Influence of soil texture on the process of subsurface drainage in saturated-unsaturated zones

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Abstract: This study addressed the problem of low drainage efficiency or even no drainage in subsurface drainage systems buried in saturated-unsaturated zones above the water table. An indoor experiment on infiltration under ponded conditions in a homogeneous soil column was performed to study the effects of soil texture on the soil wetting front morphology, soil infiltration rate, drainage efficiency of the subsurface drainage pipe, vertical distribution of soil water content and salinity along the soil column. The results showed that the drainage process of subsurface drainage pipes above the water table was quite different from that of subsurface drainage pipes below the water table. When a subsurface drainage pipe was located in sandy soil, the migration of soil water toward the bottom of the drainage pipe was significant, and the water could not be discharged into the pipe. When the drainage pipe was located in loamy clay, the movement of soil water towards the bottom of the pipe was retarded, and the water could be discharged into the pipe. During the drainage process, the drainage of the pipe can produce nonequilibrium flow in the soil, and the continuity of the nonequilibrium flow can be affected by the hydraulic conductivity of the soil above the pipe, which can result in discontinuous drainage and low drainage efficiency. The water holding capacity, permeability and aeration of soil are important factors that affect the drainage under unsaturated conditions. Eliminating the hysteresis effect and capillary barrier around the drainage pipe and adjusting water holding capacity, the permeability and aeration of soil structure through a new subsurface drainage structure may enhance the drainage efficiency of subsurface drainage pipes in saturated-unsaturated zones.

Keywords: saturated-unsaturated zone, soil texture, subsurface, drainage pipe, groundwater level
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1 Introduction

With certain areas of saline-alkali soil farmland in Xinjiang were converted from surface irrigation to drip irrigation under film mulch, the supply of subsurface water provided by surface irrigation water was effectively controlled, and the volume of extracted groundwater increased with increasing drip irrigation area[1-3]. The groundwater level in the irrigation area dramatically decreased at that time, and the salinization of the farmland soil was effectively improved to a certain extent[4,5]. The designers and managers initially believed that the drip irrigation system alone would wash salt and alkali elements below the root systems without affecting crop growth. To improve the land-use efficiency and reduce the intensity of the management of the irrigation channels and drains, the drainage systems and channels of certain farmland were abandoned or filled to provide arable land. However, the drip irrigation system after several years of operation indicated that even if the groundwater is no longer a major factor affecting soil salinization, salt still accumulates in the soil rhizosphere of farmland without a drainage system and inhibits crop growth as a function of mechanical tillage, hydrogeology, and the characteristics of the drip irrigation[6-8]. Therefore, farmers and researchers began to reconsider the necessity of establishing drainage projects in drip-irrigated farmland. For this reason, certain regions reinstated water conveyance through abandoned channels during the non-irrigation season; before winter or spring sowing, water is transported through channels to the farmland for flood irrigation and salt discharge[9]. However, existing drip irrigation systems were used to leach salt from the farmland where the drainage ditches had been filled to produce cultivated land by increasing the drip flow rate and prolonging the water delivery time[10,11]. The irrigation control index of drip irrigation was not applied to drainage technology. To ensure that the excess water and salinity in the irrigated area are discharged outside the irrigated area, the managers of the irrigated area have attempted to bury drainage pipes in the lower part of the crop root zone and to drain the salt from the root zones of the crops to reduce the salinity of the drip-irrigated farmland.

Regarding the problem of salt accumulation due to a shallow water table, shallowly buried drainage pipes below the water table can effectively control drainage, and the relevant technical theories are relatively mature, with many successful examples[12-15]. Certain scholars have studied the saturated-unsaturated flow around drainage pipes caused by the lowering of the groundwater level[16,17]. However, the unsaturated zone studied by previous authors has been small, and the drainage pipes still have a significant hydraulic relationship with the saturated groundwater. Therefore, the effect of the unsaturated zone on the drainage process of drainage pipes is relatively weak. However, few studies have been conducted on drainage pipes that are buried near the root zones of crops and no

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significant hydraulic connection with the groundwater is found, which is a concern of irrigation zone managers. Li et al.[18] monitored the drainage conditions of an irrigation zone with a subsurface water level at a depth greater than 4 m, surface water 3-10 cm in depth, and drainage pipes 60 cm in depth and spaced 5 m apart. The authors studied the salt drainage from drainage pipes in cotton fields with drip irrigation under film mulch in Xinjiang and found that for farmland where the soil above the pipes was silt loam and the soil below the pipes was silt, the horizontal drainage capacity was low, and drainage in the vertical direction was significant. Although the soil around the drainage pipes was nearly saturated in late stages, the amount of water that could enter the pipe was still very small, accounting for only approximately 5.3% of the irrigation volume. Li et al.[18] believed that when the groundwater is very deep, the water from infiltration and leaching migrates mainly vertically due to gravity, and only the water within a limited range above the subsurface drainage pipe can transmit salt to the pipe. In addition, the permeability of the pipe wall may affect the drainage efficiency of the pipe. Stormont et al.[19] found that in a highway subgrade drainage project, when the subgrade was unsaturated, the use of a conventional subsurface drainage pipe structure could result in low efficiency drainage or no drainage. Stormont considered that if the permeability of the outer filter material around the subsurface drainage pipe is excessively high, there is no drainage in the pipe. Therefore, the saturated hydraulic conductivity cannot be used as the basis for designing a subsurface drainage structure under unsaturated conditions. Wang et al.[20] observed through field experiments that the drainage in subsurface drainage pipes shallowly buried in drip-irrigated fields was good when the water table was deeper than 4 m. However, this study did not show the distribution of soil water and salinity before and after drainage by drainage pipes and did not show discharge for drainage. Therefore, it was unclear whether the drainage was due to the rise of the water table caused by excessive irrigation or unsaturated conditions. It was also unclear whether the drainage efficiency and desalination efficiency in the farmland could have been the result of drainage in the drainage pipes or natural drainage in soil. These previous studies highlighted new problems encountered in the use of subsurface drainage systems in different projects, which further confirmed that there is a considerable difference between drainage under saturated-unsaturated conditions and drainage under the traditional complete saturation conditions.

