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# Exploring Effect of Mature Tree on Suction Distribution in a Natural Slope

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**Abstract** Climate change altered variations in weather trends and rainfall fluctuations could trigger soil slope instability, causing landslides or debris flows. To mitigate such rainfall-induced slope failures, vegetated slopes are considered as an effective mechanism. For that reason, several studies have addressed the restraining of mechanical failures and advantages of evapotranspiration model in soil–plant-slope stability continuum. However, most of these investigations were examined on tree seedlings (1–2 m trunk height), which are relatively atypical and are insufficient to comprehend the vegetated slope mechanism. Besides, the variation of pore water pressure (directly related to slope stability) with different rainfall intensities are unclear. These critical measurements are required for modelling climate change-slope stability models and for practicing in long-term maintenance of man-made slopes. Therefore, this study attempted to investigate the temporal variation (suction distribution) of matured Ivy tree under different rainfall events (return periods equal to 20 years, 2 years and less than 2 years). The suction variations with different rainfall events were measured both vertically and horizontally below the root zones using jet fill tensiometers (± 1 kPa accuracy). The study provides evidence of suction distribution within the root zones, discussing the suction recovery after consecutive rainfall events and natural drying. Based on the observations, it was found that antecedent rainfall plays an effective role in suction recovery rates and changes in soil hydraulic conductivity.

**Keywords** Slope stability · Real time monitoring · Rainfall events · Suction distribution · Antecedent rainfall

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## Introduction

Variation in rainfall patterns and other forms of precipitation are amongst the critical aspects determining overall impacts of climate change. A rise in global temperature by 0.5° C in the past 100 years [1] and changes in weather patterns have caused adverse effects in predicting the rainfall schemes [2, 3]. Despite the certitude regarding the future warming on a global scale by different climate model studies, their corresponding impact on weather and rainfall are in less agreement at a detailed level [4]. Owing to this rationale, the fluctuations in terms of rainfall intensity, frequency and quantity, could trigger soil slope deformation and instability, leading to landslides and debris flows [5–7]. Apparently, these conditions are prone in the areas of tropical regions with hot and humid conditions, where the residual soils exist in unsaturated conditions [8–10]. During the event of heavy rainfall, the slope surface is envisaged to alter the soil permeability and moisture content, which further decreases the matric suction and soil shear strength, causing slope failures [11–13]. The general systematic diagram of slope failures in unsaturated and rainfall induced mediums are shown in Fig. 1.

Given the context about rainfall induced slope failures, the mechanisms and conditions leading to the initiation of failure have been perused in various laboratory and in-situ

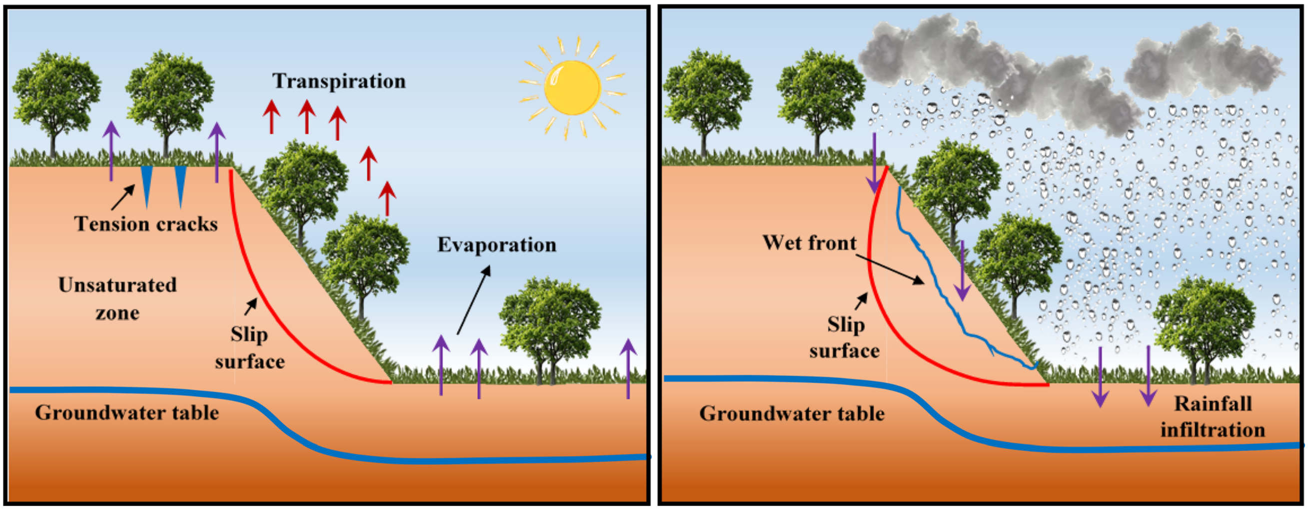



**Fig. 1** Standard variations in unsaturated and rainfall induced slope failures ( modified from Rahardjo et al. 2019)

oriented studies [14–16]. After comprehensive investigation, vegetated slopes are increasingly seen as an effective mechanism withstanding the slope failures [17, 18]. The planting layout on the slope enhances the slope stability and meets both hydrological and mechanical aspects using soil–plant root interaction. More specifically, the soil–plant continuum removes the soil water through evapotranspiration [19] and increases soil suction to restrain mechanical failures [8]. In that reference, studies have been primarily focused on the effects of vegetation in mechanical cohesion and slope stability, disregarding the strong influence of root zone dynamics [20, 21]. But if we consider the relation (Eq. 1) between shear strength and soil suction proposed by Fredlund et al. [22], the additional matric suction induced by root water uptake will increase the shear strength.

$$\text{Shear strength} = c' + \sigma' \tan\varphi' + (u_a - u_w)\tan\varphi^b \tag{1}$$

(c' is true cohesion, σ' is effective stress, $u_a$—$u_w$ is matric suction, φ' is angle of internal friction and $\varphi^b$ is rate of increase of shear strength with respect to angle of friction).

