Study of seepage patterns and calculation of infiltration coefficients of loose stacked layers on slopes under rainfall action

Chengcheng He*

College of Geodesy, Chang'an University1, Xi'an, Shaanxi, China

Abstract. Rainfall is one of the most important factors inducing landslide occurrence, and previous researchers have carefully studied the stages of rainfall infiltration as well as the factors that affect infiltration (e.g., rainfall intensity, rainfall duration, initial water content and dry density). However, previous studies using homogeneous soils were overly idealised and ignored the effects of water content and dry density on infiltration, which vary with depth. In this paper, based on indoor rainfall infiltration tests under the above initial conditions and influencing factors, the following patterns were found: (1) dry density and water content of natural soils tend to increase along the direction of gravity under long-term gravity and repeated rainfall evapotranspiration; (2) stepped dry density increases infiltration resistance, which increases the total response time; stepped initial water content decreases infiltration water volume, which decreases the total response time; stepped dry density and water content have the shortest total response time;(3) The increase in dry density delayed the sudden change point in the permeability coefficient, and the initial moisture content had little effect on the sudden change point.

1 Introduction

Rainfall is an important cause of landslide disasters in the Qinba Mountains. Rainfall leads to spatial and temporal changes in slope soil moisture, causing soil deformation and leading to reduced stability. Therefore, the study of the infiltration law of the soil body in the accumulation layer is an important basis for revealing the mechanism of rainfall-type landslide disaster. Therefore, it is extremely important to study the unsaturated-saturated infiltration law of typical accumulation layer in Qinba Mountain area.

In terms of theory, Green and Ampt[1] proposed the infiltration theory in 1911, which simplified the water content depth profile into a wet zone with fully saturated water content and an initial water content zone below the infiltration front. Accordingly, the Green.Ampt infiltration model with some physical basis was established.In 1931, Richards[2] introduced Darcy's law to unsaturated soil water flow, and established the differential equation for unsaturated flow.Translated with DeepL.com (free version)Translated with DeepL.com (free version)The influencing factors of rainfall infiltration are divided into endogenous and exogenous factors, Zhu Wei (2006)[3] found that the infiltration process, i.e., the conversion of the flow boundary and the head boundary, and the control of the initial water content found that those who have a large initial water content, the point of ponding is more in front of the unsaturated infiltration stage infiltration rate decreases more quickly. Jian Wenbin (2020)[4] conducted a one-dimensional infiltration test, by controlling the rainfall duration or total rainfall, it was concluded that the greater the rainfall intensity and the stronger the duration, the greater the rainfall infiltration and the deeper the depth of infiltration. Mansida A (2021)[5] conducted an experiment on the effect of vegetation on surface runoff and infiltration in a watershed area using a rainfall simulator to analyse the extent to which vegetation contributes to rainfall intensity in relation to the effect of surface runoff and infiltration on rainfall intensity. The results showed that changes in land cover increased surface runoff and decreased infiltration. Yizhou Zhuang (2021)[6] conducted a physical simulation experiment on rainfall-induced landslides using Weber's criterion as the rainfall similarity criterion. The results showed that the fully weathered granite slopes responded rapidly to rainfall infiltration. Further, the water content increased sharply and the matrix suction dissipated rapidly. After dissipation, the matrix suction force was transformed into pore water pressure, which accelerated the deformation of the slope. The wet peak has a large infiltration depth within the slope, and the acceleration in the deep part is lower than that in the shallow part. Wang Qing (2021)[7] found that gravel interlayer accelerates infiltration and clay interlayer hinders infiltration through indoor modelling tests, and the closer the gravel interlayer is to the surface, the earlier the higher pore water pressure and hydraulic gradient are formed, which affects the infiltration rate.

