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Influence of irrigation method on the infiltration in loess: field study in the Loess Plateau

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ABSTRACT

It is well known that loess soils are collapsible upon wetting, and subsidence or cracking or failure of structures induced by loess collapsing poses serious threat to human being. Wetting is the most important prerequisite for loess collapsing; however, how the irrigation water, both man-made and natural, infiltrates and flows in loess is not well known. For this reason, a field soaking test simulating flooding irrigation method and a rainfall infiltration test simulating dripping irrigation method were conducted in instrumented sites in the Loess Plateau. This paper presents the results from soil water meters to reveal the infiltration process in loess based on the soil water content variations. The results highlight the significance of the preferential flows when a large amount of water is irrigated to the soils (flooding irrigation). Owning to the presence of preferential paths, the water infiltrates from both shallower and greater depths to the intermediate depths, as a result, bell-shaped zone of wetting and saturated zone are developed in the soils. However, the influence of environmental factors is of dominance when the amount of irrigation water is very small (precipitation). The rain water, pore water, and water vapor transform from one to another depending on the rates of precipitation and evaporation as well as soil properties. For this reason, the maximum depth of the wetting front measured in a drought year was less than 3 m. The test results provide valuable information for interpreting the infiltration of water in loess with respect to varying irrigation method, soil heterogeneity, and environmental factors. However, such information is required for modeling the wetting-induced collapse of loess and analyzing the stability of structures built on loess.

Keywords: Loess; Irrigation method; Field soaking test; Rainfall infiltration test; Preferential paths; Water content variation; Collapse settlement; Environmental factors

1. Introduction

Loess soils are widely distributed in arid and semi-arid regions around the world, including countries such as China, Russia, and the United States [1–4]. Loess soils are typically a kind of clayey silt with an open structure, generally in a state of unsaturated condition and collapsible upon wetting. Holtz and Hilf [5] described the collapse as the result of capillary pressure approaching zero and the degree of saturation increasing to 100%. Burland [6] suggested that due to wetting, the negative pore water pressure at the inter-particle contacts decreases, leading to grain slippage and distortion. Barden et al. [7] proposed the conditions for soil collapsing including: (1) an open, partially saturated, and potentially metastable structure; such an open structure is characterized by a random particle arrangement, high porosity and significant amount of macro pores; (2) a high enough applied stress; (3) a high enough matric suction or other bonding agents to stabilize the structure when dry; and (4) the addition of water to reduce the matric suction or slake the bonding between particles. Alonso et al. [8] described the collapse as the result of stress state reaching the yielding surface due to wetting or loading or both.

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Fredlund and Gan [9] described the collapse as the failure of soil structure as the result of loss of shear strength due to matric suction decrease. Wang and Gu [10] and Wang et al. [11] submitted a mechanism for self-load collapsibility that saturated loess liquefaction caused by Earth micro-tremors and studied the influence factors of loess collapsibility. Wen and Yan [12] stated that unlike compacted soils in which matric suction contributes much to maintain the structural stability when dry, in naturally deposited loess soils clays and paurocrystalline carbonates exist as cementing materials for large-grained particles, these cementations are water sensitive and their failure upon wetting thus leads to grain slippage and rearrangement.

Not only ground subsidence induced by collapse but collapse-associated geological problems such as cracking of ground floor slabs, failure and erosion of slopes can bring intolerable damages to the structures built on or in collapsible loess especially with the recent infrastructure development in arid and semi-arid regions accompanied by the use of large amounts of water. The sources of water can be either natural, such as rainfall and fluctuation in groundwater table, or man-made, such as excessive irrigation (i.e., constant flooding method) and leakages of water or sewer pipelines [13–15]. The collapse of soils due to wetting may result in ground subsidence as much as 2%–6% of their thickness [16,17]. In Heifangtai loess platform of China, great ground settlements, cracks, depressions, sinkholes, and caves have been commonly seen since the settlement of several thousands of immigrants there and the start of irrigation projects by lifting the Yellow River water in 1960s [18,19], see Fig. 1. As per the previous investigation by the authors, the ground settlement as the result of loess collapsing in the irrigation region extending an area of about 14 km^2 could reach as large as 5 m for 30 years since the irrigation projects were used, and one more meter to the maximum ground settlement in the following 10 years [20,21]. The problem of loess collapsing due to irrigation was also met in Jingyang loess platform of China [22], as serious as that in Heifangtai platform.

In summary, the infiltration of water is the most important prerequisite for loess collapsing. However, how the irrigation water, both man-made and natural (i.e., flooding and rainfall), infiltrates and flows in loess with varying irrigation method, soil heterogeneity and environmental factors is not well known. The infiltration and soil–atmosphere interaction in various types of soils were investigated commonly using artificial rainfall test or column test or numerical modeling [23–26]. Li et al. [27] revealed the rainfall infiltration process based on a full-scale field test in a saprolite slope. The variation of volumetric water contents in the soil indicates that the maximum wetting front during the rainy reason was limited to the top 3 m, and a transient perched water table could develop in the soil during a round of very heavy rain. A full-scale field test was conducted by Zhan et al. [28] in a grassed expansive soil slope. The results indicate that the presence of grass significantly increased the infiltration rate and reduced the surface runoff; the cracks and fissures developed in the soil played an important role in the hydrological process. The results of an artificial rainfall test in the Loess Plateau show that the influenced depth of rainfall infiltration was 0–2 m in a drought year and 0–3 m in a rainy year (with the annual precipitation of 460 and 850 mm, respectively) [29,30]. The study by Gvirtzman et al. [31] suggests that the advancement of the wetting front was hampered due to the alternating silty-sand and sandy-clay loess layers, and above-hydrostatic pressure is developed within intermediate saturated layers, which enhances the wetting front advancement. The results of a full-scale field test conducted in a loess cut slope by Tu et al. [32] show that the depth of wetting front during the rainy season was within the top 2 m, while it could reach about 3 m under very high rainfall intensity, that is, 120 mm/d. The results of a field test in a cover which consists of a 0.9 m-thick compacted loess underlain by a gravel layer conducted by Zhan et al. [33] suggest that the preferential flows took place in compacted loess during the rainfall; as a result, the maximum water storage capacity was not reached at the onset of percolation. Vegetation had insignificant influence on the water storage capacity of the soil. In summary, few studies differentiated the infiltration in loess in terms of irrigation method also paid attention to the influence of environmental factors on the flow behavior of loess [34–37]. In this study, the results of two field tests representing different irrigation methods (i.e., flooding and dripping) are presented, that is, field soaking test and