In order to address this disparity, studies have been conducted to analyse soil suction distribution induced due to tree evapotranspiration [23–27]. In particular, a field study conducted by Garg et al. [23] had found that trees were able to retain higher suction than grassed and bare soil slopes. For further optimization, Ni et al. [27] investigated effects of spacing between multiple trees on leaf area index and suction distribution.

However, most of these evapotranspiration studies focused only on tree seedlings, which are at much younger stage ( ∼ 1–2 m height) with relatively shorter root depths (within ∼ 0.5 m). But, in general, most of natural slopes and man-made slopes (in long term) are likely to possess multiple and mature trees of at least 3–5 m height [28]. Supportively, studies in agriculture and forestry have shown that root water uptake generally varies with age [29] and expected to have higher shading effects [30], which may influence evapotranspiration and induced suction distributions [22]. Regardless, the temporal variation of suction distribution under varying rainfall events, within and below root zones are still misapprehended. Since in most cases, it is generally accepted that the rapid rise of pore water pressure under the root zone is critical for the initiation of slope failures [31, 32], this data insufficiency is crucial for correlating the climate change—slope stability models. Considering the aforementioned literature gaps, following objective has been devised.

The overarching aim of this study is to explore suction distributions under different rainfall events of varying intensity and duration in a natural slope containing mature trees. A specific test zone with a native tree species of *Schefflera heptaphylla* (Ivy tree) were selected and continuously monitored for a period of 120 days. These tree species' were found to be more prevalent in Asia and has the ability to resist drought at warmer environments [33]. The suction was measured at different root depths (vertical suction distributions) under varying rainfall events, which are represented in terms of return periods. In addition, the effect of antecedent rainfall below the root zone were evaluated to understand the suction recovery below root zones. Horizontal suction distributions were measured to interpret the root zone proximity. The scope of this study could assist in preliminary design/analysis of man-made slopes with mature vegetation in long term.

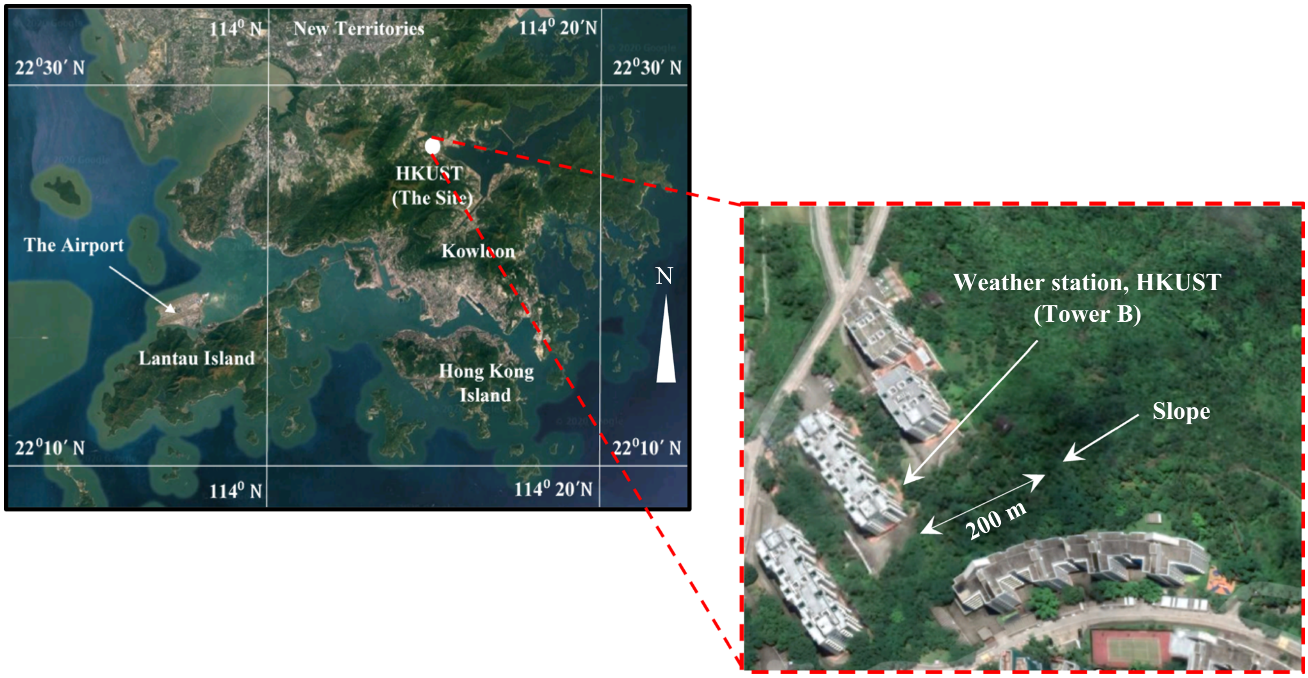



**Fig. 2** Surface topography of the investigated slope and nearby weather monitoring station

## Test Plan, Instrumentation and Procedure

The field monitoring was conducted on a natural slope located inside campus of Hong Kong University of Science and Technology (HKUST), Kowloon, Hong Kong (Fig. 2). The slope area was ascertained to be steeper by an angle of 30°, heavily weathered and underlain by the soil type of volcanic tuff. Also, the entire slope area is covered by dense vegetation due to warm and humid environment. Besides, a specific test zone was furthermore opted in the slope to examine suction distributions. The overview of the selected test zone is clearly pictured in Fig. 3. In the selected test zone, tree species of *Schefflera heptaphylla* were scattered throughout the area. At the selected test zone, two trees designated as $T_1$ and $T_2$ were chosen lying in the same row, separated by a distance of 2 m. The tree heights of $T_1$ and $T_2$ were measured to be 3.6 and 3.3 m, respectively. From the gauged tree heights, root zones of $T_1$ and $T_2$ were estimated to be one-third of tree height, i.e. 1.2 and 1.1 m, respectively [30]. In order to determine suction distribution, jet fill tensiometers (JFT's) were installed at various locations. The instrumented JFT's have an accuracy of ± 1 kPa and have the potential to avoid boundary effects on suction measurements [34].

