Article

Infiltration Law of Water in Undisturbed Loess and Backfill

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Abstract: Loess has the characteristics of complex structure and reduced mechanical strength after encountering water. In Chinese loess areas, irrigation, water storage, and rainfall affect the stability of the original loess structure and cause damage to the foundation. This paper analyzes the results of in situ water immersion test (in order to study the permeability of water storage in undisturbed loess), rainfall test (in order to study the permeability of rainwater in the backfill loess), and water storage test (in order to study the permeability characteristics of water storage in backfill loess) on the filling site and studies the permeability law of water in unsaturated layered loess and backfill remolded loess. The results of the in situ immersion test show that the vertical seepage velocity of water was very fast, and the infiltration depth was close to 25 m after 9 days of water storage, and at the interface of the new loess, the paleosol, and the old loess, the water infiltration line appeared to be refracted. Finally, the vertical and horizontal penetrations of water in the loess are analyzed, and the range of water immersion and saturation are determined. Through the rain test and water storage test of a loess-filled surface, the relationship between the moisture content and depth of the backfill loess before and after rainfall and storage is obtained. The results of rain period test show that the water infiltrated into the loess about 3 m after 25 days of rainfall. A further 90 days storage test shows that the final infiltration depth of water was about 7 m.

Keywords: loess; undisturbed loess; backfill loess; infiltration and migration; foundation pit immersion

1. Introduction

The permeability characteristics of soil have been studied for a long time. The related permeability models for calculation are established, such as Van Genuchten model, Fredlund–Xing model, etc. The Van Genuchten model and the Fredlund–Xing model are fitting models, some scatter points must be obtained through experimentation first, and then the continuous function can be obtained by fitting the scatter points. Research has been carried out on the mathematical prediction model of soil–water characteristic curves. Scholars such as Ayra and Paris [1] and Zhuang et al. [2] also proposed physical empirical models for predicting water characteristic curves based on particle size classification, particle density, and gravity. Fractal models based on pore fractal dimension and pore volume fractal dimension were established by Rieu and Sposito [3] and Pachepsky et al. [4]. Bernadiner [5] conducted a theoretical study on the capillary microstructure of the wetting front. Wang et al. [6] believed that water entering unsaturated areas might be affected by air; therefore, the analytical permeation equation considering air was established, and the calculated results were in good agreement with the experimental results. McDougall and Pyrah [7] established the permeability model of unsaturated soils under different rainfall conditions using numerical methods. Cho and Lee [8] simulated the
infiltration of unsaturated soil based on the finite element model and emphasized the importance of the permeability coefficient in the stability of water in a slope. Ng [9] used a three-dimensional numerical analysis method to study the response of a reservoir to groundwater, and the variation law of pore water pressure in unsaturated slopes under different rainfall patterns was analyzed. Trandafir et al. [10] combined outdoor, laboratory, and numerical simulations to study the development of a steep deep forest slope wetting front during rainfall. Rajeev et al. [11] used Vadose/W (GEO-SLOPE International Ltd., Calgary, AB, Canada) software to simulate the surface–atmosphere interaction of two instrument stations in Melbourne, Australia. Since the numerical simulation results were in good agreement with the measured data, they were able to predict long-term changes in humidity and temperature.

Loess structure is loose and porous with many cracks. The penetration of water in loess is very complicated. Loess is generally unsaturated. After water infiltrates into the pores of the loess, the moisture content and matrix suction of the loess will change, and its shear strength is significantly reduced [12]. Under the action of water and its own gravity, the loess has obvious collapsibility and destruction, causing geological disasters and engineering problems (Figure 1). Heavy rainfall and artificial large-scale water storage often cause safety problems. Therefore, it is very important to study the law of water penetration in loess. In mountainous areas where loess is distributed, rainfall often leads to geological disasters such as landslides and subsidence. The ground subsidence caused by irrigation of farmland is also very serious. For example, the locals in the areas of Heifangtai and Jingyang (in China) have used Yellow River water to irrigate farmland for many years, which often caused the problem of geological disasters [13,14].