Fig. 1. (a) Flooding irrigation in summer; (b) sinkholes and (c) caves induced by loess collapsing in Heifangtai loess platform.

rainfall test. In both tests, soil water meters were used to measure the soil water content changes, upon which the infiltration in loess was interpreted. The collapse settlements both on the ground and in the deep were also measured in the soaking test. The influence of environmental factors was considered in the rainfall infiltration test because there was a very little amount of irrigation water (precipitation). The results of both tests provide valuable information for interpreting the infiltration in loess with respect to varying irrigation method, soil heterogeneity, and environmental factors. Such information is required when modeling the collapse of loess due to wetting as well as analyzing the stability of structures on loess.

2. Field soaking test

2.1. Site description

To investigate the infiltration of water as well as the collapse behavior in loess soils when traditional constant flooding method is used, a field soaking test was carried out in Qingcheng County, Qingyang, China. The geographical location is seen in Fig. 2. The soil profile at the test site consists of two main strata: Q_3 loess (deposited in the late Pleistocene, above a depth below the ground level of 9 m) and Q_2 loess (middle Pleistocene, below a depth of 11 m to the maximum depth of investigation, i.e., 22 m); a paleosol layer was sandwiched between Q_3 and Q_2 loess, that is, from 9 to 11 m. Paleosol soil deposited during wet and warm period typically has red-brown color and closer structure that loess soil which deposited in dry and cold period. Physical properties including dry density, ρ_d; water content, w; liquid limit, w_L; and plastic limit, w_p of the soils determined in the laboratory after extraction of intact block samples at each meter at the site are summarized in Fig. 3. It can be seen that the natural water content increases with the depth; the void ratio varies between 1.004 and 1.188; both the liquid and plastic limits show small variations with the depth. Therefore, the soil is relative homogenous within each layer in Qingcheng site. As per the results of oedometer collapse tests, all the loess soils investigated are collapsible upon wetting, meaning that considerable collapse settlement, greater than 0.015 times of the specimen height, was observed under a low vertical pressure of 200 or 300 kPa; the loess soils above a depth of 17 m are collapsible with the self-weight. The groundwater table is at a depth more than 120 m, and the annual precipitation of Qingcheng County is about 500 mm.

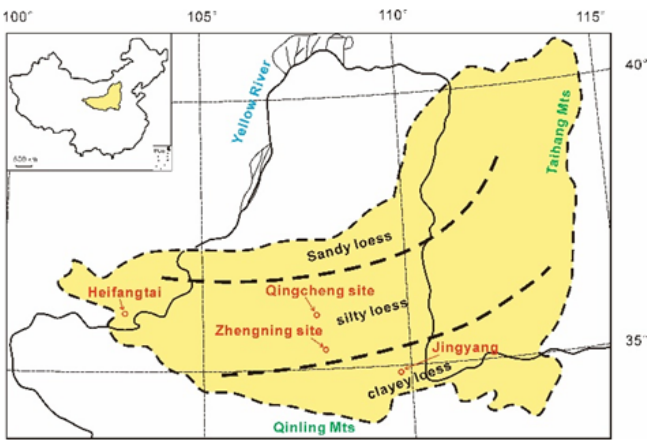

Fig. 2. Test sites on the Loess Plateau of China.

2.2. Test design

A test pit of 20 m in diameter which is greater than the buried depth of self-weight collapsible loess soils and 80 cm in depth was prepared, see Fig. 4. At the bottom of the pit, 30-cm-thick gravels of uniform sizes were paved for preventing the soil structure from being damaged by watering. Four holes of about 20 cm in diameter were drilled in the pit (i.e., ZS1, ZS2, ZS3, and ZS4) and then filled with sand gravel soils. To investigate the infiltration of water, a well of 22 m in depth (i.e., TJ1) was excavated inside the pit for the installation of soil water meters to determine the soil water content changes. The water meter has four needles of 60 mm in length that can be either pushed or buried into the soil. The output of the water meter is volumetric water content, which is obtained from the change in dielectric constant of a material formed by three or more substances. More details about how the water meter works are referred to in Li et al. [35]. In total, 15 water meters were pushed into the soils at different depths with an increasing spacing along the well wall, see Fig. 5. After the installation of all instruments, the well was backfilled with disturbed loess soils before compacting to a dry density similar to the natural value. All of the water meters were connected to an automatic data acquisition system, which is capable of reading and recording the data with a determined interval. The water meters were calibrated for a specific soil type before using in the test such that the outputs are typically within ±2% of the true values. After the test, five wells outside the pit (i.e.,

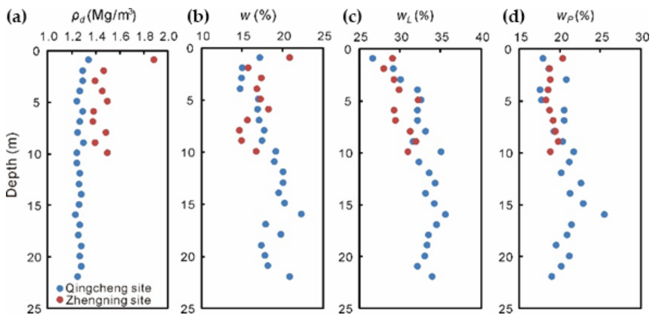

Fig. 3. Variations of (a) dry density; (b) natural water content; (c) liquid limit and (d) plastic limit with the depth at the test sites.

