The impermeability effect of soil air on the ponding infiltration experiment of soil column

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Abstract. The agricultural flood irrigation in Jingyang South Platform, Shaanxi Province caused the rise of groundwater level, which induced a large number of loess landslides. The study of water movement in unsaturated loess under irrigation is the premise of revealing the mechanism of loess landslide. In this paper, the changes of matric suction, volume moisture content and air pressure with time at different depths of unsaturated undisturbed loess are measured by indoor soil column water infiltration test. Air pressure at each point of the soil rises to about 98 Pa in a short time after the test beginning, and keeps small fluctuation up and down during the test. At the end of the experiment, the air pressure at each point of the soil returns to zero in a short time after the upper water accumulation is eliminated. During the test, the change of infiltration rate has a significant corresponding relationship with the exhaust phenomenon at the top of the soil column, and the air resistance significantly reduces the infiltration rate of water.

1. Introduction
In recent years, the loess landslides triggered by agricultural irrigation in Jingyang South Platform, Shaanxi Province, seriously endanger people's lives and property safety[1-3]. The rise of groundwater level caused by flood irrigation is the precondition of landslide occurrence. Therefore, the study on the migration law of irrigation water in unsaturated yellow soil is the basis to reveal the mechanism of landslide[4].

The essence of water movement in unsaturated soil is the substitution of water and gas in soil porosity[5]. Under the condition of flood irrigation, soil air will be compressed because it cannot be discharged in time, which will affect the normal infiltration of water[6]. Powers[7] carried out water infiltration test on a closed sand soil column, and found that when the air pressure in the soil increased to a certain value, the infiltration process might stop. Weir et al.[8] believed that the closed bubbles in the conductive layer can significantly reduce the infiltration rate of rainwater. Through the analysis of water infiltration test of dry sand column, Wang et al. thought that the infiltration rate under closed air condition is much lower than that under exhaust condition[9]. Peck[10, 11] and Touma[12] et al. observed a similar phenomenon in their experiments. However, Touma[12] found that when the gas reaches a critical value and overflows the soil surface, the air pressure will stabilize at a critical value and form a continuous channel in the soil aquifer. Many scholars have studied the critical value of gas breaking through the soil surface. Youngs and Peck[13] thought that when the air pressure in the soil reaches the air entrance value, the gas begins to overflow. Touma et al.[14] recommended that the "breakthrough value" of air pressure should be the sum of the water pressure on the surface of the soil column and the air entrance value. Moreover, when the air pressure reaches the "breakthrough value", the air will
break through the upper relative saturated soil layer to release, and then the air pressure will stabilize at a "stable value". Grismer et al.\cite{6} found that the "breakthrough value" of air pressure is not the sum of the water pressure on the surface of the soil column and the air entrance value.

In this paper, the change of water content, matric suction and air pressure at different depths of the undisturbed soil column under the condition of ponding infiltration is analyzed in order to research the law of water movement, the variation and water blocking effect of air pressure.

2. Materials and Methods

2.1. Sampling of the undisturbed soil column
Jingyang South Platform is located in the south of Jinghe River. The platform surface is flat, and the side slope is high and steep. When sampling on site, the soil layer should be uniform without cracks. Then, a circular soil column with a slightly larger diameter than the designed one is excavated at the sampling point. Press the plexiglass column barrel slowly while cutting the soil around it. The height of the plexiglass column is 100cm, the inner diameter is 30cm and the outer diameter is 31cm. There are three rows of holes along the vertical direction, which are used to install moisture meter, tensiometer and barometer during the test. Finally, when the soil is completely filled with plexiglass column, the soil column is separated from the soil at the bottom of the column with a soil cutter, and the soil column unit is taken out manually. At the same time, in order to avoid the occurrence of preferential flow during the test, the inner wall of the plexiglass column should be evenly coated with Vaseline before sampling.

2.2. Experimental instruments and process
The soil in the test soil column is Q3 loess of Jingyang North Platform. The test device is mainly composed of soil column, water supply system, moisture meter, tensiometer, barometer and data acquisition instrument. CR3000 data acquisition instrument is used to collect the data of various sensors during the test. The tensiometer is mainly composed of three parts: negative pressure sensor, clay head and water adding device. The TDR-3 moisture meter is used to measure the soil moisture content in the test, which reflects the soil moisture state in the form of voltage signal. The larger the output voltage value, the higher the soil moisture content. The ponding infiltration experiment of the soil column was carried out according to the following steps:

![Figure 1 Diagram for ponding infiltration experiment](image)

(1) Cut 3 cm off from the top surface of the column to avoid disturbing the soil. The permeable stone and filter paper with the same diameter as the soil column are installed on the bottom surface of the soil column. The soil column is placed on the waterproof bottom plate. According to the positions shown in Figure 1, the moisture meters, tensiometers and barometers are installed at the reserved holes on the side of plexiglass column. After the installation of the instruments, the data was read by the computer. To ensure that the sensor data is valid, keep the initial state of the device for two days and
check whether the data is unstable.