![Figure 1. Geological disasters caused by water immersion of loess, (a) middle of the road, (b) side of the road.](image)

Most domestic and foreign scholars studied the penetration of water in loess through theories, laboratory tests, and outdoor in situ water immersion tests [15–18]. Luo et al. [19] used field experiments, theoretical analysis, and numerical methods to study the seepage characteristics of vertical fractures of loess. The results showed that the vertical joint had a great influence on the permeability in this direction. Liu et al. [20] showed that the relationship between the saturation change and the time change in the depth direction was close to linear by the in situ experimental study of unsaturated loess; the change of unsaturated infiltration time of shallow soil with soil depth was also approximately linear in the short term, the infiltration angle in loess was close to 30 degrees. Ma et al. [21] carried out a water immersion test with a water injection hole in a large-thickness self-weight collapsible loess site and proposed a monitoring method for the horizontal displacement of the soil layer outside the foundation pit, and the correction coefficient B0 of the region was discussed. Su et al. [22] also carried out a large in situ water immersion test for large-thickness self-weight collapsible loess sites, the results showed that the shape of the infiltration zone was close to an ellipse. Li et al. [23] carried out the water immersion test in an unsaturated undisturbed loess slope and studied the formation of a transient saturated zone and the migration process of water in the loess; they also considered that the infiltration
range of water in unsaturated loess was approximately elliptical. Wang et al. [24], Huang et al. [25], Yao et al. [26], An et al. [27], and Wang et al. [28] also studied the law of water seepage movement and collapsibility in loess by a field immersion test.

The above-listed studies show little differences in water immersion depth. This might be due to similar homogeneous material composition. When the geological condition of the test site is complex and when the infiltration process passes through the loess with large differences in loess parameters, the water migration line is not a smooth curve. In the study of water penetration through soils with large differences in parameters, relevant literature believes that there will be a phenomenon of “capillary separation zone”. The particle size of the upper soil horizon is smaller, and the size of the lower soil horizon is larger; therefore, there will be capillary tension at the interface of the soil horizons, which will prevent water from penetrating. Researching water seepage in soil horizons, Gvirtzman et al. [29] conducted two large-scale outdoor experiments to study the permeability characteristics of unsaturated loess—the loess deposit was composed of alternating silt and sandy clay loess deposits. After the site test, the process was simulated by a numerical analysis program and the following conclusion was drawn: the propagation of the wetting front was hindered by the alternation of silt and sandy clay loess. In [30], the refraction phenomenon was analyzed by the law of refraction; it was considered that the inclination angle of the water flow refraction line was related to the ratio of the soil permeability coefficient.

Through the above analysis, it can be found that the water immersion test research of undisturbed loess is mainly aimed at natural disasters and has achieved certain results. In other cases, people will always treat the natural loess foundation and then carry out some engineering construction. In this case, the original state of the loess is destroyed, and its infiltration mechanism is quite different from that of the undisturbed loess. By consulting the literature, we can find that few studies have been done on the permeability of backfill and remolded soils, and these have been mainly through laboratory tests. Gao et al. [31] studied the soil–water characteristic curves of remolded clay under different compaction work and different compacted moisture content by using a conventional pressure plate instrument; the permeability coefficient of the saturated soil was measured by the variable head method. Gu et al. [32] conducted an experimental study on the permeability of undisturbed soil, remolded soil, and solidified soil of clay. The collapsibility of remolded loess was studied, and the change of loess microstructure was observed by microscope [33]. The collapsible loess was studied by the method of high-energy dynamic compaction. The effectiveness of the method was evaluated by field test and deformation test. The results showed that the collapsibility of the loess was basically eliminated [34]. Many valuable conclusions have been obtained from the indoor test, but limited by the model size, the conclusions are only of reference value. The field test is particularly true and important, and it can better reflect the water permeability characteristics in the remolded loess. The original structure of the remolded loess is changed, the pore channels are destroyed, the particles become dense, and the law of water penetration in the remolded loess becomes more complicated.