* Corresponding author: 2271996578@qq.com

Xu Jiancong (2006)[8] found that gravel content and fine-grained soil content had the greatest positive and negative effects on infiltration through several sets of infiltration tests on different graded gravel soils. Cheng Guang (2023)[9] found a positive correlation between stone content and pore ratio and infiltration coefficient through experimental study. In order to study the response of soil moisture (θ) to rainfall, Xu Tianxiang (2023)[10] used continuous high-frequency θ monitoring data at depths of 5, 10, 20, 40 and 70 cm to reveal the θ dynamics and its response characteristics to rainfall in dryland (UF), paddy field (PF) and forest land (FL). Furthermore, the cumulative increment of soil water storage in FL (190.1 mm) was larger than that in UF (160.6 mm) and PF (143.8 mm).(#br)Conclusions(#br)The land use conversion from FL to UF and PF reduced the rainfall infiltration capacity and may increase runoff potential.

The above studies have ignored the fact that the physical properties of natural soils change with depth, this paper is based on an indoor one-dimensional rainfall infiltration test using non-homogeneous gravelly soils to investigate its effect on infiltration.

2 Experimental Design

2.1. Sampling and Preparation

Figure 1 Panoramic view of the Sai Yip Leung landslide

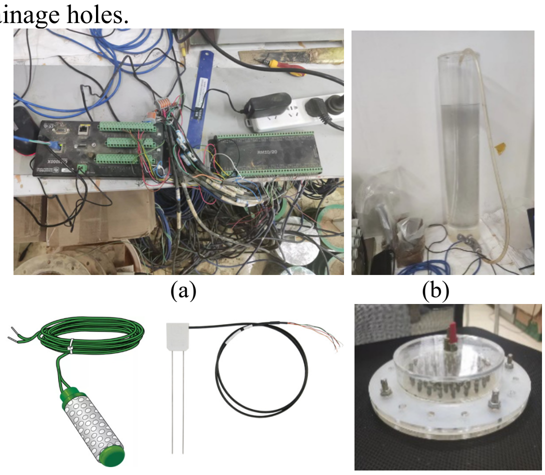
The soil samples taken in this test were gravel soil from the landslide monitoring site of Xiaohekou Village, Bamiao Town, Zhenba County, Hanzhong City, Shaanxi Province (Fig. 1 Saijianliang landslide), with a depth of 1.5 m. The soil had a natural water content of 23.2%, a density of 1.89 g/cm^3, and a pore ratio of 0.79.

When making samples, the design soil samples were first dried in an oven for 8h, and then hammered and dispersed through a 20mm sieve to remove particles with a particle size larger than 20mm (in order to eliminate the size effect). Then let the rest of the soil samples pass through 10, 5, 2 sieve in turn, the corresponding particle group separate storage, test according to the design of the proportion. A suitable amount of soil samples with particle size <2 mm were configured as 10%, 15% or 20% target mass moisture content soil samples and smothered for 24h and set aside. Finally, gravel with 27% stone content was added and mixed well. The soil samples were prepared as shown in Figure 2.

Figure 2 Soil sample preparation

2.2 Test equipment

As shown in Figure 3,This test apparatus is divided into three parts: the soil column mould is made of three plexiglass tubes with an inner diameter of 15cm and a length of 12cm spliced together. One side of the glass tube is 3cm and 7cm from the top of the reserved holes for the installation of moisture sensors and substrate suction sensors; soil water content sensor and soil water potential sensor model CS-655 and 253-L, respectively, the data acquisition instrument model CR1000; the water supply system for the series-connected Marschall's bottle and rainfall sprinkler, drainage system for the upper plane of the soil column moulds and the lower part of the drainage holes.