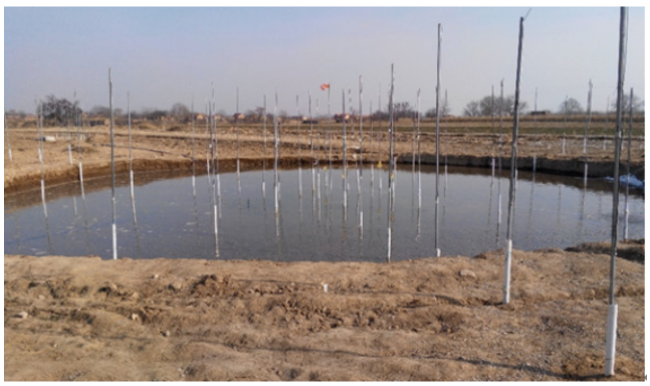

Fig. 4. Overview of the test pit for the filed soaking test.

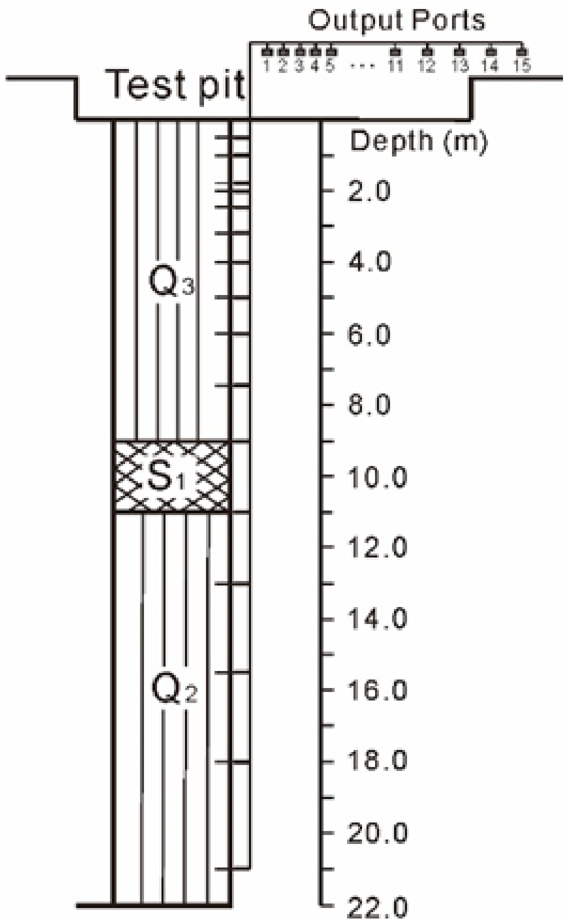

Fig. 5. Arrangement of the water meters in TJ1 well at Qingcheng site.

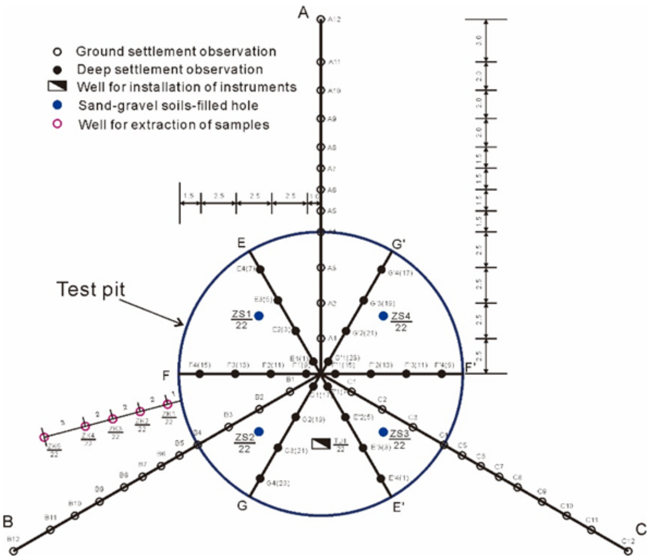

Fig. 6. Arrangement of settlement observation instruments at Qingcheng site.

ZK1, ZK2, …, ZK5) were excavated for retrieving soil samples at different depths. The soil water contents were subsequently determined in the field using alcohol burning method. The results were compared with those before the test.

Besides soil water contents, collapse settlements were observed during the test. Three reference points were set at the site for collapse settlement observation. Along three radial directions (i.e., A, B, and C axis), 37 ground settlement observation points designated as Ax, Bx, and Cx, $x = 1, 2, \ldots 12$, were set inside and outside the pit. In addition, 24-deep settlement observation points were set along six radial directions, that is, E, F, G, E′, F′, and G′ axis, as shown in Fig. 6. Ground settlement observation instrument was buried at a depth of 0.3 m for the measurement of total collapse settlement, while deep settlement observation instrument was buried at a designed depth (see the number in the bracket in Fig. 6, in meters) for the measurement of total collapse settlement below that depth. The test was started on October 5, 2013, and finished on March 30, 2014; the first 93 among the 177 d water was supplied to maintain a water level varying between 30 and 40 cm in the pit. The water supply was terminated when the daily collapse settlement was less than 0.1 cm for 5 d. During the remainder days, however, the daily collapse settlement was increased again; the settlements were measured until the daily collapse settlement was less than 0.1 cm for 5 d.

3. Rainfall infiltration test

3.1. Site description

To investigate the rainfall infiltration in loess simulating the case of dripping irrigation, a test was carried out in Zhengning County, Qingyang, China, about 60 km from Qingcheng site, see Fig. 2. A well of 1 m in diameter and 10 m in depth was excavated for the installation of instruments. Q_3 loess extending to a depth of about 8.5–9 m and the underlaying S1 paleosol were exposed. Intact soil samples were retrieved at different depths during excavation of the well and their physical properties were determined, as summarized in Fig. 3. It can be seen that the dry density is typically a little greater than that at the same depth at Qingcheng site (Fig. 3(a)), this could be because Zhengning site was at an abandoned yard while the field soaking test was conducted in a farmland. While the natural water content and Atterberg limits are close for the soils at the same depth at both sites. The annual precipitation is less than 500 mm, while the annual evaporation can reach up to 1,500 mm in Zhengning County. For these reasons, the two sites have the similar stratigraphic and meteorological conditions.