Based on the above analysis, water is an important factor that causes structural damage to loess. Therefore, it is useful to study the law of water infiltration in loess. In this paper, the in situ foundation pit immersion test was first carried out in the suburb of Xi’an, China. After the experiment, the law of water seepage movement was studied by recording the change of water meter and measuring water content by digging hole sampling. Then, selecting a backfill site on the loess plateau, a rainfall water infiltration test and a surface water storage test were carried out. Through the comparative analysis of the two experiments, the permeability of undisturbed loess and remolded loess was deeply studied. More and more engineering constructions are carried out on loess sites. Loess is a material that is very sensitive to water. When water infiltrates into the loess, it will significantly reduce the strength of the loess and cause problems such as collapsibility. Therefore, it is necessary to study the permeability of water in loess.
2. Overview of In Situ Immersion Test

2.1. Test Site Topography

The test site (Figure 2) is located in the suburb of Xi’an (east longitude 107°4’–109°49’ and northern latitude 33°42’–34°45’), China, the site is relatively flat, surrounded by weeds and trees, and the geomorphic unit belongs to the third grade terrace (engineering geological division of collapsible loess in China) of the Chan River (a river located in Xi’an, China). The specific data are as follows: 0–0.5 m is Q4 eol of tillage loess, 0.5–13.1 m is Q3 eol of new loess, 13.1–16.5 m is Q3 el of paleosol, 16.5–28.8 m is Q2 eol of old loess (Q4 eol is Holocene loess, Q3 eol and Q3 el are Upper Pleistocene loess, Q2 eol is Middle Pleistocene loess) (Q4 mL, yellowish brown, silty clay, hard plastic) (Q3 eol, yellowish brown, hard plastic, local plasticity, loess fabric is nonuniform, wormhole, macropores, collapsibility) (Q3 el, reddish brown, hard plastic, local plasticity, aggregate structure, pinhole pore, calcareous striation, calcareous concretion, there are more calcareous concretions at the bottom, a thin layer of calcareous concretion in local areas, thickness 3–5 m, collapsibility) (Q2 eol, brown-yellow, hard plastic, local plasticity, loess fabric is nonuniform, pinhole pore, macropores, calcareous concretion, thickness 3–10 m, collapsibility).

![Figure 2. Panorama of the test site.](image)

2.2. Physical and Mechanical Properties of Loess at the Test Site

In order to study the physical and mechanical properties of loess in the test site, three exploration wells were excavated at the test site, numbered CS5-22, CS5-23, and XS5-22, respectively. The excavation depth was 30 m; two samples were taken from each exploration well at different depths. Some of the samples are shown in Figure 3. The results of natural water content (ω), saturation (Sr), dry density (ρd), natural density (ρ), and void ratio (e) with depth are shown in Figure 4.

![Figure 3. Loess samples with different depths, (a) 5 m depth, (b) 8 m depth, (c) 10 m depth, (d) 15 m depth, (e) 20 m depth, and (f) 25 m depth.](image)
2.3. Determine Test Pit Size

According to the loess parameters and considering the site conditions, the lower limit depth of the collapsible loess horizon of the test site was 27 m, in order to make all the collapsible loess horizons below the bottom of the test pit saturated with water, the diameter of the test immersion test site and deep punctuation points were determined to be 26 m. The design depth of the water in the test pit was 0.5 m. After excavation and leveling, a layer of gravel (particle size was 0.01–0.03 m) with a thickness of 0.1 m was laid on the bottom of the pit. By analyzing the parameters of loess samples, the following conclusions were drawn:

(1) The water content was generally between 17% and 24%, of which the water content was lower at 12–18 m. Saturation and water content were closely related, which showed that the higher the water content was, the higher the saturation was. The saturation of the new loess horizon was between 50% and 60%, and the difference between the paleosol horizon and the old loess horizon was obvious.

(2) The variation in curve behavior of dry density and natural density with depth was basically the same. The density and natural density of paleosol horizon were the largest. The density and natural density of old loess horizon was slightly smaller than that of the new loess horizon.