(a) (b)

(c) (d) (e)

Figure 3 (a) Data acquisition system, (b) Mars bottle, the (c) 253-L soil water potential sensor, (d) CS-655 soil water content sensor, (e) rainfall nozzle

2.3 Test content

The aim of this test was to investigate the effect of non-homogeneous gravelly soils on the infiltration pattern, but it was too difficult to replicate soils with continuously varying water content and dry density in the field, so the soil columns were divided into three segments, with the physical properties of each segment remaining consistent. As a result, infiltration tests were carried out for the following conditions, with a uniform design rainfall intensity of 22 mm/h, rainfall until water flows out of the lower drainage holes or up to 8 h of rainfall, and a monitoring calendar of typically 12 h. The specific conditions of the soil column are shown in Table 1:

Table 1 Pilot programme table

programme	depths/cm	dry density g/cm3	moisture content/%
1	0-32	1.35	10
2	0-10	1.2	10
	10-22	1.35	10
	22-32	1.6	10
3	0-10	1.35	10
	10-22	1.35	15
	22-32	1.35	20
4	0-10	1.2	10
	10-22	1.35	15
	22-32	1.6	20

Scheme 1 is the control group; Scheme 2 keep 10% initial mass moisture content unchanged, let the dry density from bottom to top in order to reduce, specific for 1.6, 1.35 and 1.2 g/cm^3, respectively, through the control of different depths of the degree of compaction obtained; Scheme 3 keep 1.35 g/cm3 dry density unchanged, let the initial mass moisture content from bottom to top in order to reduce, specific for 0.1, 0.15 and 0.2, obtained by controlling the soil-water ratio during sample preparation; Scheme 4 changed the water content and dry density at the same time, while all the schemes left a 2 cm waterlogging space.

Rainfall conditions: Scenarios 1 and 2 end with 8h of continuous rainfall, Scenario 3 ends with 7h of continuous rainfall, Scenario 4 ends with 6h of continuous rainfall, and Scenario 5 has intermittent rainfall, with a 1h stoppage for every 2h of rainfall, and ends with 8h of net rainfall.

3 Test Results And Analyses

3.1 Basic Laws of Seepage

(1) The time-varying curves of water content and matrix suction can be divided into three stages, and the time of each stage coincides almost exactly, taking the sensor data at the depth of 14cm in Scheme 1 as an example: the soil body was in the first stage, i.e. the initial unchanged section, before 156min. At this time, the wet front did not arrive, the water content is almost unchanged, the matrix suction is unchanged or slowly increasing; the second stage is the rapid growth of the section, the wet front arrives, the water content increases rapidly to nearly the maximum, the matrix suction increases rapidly close to the maximum value; the third stage is the final stability of the section, the wet front continues to move downward, the water content grows slowly to the saturation or to reach the maximum value, if there is no subsequent rainfall replenishment, the water content will decline slowly and the matrix suction slowly climbs. If there is no subsequent rainfall recharge, the moisture content will slowly decrease, and the matrix suction slowly climbs to the maximum and then stabilises.

(2) According to the time-varying curve of water content and mechanism suction (Figure 4), take the root of its obvious change as the response time of the corresponding sensor. Programme 1, A1-A6 response time were 9, 50, 156, 207, 303 and 365min, A1A2 sensor response time difference of 41min less than the A3A4 sensor response time difference of 51min less than the A5A6 sensor response time difference of 62min, which and in the rainfall at the beginning of the soil body is drier seepage faster and with the infiltration of slower laws want to match. B1-B6 law is similar to the follow-up will not be described.

(3) The volumetric water content of the soil body in Scheme 1 is around 0.45, which is less than the saturated water content of 0.5. The reason for this is that the specimens of the soil-rock mixture are too large to be in the airtight condition, the seepage flow is always kept from high to low during the test and the bottom of the specimen is a permeable environment, so the test can't make the specimen completely saturated.The starting value of the measurement of the sensor of B1-B6 is around -175 kpa, which is influenced by the measurement range and accuracy of the sensor. The maximum substrate suction is around -15kpa due to the measurement range and accuracy of the sensor, and will not reach 0 or show a positive number even if rain continues to fall.