3.2. Instrumentation system

The same type of water meter was used to measure the soil water content changes due to the infiltration of rainfall. In total, 22 water meters were pushed into the soils at different depths along the well wall. More water meters were set within the top 2 m. The spacing between two water meters was 0.1 m within the top 1 and 0.2 m from 1 to 2 m. Below 2 m, the water meter was set every other meter along the well wall (i.e., 3, 4, …, 10 m). Fig. 7 shows the arrangement of water meters at the test site. Similarly, all output ports of the water meters were attached to a data acquisition system, which, however, can transmit the data to a computer through wireless internet connection. In other words, the data were remotely collected. After the installation of all water meters,

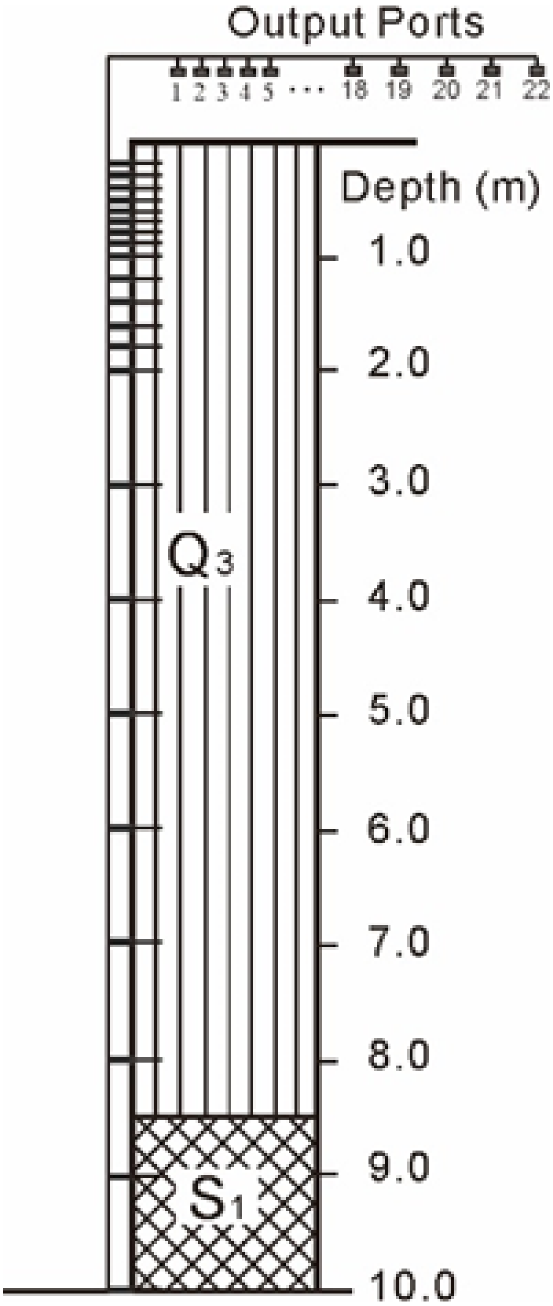

Fig. 7. Arrangement of the water meters at Zhengning site.

the well wall was treated for preventing possible evaporation from influencing the soil water contents. The well wall was painted with straw-reinforced mortar, cement mortar, and waterproof paint, successively. During the test, the well was covered with a concrete plate.

4. Results of the filed soaking test

4.1. Water consumption and infiltration

As introduced earlier, water was supplied in the first 93 d of the entire test period to maintain a water level varying between 30 and 40 cm in the pit. The daily and accumulated

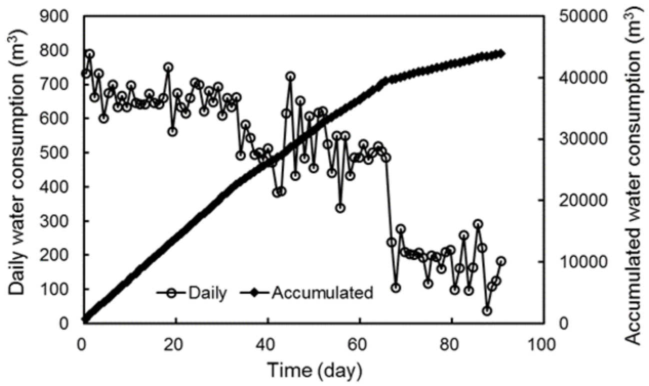

Fig. 8. Daily and accumulated water consumption.

water consumption is summarized in Fig. 8. The daily water consumption varies depending on the soil infiltration capacity and can be seen to experience three stages. In the first stage (i.e., the first 35 d), the daily water consumption reached up to 800 m^3 and averaged about 660 m^3. That could be attributed to the four sand-gravel soils-filled holes in the pit (i.e., ZS1, ZS2, ZS3, and ZS4), which were firstly penetrated by water due to high permeability (or high flux per unit width upon the same loss of water head in comparison to loess soils) once the water was injected to the pit. As long as the holes were filled with water, the soils within each layer (i.e., Q_3 or paleosol or Q_2 layer) could be regarded as homogeneous and unsaturated. In addition, the intact loess soils were at a low-saturation state (i.e., less than 50%), under such a condition, water infiltrated at a rapid rate after the water content in the topsoil was increased, due to the high matric suction gradient and gravity potential. However, the rate of infiltration would decrease with the depth because of the decreasing matric suction gradient and gravity potential [38]. During this stage, the water level was in actual less than 30 cm in the pit due to the quick infiltration of water as well as the limitation of water supply system. In the second stage (i.e., from the 36th to the 67th day), the average daily water consumption was about 510 m^3. In the third stage (i.e., from the 68th day to the termination of water supply), the daily water consumption averaged about 180 m^3; the soils within the saturated zone were almost saturated.