The drainage process of a subsurface drainage pipe is a process of soil water absorption, dehumidification and ultimately drainage into the pipe. Whether soil water can be discharged from the soil is an essential condition determining whether soil water enters a subsurface pipe. Therefore, the soil around the drainage pipe is the main factor affecting the drainage process of the pipe. Under conditions with ponded infiltration and where there is no significant hydraulic connection between the drainage pipe and groundwater, the saturated-unsaturated soil environment formed by farmland often results in the surface saturated and the soil around the drainage pipe being unsaturated. Under unsaturated conditions, soil water cannot overcome the subsurface pipe inlet resistance and discharge into the pipe when there is insufficient water pressure head around the pipe. However, the research results of Li et al.[18] and Stormont et al.[19] showed that drainage pipe can discharge water in unsaturated soil, and there is room to improve the drainage efficiency. For how to adjust the efficiency, the characteristics of the migration of soil water and salt by infiltration to subsurface drainage pipes under saturated-unsaturated conditions should be studied and used as the basis for adjusting the drainage efficiency of drainage pipes. Few scholars have conducted detailed small-scale studies on the characteristics of soil water migration around subsurface drainage pipes under saturated-unsaturated conditions. The results of most studies at the field scale and watershed scale do not reflect the characteristics of soil water transport around subsurface pipes.

Therefore, the soil texture, a sensitive influencing factor, is the main subject of this research. To address the engineering problem of low drainage efficiency and even no drainage in the saturated-unsaturated area of farmland, soil column tests were conducted to observe the characteristics of soil water infiltration and drainage around pipes and distribution characteristics of water and salt before and after drainage when drainage pipes are buried in unsaturated zones. Based on the influence of soil texture on the drainage process of drainage pipes under unsaturated conditions, the causes and mechanism of low drainage efficiency of drainage pipes under unsaturated conditions were analyzed to provide an experimental basis for the structural design of adjusting the drainage efficiency of drainage pipes under unsaturated conditions.

2 Materials and methods

2.1 Soil properties

In this study, loamy clay and sandy loam with significantly different soil water hysteresis effects were selected as the test soils. The loamy clay was obtained from the topsoil (0-20 cm) of the sulfate saline-alkaline farmland in the experimental fields of Shihezi University (85°94′E, 44°27′N), with an initial soil salinity of 4.3% (g/kg) and an initial soil water content of 5.8% (mass ratio). The sandy soil was obtained from the aeolian sandy soil of the 150th Regiment of Shihezi (86°06′E, 45°06′N), with an initial salinity of 0.1% (g/kg) and an initial soil water content of 7.1%. After the soil samples were collected, the basic physicochemical properties were measured after rolling, crushing, air drying and sieving. The soil texture was analyzed using the sieving method and hydrometer method. The soil classification method was based on the ISRIC/FAO methods[21]. The water content, field capacity and saturated water content of the air-dried soil were measured using the cutting ring method.

The basic physical property parameters of the experimental soil are shown in Table 1. The soil water characteristic curves of T1, T2 and T3 soils at low suction are shown in Figure 1.

Table 1 Physical soil properties

Soil No.	Type of soil	Bulk density /g·cm^{-3}	Mechanical composition/%			Saturated water content/% (mass ratio)	Field capacity/% (mass ratio)	Saturated hydraulic conductivity /cm·d^{-1}
			Sand grains (2-0.02)	Silt particles (0.02-0.002)	Clay particles (0-0.002)			
T1	Loamy clay	1.45	28	29	43	43	28	9.02
T2	Loamy clay	1.33	28	29	43	45	26	17.15
T3	Sandy soil	1.45	85	9	6	34	20	1123.1

Note: Particle size is in millimeters.

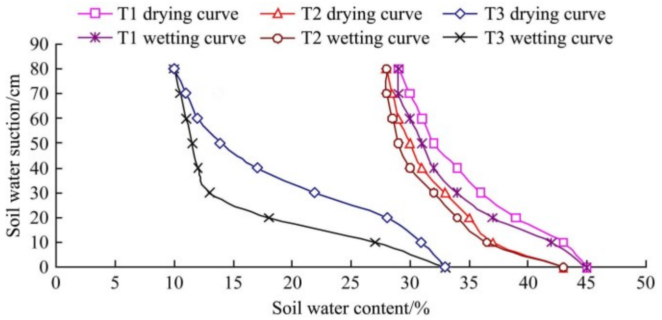


Figure 1 Soil water characteristic curve of each treatment

2.2 Experimental design

The test device is a cylindrical Plexiglas column with an impervious bottom. Each Plexiglas column has a height of 115 cm and an inner diameter of 20 cm. Porous PVC drainage pipes were installed along the depth direction of the variation in water content, at the depths of 30 cm, 50 cm and 70 cm, 90 cm. The open-hole percentage of the drainage pipe is 26% with an aperture diameter of 0.5 cm. The drainage pipe is covered with permeable nonwoven fabric, and there is no outer packaging material. For the convenience of soil sampling, 4 rows of sampling holes were uniformly set around the soil column at intervals of 10 cm with an aperture of 1.5 cm from the top of the soil column downward. In the tests, rubber stoppers were used to block the sampling holes. Figure 2 shows the test device.