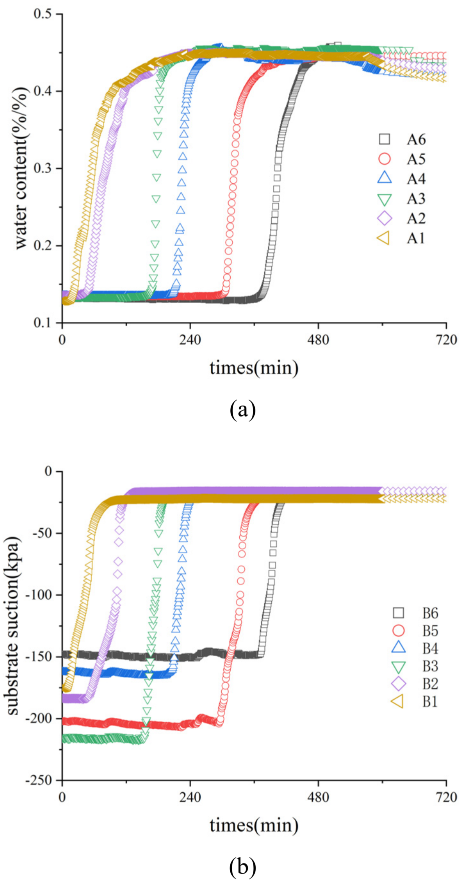
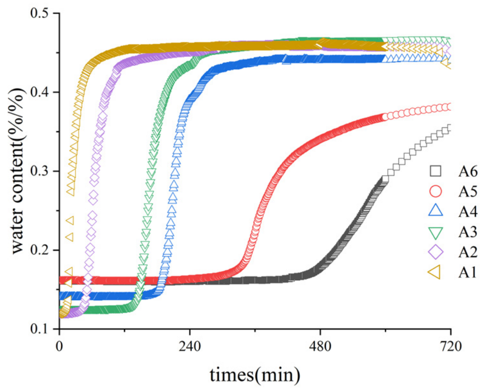
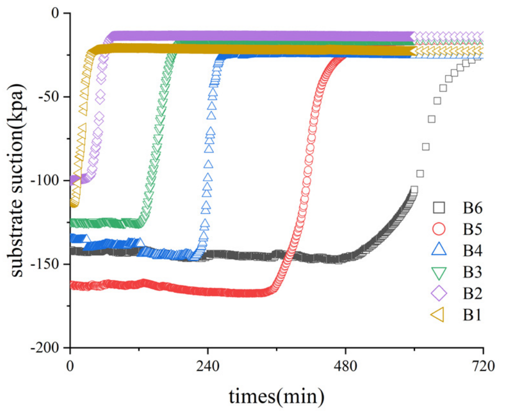


Figure 4 Scheme 1 (a) time-varying plot of volumetric water content, (b) time-varying plot of substrate suction

3.2 Seepage characteristics under stepped dry density conditions



(a)



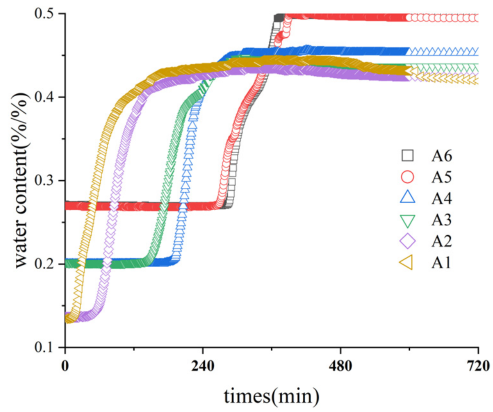
(b)

Figure 5 Scheme 2 (a) time-varying plot of volumetric water content, (b) time-varying plot of substrate suction

