had been made specifically for this research.

The modified seepage tester on cracked soil as shown in Figure 6 was used to determine the infiltration rate of soil that had cracked. The concept of this tester was to calculate the rate of water passing through cracks with variations in the pressure given. During the analysis, the sample was wrapped in a membrane and inserted into a chamber filled with water. The water was given confined pressure with a pressure value of 0.1 bar greater than seepage pressure passing through soil cracks. A total of 8 variations of seepage pressure were used namely 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4 bar.

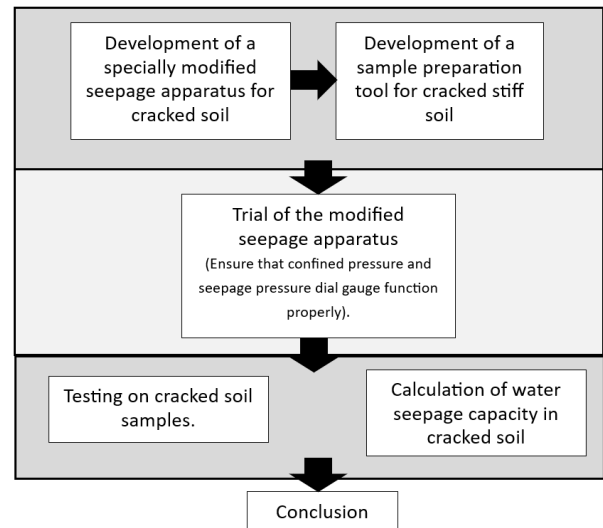


Fig.2. Research Methodology.

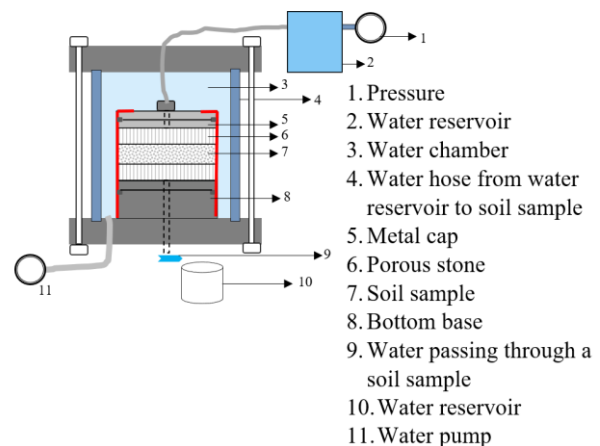


Fig.3. The concept of modified seepage apparatus.

The sample used during the analysis was remolded clay with consistency equivalent to stiff soil. The volume weight of compacted remolded soil sample was 1,728 t/m³ and water content (wc) = 21.13%. Following this process, the soil sample was molded specially (Figure 5) and cracked with a

cutting tool (Figure 6), followed by pressing with a tool as shown in Figure 7. The molded and cracked soil sample was then wrapped with a membrane was shown in Figure 8. During the process (Figure 9), the test was conducted with several variations of cracks. These differences included 1 to 4 cracks having the same crack width, where 1 crack with sand material inserted was retained by sieve number #10 and #4. Other variations included 1 crack with a wider dimension using a thin steel plate with holes resembling cracks.

