Effect of cavity structure on the saving up and dissipation of moisture in loess soil

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Abstract: Technique of loess cavity structure is a kind of technology which can increase the seepage volume of rainfall water and prolong the storage time of water in the soil, but popularization and application of the technology needs theoretical support. This paper uses the method of combining indoor experiment to study the laws of water storage and evaporation dissipation in the loess soil with cavity structure under heavy rain. Results show that, vertical movement of moisture in the soil profile shows as hierarchy, and the cavity layer is the high water-holding-capacity zone; presence of the cavity structure retains more water in the soil body, reduces or prevents the water leakage to the deeper soil, and increases the water storage capacity of the loess soil by 4.7%; cavity structure can reduce the soil evaporation of 12.6%, and significantly inhibits soil evaporation. The study confirms the remarkable function of seepage improved and anti-evaporation of loess cavity structure technology, thus build a solid theoretical basis for the popularization and utilization of it.

1. Introduction
Precipitation in the arid and semi-arid loess plateau area of China is generally occurred in the summer from July to September, and as the form of heavy rain. So it is one of the effective ways to solve the agricultural water scarcity in this area by promoting the water accumulation in crops growing period, while reducing the evaporation of soil and deep leakage loss of water[1]. Scholars from Northwest A&F University proposed a new method, the loess cavity technology[2-4]. This technology makes full use of the characteristics of the solid vertical structure of the loess, using macro-blasting and expansion to make holes with about 30-40cm diameter, and furthermore to produce cavity layer in the loess at 60 to 90cm below the soil surface, its laying density is 1 per m². Thus the soil in the upper part of the cavity layer is loosened, and enhances more rainfall water permeate into the upper soil, at the same time to deduce the runoff losses. The soil in the lower part of the cavity is compacted, thus forms a relative aquifuge and water storage zone, which is of great significance to inhibit the subsurface soil moisture from rising along the capillary pipe to evaporate, and also prevent the water from leaking down into the deep soil. Thus the upper and lower soil and cavity layer jointly act to achieve the purpose of decrease evaporation and increase the water storage. Former experiment in the winter wheat land proved that after rainfall, the cavity structure in farmland can increase the soil moisture content and deduce the evaporation, and thus promote the increasing of crop yield[5]. The loess cavity structure technology has been proved one of the effective methods to make full use of precipitation resources and improve the utilization rate of it in the loess areas. However, the popularization and application of the technique has not been supported by effective theoretical research.
Uses seepage trough as main instrument, then simulate the process of precipitation seepage and soil moisture transportation in the loess while heavy rain occurs, therefore study the movement and dissipation law of water in unsaturated loess with cavity structure, then calculate the changing of soil moisture content, obtain the increased value of water storage and decreased value of water evaporation in cavity structure loess. To disclose the water accumulation efficiency of the unsaturated loess with cavity structure through effect infiltration, transport and dissipation of water. It has great theoretical and application value to clarify the water storage and water conservation capacity of the cavity structure loess, thus to promote the utilization level of precipitation resources in the arid and semi-arid loess area, and to improve the utilization safety of agricultural water.

2. Experimental Scheme

2.1. Instruments and materials

2.1.1. seepage trough: Main instrument in the experiment are two semi-cylindrical plexiglass seepage troughs with a diameter of 1m and a height of 1.6m. Small holes are drilled on the front and side of them to measure soil moisture content by insert the moisture sensor probe into them. Front surface of the trough is engraved with a coordinate square of 1×1cm, which makes it easy to observe the changing process of the wetting front in the profile and record the location data. In order to avoid the effect of gas phase resistance in the soil on soil moisture infiltration, an vent is opened at the bottom of the trough. Two seepage troughs undertake the tasks of control group (no cavity structure) and cavity loess experimental group respectively, jointly explore the law of the transportation and dissipation of cavity structure loess, also provide boundary conditions and parameter adjustment and verification basis for the further simulation of the moisture movement of the cavity loess and the dissipation model.

2.1.2. Soil Moisture Meter: Soil Moisture Meter FD-T is used in experiment, it measures the moisture content range from 0 to 100%, the accuracy of the moisture content is 0 below to 10%, 0.5% of 10 to 40%, 0.1% of 40 to 80%, the operating temperature is -5°C to 50°C, the response time is 1 second. The instrument has 20 gears and needs to be calibrated before use. Then, insert the probe into the soil body, adjust the different gears in turn, and record the values. The mass moisture content of the same soil sample to be measured by drying method, after calculation and conversion to volume water content, and the value of the different gears was compared to determine the soil moisture meter to measure the soil moisture content.