The experimental procedure includes installation of JFT's at the specified location in both horizontal and vertical directions. Before installation, ceramic tip of each JFT was saturated. Tube of JFT was filled with de-aired water. Any air bubbles inside the JFT amid calibration were removed by pressing the pump at the top of JFT repeatedly. Details of instrumentation and its corresponding installation procedures are mentioned in Garg [25].

In regard to measuring vertical suction distributions, the JFT's were installed at depths of 0.1, 0.3 and 0.5 m, respectively. While, for measuring horizontal distributions, the JFT's were installed at the distances of 0.3, 0.9 and 1.5 m away from trunk of $T_1$. The horizontal instrumentation plan was to ensure suction measurement below the root zone of $T_1$, near to the centre between $T_1$ and $T_2$ (where there was no influence of any root zone) and the root zone of $T_2$. The detailed surface plan with respect to instrumentations enclosing tree root zones are shown in Fig. 3. During each JFT installation, a hole was drilled using an auger until the targeted installation depth (here 150 mm) was reached. After installation, the gap between JFT and surrounding soil was backfilled with moist in-situ soil, thereby preventing the preferential flow along the clearance. Upon the completion of JFT installation, suction and other atmospheric parameters were recorded for 120 days (from April 18, 2013 to August 15, 2013). For atmospheric parameters including hourly rainfall amount, net radiation, relative humidity, air temperature and wind speed, the data were obtained from HKUST weather station, situated 200 m far from the natural slope. The data for atmospheric data were ± 6% in accordance with Hong Kong weather maps, which might be due to similar cloud covers [36].