(3) The void ratios between the loess horizons were quite different; the paleosol horizon had a small void ratio between 0.6 and 0.9; the old loess horizon was relatively stable and varied from 1.0 to 1.2.
2.4. Embedding of Moisture Meter

Moisture meters were installed inside and around the foundation pit to monitor the changes in water content and saturation. The soil moisture meters were buried by the pre-drilling method, and the specific embedding position and embedding method of the moisture meters are as follows:

According to the stratification conditions of the strata, the moisture depths of each group were set to: 5 m (SJ3 and SJ8), 10 m (SJ1 and SJ6), 15 m (SJ5 and SJ10), 20 m (SJ2 and SJ7), and 25 m (SJ4 and SJ9). SJ1, SJ4, and SJ8 were approximately on a circumference with the radius of 8 m; SJ2, SJ5, and SJ9 were approximately on a circumference with the radius of 10.5 m; SJ3, SJ6, and SJ10 were approximately on a circumference with the radius of 5.5 m. Two rows of moisture meters with different depths were arranged outside the pit, the depths of each row were 8.0 and 16.0 m, respectively. Among them, there were 4 moisture meters at a depth of 8.0 m, which were SJ11–SJ14. There were 4 moisture meters at a depth of 16.0 m, which were SJ15–SJ18 (see Figure 5 specifically).

Figure 5. Plane diagrams of water content testing holes.

2.5. Punctuation Layout

The deep punctuation points were arranged for the range of 0–26 m below the surface, numbered L1–L4, H1–H4 (Figure 6). The samples were sampled by static pressure method, and the moisture content and density of the samples were tested.
2.6. Layout of Water Level Observation Holes

In this test, three drainage-level observation holes (SW1–SW3) were arranged in the northwest direction of the test pit, the holes were filled with gravel, and their depth was 26 m. The first water level observation hole was 3 m away from the edge of the test pit, and the distance between the observation holes was 3 m. There were three water level observation holes in total.

2.7. Determination of Influencing Range of Immersion

Boreholes L1, H3, CS5-22, and XS5-22 were drilled in the test pit before immersion, a group of samples was taken every 0.5 m for a water content test. After stopping the immersion, two drills (ZK1 and ZK2) were drilled at the test pit, and a group of samples was taken every 0.5 m to test the water content and saturation. A total of 315 groups of water content tests were completed before and after the experiment. In order to determine the influence range of the test pit immersion in the radial direction, four holes (ZK3–ZK6) were drilled outside the test pit after the test. A sample was taken every 0.5 m for the water content test, and a total of 307 groups of water content tests were completed.

2.8. Observation of Infiltration Range

The observation of moisture meters was based on a method of timed observation. During the pre-immersion period (24 November–6 December 2013), all moisture meters were read every two hours; during the mid-immersion period (7 December–23 December), the moisture meters were read four times a day; during the late-immersion period (24 December 2013–13 January 2014), the moisture meters were read twice a day; and once a day after water shut down (14 January–27 January).

2.9. Test Water Injection Volume

Water was injected into the test pit by water pipe at the site, and a water meter was installed at the water outlet to observe the water injection amount of the test. A scale was set at the side of the test pit to record the water head. The water head was kept at 30–40 cm during the immersion process. Once the water level dropped to nearly 30 cm, the water was injected into the test pit. Time, water meter reading, and water level height were recorded before and after the injection of water.
3. Analysis of Test Results

3.1. Monitoring of Experimental Water Injection Volume and Water Meter

The test began to inject water on 24 November 2013 and stopped water on 13 January 2014. It lasted for 51 days. The total water injection volume was 14,492 m$^3$.

From Figure 7, we can find that the amount of water injected in the early stage was very large, the average injection of water reached 347 m$^3$/day from the 2nd day to the 18th day, the maximum value appeared on the 5th day, and the injection volume was 443 m$^3$. The obvious fluctuation occurred from the 18th day to the 27th day, because the water infiltrated reaching the soil horizon with a lower permeability coefficient. The water injection curve tended to decrease overall and was generally maintained between 220 and 260 m$^3$. After the 43rd day, the water injection increased slightly, with a daily average of about 290 m$^3$. The influence of evaporation and rainfall was less than 1%, so they were not considered.