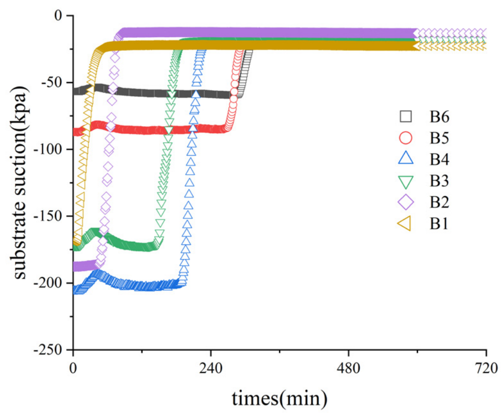
(1) As shown in Figure 5,A1-A6 response time were 9, 41, 131, 182, 329 and 466min, respectively, in the depth of 18cm before the programme 2 response time is earlier than the programme 1, because the specimen of the upper 10cm programme 2 dry density is less than programme 1, the middle 12cm programme 2 dry density is equal to the programme 1, the upper 22cm of the overall programme 2 dry density is smaller and therefore faster seepage. The total response time of scheme 2 is significantly larger than that of scheme 1 because the dry density of the lower 10cm scheme 2 is larger than that of scheme 1. The increase in dry density reduces the infiltration channel and narrows the cross section, which restricts the flow of water and greatly slows down the seepage rate.The response time difference of 32min for A1A2 is smaller than that of 51min for A3A4, and is much smaller than the response time difference of 137min for A5A6. This is another strong evidence that the increase of dry density will reduce the seepage velocity, and also shows that the increase of dry density and the slowing down of seepage velocity is not a linear relationship, which is similar to the exponential relationship.

(2) A1A2 maximum volumetric water content of about 0.46, much smaller than the saturated volumetric water content of 0.556, considering the upper layer of soil wetting brought about by seepage, the dry density of its deformation is about 1.35, the maximum volumetric water content of 0.5, the upper layer of the soil is close to saturated; A3A4 maximum volumetric water content of 0.465 and 0.445, respectively, the middle layer of the soil is close to saturated; A5A6 first 12h The maximum volumetric water contents were 0.38 and 0.355 respectively, but both were nearly saturated with a volumetric water content of 0.41 at 16h.

3.3 Seepage characteristics under stepped water content conditions



(a)



(b)

Figure 6 Scheme 3 (a) time-varying plot of volumetric water content, (b) time-varying plot of substrate suction

(1) As shown in Figure 6,The response times of A1-A6 are 10, 51, 148, 185, 267 and 284 min, respectively. Influenced by the initial state of the soil column, the response time of scheme 3A1A2 is approximate to that of scheme 1, whereas the response time of A3A4 is earlier than that of scheme 1, and the response time of A5A5 is even earlier than that of scheme 1, because the increase of the initial water content reduces the amount of water needed to reach the maximum, and the flow of water can be transported more quickly to the The response time difference of A1A2 is slightly larger than that of A3A4 by 41 min and 37 min, which is the result of the superposition of the decrease of infiltration rate

with the saturation of topsoil and the increase of seepage rate by the increase of initial water content, and the response time difference of A3A4 is larger than that of A5A6 by 17 min, which indicates that the latter's effect is larger than that of the former at this time.

(2) A1A2 from 0.135, A3A4 from 0.2, the maximum value of 0.44 or so, the upper and middle layers are always unsaturated seepage. A5A6 from 0.27 to the maximum value of 0.5, the soil body is saturated, presumably because of the mould of the lower part of the drainage holes of small caliber, and may be blocked by the migration of fine-grained soil, so that the rainfall below the column of the soil to pool, so the A5 in 0.45 and 0.475 Two stops make A6 reach the maximum before A5.

(3) The starting value of the B1-B4 sensors is smaller at around -175 kpa than that of the B5-B6 sensors at around -75 kpa, the latter approximating the substrate suction of the B3-B4 sensors at a moisture content of 0.27, with the seepage partially completed earlier.