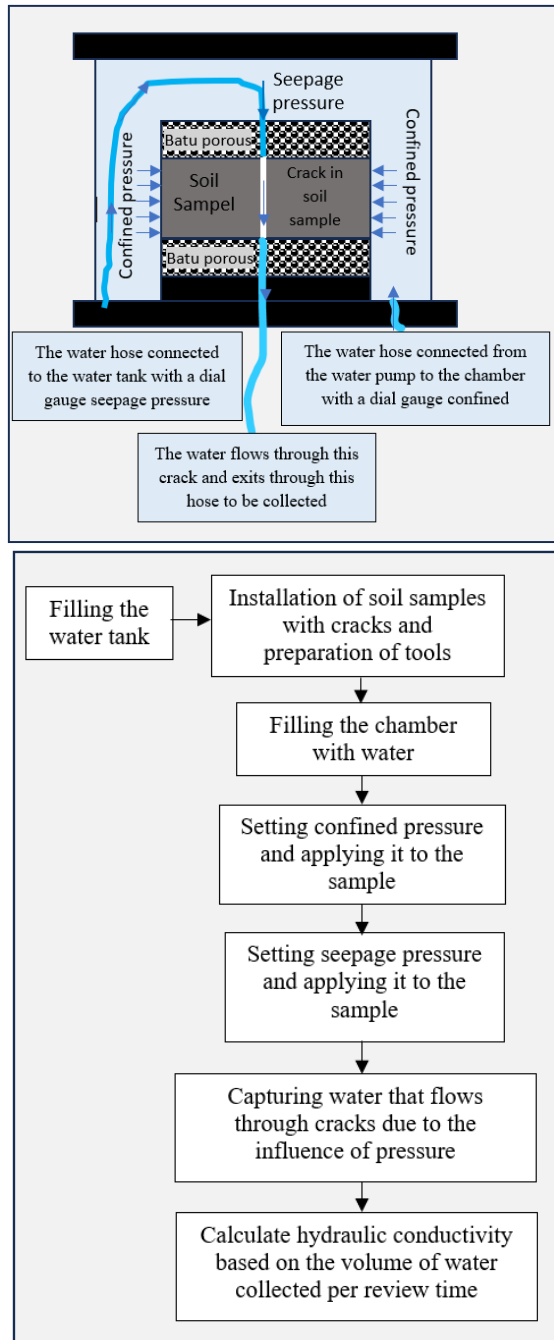


Fig. 4. Cracked soil infiltration modification test tool and sequence of cracked soil sample testing process with infiltration test tool.

The sequence of the research procedure using the modified apparatus is as follows:

- **Sample Preparation.**
Prepare the test sample by creating cracks. Place the sample in a waterproof membrane and temporarily store it;
- **Installation.**
Position the sample in the testing apparatus, Leakage Check. Ensure the sample is securely installed with no leaks. Insert the sample into the test chamber. Tightly seal the apparatus and fill the chamber with water.
- **Applying Confined and seepage Pressure.**
Set the confined pressure and apply it to the sample. Set the seepage pressure and apply it to the sample.
- **Water Flow Observation**
Capture the water flowing through the crack due to the applied pressure. Calculate the hydraulic conductivity based on the volume of collected water. During testing, it is crucial to ensure that the water exiting the monitoring tube is water that has passed through the soil crack and not leakage from the gap between the membrane and the test sample.



Fig. 5. Photo of infiltration modification test tool on cracked soil.

4.2. Results of Seepage Tests on Cracked Soil

Seepage test was conducted on 164 samples with different variations. Since there were obstacles to water flow through cracks in samples with a height

(H) = 7 cm, then the sample height was modified to 1.5 cm. The change in sample height was made because the results from the 7 cm sample were less convincing, particularly under high confined pressure. Taller samples tend to cause the soil cracks to close when subjected to high confined pressure. Additionally, testing was conducted with 8 variations of seepage and confined pressure with 3 samples in each difference. Variations in seepage testing samples on the soil were shown in Table 1.

The observations of water seeping through cracks under varying seepage and confined pressure conditions are as follows: The observations on crack 1 did not reveal any significant influence of seepage pressure on the volume of water flowing through the crack. In contrast, for crack 2, the results indicate that the greater the seepage pressure passing through the crack, the higher the volume of water flowing through it. A similar pattern was observed in crack 3; however, beyond an applied pressure of 3 bar, the volume of water flowing through the crack decreased.



Fig.6. Molds for making the cracked soil samples.

Further findings include the average volume of water flowing through the cracks: Water flow through crack 1 = 4.204 ml; Water flow through crack 2 = 6.89 ml; Water flow through crack 3 = 15.874 ml. These measurements were recorded over a 20-minute observation period. The total observation time was 80 minutes, with water discharge passing through the cracked sample recorded at approximately 20-minute intervals. As

the confined pressure applied to the sample increased, the volume of water flowing through the cracks decreased. This was attributed to changes in the crack dimensions due to the lateral pressure exerted. Additionally, larger crack dimensions and the presence of sand within the cracks resulted in a greater volume of water flowing through them. Under the same seepage pressure, an increase in the number of cracks led to a higher total volume of water passing through the cracks. These findings were then used to calculate the hydraulic conductivity of the cracked soil.



Fig. 7. A pressure tool to create cracks in soil samples.



Fig. 8. Soil sample after crack modeling.



Fig. 9. The process of draining water into cracked soil samples with different heights.

Table 1. Sample variations for seepage testing on cracked soil

No.	Information	Sample height (cm)	Number of samples
1	1 crack	7	24
2	2 cracks	7	24
3	3 cracks	7	24
4	1 crack	1.5	24
5	2 cracks	1.5	24
6	3 cracks	1.5	24
7	4 cracks	1.5	3
8	1 crack with high pressure (2.5 bar)	1.5	3
9	2 cracks with high pressure (2.5 bar)	1.5	3
10	1 fine sand cracks, high pressure (2.5 bar)	1.5	3
11	2 fine sand cracks, high pressure (2.5 bar)	1.5	3
12	3 fine sand cracks, high pressure (2.5 bar)	1.5	3
13	1 coarse sandy crack, pressure 0.5 bar	1.5	3
14	2 mm thin plate; pressure 1.5 bar	1.5	2

Note: fine sand (retained by sieve number 10), coarse sand (retained by sieve number 100).