Figure 8 is the moisture meter monitoring curve. The readings of moisture meters SJ3 and SJ8 with the depth of 5 m started to change from the 4th to the 5th day; the readings of moisture meters SJ4 and SJ9 with the depth of 25 m started to change from the 15th; SJ3, SJ5, and SJ6 were damaged after using for a period of time, so only part of the data were drawn; SJ7 was damaged after the start of water immersion, and its data were not drawn. Among them, SJ5 and SJ10 with a depth of 15 m were in the paleosol horizon, when the moisture meter values of the two were in a stable state, the measured mass water content was about 23%, which was significantly smaller than the moisture value of other groups. The mass moisture content measured by SJ20 with a buried depth of 20 m was at the highest value, it was higher than that of SJ4 and SJ9, both of which had a depth of 25 m, indicating that the loess was denser along the depth direction. SJ1–SJ10 moisture meters were buried in the test pit radius. After removing the damaged moisture meters, the other moisture meters reached a stable state after a period of rapid growth, indicating that the loess at this area had not reached saturation. Their readings did not decrease after water shutdown. It can be concluded that the horizontal influence range was about 20 m at the depth of 8 m.

Moisture meters SJ15–SJ18 were close to SJ11–SJ14 (Figure 9), and their buried depth reached 16 m. From Figure 10, only the SJ15 and SJ16 values increased, and SJ17 and SJ18 did not change. The moisture meters SJ14 (8 m depth) and SJ17 (16 m depth) were located approximately on the circumference of the radius of 20 m, none of them changed in value. The above phenomena mean that both the depth range of 0–16 m and the transverse range of 7 m from the pit edge were non-infiltrating areas.
According to the monitoring results of moisture meters inside and outside the pit, it can be concluded that the vertical seepage rate of water was much faster than the horizontal seepage rate. Some loess samples taken after water shutdown are shown in Figure 11.
3.2. Determination of the Extent of Infiltration

We based the extent of water infiltration on the change of water content in loess in the boreholes, in combination with the monitoring results of the moisture meters to determine the range of water immersion. The cracks caused by collapsibility are shown in Figure 12, and the change of water content outside the test pit before and after immersion is shown in Figure 13. Punctuation points L1 and H3 were located in different positions, and the depth of excavation was 26 m. The water content tests of the two were relatively close, indicating that the stratum distribution was relatively stable. The change of water content (ZK1–ZK6) can be compared and analyzed by using the data of punctuation point L1. Among them, ZK3 was closest to the edge of the pit, but the moisture content started to change from 3.5 m, it indicated that the water migration line was inclined outward. ZK3 and moisture meters SJ11 (8 m), SJ12 (8.0 m), and SJ15 (16.0 m) were in close proximity, and the data indicated that there was moisture infiltration in the depth direction. ZK4 was close to SJ13 (8.0 m) and SJ16 (16.0 m), the water content of ZK4 started to change at the depth of 7 m, which was consistent with the data of the moisture meter. ZK5 and moisture meters SJ14 (8.0 m) and SJ17 (16.0 m) were close to each other, and the positions of ZK6 and SJ18 (8.0 m) were close, they all had the same trend.