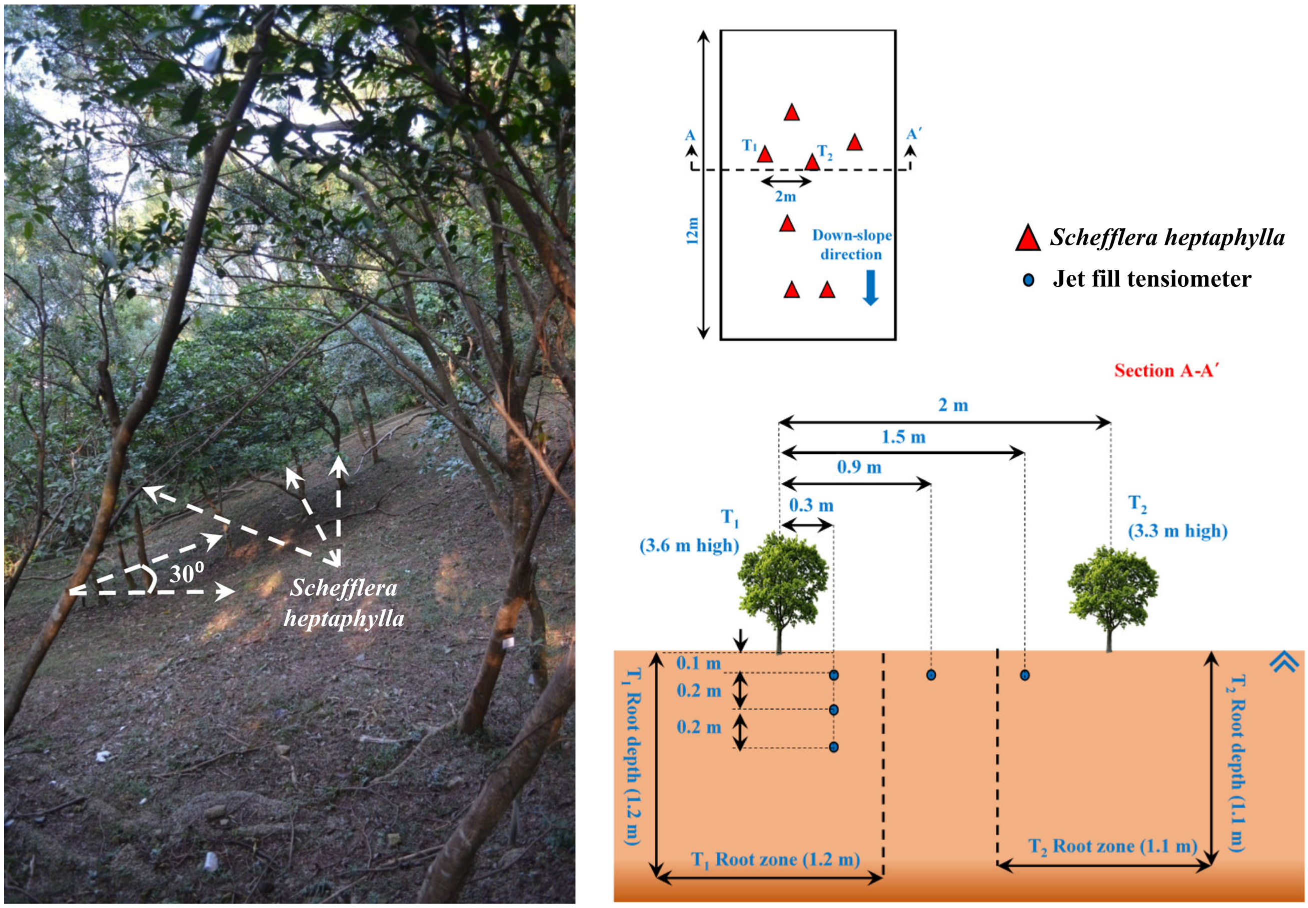



**Fig. 3** Overview and surface plan of the slope and tree species along with instrumentation particulars

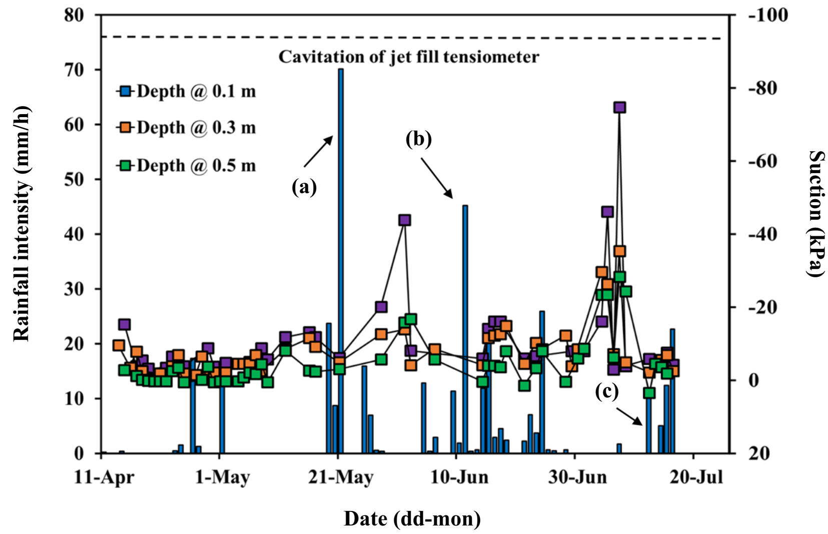
## Results and Discussion

### Vertical Soil Suction Distribution in a Mature Treed Slope

The rainfall record obtained during the slope monitoring period and suction distributions within the root zone of $T_1$ are plotted in Fig. 4. It can be observed from the figure that higher rainfall intensities were identified during the months of May and June in 2013. On the other hand, rainfall events observed during the month of July was found to be intermittent, which might facilitate effective suction rebound after consecutive natural drying and rainfall. At the initiation of monitoring period, the measured suction at the depths of 0.1, 0.3 and 0.5 m were 15, 9 and 3 kPa, respectively. Hereafter, the suction readings were found to vary in relatively smaller magnitudes until early May depending on the events of natural drying and rainfall. Since there was minimal rainfall from May 1 to May 19, suction measurements were found to increase gradually, reaching to a maximum of 13, 11 and 8 kPa corresponding to the depths at 0.1, 0.3 and 0.5 m. The trend of soil suction distribution with depth is consistent with that of slope study investigated by Garg et al. [23]. But, the magnitude of increase in duration of drying and relative humidity is much smaller in this study. The difference might be due to minimized evaporation in soil caused by shading effects of canopy in mature trees. Furthermore, the slope in the present study is located within urban densely populated buildings, which may induce shading effects, thereby limiting evaporation and soil suction. Another plausible difference could be due to variation in soil type between two studies. Therefore, more studies are needed to systematically analyse any effects of shading caused by trees itself or surrounding in urban areas on soil moisture and water dynamics in field.

After longer duration of preceded natural drying, the suction values were found to drop immediately around 5 kPa due to the succeeding rainfall events from May 19 to May 27. However, the trend of suction recovery was observed to be higher during intervals from May 28 to June 13 and July 1 to July 14, even though the drying period was shorter. The relatively higher suction recovery was majorly observed at the shallowest depth of 0.1 m. It could be possibly interpreted from relative humidity and radiant energy, since it is well known that these parameters will

Fig. 4 Recorded rainfall intensity during the experimental period and corresponding suction responses at three different depths




**(a)** Total rainfall of 147 mm for 2 hours (equivalent to 20 years return period)

**(b)** Peak rainfall intensity of 30 mm for 1 hour (equivalent to 2 years return period)

**(c)** Peak rainfall intensity of 12 mm for 1 hour (equivalent to <2 years return period)

affect total evaporation from soil [37]. To understand this observation, a graph on relative humidity and daily sunshine hours measured during the monitoring period were plotted with trend lines indicating moving average (Fig. 5). As observed from Fig. 5, relative humidity was nearly 80–90% till May 28th, beyond which, it was found to drop to around 73% and again gradually rises to 90% and above till 10th June. Further, relative humidity lies at an average of around 80% between 1st July and 14th July. In addition to this, total daily sunshine hours rise rapidly close to 12 h daily during last week of May. Total daily sunshine hours are generally higher between time periods from 1st July to 14th July than initial weeks of monitoring period. These observations indicate that suction may tend to be generally higher during later period of monitoring period (i.e., May 28th to July 14th) than that during initial stages. The effect is more visible at shallower depth of 0.1 m than at deeper depths and are similar to those in previous studies, where moisture gradients are higher at surface than at sub-surface [38–40]. This suction increase also decreases the hydraulic conductivity, thereby hindering the water flux at higher depths towards the root zone [41, 42].