The initial water contents of Q_3 loess soils (i.e., 20%–25%) are lower than that of Q_2 loess soils (i.e., 25%–30%), and the variation of water content in Q_3 loess was found different from that in Q_2 loess, so the water content variations of Q_3 and Q_2 loess soils are depicted in Figs. 9(a) and (b), respectively. In Fig. 9(a), the greater the depth, the longer the lag between the test commencing and increase of soil water content. For example, the soil water content at 0.5 m depth was increased since the 7th day, whereas that at 2.5 m was increased since the 10th day, and at 6 m since the 15th day after the test began. The soil water contents increased at a near constant rate before reaching the saturated state, irrespective of the buried depth. It can be seen that the Q_3 loess soils above 9.0 m depth were saturated 10–20 d after the start of the test. The Q_3 loess soils remained saturated as long as the 30-cm-height water level was maintained in the pit; however, the water contents were decreased once the water supply was terminated. In Fig. 9(b), it is interesting to note that the Q_2 loess soils at shallower depths showed a quick

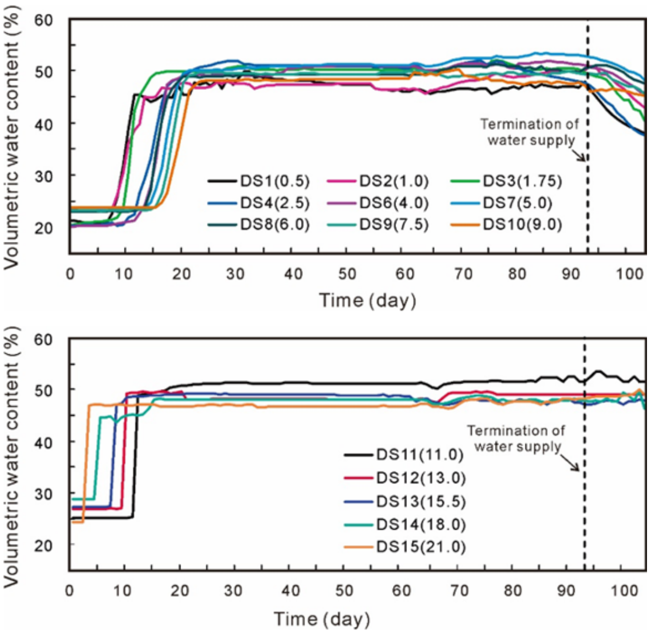

Fig. 9. Water content variations of (a) Q_3 loess soils and (b) Q_2 loess soils.

response to soaking than that at greater depths. For example, the water content of soil at 11 m depth was increased since the 14th day, whereas that at 15.5 m was increased since the 8th day and at 21 m since the 3rd day after the start of the test. In addition, unlike Q_3 loess soils, Q_2 loess soils at various depths were almost saturated at once when they reacted to soaking. The saturated water contents were maintained in Q_2 loess soils even after the termination of the water supply.

In summary, the water infiltrated from both ends to the intermediate depths for the soils at both shallower and greater depths were wetted earlier than that at intermediate depths, and the Q_2 soils at greater depths achieved full saturation immediately after the test commenced. This could be attributed to the preferential flows or preferential paths produced by the holes drilled in the pit and filled with sand-gravel soils (i.e., ZS1, ZS2, ZS3, and ZS4, see Fig. 6). As the water was injected to the pit, water infiltrated into the topsoil through the inter-particle paths, meanwhile, a large amount of water penetrated such preferential paths due to high permeability; as a result, preferential flows were developed in the soils. When water reached the bottom of such preferential channels, water would have infiltrated radially under the effects of matric suction gradient and positive water pressure. For these reasons, the water accumulated on ground surface infiltrated downward and that in the preferential channels infiltrated radially after the water began to accumulate in the preferential channels. However, the paleosol layer as a relatively impermeable layer sandwiched between Q_3 and Q_2 loess highlighted the difference in water content variation in Q_3 and Q_2 soils by preventing the exchange of soil water between them.

After the test, soil samples were retrieved at different depths in five wells (i.e., ZK1, ZK2, …, ZK5), their water contents were then determined in the field using alcohol burning method and compared with that before the test, see Fig. 10

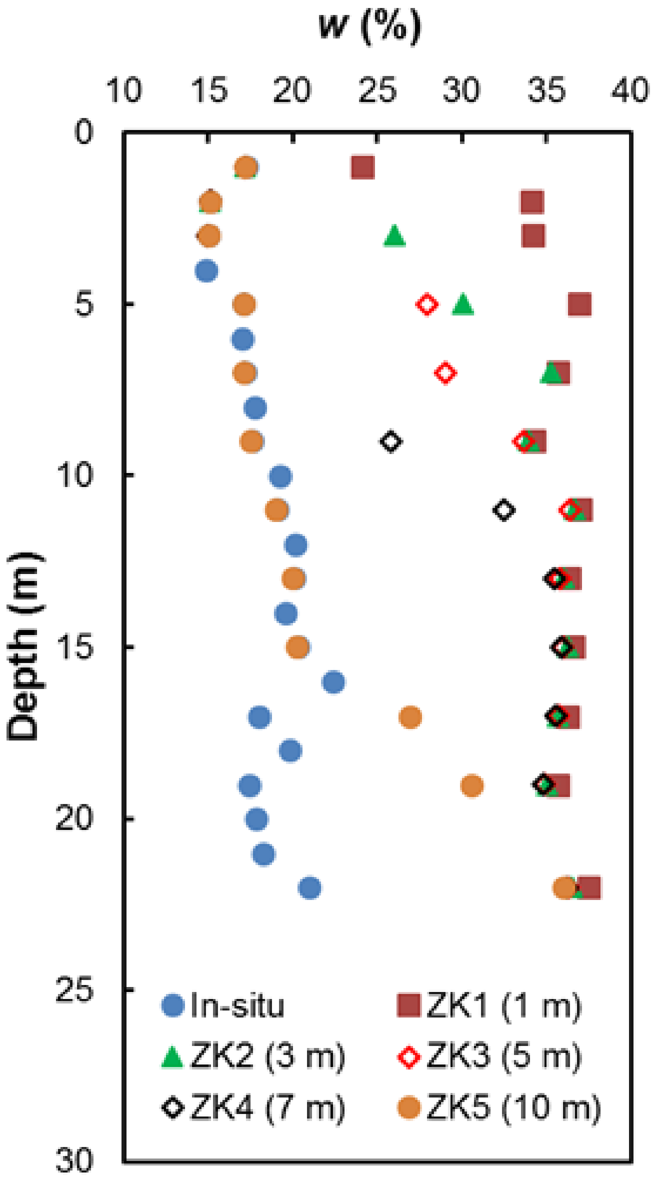

Fig. 10. Comparison between water content profiles before and after test.

(the number in the bracket in the legend represents the distance of the well to the pit, see Fig. 6).