The results of hydraulic conductivity tests of soil with cracks and varying pressures were shown in Table 2. The outcomes of these values were obtained from the analysis of the amount of water passing through cracks which was influenced by number and width of cracks with variation of the pressure given. From the results of hydraulic conductivity values, it

is obtained that speed of water seepage passing through soil with 1 crack was smaller than soil with 2 cracks. In addition, water seepage through 2 cracks was smaller than soil with 3 cracks.

In soil experiencing greater pressure (2.5 bar), speed of water seepage flowing through soil with 4 cracks was greater than soil with 1 to 3 cracks. Water seepage through samples with crack 1, 2, and 3 with wider dimensions and presence of sand at the same pressure conditions was greater when compared to soil with ordinary cracks. Moreover, speed of water seepage in soil with cracks was more than 10^{-4} cm/second. The speed of seepage raised with the increasing number of cracks in the soil. In addition, as crack and sand the soil contained became wider, the water seepage rate increased.

The number of cracks (1 to 4) can have a greater impact on hydraulic conductivity than crack width, as multiple cracks provide more flow pathways through the soil. While crack width determines the capacity of an individual flow path, a higher number of cracks facilitates broader water distribution across the soil matrix and may enhance connectivity between flow domains. Technically, hydraulic conductivity in cracked soils is influenced not only by the dimensions of individual cracks (which affect local permeability) but also by the overall crack network structure and density, which govern flow continuity and infiltration dynamics.

Table 2. Range of hydraulic conductivity values with variations in the number and width of cracks.

Information	Hydraulic conductivity (cm/s)
Crack 1	4.23×10^{-5} - 1.65×10^{-3}
Crack 2	5.51×10^{-4} - 1.83×10^{-4}
Crack 3	2.43×10^{-4} - 1.24×10^{-3}
Crack 4 (high seepage pressure=2.5 bar)	8.34×10^{-4} - 4.76×10^{-4}
Crack 1 (with sand retained by sieve number #100)	6.66×10^{-4} - 1.86×10^{-3}
Crack 2 (with sand retained by sieve number #100)	2.31×10^{-4} - 1.04×10^{-3}
Crack 3 (with sand retained by sieve number #100)	3.44×10^{-3} - 1.10×10^{-3}
Crack 1 (with sand retained by sieve number #100)	2.3×10^{-3} s/d 3.1×10^{-3}
Crack 1 (with thin plate 2 mm)	1.01×10^{-3}

An increase in crack count expands the total cross-sectional area available for water movement and can improve connectivity between surface and subsurface layers. This is particularly important in dual-permeability models, where both matrix and

fracture domains interact. In contrast, a single wide crack may not significantly enhance overall flow if it is poorly connected or isolated. Therefore, both crack geometry (width and depth) and distribution (count and spacing) jointly influence soil hydraulic conductivity. In many cases, the number of cracks plays a dominant role due to enhanced network effects and greater infiltration potential.

Seepage coefficient value of soil with cracks from the test results using modified tools in this research was greater than the coefficient of hard clay soil from previous investigations. A comparison of seepage coefficient values of clay soil without and with cracks was shown in Table 3.

Table 3. Comparison of seepage coefficient values of clay soil without and with cracks based on previous research.

Reference	Cohesive soil seepage coefficient (cm/s)	Seepage coefficient of clay soil with cracks (cm/s)
Eko Andy (2012) [19]	3.87×10^{-5} (MH) 1.86×10^{-6} (MH) 0.001 cm/s (weak layer-ML)	0.1 (assumptions on cracked soil)
Zhang (2021) [20]	3.4×10^{-5} (Silty clay) 9.2×10^{-4} (Weathered silty mudstone)	4.1×10^{-2} (tension crack)
Li dkk (2016) [21]	1×10^{-6} s/d 6.2×10^{-6} (clay without cracks and roots)	9.6×10^{-6} s/d 1.3×10^{-4} (clay with crack) 3.9×10^{-5} s/d 4.5×10^{-3} (clay with roots and crack)

5. NUMERICAL MODELING RESULTS

Laboratory test using modified tools showed that permeability coefficient increased as the number and width of cracks raised, particularly when the cracks were filled with sand. Therefore, in this sub-chapter, slope modeling was conducted on cracked soil with variations in the value of soil permeability coefficient. The variations in the coefficient used were 0.0001, 0.001, and 0.01 m/s. Moreover, the results of slope stability analysis with variations in cracked soil permeability coefficient were shown in Figure 10.

The results in Figure 10 showed that as seepage coefficient value of cracked soil became greater, safety factor value on the slope became smaller when it rained. Additionally, differences in

permeability coefficient values of cracked soil caused different changes in soil pore water pressure due to cracks. These changes in pore water pressure due to cracks were shown in Figure 11.