2.1.3. Physical properties of the experimental soil: The sample soil takes from farmland of Yangling, Shaanxi Province, China. The soil type is Lou-earth, its texture type is silt loam, in accordance with the classification criteria of the USDA, and with high homogeneity. The particle composition of soil is determined by density metering is show in table 1.

| Sample place                     | Soil type | Soil texture | Clay/% (<0.002 mm) | Silt/% (0.002-0.05 mm) | Sand/% (>0.05 mm) | volume-weight/ (g/cm⁻³) |
|---------------------------------|-----------|--------------|--------------------|------------------------|------------------|------------------------|
| Yangling, Shaanxi Province     | Lou-earth | Silt Loam    | 13.38              | 77.7                   | 8.92             | 1.25                   |
2.2. Experimental Designing

Figure 1. Seepage trough of cavity group      Figure 2. Seepage trough of control group

The loess is taken over through a dressing riddle of 5mm, then fill into the trough. To maintain the homogeneity, keep the soil particle free falling under gravity, thus simulate the accumulation process of natural loess. The filling height is 140cm. One of the trough is filled with two hemispherical baskets at 36cm below the surface, to simulate the cavity structure, whose diameter is 22cm. Two groups of troughs are shown in Figures 1 and 2.

Ponding infiltration method is used to simulate the heavy rain situation. According to China Meteorological Administration's definition of storm rain, storm rain refers to 50mm rainfall in 24h. After calculating the experimental conditions, at least 19.65L water should be pour into the trough in experiment. According to the previous experience, 30L of water can affect the soil depth of 60 to 80cm through seepage, so the ponding water volume is determined as 30L. In the experiment, effect of the cavity structure on water storage and dissipation is investigated by measuring soil moisture content at different times and locations by inserting the soil moisture meter into the observation hole. The soil depth of the observation area is 100 cm, with observation holes laid every 15cm according to gradients of 0-15, 15-30, 30-45, 45-60, 60-75cm. The position of the observation hole is shown in Figure 3, and the observation hole is numbered by row and column, such as 1-1, 1-2, 2-1 to 5-5.

At the beginning of the experiment, the wetting front moves faster, and the time interval of measurement observation is 10-15min. When movement rate of soil moisture slows down, the observing time interval extends to 30min. Continuous observation of soil moisture content changes and wetting front outlines at different times and locations, lays a consolidated foundation for comparative analysis of the spatial and temporal variation characteristics of moisture in the cavity loess, thus disclose the mechanism of how the cavity loess to regulate soil moisture, increase precipitation infiltration and inhibit soil surface evaporation.

Fig 3. The position of observation hole
3. Result and Discussion

3.1. Vertical change of soil moisture content
In experimental group, observation holes are set around the cavity (see figure 3), mainly used to obtain the moisture content of the loess soil, thus study the effect of the cavity to water movement. Observation holes are also available in the same location in the control group. The experiment was done from January 6th to 15th, 2019, and repeated from January 20th to 30th. When experiment begins, the initial moisture content of loess soil was measured as 11.3% and the indoor temperature was 20°C.

Figure 4 (a, b) shows that as water seeps downward, the moisture content of the middle 30-60cm increases rather rapidly, but at the deep soil, it increases slowly. Therefore, in the same time, the vertical change of moisture content on the soil profile reflects a nonuniformity character[6]. From 0-30 cm, the moisture content is significantly affected by precipitation, and increases rapidly; here the moisture content is most sensitive to simulated rainstorm conditions, so this zone can be called as Moisture Rapid Change Layer (MRCL). And zone of 30-60 cm for the soil middle layer, after rainfall soil moisture content changes significantly, the response to simulated rainstorms is faster, the lag time is short, can be called Moisture Active Layer (MAL). Below 60cm, the soil moisture content rise slowly, the response time to simulated storm also has a significant time lag, can be called Moisture Stabilization Layer (MSL).

![Figure 4. Change of soil water content with depth in cavity group (a) and control group(b)](image)

It can be see, in the process of water infiltration, the moisture content in 30-45cm in two group’s profile all higher than other depths, and it also changes rapidly (MAL), showing that this layer’s water holding ability is strong but unstably, especially in the cavity group[7]. The cavity is exactly located at 25-47cm of the profile, which overlaps with the area of this zone. It is evidently that the presence of cavity structure enhances the soil’s ability to store water.

3.2. Changing pattern of soil moisture content
From Fig.5, it can be see, after 2hr of the experiment, wetting front reaches to 30cm, initial soil moisture content value here changes to its maximum, but in a few hours, it decreased rapidly, and until the end of the experiment, this decreasing trend standing for. However, during this process, the water content of the cavity group is always greater than that of the control group, indicating that more water remains above the cavity zone. At the end of the experiment, moisture content of the cavity group is 31.3%, 1.8% higher than that of the control group, 29.5%.
Figure 5. Comparison of soil water content with time at depth 30 cm

Figure 6 shows that 13 hr later, the water affects to 45 cm, here the soil moisture content increases rapidly, at 57 hr, it reaches the largest value, 31.4% in the cavity group and 30.2% in the control group. Then, the soil moisture content decreases slowly. This result tell us, in the experiment, the moisture content of the cavity group always greater than that of the control group, and more water remains in the cavity zone. At the end of the experiment, the soil moisture content here is 29.8% of the cavity group, 1.4% higher than it in the control group, 28.4%.