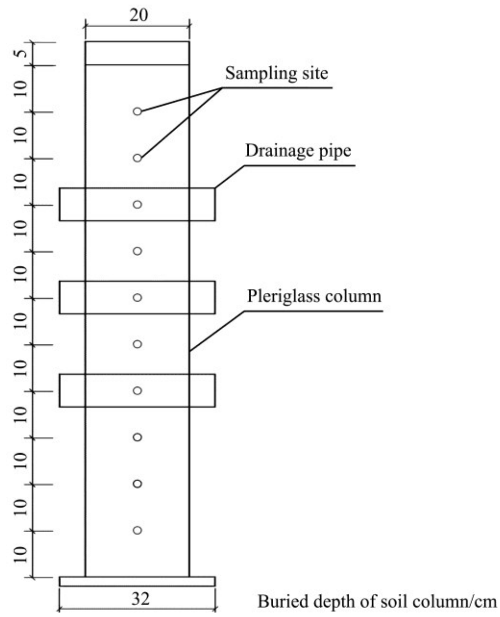


Figure 2 Experimental apparatus for soil column

The soil treatments were divided into three groups: T1, T2 and T3. Duplicates were set for each treatment, and the final data were average values of duplicates. Before loading the soil column, petroleum jelly was applied to the inner wall of the soil column to reduce the effects of the wall during the infiltration process. The soil was then loaded in layers according to the dry bulk density of each soil, 5 cm at a time. After the first layer was compacted, the surface was brushed and the next layer was loaded to ensure good contact between the upper and lower layers. The total filling height of the soil column was 110 cm. Pure water (conductivity of 0.005 mS/cm) was used in the experiment to conduct the gravity infiltration tests. Before draining the drainage pipes, the water infiltration head was maintained at 1-3 cm.

The three experimental groups were simultaneously and continuously irrigated. The time when apparent water drops reached the wall of the drainage pipe was used as the drainage time of the drainage pipes. The time of the pipes that draining firstly stop draining and the wetting front of the corresponding pipe restored stability were taken as the end of the corresponding experiment. If there was no drainage from the pipe, the moment when the wetting front reached the bottom of the soil column was taken as the end of the experiment. After the start of the test, the wetting front migration conditions of each soil column were regularly observed. The soil samples were collected from each sampling hole along with the vertical profile at the beginning and end of the subsurface drainage in order to analyze the distribution characteristics of the soil water and salt during the drainage period.

2.3 Methods

2.3.1 Measurement of soil water content

Many kinds of water salt dynamic detectors are affected by the high salt content in the test soil, which will cause measurement deviation. Therefore, the traditional drying method was used to measure soil water content. According to the test requirements, a 1.5 cm diameter small auger was used to obtain the soil samples from the soil column for weighing, and the samples were then placed in the oven at 105°C. After 24 h of drying, the samples were cooled to room temperature and weighed. The mass content was measured by the drying method:

$$\theta=(m_2-m_1)/(m_1-m_0)\times100\% \tag{1}$$

where, θ is the moisture content of the soil, %; m_0 is the mass of the aluminum box, g; m_1 is the combined mass of the dry soil and the aluminum box, g; m_2 is the combined mass of the wet soil and the aluminum box, g. The subsurface drainage volume was measured using a measuring bucket with a volume of 1000 mL.

2.3.2 Measurement of soil salinity

The soil salinity was measured using the residue drying method, and the electrical conductivity of the leachate was measured (soil-water ratio 1:5). The calibration equation for the soil conductivity and salinity is as follows:

$$S=0.00049EC-0.07729 \quad (R^2=0.99747) \tag{2}$$

where, S represents the soil salinity, %; EC represents the soil conductivity, μS/cm.

2.3.3 Measurement of relative rate of change of salt content in soil

The salinity at the end of each treatment was compared with the initial salinity. The relative rate of change in the salinity was ，calculated as follows:

$$\eta=(\omega_h-\omega_0)/\omega_0\times100\% \tag{3}$$

where, η is the rate of change of the salinity relative to the initial value, %; ω_h is the salinity at different depths at the end of the experiment, g/kg; ω_0 is the initial salinity, g/kg.