The variation of the infiltration line over time can be plotted using the data of the moisture meters. The moisture meters at the depth of 5, 10, 15, 20, and 25 m began to change at the time of 41, 95, 127, 161, and 214 h. The moisture meters SJ11 (8.0 m) and SJ15 (16.0 m) started to change at the time of 117 and 382 h, respectively. According to the position of the late crack, the influence range of water infiltration on the surface was 10 m, and the influence range of 8 and 16 m depth were 6.2 and 8.8 m from the side of the pit. The whole diffusion process of water over time depended on the monitored data of the moisture meters. The time when the moisture meter SJ11 started to change was at the time of 117 h; and the time when the moisture meters SJ1 and SJ6 at 10 m in the pit started to change was at the time of 95 h; the time when the moisture meters SJ5 and SJ10 at 15 m in the pit started to change...
was at the time of 127 h; the moisture meter SJ12, which was 3 m away from the edge of the pit and buried 8 m deep, started to change at the time of 234 h; while SJ15, which was 2 m away from the edge of the pit and buried 16 m deep, started to change at the time of 382 h. However, SJ15 and SJ16 were located at the area of paleosol, which indicated that there was shrinkage in this area. The infiltration line can be drawn using the above data, it is shown in Figure 14.

Figure 13. Comparison of water content before and after water immersion, (a) in the test pit, (b) 3 m from the edge of the pit, (c) 6 m from the edge of the pit, (d) 9 m from the edge of the pit, and (e) 12 m from the edge of the pit.

A transient saturation zone will be formed during water infiltration [35]. With the increase of water infiltration, according to the principle of potential energy, the balance of the area would be broken, the wetting front would continue to advance, and the infiltration area would gradually increase. In Figure 14, between the new loess horizon and the old loess horizon, there was dense loess with a relatively low permeability coefficient. The infiltration line of water in the loess was not a smooth curve and refraction occurred. The infiltration line of water in the paleosol horizon had a shrinkage phenomenon, which was obviously contrasted with new loess horizon and the old loess horizon. The main reason was that the lower permeability coefficient and slower permeability rate of the paleosol played the role of a waterproof layer, and then led to the acceleration of the lateral infiltration rate of water. After water passed through the area of paleosol, the infiltration pattern and streamline were close to the initial state. Figure 15 was the test result in the literature. The soil was mainly silty and sandy clay and the two were alternately distributed. Comparing the experimental results in this paper with the calculation results in the literature, it was found that the infiltration path was significantly different. The shape of water infiltration in this paper was similar to a “horn”,

Figure 14. Immersion line change with time.
while the shape in the literature was similar to an “apple”. This phenomenon shows that different soil parameters have obvious effects on infiltration.

Figure 14. Immersion line change with time.

Figure 15. Immersion line change with time [29].

3.3. Determination of Saturation Range

According to the water contents obtained from the loess samples in ZK1–ZK6 after immersion, the water contents were compared with the original loess samples of CS5-22 and XS5-22 (Figure 16). When the difference between the two was large, the original loess sample was taken at interval of 1 m for indoor test. At the same time, using a cutting ring to cut samples on site, the saturation was calculated according to the water content and the natural density. The combination of the two determined the saturation range. It is generally believed that when the saturation Sr > 85%, the loess is considered to be saturated. In this paper, the saturation range was drawn with Sr > 85% as the saturation limit.
From the Figure 16, it can be seen that the lower area (18–27 m deep) had reached saturation. Infiltration. It indicated that the loess had reached saturation in the vertical range under the test pit and was then accompanied by evaporation of water and further downward infiltration after water stoppage, resulting in the saturated loess in the upper area becoming unsaturated. The lateral and vertical saturation outside the test pit radius needed to be further judged according the data of ZK3–ZK6. The depth of ZK3 was 8 m, and the increase in the value of water content in the upper area was less than that in the lower area. The loess sample in the lower area was selected for moisture content detection and saturation calculation, indicating that the 7–8 m depth area had reached saturation. ZK4 was 21 m deep, and the areas with obvious water content change were 4–8 and 18–22 m deep. The calculation results showed that the loess taken from ZK4 was saturated. However, the loess taken from ZK5 and ZK6 had not reached saturation. Based on the above calculations and analysis, the range of saturation can be drawn as shown in Figure 17.

**Figure 16.** Saturation change, (a) saturation change of ZK1, ZK2, (b) saturation change of ZK3, ZK4, and (c) saturation change of ZK5, ZK6.