Figure 6. Comparison of soil water content with time at 45 cm

Figure 7 shows that at depth 60 cm, which is far from the soil surface, and until 60 hr in cavity group and 80 hr in control group after the experiment beginning when the wetting front reach here. After this, the moisture content constantly increases. However, contrary to the upper soil, the moisture content of the control group here is always greater than that of the cavity group, indicating that more water seepage into the depth of the control group than in the cavity group, or, more water in the cavity group remained near the cavity zone but not seep down. At the end of the experiment, moisture content of the control group is 24.2%, the cavity group is 21.8%, and the moisture content difference is 2.4%, plus 20 hr late.

Figure 7. Comparison of soil water content with time at 60 cm
By observing and analyzing the moisture content in different depth, it can be included that the soil moisture content changes over time in different depth. Comparing the cavity group with the control group, the moisture content of the soil in the cavity group in 30cm and 45cm is higher than that of the control group in the same time, and the moisture content of the cavity zone was 1.9% higher than the control group on average. And at 60cm which below the cavity zone, the moisture content of the cavity group was 2.4% lower than that of the control group. In other words, in the process of seepage, the presence of the cavity causes the water to seep slowly through the cavity zone, and more water remains in the soil around the cavity. Overall, the existence of the cavity first accelerates the moisture seep into the cavity zone, then retains more water in the cavity zone, at the same time to hinder deep leakage. These are the embodiment of cavity structure plays a significant role for soil water storage.

3.3. Effect of cavity structure on water storage capacity

Effect of soil water storage can be further analyzed by soil water storage capacity, soil water storage formula[8] is as follows:

\[ S_i = \theta_i h_i \]  
(1)

\[ S = \sum_{i=1}^{n} S_i \]  
(2)

Here: \( S_i \) is the soil water storage of each layer, mm, and \( \theta_i \) is the soil volume water content, \( h_i \) is each layer’s thickness, in this experiment, it is 15cm; \( S \) is the total water storage, mm; \( n \) is the number of soil stratification serial.

Figure 8 shows the soil water storage in different depths of cavity group and control group when experiment finished. The total initial water storage of 0-75cm is 84.75mm, at the end of the experiment, this value is, 188.1mm in cavity group, and 186.75 mm in control group. At different depth, compare to initial value, average soil water storage increasing of cavity group and control group, 0-15cm is 2.44 times ,30-45cm, 2.58 times, 45-60cm, 2.04 times, and 60-75cm it is 1.31 times. Increasing rate of 0-45cm is significantly greater than 45-75cm. Soil water storage in 0-45cm occupy an average of 69.75 percent of the total water storage, and it can be seen that most of the water is stored in the MRCL and MAL, which can provide water for crop growth continuously.

It also can be see that the soil water storage in 0-45cm in the cavity group is higher than that of the control group, while the soil water storage in 45-75cm cavity group is lower than that of the control group. The cavity zone is located at 25-47cm, the presence of the cavity structure slows down the velocity of water movement, so that more moisture remains in the cavity zone and the upper soil, reducing the water’s deep seepage. The water in the cavity group in 0-45cm is 133.65 mm, and the corresponding value of the control group is 127.65 mm, that means 6 mm water storage in the cavity
group and 4.7% increasing in soil water storage capacity. It can be seen that the cavity structure improve the soil water storage capacity evidently.

3.4. Effect of cavity structure to moisture dissipation

Evaporation of soil moisture is an important way of water losses in farmland, and inhibiting evaporation becomes a key technical goal for efficient agricultural water utilization in arid and semi-arid areas. A large number of studies have been carried out on how to inhibit soil evaporation, among which, the most common method is mulching, which is widely used in the actual agricultural production[9]. The cavity structure technology reduces the evaporation of soil moisture by changing the upward motion channel of deep soil water. In this paper, the inhibition of cavity structure to soil moisture evaporation and dissipation is discussed by means of experimental simulation. The seepage trough is located indoors, so open the door and windows and fans for ventilation, the experimental date is July 14, 2019 to September 12, 2019, 60 days in total. This time, the initial moisture content of the experimental soil is higher than the former experiment. So the wetting front movement speed is faster, and the final depth of wetting front is greater than the experimental done in January 2019. This is because the initial water content of the soil is higher, so the soil moisture content reaches saturation or near saturation state more quickly, capillary water and gravity water in the soil can move freely, prompting the wetting front to move downward, and ultimately the depth of the wetting front is also deeper[10].