In general, the longer the distance to the pit, the larger the increase in the water content due to soaking could be, especially at the shallower depths. The large increases in the soil water contents at greater depths provide evidence to the radial infiltration discussed above. For example, in ZK5, which is the furthest from the pit, the water content of the soil at the well bottom increased as much as that in other wells, while the upper Q_3 loess soils were even not affected. Upon the measured data, the saturated zone and zone of wetting could be drawn, as shown in Fig. 11, suggesting that the soils within the zone of wetting were wetted while the soils within the saturated zone were saturated due to soaking. The downward flows dominated in the upper soils due to the more significant effect of gravity and the increasing soil permeability with the soil degree of saturation.

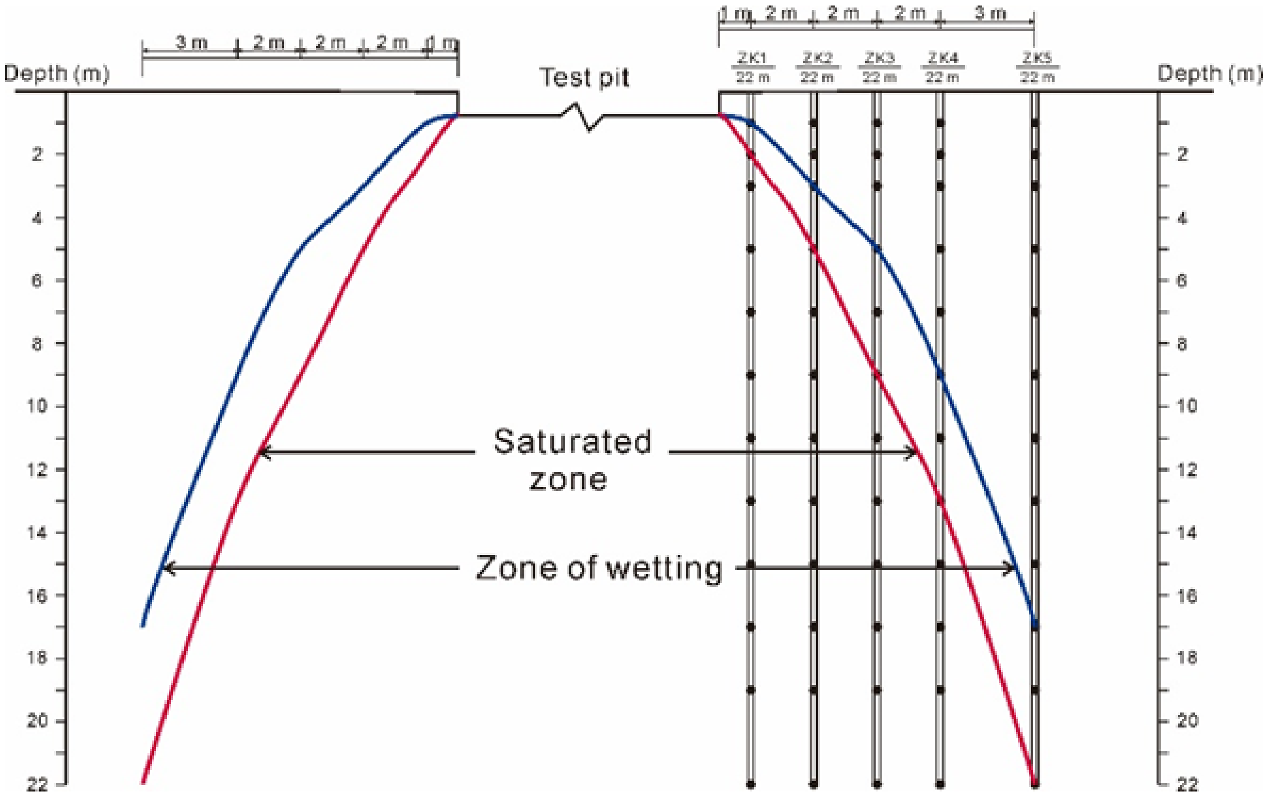

Fig. 11. Saturated zone and zone of wetting.

However, the effects of matric suction gradient and positive water pressure were much greater in the preferential channels, resulting in the radial infiltration as significant as the downward infiltration.

4.2. Collapse settlements and cracks

Fig. 12 summarizes the development of ground settlements (i.e., total collapse settlements) with respect to time measured at different locations along A axis. The ground settlement was primarily related to the distance from the observation point to the central pit; in other words, the soil could be considered homogeneous and the deformation problem could be one dimensional in this experimental study. In general, the central pit experienced the largest total collapse settlement, that is about 50 cm; and the further the distance to this center, either inside or outside the pit, the smaller the total collapse settlement could take place due to soaking. Owing to the difference in collapse settlements along the radial directions, cracks which were crossed each other were gradually developed around the test pit. In Fig. 12, it is shown that there were almost no collapse settlements taken place in the first stage (i.e., the first 35 d, see Fig. 8), except for A1 and A2 at which collapse settlement took place on about the 5th and 15th day after the start of the test. This could be because a very large amount of water penetrated the sand-gravel soils-filled holes (i.e., preferential channels) after the water was injected to the pit, only a little amount of water infiltrated the topsoil in the first stage. In addition, the water level was not well maintained in the pit in this stage due to the quick infiltration of water as well as the limitation of water supply

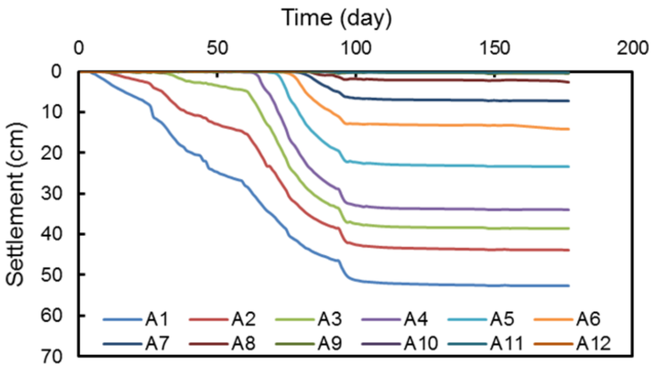

Fig. 12. Development of ground settlements measured at different locations.

system. During the test, the water supply was terminated when the daily collapse settlement was less than 0.1 cm for 5 d; however, it is interesting that significant collapse settlements (as high as 6 cm) were measured at most of observation points even after the water supply was terminated. The collapse deformation due to soaking was completed in about 10 d after the termination of water supply.