2.3.4 Measurement of wetting fronts

After the infiltration began, the wetting front was drawn on the Plexiglas soil column with a marker. The wetting fronts of the sandy soil columns with rapid infiltration were drawn once every 5-10 min and that of the loamy clay column with slow infiltration was drawn once every 2-6 h until the end of the experiment. At the end of the experiment, the wetting fronts were transcribed onto 1:1 coordinate paper and then scanned into a computer using a scanner to acquire a set of vector images corresponding to the spatial characteristics of the wetting front during infiltration.

$$\upsilon=\Delta h/\Delta t \tag{4}$$

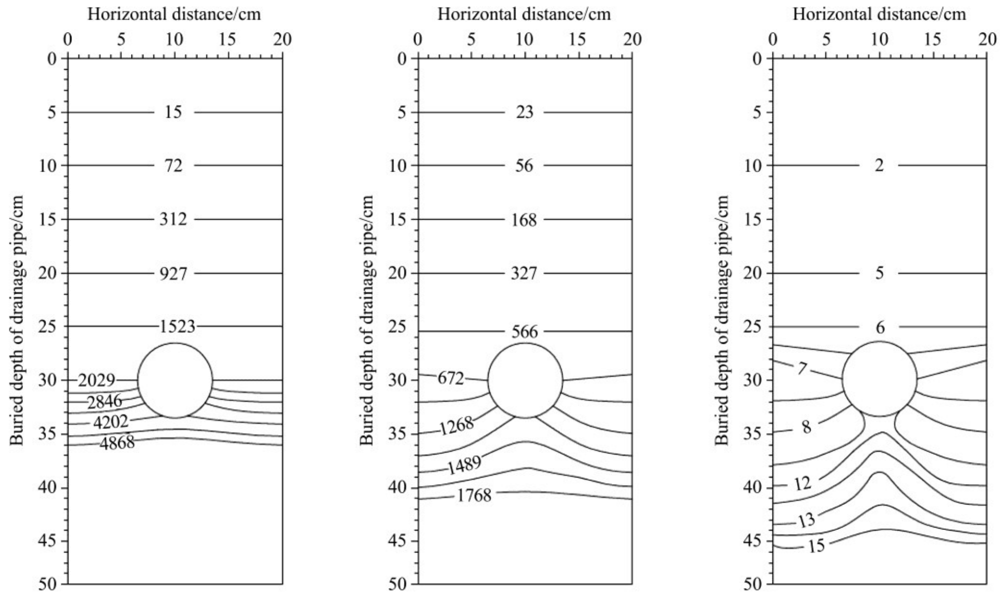
where, υ is the migration rate of wetting front, cm/h; Δh is the wetted front distance at the adjacent time, m; Δt is the time difference between adjacent times, h.

3 Results and discussion

3.1 Distribution characteristics of flow around the subsurface drainage pipe

As a heterogeneous boundary in the soil, the drainage pipe causes the wetting front to be dynamically unstable when water infiltration occurs, resulting in a non-uniform flow field with a relatively large difference in velocity. In addition, the distribution of the nonuniform flow field is different for different soil textures. The seepage field can reflect the convergence pattern of the flow of soil water into a drainage pipe; therefore, whether the seepage field formed by different soil materials is conducive to the drainage of a drainage pipe can be preliminarily determined.

In all the treatments except for T1, the wetting front of treatment T2, T3 exceeded a depth of 80 cm by the end of the experiment, while in T1 treatment the wetting front only moved to a depth of approximately 39.6 cm. At the start of the infiltration experiment, the wetting front of all the treatments above 25 cm depth was approximately horizontal and the soil water was evenly infiltrated. When the wetting front moved from 25 cm to 30 cm, the wetting front of treatment T2 had a trend of accelerating the migration above the drainage pipe to form a funnel-shaped wetting front, while the wetting front of T1 and T3 was still horizontal. As the wetting front moved below the drainage pipe at a depth of 30 cm, all the wetting fronts gradually changed from a horizontal straight line to a curve. With the extension of the infiltration, the wetting fronts on both sides of the drainage pipe overlapped until the wetting front gradually changed from a curve to a horizontal line. When the soil water moved below the drainage pipes at 50 cm and 70 cm, the wetting front had morphological features similar to those of the wetting front around the drainage pipe at 30 cm, and the morphological changed with unit time decreased as the depth of the drainage pipe increased. The pattern of the wetting front around the drainage pipe at 30 cm from each experimental treatment was typical, with the soil column surface as the starting position of infiltration and the wetting front moving to the center of the pipe at time 0. The time distributions of the flows around the drainage pipes are shown in Figure 3. During the entire process that the wetting front losing stability and restoring stability, there were no drainage phenomena in any drainage pipes, except for T1.



a. T1 treatment b. T2 treatment c. T3 treatment

Figure 3 Patterns of the flow of the wetting front around the drainage pipe (time unit: min)

Figure 3 shows that for treatment T1, the wetting front was deformed at 2029-4868 min. For this treatment, the amplitude of the wetting front deformation was 6 cm, the amplitude of the wetting front deformation per unit time was 0.002 cm/min, and the amplitude of the wetting front deformation was the smallest. For T3 treatment, the wetting front deformation occurred at 7-15 min, the amplitude of the wetting front deformation was 18 cm, the amplitude of the wetting front deformation per unit time was 1.2 cm/min, and the amplitude of the wetting front deformation was the largest. For T2 treatment, the wetting front deformation occurred at 672-1768 min, the amplitude of the wetting front deformation was 11 cm, and the amplitude of the wetting front deformation per unit time was 0.02 cm/min. According to the above experimental phenomena, the amplitude of the wetting front deformation per unit time of T3 is the largest and that of T1 is the smallest, while that of T2 is between the two treatments.