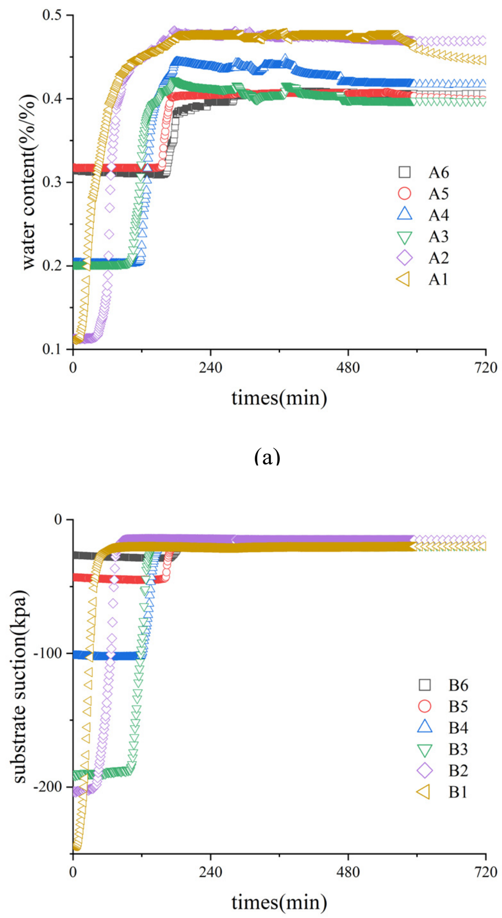
3.4 Seepage characteristics at stepped water content and dry density

(1) As shown in Figure 7,The response times of A1-A6 are 8, 38, 98, 114, 155 and 163 min, respectively, and the response times are getting faster and faster. the response time difference of 30 min for A1A2 is almost twice as much as the response time difference of 16 min for A3A4, while the response time difference of A3A4 is equal to two times as much as the response time difference of 8 min for A5A6, and the response speed of water content rate is nonlinearly increasing.

(2) It can be seen that A1A2 from 0.12, the maximum value are around 0.48, observed that the seepage makes the upper layer of wetting about 1.1cm, the maximum volumetric water content after wetting 0.5, the upper layer of the soil is nearly saturated; A3A4 from 0.2, the maximum of 0.44 and 0.42, respectively, the middle layer of the soil is always in the non-saturated; A5A6 from 0.32 to the maximum value of 0.41, saturated state is reached.

(3) B1-B6 initial value is increasing, B5B6 initial value is only -35kpa less than half of the initial value of B5B6 of Scheme 3, because its initial volumetric water content has reached 0.32, and saturation is 0.762 greater than that of Scheme 4 saturation 0.52, which is in line with the results of the research of the previous soil-water characteristic curve, namely, the substrate suction and the effective saturation is a non-linear relationship.

(4) The total response time of Scheme 4 is smaller than that of Scheme 1 and Scheme 3, on the one hand, the increase of initial water content shortens the response time, on the other hand, although the increase of dry density increases the response time, but the dry density of the upper layer of soil in Scheme 4 is smaller, and according to the results of the previous research, the closer the top layer of soil, the greater the influence on the overall seepage rate, and the combined result is that the response time of Scheme 4 is the shortest.



(b)

Figure 7 Scheme 4 (a) time-varying plot of volumetric water content, (b) time-varying plot of substrate suction

4 Calculation of Permeability Coefficient

4.1 calculation method

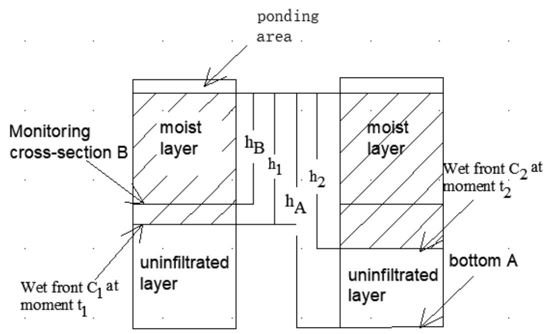


Figure 8 Wet front movement diagram

In this paper, the traditional wetting front advance method is extended to solve the unsaturated infiltration coefficient under waterlogged conditions. Fig. 8 shows the movement of the wetting front during rainfall infiltration, with B as the monitoring cross-section and A as the bottom surface, and the wetting front is located at C_1 and C_2, respectively, at moments t_1 to t_2. When the wetting front did not cross the bottom surface of the soil column, the flow rate through the monitoring cross-section B during the moments t_1 to t_2 was:

$$Q_B = \int_{h_B}^{h_A} \theta(h,t_2)Adh - \int_{h_N}^{h_A} \theta(h,t_1)Adh \quad (1)$$

Where: θ (h, t) is the volumetric water content distribution function of the vertical soil column, A is the cross-section area of the soil column, and h_B and h_A are the vertical distances of cross-section B and cross-section A from the infiltration surface, respectively.