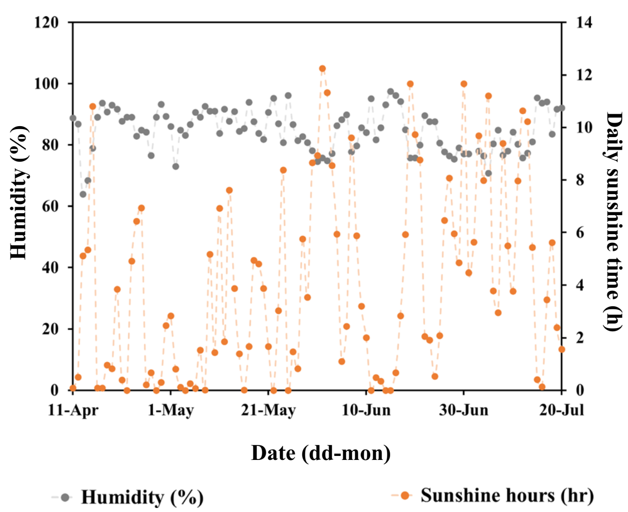



Fig. 5 Variation of relative humidity and daily sunshine hours during monitoring period

## Suction Retained in Mature Treed Slope Under Influence of Different Rainfall Events

Three different rainfall events (refer to Fig. 6) were taken into account during the time period of May 22 (70 mm/h), June 24 (45 mm/h) and July 12 (12 mm/h), representing the return period equivalent to 20 years (rainfall event A), 2 years (rainfall event B) and less than 2 years (rainfall event C) respectively. The rainfall event A comprised a total of 195 mm rainfall between the start of rain and the time of measurement, where the peak intensity of 70 mm/h had been observed. Rainfall event B includes a total of 84 mm rainfall in between the rain inception and time of measurement. The peak rainfall intensity during event was 26 mm/h. In rainfall event C, only a total of 34 mm rainfall was observed between the initiation time and measurement time. The rainfall duration including a peak intensity (12 mm/h) was much lower than rainfall events A and B. The retained suction was measured 12 h after the start of rain on May 22 and June 23, whereas on July 12, it was measured after 6 h, after the rain had stopped. These timelines were chosen, since most of the slope failures take

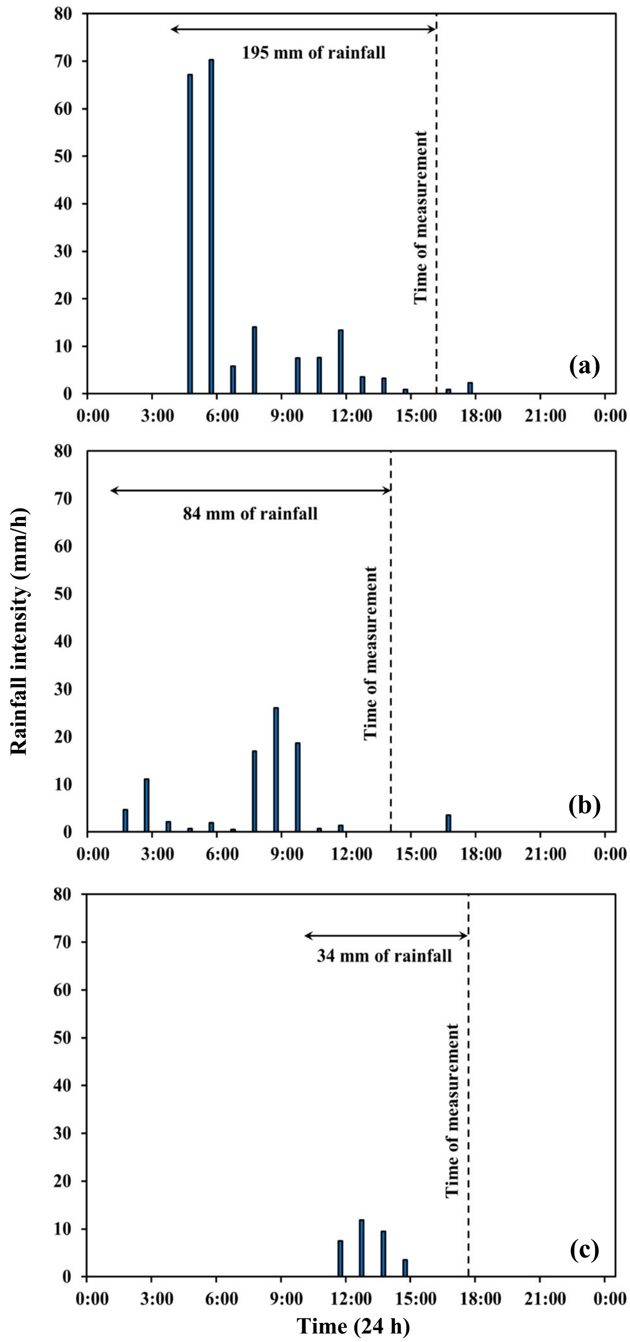



**Fig. 6** Recorded rainfall events equivalent to **a** 20 years return period; **b** 2 year return period; **c** less than 2 year return period

place during or mainly after rainfall due to the movement of wetting front.

The suction distributions before and after rainfall (referred as initial suction and retained suction) under three different rainfall events (Fig. 5) for $T_1$ are plotted in Fig. 7a and b. Prior to the rainfall event A, the initial suction at the depth of 0.1 m was 12 kPa, and decreases with depths to 9 and 4 kPa at depths of 0.3 and 0.5 m, respectively. After being subjected to the rainfall event A, the retained suction at the shallowest depth (i.e. 0.1 m) was found to be 4 kPa, whereas at higher depths, the suction reduced to around 1–2 kPa. Considering the error in suction measurements of ± 1 kPa, it can be assumed that suction is almost negligible at deeper depths. These results are also consistent to observation in soil vegetated with tree seedlings [43].