The converging pattern of the wet front to the pipe is similar to that of the flow line caused by head loss at the inlet of the pipe in the saturated condition. The characteristics of the wetting front migration around the drainage pipe indicated that it was difficult to form a continuous gradient field of water potential between soil and drainage pipe even if drainage pipes are also porous media as an internal boundary influencing factor. Therefore, soil water could not transmit to the drainage pipe immediately, but only bypass the drainage pipe and move to the lower part of the soil. This phenomenon was similar to the capillary barrier phenomenon. Capillary barrier originates in unsaturated conditions whenever a finer-grained soil lies upon a coarser-grained soil, which retards infiltration of soil water into coarser-grained soil due to capillary tension in the finer-grained soil. The lower coarser layer is nonconductive at high suction. Soil water in the finer-grained soil flows along with the interface until the water content and pressure in the finer soil reach a level sufficient to break the capillary barrier[22].

Compared with the tested soil, the drainage pipe is a macroporous medium; therefore, a similar flow pattern around the drainage pipe appeared in the experiment, and the soil texture affected the deformation range of the wetting front. For the same infiltration depth, the sandy soil with strong water vertical diffusion capability and weak horizontal diffusion capability was most affected by the drainage pipe boundary. The amplitude of the wetting front deformation per unit time was significant, and the migration of the soil water to the lower part of the drainage pipe was obvious, while the convergence to the drainage pipe was the weakest. Conversely, the loamy clay, with weak vertical water diffusion capacity, was relatively less affected by the drainage pipe boundary, and the amplitude of the wetting front deformation per unit time was relatively small. In particular, the loamy clays with a relatively high bulk density were less affected by the pipe boundary, the soil water migration to the soil below the drainage pipe was the weakest, and the confluence in the horizontal direction to the drainage pipe was more significant. The water repellency of UPVC drainage pipe material will aggravate this phenomenon.

3.2 Soil water infiltration

Analysis results based on a large amount of experimental data and field observation data showed that the air in the unsaturated zone significantly impacted the water infiltration process. After ponding, the increasing air pressure in the soil can decrease the hydraulic conductivity of the infiltration flow and reduce the infiltration rate[23-25]. Subsurface drainage pipes, as the escape pathways for air entrapment and water in soils, can exert different effects on soil water infiltration processes when the pipes are buried at different depths. In this study, the velocity of the wetting front was used to reflect the characteristics of the soil water infiltration rate.

Figure 4 shows that the wetting front of T1 only moved to 39.6 cm at the end of the test, while the wetting front of T2 only moved to 82.2 cm at the end of the test. The wetting front of T3 rapidly moved to the bottom of the soil column with a stable, linearly varying infiltration rate. The infiltration rates of T1 and T2 were relatively low, and the infiltration velocity of the wetting front decreased with increasing bulk density. Before the end of all infiltration experiments, except the pipe for the T1 treatment drained at the depth of 30, the pipe for T2 treatment at the depth of 70 cm drained, all other drainage pipes had no drainage.

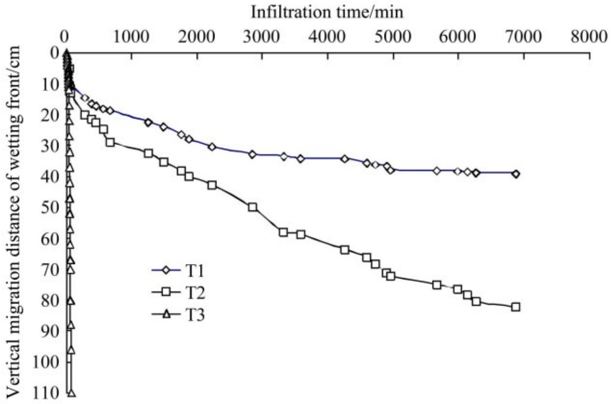


Figure 4 Wetting front movement curves of each treatment

It can also be seen from Figure 4 that the local acceleration trend of wet front appears at the 50 cm buried depth of T2, but other treatments have no obvious characteristics. Figure 5 can better reflect the characteristics of soil water migration rate around the drainage pipe. It can be seen from Figure 5 that the local acceleration trend of infiltration rate occurs at each buried place of concealed pipes. This pattern may be related to the discharge of air entrapment from soil by drainage pipes. These phenomena also occurred when the drainage pipe was buried below the groundwater level[26,27].