It is assumed that the infiltrating front moves a distance of Δh , and that the volumetric water content distribution function θ(h, t) and the matrix suction distribution function ψ(h, t) are smooth for a smaller time $\Delta t = t_2 - t_1 = 10$ min. Eq. (1) can be deformed as:

$$Q_B = \frac{\left[\theta(h_B,t_2)+\theta(h_B,t_1)\right]A\Delta h - 2\theta_0 A\Delta h}{2} \quad (2)$$

Where: θ_0 is the initial volumetric water content of the vertical soil column.

Assuming that the permeability coefficient k of the unsaturated soil does not change during the time period Δt, according to Darcy's law

$$Q_B = \mathrm{k}iA\Delta t \quad (3)$$

Where: k is the coefficient of permeability of unsaturated soils; i is the hydraulic gradient and there are

$$i = \frac{dh + \frac{d\Psi}{r_w} + dH}{dh} = \frac{d\Psi}{r_w dh} + 1 + \frac{dHdt}{dtdh} = \frac{\Psi(h_B,t_1)-\Psi(h_B,t_2)}{r_w \Delta h} + 1 + \frac{v_j}{v_s} \quad (4)$$

Where: r_w is the heaviness of water, v_j is the velocity of ponding, and v_s is the speed of advance of the wetting front. At the beginning of the rainfall, there is no accumulation of water and at the end of the rainfall, when the depth of accumulation of water is fixed, v_j is 0. In order to simplify the operation of the middle of the rainfall, v_j/v_s is set as a constant a. Substitute the flow rate of Q_B, the hydraulic gradient i, and $v_s = \Delta h / \Delta t$ into the Darcy's Law Expression (3), and simplify the coefficient of infiltration of unsaturated soils to be:

$$k = \frac{Q_B}{iA\Delta t} = \frac{\left[\theta(h_B,t_1)+\theta(h_B,t_2)-2\theta_0\right] r_w v_s^2 \Delta t}{2\left[\Psi(h_B,t_1)-\Psi(h_B,t_2)+(1+a)r_w v_s \Delta t\right]} \quad (5)$$

4.2 Permeability coefficients under the influence of different factors

In Eq. (5), θ(h, t) and ψ(h, t) are obtained experimentally, v_s and v_j are converted from the recorded ponding moments and response times, θ_0 is obtained by converting the dry density to the water content, and S_e is obtained by converting the water content. r_w = 10kN/m3 and Δt = 10 minutes.

In scenario 2, v_s = 0.0644 cm/min and v_j = 0.025 cm/min, which are substituted into Equation 5 to obtain a plot of permeability coefficient versus saturation S_e for scenario 2 (Figure 9):

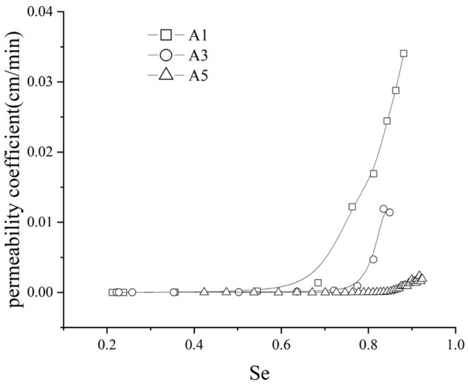


Figure 9 Scenario 2 permeability coefficient versus saturation plot

(1)The overall law of permeability coefficient and saturation degree is: when the saturation degree is lower than a certain value, the water flow is preferred to penetrate through the small pore space, and the small pore space is strong to water adsorption, resulting in water infiltration difficulties, the permeability coefficient is small and fluctuates up and down in a certain value. When the saturation degree is higher than a certain value, the small pore space is almost saturated, a large number of water flow through the large pore space infiltration, and the large pore space on the water adsorption is weak, so the permeability coefficient increases until the maximum, the value is defined as the limit value.