The results of parts of deep settlement observations are summarized in Fig. 13. The depth at which the instrument for settlement observation was placed is seen in the bracket in the legend. The data measured at a designed depth represent the total collapse settlement taken place in the soils below that depth. In general, the shallower the buried depth of the instrument, the greater the collapse settlement would be measured. The development of deep settlement with time seemed similar to that of total collapse settlement; significant collapse settlement took place in the second stage (i.e., from the 36th to the 67th day), and the collapse settlements at most points were increased before leveling off after the water supply was terminated.

5. Results of the rainfall infiltration test

The infiltration of rainfall is significantly influenced by environmental factors, such as precipitation, evaporation, wind speed, and atmospheric temperature, vegetation factors, for example, leaf area index, as well as topographic characteristics, for example, slope gradient. The test site was leveled and the weeds were removed before the test, therefore, the influence of environmental factors could be dominated. For these reasons, the daily data of precipitation and evaporation in Zhengning County in the year of 2013 are shown in Fig. 14, for better interpreting the soil water content variations due to rainfall infiltration. It shows that the region where the test site is located had a low annual precipitation of a little more than 300 mm in 2013, while the annual evaporation was as high as 1,400 mm. Both daily precipitation and evaporation increased significantly in spring (from March to May), reached their maximum levels by the end of summer (i.e., August) and decreased in autumn (from September to November) and winter (from December to February). The region has four distinct seasons.

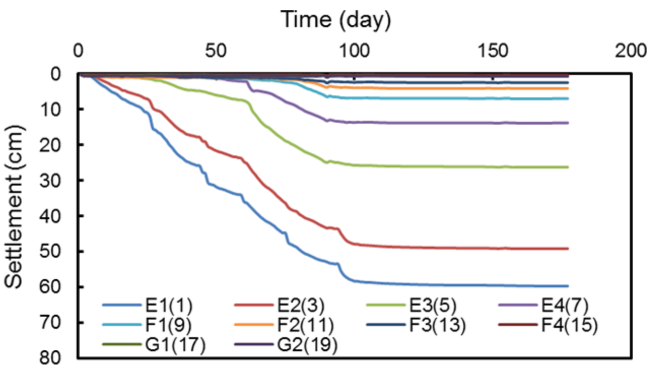

Fig. 13. Development of collapse settlements measured at different locations and depths.

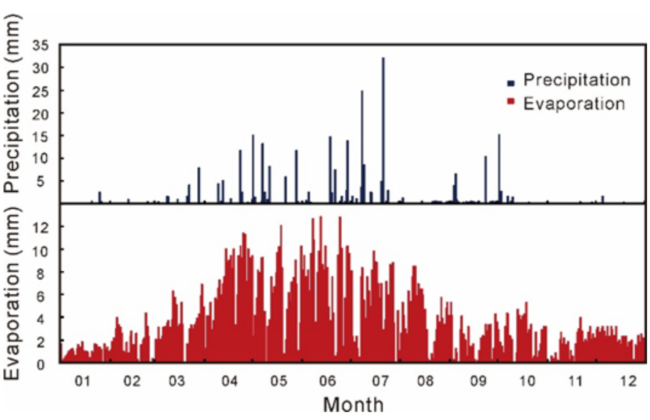

Fig. 14. Daily data of (a) precipitation and (b) evaporation in Zhengning County in 2013.

The soil water contents at various depths were measured every other day for a whole year of 2013. The water content variations of Q_3 loess soils above 4 m are summarized in Fig. 15 because the soil water contents below 4 m almost maintained constant throughout the test period. It can be seen from Fig. 15 that the zone of wetting due to rainfall infiltration extended to a depth less than 3 m in the test site for the water content at 3 m underwent negligible changes throughout the year, less than 1%, while the water content at 2 m varied with the changing precipitation or evaporation. Above the depth of 2 m, the response of soil water content to environmental factors was less pronounced with the depth. In other words, the topsoil was more sensitive to the changes in environmental factors, such that the soil water content would increase immediately as the rain falls and drop when the rain stops due to the increasing evaporation. For example, the soil water contents at 0.6 and 1.0 m were decreased from late March to mid-July due to the higher rate of evaporation than precipitation, while the changes of water contents at 1.4 and 1.6 m were much gentle although it rained many times and even evaporation was increased to its maximum level. In addition, the soil water content at 2 m was always increased till early autumn. In late summer (in late July), the soil water contents above 2 m experienced several sudden increases due to heavy rainfall events. However, unlike the soils at 0.2, 0.6, and 1.0 m, the soils at 1.4 and 1.6 m were almost not affected by the heavy rainfall event in early October. This suggests that the rainfall intensity plays important role in influencing the infiltration of water; only the rainfall with quite large intensity could affect the soils at relatively deep depths immediately. In autumn, the soil water contents at different depths were all decreased without recharge from rainfall, the shallower the depth, the more dramatic the water content decrease.

6. Discussion

A comparison is preferable to be made between the field soaking test and rainfall infiltration test for better interpreting the infiltration in loess with varying irrigation method. Especially at the beginning of the soaking test, the majority of the irrigation water penetrated the sand-gravel soils-filled holes (preferential paths) due to high permeability. Little water infiltrated the topsoil through the inter-particle paths until all the preferential paths were saturated with water. Owing to the much higher permeability of sand-gravel soils than loess soils, the water level was not well maintained even

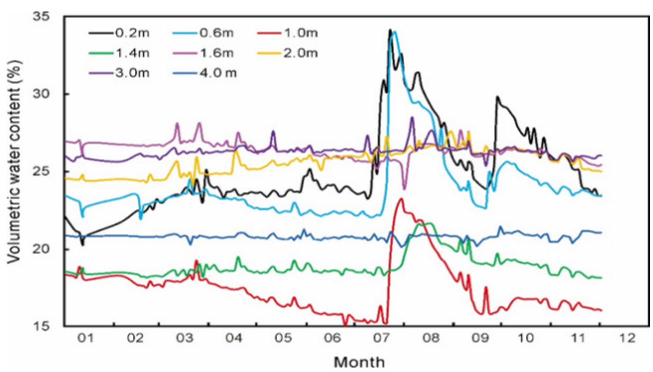

Fig. 15. Water content variation of Q_3 loess soils at various depths.