The initial suction before rainfall event B (2-year return period) at depths of 0.1 m and 0.3 m were 14 kPa, while at 0.5 m, a value of 8 kPa was obtained. After the rainfall event B, the retained suction below the root zone of $T_1$ was 6, 3 and 1 kPa at 0.1, 0.3 and 0.5 m, respectively. The trend of decreasing suction distribution shows that there was likely to be a rapid movement of wetting front under total head gradients during rainfall event B. This wetting front might have caused suction at deeper depths to reduce significantly, whereas causing lesser suction recovery at shallower depths [44].

The initial suction before rainfall event C was measured to be 75, 35 and 29 kPa at the depths of 0.1, 0.3 and 0.5 m, respectively. Following the short-term rainfall event C, the suction drops substantially ranging between 4–5 kPa at the depths of 0.1 and 0.3 m. However, this sudden drop was not observed at highest depth (i.e. 0.5 m) and the measured retained suction was around 25 kPa. This observation indicates that the wetting front is unlikely to reach at deeper depths under rainfall intensity merely equal to 34 mm (i.e., less than 2-year return period) as compared to that of rainfall events A and B. The lateral suction distributions (Fig. 8) with respect to rainfall event C was performed to scrutinize the suction retention along the root zone in lengthwise orientation. In that case, the suction values corresponding to the rainfall events occurred during July 7 and July 12 were measured along with suction increase in between the rainfall events. The initial suction values was at a maximum of 64 kPa at 0.3 m, 53 kPa at 0.9 m and 75 kPa at 1.5 m, because of extensive natural drying event from July 8 to July 11. The suction values dropped forthwith to values between 1 to 4 kPa, after a peak rainfall intensity of 11.95 mm/h rain occurred on July 12. Since the readings were taken just below the depth of 0.1 m, the suction values were found to be constantly destroyed, as observed in the previous cases. While examining the suction increase during the drying event, the suction value at 0.9 m was found to be lesser than the other two values, while the greatest value was found at the distance of 1.5 m. The lesser value at 0.9 m is probably due to the soil underneath the location might be more uniform compared to other two positions, as there was no influence of root zones. Nonetheless, the highest value at 1.5 m was plausible because the position 1.5 m is quite distant within the $T_2$ root zone, whereas the position at 0.3 m is closer to the proximity of $T_1$ root zone.