From the Figure 16, it can be seen that the lower area (18–27 m deep) had reached saturation and the upper area was not saturated. The main reason was that the reading stability of the water meters SJ1–SJ10 in the test pit would not change when the water supply was sufficient after a certain period of infiltration. It indicated that the loess had reached saturation in the vertical range under the test pit and was then accompanied by evaporation of water and further downward infiltration after water stoppage, resulting in the saturated loess in the upper area becoming unsaturated. The lateral and vertical saturation outside the test pit radius needed to be further judged according the data of ZK3–ZK6. The depth of ZK3 was 8 m, and the increase in the value of water content in the upper area was less than that in the lower area. The loess sample in the lower area was selected for moisture content detection and saturation calculation, indicating that the 7–8 m depth area had reached saturation. ZK4 was 21 m deep, and the areas with obvious water content change were 4–8 and 18–22 m deep. The calculation results showed that the loess taken from ZK4 was saturated. However, the loess taken from ZK5 and ZK6 had not reached saturation. Based on the above calculations and analysis, the range of saturation can be drawn as shown in Figure 17.

**Figure 17.** Scope of infiltration zone and saturation zone.

### 4. Surface Water Infiltration Characteristics of Loess Filling Site

A landfill site in a city (east longitude 107°41′–110°31′, northern latitude 35°21′–37°31′) on the Loess Plateau of China is located in the semi-arid warm temperate continental monsoon climate zone.
and belongs to the Loess Hilly and gully landform. The loess filler is mainly the (Upper Pleistocene \(Q_3^{el}\) Malan Loess and the Aeolian, Residual (Middle Pleistocene \(Q_2^{el+el}\) Lishi loess. The filling near the ground was mainly Lishi loess with high clay content, the filling body was compacted by the construction technology of impact rolling and local dynamic compaction (\(Q_3^{el}\) yellowish brown, hard plastic, local plasticity, loess fabric is nonuniform, wormhole, macropores, collapsibility) (\(Q_2^{el}\), brown-yellow, hard plastic, local plasticity, loess fabric is nonuniform, pinhole pore, macropores, calcareous concretion, thickness 3–10 m, collapsibility) (\(Q_2^{el}\), reddish brown, hard plastic, local plasticity, aggregate structure, pinhole pore, calcareous striation, calcareous concretion, there are more calcareous concretions at the bottom, a thin layer of calcareous concretion in local areas, thickness 1–3 m, some areas can reach 5 m).}

4.1. Rainfall Infiltration at the Filling Site

Since July 2013, the construction site had experienced several consecutive heavy rain falls. Among them, from 1 July to 12 August, there was rainy weather for 11 days. In order to determine the infiltration depth of precipitation in the filling area, on 25 June, in the low-lying area of the central line of the filling area valley, two water content test points W1 and W2 were selected to determine the water content of the filling loess. The infiltration depth of surface water after rainfall was measured with field loess sampling on 19 August. During the period, rainfall lasted for 25 days and the accumulated rainfall reached 599.6 mm. The test results of the filling water content before and after the rainfall are shown in Figure 18.

![Figure 18. Test results of filling moisture content before and after rainfall.](image)

Before rainfall, the change trend of surface and deep area of filling loess was basically the same. After rainfall, some surface water was discharged in the form of surface runoff and evaporation, and another part of surface water seeped through the loess pores under the action of gravity, and the water content of upper loess increased obviously. However, the change of water content in the lower area was very small, mainly due to the small thickness of rainwater accumulation, the water pressure due to gravity was small, and the driving force of water penetration was mainly matrix suction. The original pore structure of the remodeled loess was destroyed, the matrix suction was very small, the water flow channel was blocked, and the gas between the loess particles was difficult to exhaust. When the gas pressure and matrix suction reached equilibrium, the flow of water would stagnate.
Compared with the moisture content data at W1 and W2 points on 25 June before and after rainfall, the influence depth of rainfall was between 2.0 and 3.0 m.