(2) According to the diameter of the soil column, the water required for 1 cm design constant head is calculated and supplied at the beginning of the test. The water supply and drainage valves were opened simultaneously to maintain 1 cm constant water head. Start the measurement system and record the time at the beginning of the test and the corresponding initial value of each measurement. Observe the process of water infiltration and various phenomena during the experiment;

(3) The whole test process is divided into the following three stages: the first stage is the water infiltration process under the condition of sealing soil column bottom, which starts at 14:10 on October 29, 2017 and ends at 21:07, October 29, 2017, totaling 418 minutes; the second stage is to stop water supply and observe the redistribution process of water after the response of the third row of sensors is finished, starting at 21:08 on October 29, 2017 and ending at 6:59, November 13, 2017, totaling 9076 minutes; the third stage is to close the bottom valve and add water again when the water in the soil is relatively uniform, starting at 17:00 on November 13, 2017 and ending at 19:10, November 13, 2017, totaling 731 minutes.

3. Results and discussion

3.1. First stage of the experiment

Figure 2 (a) displays the air pressure changes at five depths of the soil column during the experiment. As shown in Figure 2 (b), the readings of all barometers rise to about 98 Pa three minutes after the start of the experiment. During the test, the gas pressure decreases with the release of air from the soil, and then increases until the next time the soil releases air. The air pressure kept fluctuating at 99.99pa. At the end of the first stage of the experiment, the water layer on the top of the soil column dissipated and the air pressure of the soil quickly disappeared (Figure 2 (c)). During the test, the air pressure values at different depths of soil are basically the same, which shows that the pore connectivity in soil is well, and the air in the soil is a whole.

![Figure 2 Variation of the air pressure in the soil column with time (Pa): (a) Total test process; (b) Beginning of the test; (c) Ending of the test](image-url)
The variation of matric suction at the depth of the first tensiometer in Figure 3 (a) can be divided into three stages: the stable stage before the wetting front reaches; the rapid decreasing stage after the wetting front arrives; and the stable stage when the matric suction tends to zero after the wetting front reaches a certain period of time. Comparing the matric suction of the first three tensiometers with time, it can be seen that the closer the sensor is to the surface, the faster the change of matrix suction will be when the wetting front arrives. According to Fig. 3 (b), the changes of water content at the depths of the first three moisture meters can be divided into three stages: stable stage, rapid rise stage and slow rise stage. During the test, the readings of the fourth and fifth tensiometers and moisture meter did not change, indicating that the wetting front did not reach its position in the first stage of the test.

![Figure 3 First step of the test: (a) Matric suction (kPa); (b) Volumetric water content (%)](image)

3.2. Second stage of the experiment
After the first stage of sealing water infiltration, the test entered the stage of soil water redistribution without ponding on the soil surface. As we can see from Figure 4, the state that the matric suction and water content of different depths are greatly different changes to the uniform state that the matric suction and moisture content are approximately equal during the second stage of the experiment.

![Figure 4 Second step of the test: (a) Matric suction (kPa); (b) Volumetric water content (%)](image)

3.3. Third stage of the experiment
The third stage of the test is to continue water infiltration under closed air condition after the soil water redistribution. The changes of matric suction and water content are shown in Figure 5. The reading of the fifth tensiometer shows that the bottom of the soil column is completely saturated at the end of the test, so the positive pressure appears. The second half of the fifth moisture meter rises first and then
decreases, which indicates that the soil is saturated and then collapsible, which leads to the decrease of porosity.

Figure 5 Third step of the test: (a) Matric suction (kPa); (b) Volumetric water content (%)

Figure 6 Variation of the air pressure during the test (Pa): (a) Total test process; (b) Beginning of the test; (c) First sensor

Figure 6 describes the change of air pressure during the third stage of the test. The variation of barometer readings is obviously different with that of the first stage of the experiment. Firstly, the rise of the barometer reading was significantly delayed at the beginning of the test, and the maximum
value was not as high as that of the first stage. In addition, a downward fluctuation appeared soon, instead of stabilizing to the maximum value. Secondly, the air pressure at the depth of the first layer sensor is the most unstable with three obvious oscillations. Moreover, the change is related to the change of volume water content, which may be caused by the collapse of soil and the change of soil structure under the condition of water infiltration. The last four barometers only experienced a long time fluctuation, and the pressure difference returned to stable.

Figure 7 Relationship between infiltration rate and time

Figure 7 illustrates that the infiltration rate fluctuates obviously with time, which is consistent with the phenomenon of continuous bubble overflow on the upper surface of soil layer during the test. It means that the air overflow hinders the infiltration of water and affects the infiltration rate of soil.

4. Conclusions
The main conclusions of this paper are as follows:

(1) Through the laboratory undisturbed loess soil column infiltration test, the change law of water content and matric suction at each observation point is obtained. At the beginning of irrigation infiltration, the initial water content is relatively small, and the volume water content increases rapidly. As the wetting front moves forward, the potential energy gradient between the subsoil and the upper soil layer decreases, and the migration speed of the wetting front also decreases obviously. The change curve of volumetric water content with time gradually becomes relatively straight.

(2) During the process of water infiltration under constant water head, the air pressure in the soil will increase due to the closure of the bottom of the soil column. Three minutes after the start of the test, the readings of all barometers increased to about 98pa. Then, with the intermittent discharge of air from the soil surface and the formation of channels, the readings of differential pressure gauges fluctuated slightly. The air pressure at each point is basically the same, which is mainly due to the good connectivity of the pores in the soil.

(3) When the water layer on the soil surface subsides, the air pressure in the soil disappears quickly. It can be seen from the variation of infiltration rate that the normal infiltration of water is hindered by the exhaust process from the surface of the soil column when the bottom of the soil column is sealed up.

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