(2) Taking the positions 1, 3 and 5 of the scenario 2 sensors as cross sections, the cut-off values for each cross section are 0.6, 0.7 and 0.8, respectively, and it can be seen that the cut-off values increase with the increase in dry density. And the maximum permeability coefficient decreases rapidly with the increase of dry density.

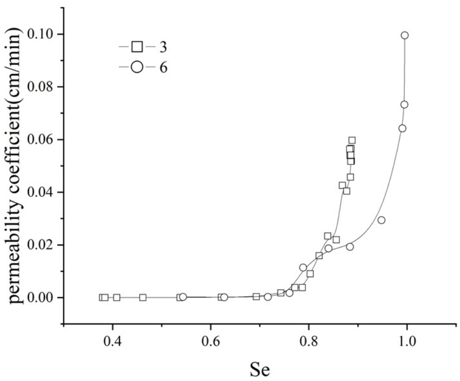


Figure 10 Scenario 3 permeability coefficient versus saturation plot

In scenario 3, v_s = 0.1056 cm/min and v_j = 0.032 cm/min, which are substituted into Equation 5 to obtain a plot of permeability coefficient versus saturation S_e for scenario 3 (Figure 10):

(3) Taking the cross sections at locations 3 and 6 of the sensor in Scheme 3, the cut-off values for both sections are 0.7, which shows that the initial moisture content does not have a significant effect on the cut-off values.

5 Conclusions

In this paper, a one-dimensional rainfall infiltration device, combined with a matrix suction sensor and a soil moisture sensor, was used to study the infiltration of gravelled soils in different initial states, and the following patterns were found:

(1) Natural soils tend to show an increase in dry density and water content along the direction of gravity under long-term gravity and repeated rainfall evaporation;

(2) The time-varying curves of water content and matrix suction can both be divided into three stages, and the time of each stage almost exactly coincides with the first stage, i.e., the initial invariant section. At this time, the wet front did not arrive, the water content is almost unchanged, the matrix suction is unchanged or slowly increasing; the second stage is the rapid growth of the section, the wet front arrives, the water content increases rapidly to nearly the maximum, the matrix suction increases rapidly close to the maximum value; the third stage is the final stability of the section, the wet front continues to move downward, the water content grows slowly to the saturation or to reach the maximum value, if there is no subsequent rainfall replenishment, the water content will decline slowly and the matrix suction slowly climbs. If there is no subsequent rainfall recharge, the moisture content will slowly decrease, and the matrix suction slowly climbs to the maximum and then stabilises.

(3) The increase in dry density reduces the infiltration channels and narrows the water cross section, limiting the flow of water and greatly slowing down the rate of seepage and lengthening the overall response time. The increase of initial water content reduces the amount of water needed to reach the maximum, and the water can be transported to the lower layer faster, which reduces the total response time. The response time is the shortest under the condition of stepped dry density and water content. On the one hand, the increase of initial water content shortens the response time, and on the other hand, although the increase of dry density increases the response time, the dry density of the upper soil layer of Scheme 4 is smaller, and according to the results of the previous research, the closer to the top of the soil layer, the more influence on the overall seepage velocity, and the combined result is that its response time is the shortest.

(4) The increase in dry density resulted in larger permeability coefficient cut-off values, and the initial moisture content had little effect on the cut-off values. At dry densities of 1.2, 1.35 and 1.6 g/cm^3, the soil cut-off values are 0.6, 0.7 and 0.8, respectively.

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