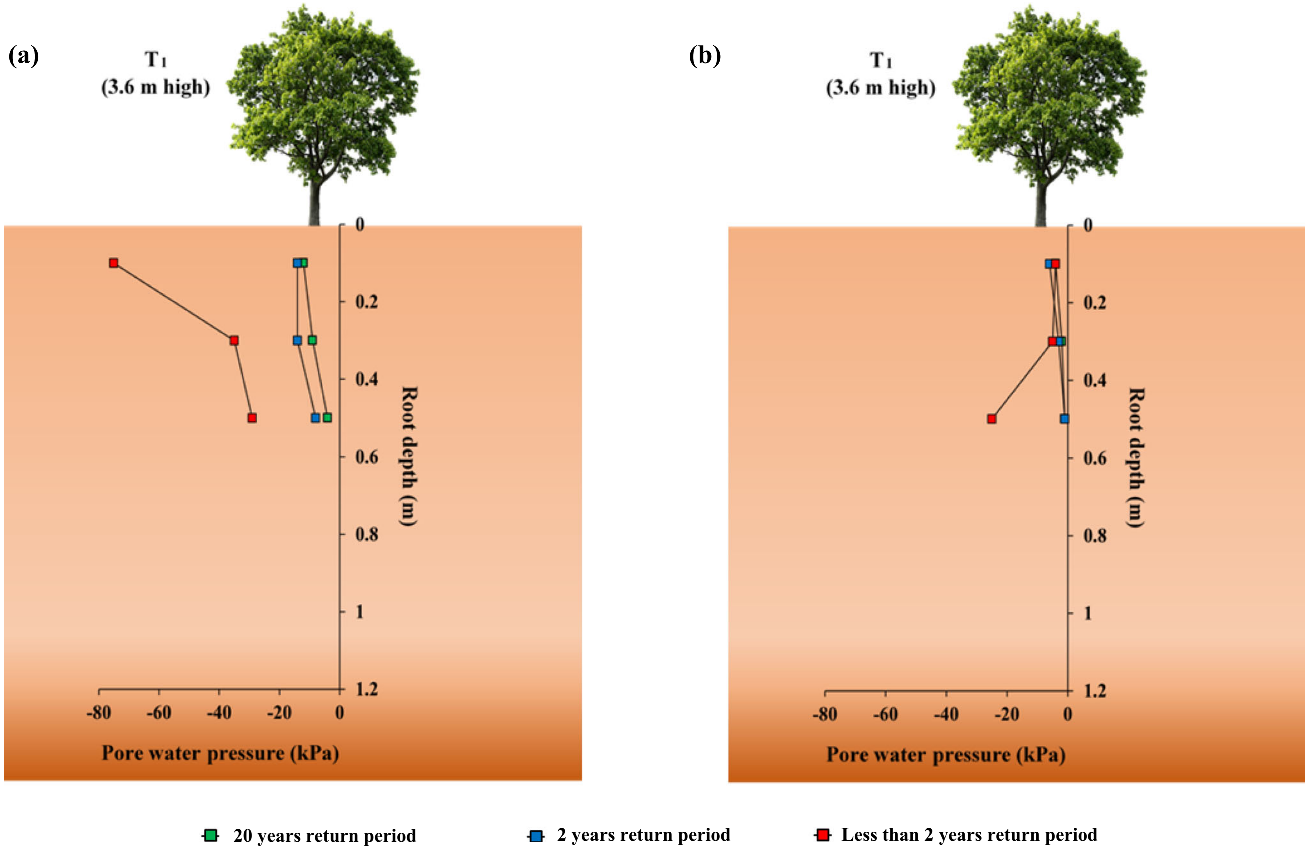



**Fig. 7** Suction distribution with respect to different rainfall events **a** Initial suction; **b** Retained suction

## Effect of Antecedent Rainfall on Suction Distribution

In accordance with the attained results, it could be interpreted that the initial suction at May 22 and June 23 was found to be less due to the antecedent rainfall occurred prior to the examined day. In the first two rainfall events (A and B), owing to the antecedent rainfall events, the suction recovery was persistent at all the depths. Meanwhile, at rainfall event C, where there was no antecedent rainfall, the initial suction was higher due to the prolonged natural drying for the past 5 days. Yet after a very small amount of rainfall, the recovered suction at shallowest depth was much higher than the deeper root depths. This clearly shows the increased suction reduces the hydraulic conductivity leading to less infiltration rate at deeper root zones, while any suction retained at shallow depth is apparent [26, 45].

The effect of antecedent rainfall, not only has a significant influence on suction recovery, but also expected to indirectly affect the water permeability co-efficient in soil [46]. For in-depth understanding of the phenomenon, suction distribution for three consecutive days from July 31 to August 3, 2019 was closely monitored (Fig. 9). There was no observed rainfall on July 31. This was followed by the rainfall of 19 mm from August 1 to August 2 and 30 mm from August 2 to August 3. The initial suction before the rainfall at depths of 0.1, 0.3 and 0.5 m was measured to be 12, 6 and 13 kPa, respectively. After the first rainfall event, the suction reduced to 8, 4 and 6.5 kPa corresponding to the depths at 0.1, 0.3 and 0.5 m. The suction values further reduced to 6, 1.5 and 1 kPa after the second rainfall event. Upon the results, it could be inferred that the 1$^{st}$ rainfall event might have enhanced water permeability before the initiation of 2$^{nd}$ rainfall event. The increased water permeability simultaneously leads to an excessive infiltration and sub-surface flow under consecutive rainfall events [47]. Therefore, the suction recovery depends on the attributes of prior rainfall events and is expected to be higher when there is no antecedent rainfall. Further it would also depend on initial soil suction before antecedent rainfall. It should be noted that the role of root water uptake in suction recovery is significant if there is a gap between two rainfall events.