though the daily water consumption was very high in the first dozens of days during the test period. As a result, preferential flows were developed in the soils. Under such conditions, the water accumulated in the pit infiltrated downward under the effects of water gravity and matric suction gradient, in addition to recharging the preferential channels, while the water in the preferential channels infiltrated radially under the effects of matric suction gradient and positive water pressure. The water infiltrated from both ends to the intermediate depths, resulting that the soils at both shallower and greater depths were wetted earlier than the soils at intermediate depths (see Fig. 9). Outside the pit, the soils at greater depths experienced more pronounced changes in water content than that at shallower depths (see Fig. 10), such that bell-shaped zone of wetting and saturated zone were developed in the soils due to soaking, as shown in Fig. 11. In the test, a very large amount of water (i.e., about 44,000 m^3) was injected to the pit, and the soils within the depth concerned (i.e., 22 m) were all significantly affected due to soaking. Because the soils below 22 m were not measured, the maximum depth of wetting front could not be exactly determined.

Unlike the flow behavior in the soil due to soaking, the infiltration of rainfall is rather complex as it is significantly influenced by environmental factors, that is, precipitation and evaporation (other factors such as relative humidity, atmospheric temperature, and wind speed have an influence by controlling the rate of evaporation). Therefore, the soil water contents vary under the combined effect of precipitation and evaporation. In other words, the rain water, pore water, and water vapor transformation from one to another depending on the rainfall intensity, rate of evaporation, as well as soil properties (pore-size distribution). As per the test results, the pore water includes bound water and a little free water in the soil structure even if the soil water content is decreased to its minimum value [39]. For this reason, when the rain water infiltrates the topsoil, the water is firstly absorbed and held in small-sized inter-particle pores. The remainder of the water, however, flows downward due to the gravity potential and matric suction gradient. It is difficult to remove water from the small-sized inter-particle pores without great enough matric suction gradient. Once the rain stops, the water content in the topsoil is decreased due to the increasing rate of evaporation, which also contributes to producing an opposite matric suction gradient that can trigger upward water flow in the soil. The rainfall intensity or the total amount of a round of rain has a control over the zone of wetting. For example, in the rainy season (e.g., from May to July), the wetting front advanced progressively due to the high rate of precipitation or large amount of a round of rain. Each rainfall event contributed to increasing the soil permeability within the wetted zone and promoting the wetting front. This can be inferred from the variation of water content at 2 m which was increased to its maximum value after the rainy season. However, when the rain stops, a transformation of pore water in the topsoil into water vapor which then escapes to the atmosphere (i.e., soil water evaporation) is triggered due to the increasing atmospheric temperature and decreasing relative humidity. As the water content in the topsoil decreases, an upward water flow is triggered in the soil due to the opposite matric suction gradient. Based on this mechanism, the water contents at some depths (especially at intermediate depths) would maintain a state of dynamic stabilization in response to the varying environmental factors. The water contents at these depths would remain constant for some time without significant changes in precipitation or evaporation. This reasoning can explain the test result that the water contents at 1.4 and 1.6 m did not change much from January to mid-July; whereas the water contents of the soils either above or below these depths (e.g., 1 and 2 m) showed pronounced changes at the same time period. At Zhengning site, the ground subsidence was not measured and no evident collapse settlements were observed.

This comparison suggests that the infiltration of water in loess soils varies with irrigation method. With preferential paths in the soil, water firstly penetrates preferential paths due to high permeability. Very little amount of water infiltrates the soil through inter-particle paths until all preferential paths are saturated with water. As a result, the water accumulated on ground surface infiltrates downward to the soils, and the water in the preferential paths infiltrates radially under the effects of matric suction gradient and positive water pressure. As a result, bell-shaped zone of wetting and saturated zone that extends to a depth greater than 22 m (depth of the preferential paths) were developed in the soils. On the contrary, without preferential paths, when the amount of irrigation water is fairly small, the flow behavior is significantly influenced by environmental factors. The rain water infiltrates into the soils and flows downward due to the gravity potential and matric suction gradient, while upward water flow and eventually soil water evaporation can be triggered due to the increasing evaporation rate in the atmosphere after the rain stops. For these reasons, the maximum depth of the wetting front due to rainfall infiltration was less than 3 m.

7. Conclusions

To investigate the influence of irrigation method on the infiltration in loess, two field tests were conducted in the Loess Plateau of China. One is the field soaking test simulating flooding irrigation method, in which a very large amount of water was irrigated to the soils. The other is the rainfall infiltration test simulating dripping irrigation method conducted in a drought year with the annual precipitation a little more than 300 mm. Based on the test results, several important conclusions can be reached:

Results of the soaking test indicate that water firstly penetrates the preferential paths as the water is irrigated to the soils. Very little amount of water infiltrates the soils through the inter-particles paths until all preferential paths are saturated with water; preferential flows are developed in the soils. The water accumulated on ground surface infiltrates downward due to the gravity potential and matric suction gradient, while the water in the preferential paths infiltrates radially under the effects of matric suction gradient and positive water pressure. As a result, the water infiltrates from both ends to the intermediate depths, resulting that the soil water contents at both shallower and greater depths increase earlier and more pronouncedly than the soils at intermediate depths; bell-shaped zone of wetting and saturated zone are finally developed in the soil due to soaking.

The influence of environmental factors is of dominance when the amount of irrigation water is fairly small. The rain water, pore water, and water vapor transform from one to another depending on the rates of precipitation and evaporation as well as soil properties. When the rain water infiltrates the topsoil, downward flow is triggered due to the gravity potential and matric suction gradient. However, once the rain stops, a transformation of pore water in the topsoil into water vapor which then escapes to the atmosphere is triggered due to the increasing rate of evaporation, thus an opposite matric suction gradient that can trigger upward water flow in the soil is produced. As a result, the maximum depth of the wetting front measured was less than 3 m.

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