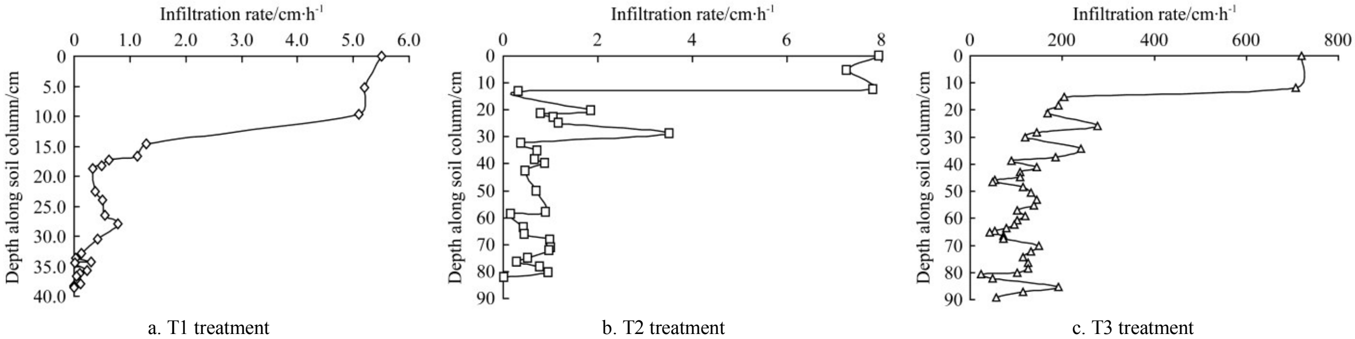


Figure 5 Infiltration rate of each treatment

According to the characteristics of accelerated infiltration of soil water around drainage pipes, it can be inferred that drainage pipes, as the boundary of porous media in saturated-unsaturated soils, can inhibit the discharge of soil water into buried pipes due to the capillary barrier. But they cannot prevent the discharge of retained gas from buried pipes. This exhaust function will promote the convergence of soil water to the drainage pipe. However, when the soil water accumulation around the drainage pipe is insufficient to destroy the capillary barrier, soil water will not be discharged into the drainage pipe.

3.3 Soil water discharge process

For T1 treatment, the wetting front reached 34.4 cm at 4202 min, free drainage from the top and side walls of the pipe at a depth of 30 cm occurred with the drainage flow of 0.3-0.8 L/h·m along the pipe. The drainage flow was unstable, and yellow salt crystals appeared at the bottom of the pipe but could not be discharged. At 4538 min, the draining of the pipe in T1 treatment stopped, and holes of the top and sidewalls in the pipe wall were blocked by yellow salt crystals. At 4868 min, the infiltration rate of the soil water in T1 soil column was low and the migration depth of the wetting front was almost constant. At the end of each experiment, the wetting front had not reached the second pipe.

For T2 treatment, the wetting front reached 82.2 cm at 6268 min. The pipe at a depth of 70 cm drained first, and the discharge along the drainage pipe was 0.5-1.8 L/h·m. The drainage flow rate was unstable, and only freely drained on the top and sidewalls of the pipe. Clear water drops were visible at the bottom wall but they could not be discharged. At 6880 min, the drainage of the pipe stopped, with a small number of yellow salt crystals on the pipe wall and no obvious blockage of the outlet hole, while the other two pipes did not drain.

For T3 treatment, the wetting front reached the bottom of the soil column at 135 min, and none of the pipes drained. If the soil was continuously irrigated, the drainage would start at the bottom of the drainage pipe. However, it was obvious that the drainage was due to the soil water reaching saturation at the bottom of the soil column and rapidly rising to the pipe. Therefore, under unsaturated conditions, there was no drainage in the pipes for T3 treatment.

The drainage process of drainage pipes is a process of soil water absorption, dehumidification and ultimately drainage into the pipe. Under unsaturated conditions, the soil around the drainage pipe is influenced by hysteresis; the matric suction of the dehumidification process is greater than that of the absorption process. And as a result, although hindered from draining out of the soil, soil water is more likely to migrate to deep soil under the action of matric suction without external force. Lighter soil leads to greater hysteresis and greater difference that the matric suction of the soil water has to overcome. Figure 2 shows that the hysteresis effect in T3 was the greatest, and the difference between the suction forces in the drying-wetting cycles in T3 was greater than those in T2 and T1. Therefore, T3 was the first to exhibit that the water could not be drained. While T1 and T2 were also affected by hysteresis, these samples could be drained, indicating that there were other factors affecting the drainage process of the drainage pipes.

Figure 4 shows that the change in the soil water infiltration rate was almost zero for the pipe 39.6 cm deep in T1 treatment and the pipe 82.2 cm deep in T2 treatment. According to the relationships among the water infiltration, the pressure in front of the wetting front, the soil infiltration rate, and the soil burial depth[28,29], the soil depth was inversely proportional to the pressure and infiltration rate. This indicated that deeper soil has greater residual pressure and lower infiltration rate. In the repeated treatment of this experiment, the micro differential pressure meter was used to measure the air pressure change in soil. However, it is difficult to determine the direction of air pressure migration in unsaturated soil, and accurate air pressure data could not be measured. Even so, it can be seen from Figure 3 and Figure 5 that the infiltration rate of the soil water around the pipe increases with the increase significantly, while that of the lower part of the pipeline decreases significantly. It can be inferred that the drainage pipe has the obvious function of exhausting and promoting soil water to converge into the pipe. But the effect of exhausting the air under the pipe is limited. Air entrapment will still accumulate in the wetting peak and prevent soil water from continuing to infiltrate.

Under this barrier effect, soil water holding capacity increased, which leads to the soil water gradually saturates near the drainage pipe. With the increased water content around the drainage pipe, the capillary barrier around the drainage pipe is destroyed and the hysteresis effect disappears. Soil water overcomes the resistance at the entrance of the pipe and is discharged into it under the action of gravity. Good aeration occurred at 30 cm and 50 cm in treatment T2 and at any depth in T3, which led to faster infiltration rates in the soil. Therefore, soil water is hindered from accumulating around the drainage pipe and cannot be drained from pipe.