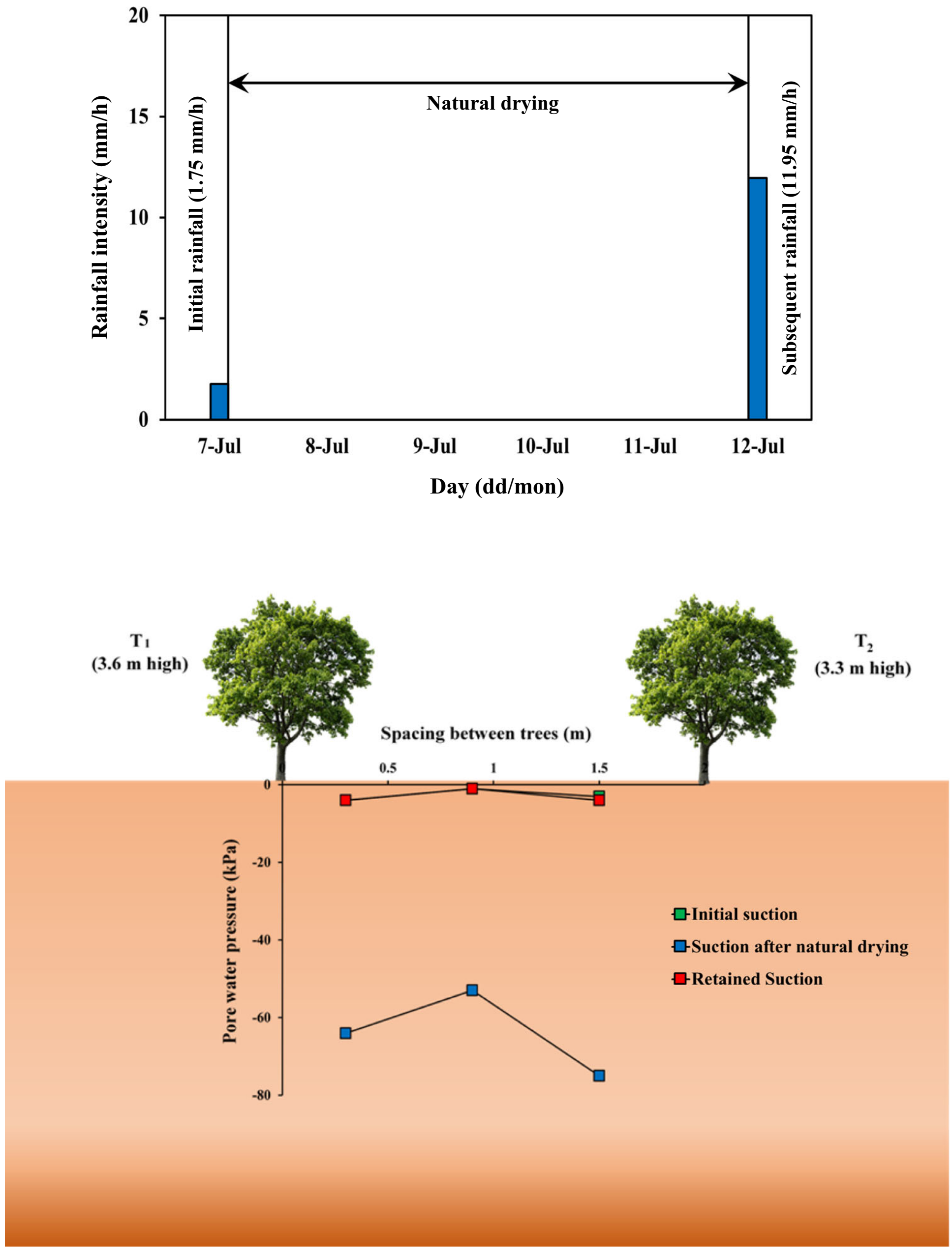



**Fig. 8** Effect of rainfall and natural drying in lateral suction distribution

## Summary and Conclusions

This study presents the temporal variation of suction distribution within and below the root zones under different rainfall events. Real time monitoring of a test zone in natural slope was conducted for a period of 120 days. Based on the attained outcomes, following conclusions were inferred:

1. Suction at shallower root depths were found to be continually destroyed at both rainfall and natural drying, irrespective of intensity and duration. During the events of natural drying, suction values are significantly higher at shallower root depths than higher root depths due to the higher total head gradients caused by increased root water uptake.
2. During any rainfall events after natural drying, the suction values at shallower depth suddenly drops to minimum, indicating rapid suction recovery. However, at deeper depths, the suction recovery rate was both less and delayed. This is mainly attributed to the decrement of hydraulic conductivity caused by increased suction at shallower depths, hampering the water flux towards the higher root depths.
3. The wetting front of the root zones were found to be affecting at higher depths for rainfall events greater

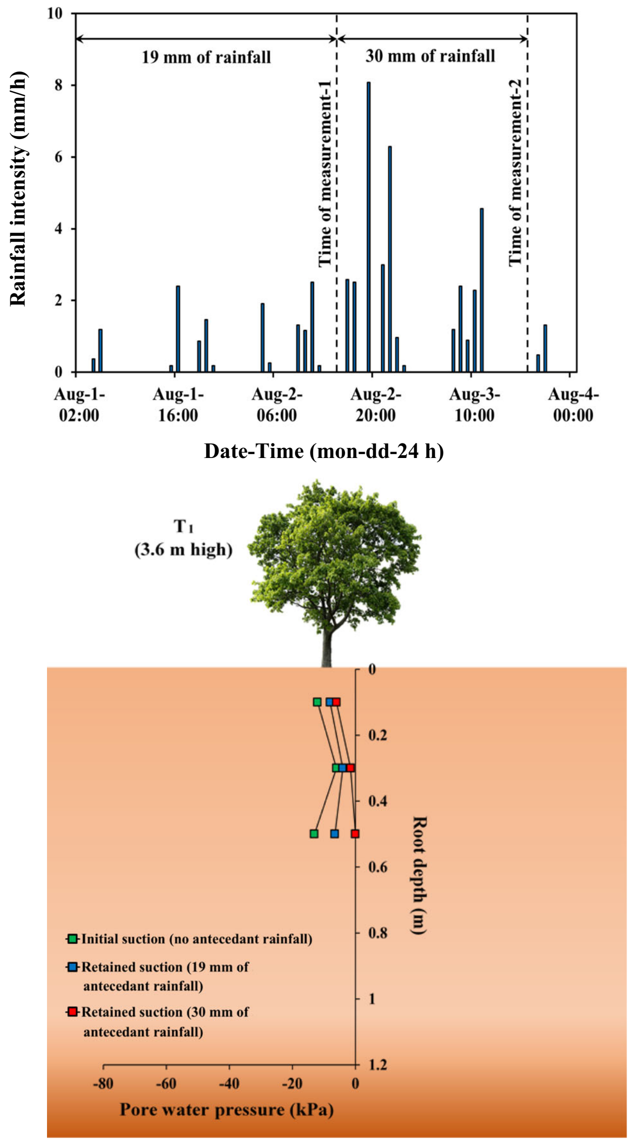



**Fig. 9** Effect of consecutive antecedent rainfall in suction distribution

than 2 years return period. Contrastingly, at rainfall event less than 2 years return period, the wetting front was unlikely to reach deeper depths due to less amount of rainfall.

4. Suction recovery below the root zones are found to be consistent when the slope is subjected to antecedent rainfall. It is ascribed that hydraulic conductivity is altered differently when antecedent rainfall event becomes valid. Therefore, the suction recovery differs depending on the individual root zone moisture dynamics of rainfall event comprised with and without antecedent rainfall.
5. In horizontal suction distribution, suction value during natural drying are found to be smaller at distance closer to root proximity zone, whereas the value is higher at distant root zones. At lateral distance where there was no influence of root zone, the suction value was lesser than root influence zones, clearly indicating the root water uptake within the root zone.

In conclusion, the root water uptake induces additional soil suction (as compared to bare slope, which is mainly subjected to evaporation). This increased suction will in turn reduce unsaturated permeability, which is further expected to slow down the movement of wetting front during rainfall. This confirms higher suction (i.e., at deeper depths) retention in rooted soil as compared to bare soil. Overall, the study supports the soil root interaction as an effective mechanism to counteract the slope failures.

## Limitations and Future Scope

It is important to emphasize that suction distributions were measured based on the experimental design adopted in this study. Also, the measured results reveal only the effects of single tree species at given atmospheric condition. Further studies are needed to investigate the temporal variations in different root systems, slope angle and soil medium on suction distributions.

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**Declarations**

**Conflicts of interest** The authors declare no competing conflicts of interest.

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