When seepage experiment start, the evaporation of soil moisture also begin to occur. When wetting front move down, there is also a part of the moisture evaporate out of the soil surface [11]. That means, the decrease of soil moisture is partly due to soil evaporation and other due to seepage. In order to eliminate the effect of water seepage on the changing of moisture content, after the ponding water disappeared completely, put the instrument stand for 72 hours, so that the water in the soil could fully redistributed. After that, observation on soil moisture evaporation begins to do.

![Figure 9. Comparison of soil moisture evaporation intensity](image)

Figure 9 shows that the evaporation intensity is greater when soil moisture content is higher, and with the decrease of soil moisture content, the evaporation intensity decreases rapidly. After 10-20 days of the experiment, the surface of the experimental soil gradually formed a dry soil zone, soil moisture evaporation entre the stage of diffusion, at this time, gaseous water from the deep soil moisture vaporization diffusion to the atmosphere through the soil pores, soil’s capacity of evaporation is low. It seems that when soil has sufficient water content, the evaporation intensity of the control group will keep higher than cavity group, when dry soil zone forms gradually, the evaporation intensity becomes lower and shows an almost similar decreasing character in two groups.

In depth of 30cm, where is above the cavity zone, the change of the soil evaporation intensity is more consistent (Figure 10-a), whether in cavity group or in control group. But figure 10-b tell another story on depth of 45cm, where the soil evaporation intensity of the control group is veritably greater than that of the cavity group. Depth 60cm and 75cm are below the cavity zone, and here, the soil evaporation intensity of control groups are greater than that cavity groups (Figure 10-c, Figure 10-d).
In summary, in the process of water evaporation, the cavity structure has little effect on it above the cavity zone, but mainly affecting the soil evaporation intensity in the lower position of the cavity zone. Presence of cavity structure reduces the evaporation intensity of the soil on and below the cavity zone, thus to reduce the moisture losses and retain more water in the soil for a rather long time. In the evaporation process, the principle of the cavity structure inhibits soil evaporation comes from that the cavity structure breaks the whole structure of the soil, blocks a part of the water rise along the capillary pipe, the water’s rising channel is reduced, the soil evaporation under the cavity is also reduced, so more water will be stored in the soil. Volume of evaporation can be calculated by using the water balance equation[12]:

\[
ET = P - R + (S_i - S_f)
\]  

Here \(ET\) is the actual evaporation (mm) during the experiment; \(P\) is the simulated precipitation (mm) in the course of the experimental; \(R\) is the rainfall yield (mm), because the soil surface is lower than the seepage channel wall, all rainfall can seepage, precipitation runoff can be ignored; \(Si\) and \(Sf\) is the initial and final total water storage (mm) in the soil loess before and after the experiment.

According to formula 3, during the 60-day experimental observation period, the cumulative evaporation of the cavity group is 37.45 mm, and the cumulative evaporation of the control group is 42.85 mm, 5.4 mm more than the cavity group, this means that the presence of cavity structure reduce the evaporation of soil moisture by 12.6%, and the cavity structure had a significant effect on inhibiting soil moisture evaporation.

4. Conclusion
This paper takes soil moisture content change as the parameter, focuses on the effect of cavity structure on soil moisture storage and dissipation, and obtains the following main conclusions:
The vertical movement of moisture in the loess profile reflects the hierarchy, depth 0-30 cm is the soil moisture velocity change zone, the rainfall response is most sensitive to simulated rainstorm conditions; depth 30-60 cm is soil moisture active layer, after rainfall, the soil moisture content changes significantly; while depth below 60 cm is the soil moisture stable layer, here the moisture content changes little, and rises slowly, its response to simulated rainstorm has obvious time lag. Among them, the cavity loess at the depth of 30 to 45 cm has high water content, good water holding capacity, and is the zone of high water holding capacity.

2. The soil moisture content of the cave cavity group in depth of 30 cm and 45 cm is higher than that of the control group, and the soil moisture content of the cavity zone was 1.9% higher than the control group on average. At 60 cm under the cavity zone, the soil moisture content of the cavity group was 2.4% lower than that of the control group. The presence of cavity structure accelerates the water seepage in the upper soil, stores more water in the cavity zone, and reduces its leakage to deep soil. It can increase soil water storage capacity by 4.7%.

3. Existence of the cavity structure reduces the evaporation intensity of the soil below the cavity, so more water is retained in the soil. At the end of the evaporation experiment, the cavity group evaporated 5.4 mm less than the control group, means to reduce the evaporation of soil moisture by 12.6%, and the cavity structure had a significant effect on soil evaporation.

Acknowledgements
We thank to Dr. Xianwen Li for assistance with relative HYDRUS imitation work. The research was supported by a National Natural Science Foundation of China (51179160).

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