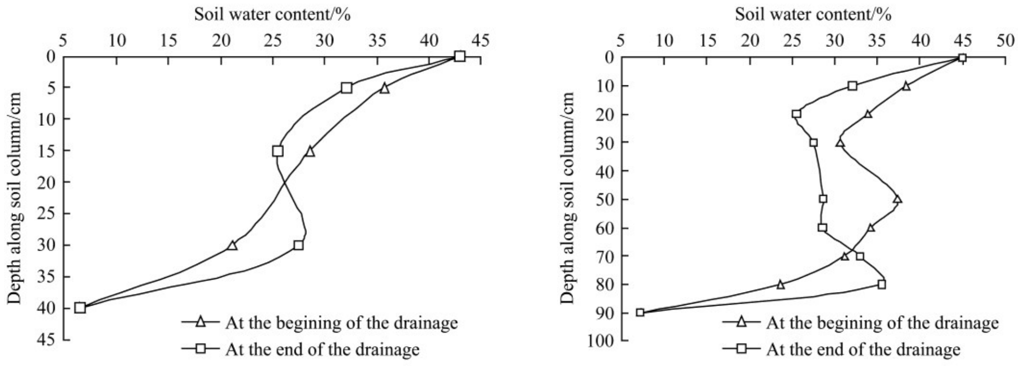
According to the characteristics of the drainage process, it can be inferred that structure with good water permeability and air permeability at the upper part and good water holding capacity at the lower part of the drainage pipe is more beneficial for drainage. Qin et al.[30] modified the outer envelope around drainage pipe to suppress bypass flow around the subsurface drainage pipe based on the infiltration characteristics of soil and found that this measure can improve the drainage efficiency of subsurface drainage pipe. Nie et al.[31] adjusted the air pressure of the soil around a drainage pipe by creating artificial large pores directly connected with the pipe, which induced the matrix flow around the pipe to migrate to the pipe and significantly increased the drainage efficiency These technical measures for adjusting the drainage efficiency of a drainage pipe to a certain extent verified the main factors affecting the drainage of subsurface drainage pipe under unsaturated conditions. However, these technical measures alone may not be sufficient and more engineering conditions and technical measures should be combined to design a reasonable drainage pipe.

3.4 Distribution of soil water content at the start and end of drainage

At the beginning and end of the discharge of the drainage pipes, samples were taken to analyze the distribution of the soil water content. During the entire experimental process, the pipe 30 cm in depth in T1 treatment, the pipe 70 cm in depth in T2 treatment, and the pipes in T3 treatment were drained in a saturated state; therefore, these samples were not analyzed. The characteristics of the soil salinity and water content were analyzed only in T1 and T2 treatments.

Figure 6 and Table 2 show that at the beginning and end of the drainage pipes in T1 and T2 treatments, the soil water content varied along the vertical direction of the soil column between the field capacity and saturated water content and exhibited significant fluctuations. Locally saturated zones around the pipes were not found. The drainage time of the pipe at the depth of 30 cm in T1 treatment was short. The holes in the top and side wall of the drainage pipe were blocked by salt crystalline hydrate in the soil, causing the soil moisture content after the drainage stopped to be higher than that before drainage, and the drainage pipe no longer drained. The drainage time of the pipe at the depth of 70 cm in T2 treatment was longer than that of T1. The soil water content above 70 cm is lower than that before drainage, and the soil water content below 70 cm is higher than that before drainage, which showed a nonequilibrium characteristic of preferential flow. This effect may be due to the low permeability of loamy clay above the pipes and the inability to replenish water to the drained soils in time, causing the intermittent drainage of the drainage pipes in the experiment. This result indicates that the drainage process under unsaturated conditions is a nonsteady discontinuous process, which differs from the drainage of drainage pipes under saturated conditions.

The water contents at a depth of 30 cm were all close to 30% for T1 and T2 treatments, and the drainage occurred at a depth of 30 cm for T1 treatment, but no drainage occurred for T2 treatment at the depth of 30 cm. The soil textures of T1 and T2 were the same, and the only difference was the bulk density, which caused the differences in the aeration and water-holding capacities of the two soils. Based on the relationship between the degree of soil compaction, soil water holding capacity and gas diffusion capacity, a lower soil compaction rate leads to weaker soil water holding capacity and stronger gas diffusion capability in the soil[32]. This characteristic will cause the soil water around the drainage pipe to infiltrate into the bottom of the drainage pipe quickly when the drainage pipe is in soil with lower bulk density, which will make it difficult for the soil water to accumulate around the drainage pipe and form a stable hydraulic pressure. Table 1, Figure 2 and Figure 3 show that T1 soil has a high soil density. For the same water content, the soil suction capacity and field water-holding capacity were both greater than those of T2, and the hydraulic conductivity was lower than that of T2. These characteristics make the soil water easily accumulated around the pipe in T1. In addition, the bulk density of T1 was relatively high and the air diffusion coefficient in the soil was lower than that of T2, making a higher air pressure accumulated at the corresponding soil depth. When sufficient air pressure potential was formed inside and outside of the drainage pipe, T1 soil drained more easily.



a. T1 treatment

b. T2 treatment

Figure 6 Distributions of soil water content in soil columns of T1 and T2 treatments at beginning of drainage and after drainage