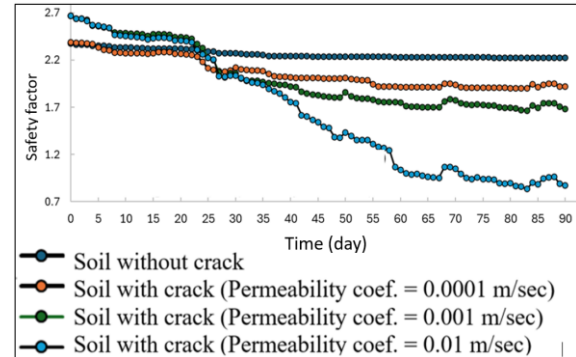


Fig. 10. Reduction in slope safety factor value with variations in permeability coefficient at the crack.

The changes in pore water pressure in cracked soil observed in this analysis are consistent with findings from previous studies. Cheng et al.[22] stated that an increase in pore water pressure plays a key role in the expansion of tension cracks and significantly reduces the shear strength of intact rock. Elevated pore water pressure lowers the effective stress, thereby influencing both the crack formation mechanism and its propagation path. Additionally, research by Yang and Liu [23] found that variations in tensile strength had minimal impact on pore water pressure. However, crack width development was affected by evaporation and rainfall infiltration.

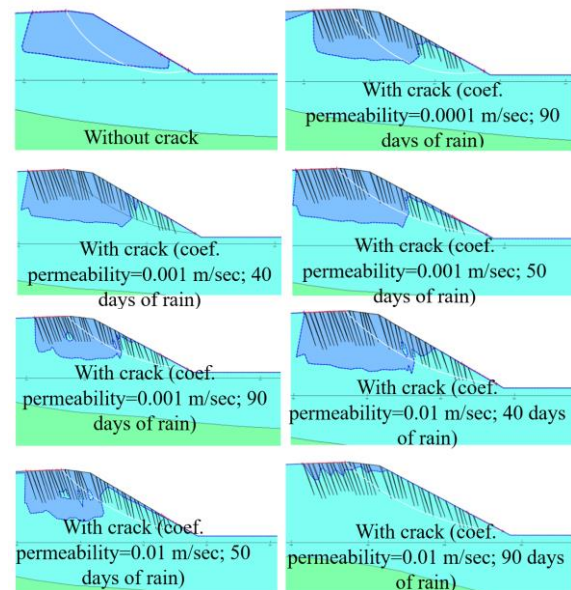


Fig.11. Changes in pore water pressure slope in soil with cracks when crack permeability coefficient varied.

Additionally, as shown in Figure 8, when cracked soil experiences rainfall for more than 40 days, a transition from an unsaturated to a saturated condition occurs, particularly at the crack tips. The presence of cracks can also lead to water entrapment at the crack ends. This phenomenon is evident from geoelectrical field observations, where certain locations exhibit low resistivity values, as shown in Figure 8. These findings are consistent with the study by Sari et al. [10], which found that cracks contribute to weathering and water entrapment, as observed through ERT (Electrical Resistivity Tomography) measurements in the field. This study aligns with the work of [24] on fractures and seepage in rock formations. Furthermore, the findings contribute to the existing body of knowledge on rainfall-induced landslide mitigation, particularly in cracked soils—a common phenomenon in tropical regions [25],[26].

Overall, this study confirms that cracks in soil significantly impact pore water pressure by increasing permeability, causing pressure variations, and altering seepage behavior. Understanding these effects is essential for evaluating soil stability, groundwater movement, and hydraulic conductivity in geotechnical and engineering applications.

6. CONCLUSION

In conclusion, this research determined the soil seepage capacity based on the results of hydraulic conductivity values on cracked soil by forming a special modified test tool. The results obtained from this research included:

1. Hydraulic conductivity value in cracked soil was greater than compared to uncracked soil. This outcome was proven from the results of laboratory observations of modified soil seepage test equipment on cracked soil. As the number and width of cracks become greater, hydraulic conductivity value increased. This conductivity value varied between 1.01×10^{-3} cm/second to 4.23×10^{-5} cm/second. Following the discussion, hydraulic conductivity value was influenced by the number and width of cracks in the soil.
2. The presence of cracks on the ground surface with high hydraulic conductivity values was a path for rainwater to enter deeper layers. Surface cracks caused the formation of perching water table in deeper layers. These results were proven from numerical modeling with coupled programs SEEP/W and SLOPE/W.
3. Cracks in soil reduced slope stability as observed from the decreasing safety factor value. As the crack and its hydraulic conductivity value became larger, the level of decrease in the safety factor became greater when compared to soil without cracks.

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