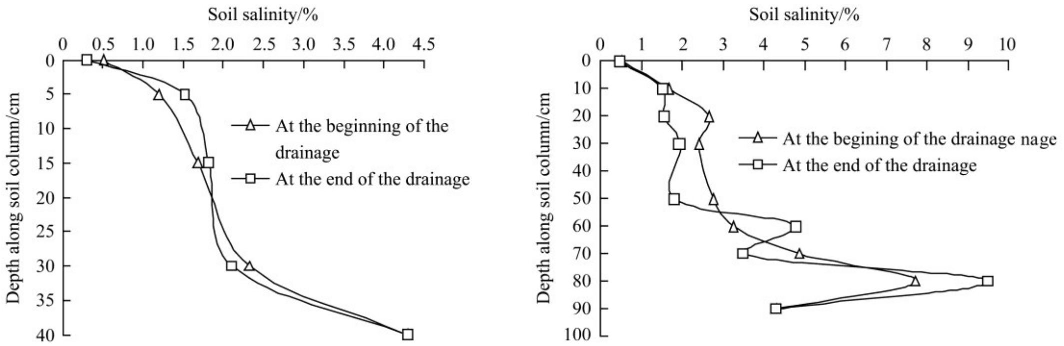
Table 2 Desalination rate at beginning of drainage and after drainage of T1 and T2 treatments (%)

Soil depth	Drainage period	0	10	20	30	40	50	70	80	90	100
T1 treatment	at the beginning of drainage	−93	−65	−65	−51	0	0	0	0	0	0
	After drainage	−93	−65	−58	−51	0	0	0	0	0	0
T2 treatment	at the beginning of drainage	−88	−61	−38	−44	−43	−36	−24	+13	+79	0
	After drainage	−89	−65	−64	−54	−56	−58	+11	−19	+121	0

Note: "−" indicates desalination; "+" indicates salt accumulation.

3.5 Distribution of the soil salinity at the beginning and end of the drainage

Figure 7 shows the soil salinity distribution at the beginning and end of the drainage for the pipe at 30 cm depth in T1 treatment and the pipe 70 cm in depth in T2 treatment. Compared with the background soil salinity, the two treatments generally had a higher desalination rate in the upper soil layer than in the lower layer soil. Above the drainage pipe and near the wetting front, the two treatments showed obvious salt accumulation. Salt accumulation at the wetting front is a common phenomenon, while the accumulation of salt above the drainage pipe is rare. This effect may be related to the composite interface formed by soil, drainage pipe, and atmosphere. When the pipes were drained, the converging capacity of the surrounding soil water to the drainage pipes increased and the accumulation of salt near the pipes also increased. However, with the weakening of the drainage process, both the soil water velocity and the soil water content decreased, and the salt that converged around the drainage pipe could not be discharged. When the salt accumulated around the pipe reached a certain extent, the salinity exceeded the solubility of the soil water, the salt was dissolved out and attached to the wall of the drainage pipes under evaporation. This was also proved by the fact that there was more yellow salt crystallized in the inner wall of the drainage pipes after the drainage of the drainage pipes stopped in T1 and T2 treatments.



a. T1 treatment

b. T2 treatment

Figure 7 Distributions of salt content in soil columns of T1 and T2 treatments at beginning of drainage and after drainage

With respect to the desalination rate, there was no significant difference in the desalination efficiency of T1 treatment before and after drainage at 0-40 cm, which indicated that the drainage efficiency of drainage pipes is low. In treatment T2 at 5.0-82.2 cm, the desalination efficiency before and after drainage varied considerably and exhibited nonlinear variation with fluctuations, which indicated that the drainage efficiency of drainage pipes was higher than that in T1 treatment. This finding indicated that the extent of the drainage process in T2 treatment was greater than that in T1 treatment with the soil column depth.

4 Conclusions

In this study, indoor experiments on water infiltration into thin-layered homogeneous soil columns were performed to simulate the effects of soil texture on the drainage of drainage pipes when the local surface is saturated and the lower part is unsaturated soil. The following conclusions can be drawn:

1) Under saturated-unsaturated conditions, there was a significant difference in the influences of different soil textures on the drainage process of drainage pipes. When the drainage pipe was located in sandy soil, the migration of soil water to the bottom of the pipe was significant and could not be discharged into the pipe; when the pipe was located in loamy clay, the movement of the soil water toward the bottom of the pipe was retarded. When the change in the infiltration rate in the corresponding soil layer approached zero, the pipe buried in the soil drained more easily. During the

drainage process, the drainage of the drainage pipe could generate nonequilibrium flow and the sustainability of the preferential drainage could be affected by the unsaturated characteristics of the upper portion of the drainage pipe, resulting in a discontinuous drainage process.

2) The drainage process of drainage pipes under saturated-unsaturated conditions was an unsteady flow process. Gravitational potential and pressure potential should be considered, and the effects of surface hysteresis, capillary barrier, air pressure potential on the drainage process, conversion of the unsaturated zone and saturated zone should also be included in the consideration. The water holding capacity and permeability of soil are two important factors that affect the drainage under unsaturated conditions.

3) The saturated hydraulic conductivity of soil can no longer be used as the basis for the design of drainage projects under saturated-unsaturated conditions. The new subsurface drainage structure under saturated-unsaturated conditions should start after adjusting water holding capacity, the permeability and aeration of soil structure, and eliminating the effect of capillary barrier and hysteresis effect of unsaturated soil water. Technical means should be used to inhibit the rapid vertical movement of soil water around the drainage pipe in order to reduce the bypass flow of soil water around the drainage pipe and aerate soil above the drainage pipe in order to horizontally converge to drainage pipes, which can help direct the soil water into the drainage pipe.

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