4.2. Filling Site Water Storage Test

In order to obtain the infiltration of surface water under extreme conditions, a special water storage test was carried out in the filling area in front of a flood control dam from early July to late September 2013. Two drilling sampling holes (Figure 19) were set at 2.5 m near the water surface edge of the flood control dam top to measure the change of loess moisture content along the depth direction. The dry density test results of the loess in XS-2 are shown in Table 1. The distribution of compactness was relatively balanced, and the lower area mass density was relatively large. In addition, through laboratory experiments, it was found that the permeability coefficient of natural loess was generally 0.02–0.30 m/day; after compaction, the permeability coefficient was generally 0.001–0.110 m/day, and the penetration coefficient of individual points was very small, up to $1.1 \times 10^{-5}$ m/day. The permeability coefficients of natural loess and compacted loess show obvious dispersion, and the permeability of compacted loess was lower than that of natural loess by 1–2 orders of magnitude. The moisture content test results before and after the accumulations of water are shown in Figure 20. According to the moisture content test results in Figure 20, and combined with on-site drilling, the surface of the filling area was subjected to long-term water storage for nearly 3 months, and the infiltration depth of the water at the test point was about 7.0 m.

![Figure 19. Location of measuring points.](image)

![Figure 20. Test results of water infiltration depth.](image)
### Table 1. Density test results.

| Loess Sample Number | Loess Depth (m) | Dry Density $\rho_d$ (g/cm$^3$) |
|---------------------|-----------------|---------------------------------|
| XS2-1               | 0.8             | 1.60                            |
| XS2-3               | 2.6             | 1.72                            |
| XS2-4               | 3.8             | 1.52                            |
| XS2-5               | 4.4             | 1.67                            |
| XS2-6               | 5.9             | 1.68                            |
| XS2-7               | 6.4             | 1.57                            |
| XS2-8               | 10.4            | 1.69                            |
| XS2-9               | 13.2            | 1.69                            |

5. Discussion

In this paper, the foundation pit immersion test of undisturbed loess was first conducted. During the test, the water level in the test pit was maintained at 0.5 m, and the water injection amount was monitored every day. In the first 5 days of the test, the amount of water injected increased rapidly, especially on the 5th day. By monitoring the results of the moisture meter and from Figure 14, it can be seen that in the first 5 days, the water mainly infiltrated through the new loess, indicating that the new loess was very permeable. After the 5th day, the single-day water injection volume decreased rapidly, and reached a relatively stable state by the 10th day. According to the monitoring of the moisture meter, the water had infiltrated through the paleosol and the old loess during this period. After the 17th day, the water injection rate decreased rapidly, indicating that the water reached the clay area. In 10th–17th days, the water infiltration in the soil was dominated by lateral movement. When the lateral diffusion was stable and the downward diffusion was blocked, the water injection volume would be significantly reduced. After the water infiltrated through the clay area, the water injection volume gradually increased. Since geological exploration was only carried out for 26 m, the fluctuation of the later water injection volume cannot be analyzed in detail.

Then, the water infiltration range was determined according to the change time of the moisture meter. Moreover, the final infiltration range was determined through ZK3–ZK6. The soil under the test pit can be divided into new loess, paleosol, and old loess. The paleosol is relatively dense and has low permeability. As a result, when water infiltrated through here, the streamline bent and the lateral infiltration of water was blocked. After passing through the paleosol and reaching the old loess area, the water infiltration line was closer to the beginning. Its final shape was close to a “horn”. It can be seen from Figure 15 that the law of water movement in the literature was quite different from the results of this paper, and the final infiltration shape was similar to an “apple”. This might be related to its large vertical permeability coefficient. When the vertical permeability was very large, the lateral permeability would decrease. It can be seen that although they were all loesses, there were obvious regional differences, resulting in the different permeability of the loesses. Due to the huge water injection volume of 14,492 m$^3$, the influence of its own gravity, and strength reduction, cracks appeared around the test pit (Figure 12), indicating that the loess has subsided, which is an important reason for the occurrence of geological disasters. [19–21] also did the similar immersion tests, most of the test results showed that the undisturbed loess had strong water absorption and permeability, the infiltration rate of water was very fast, and the loess showed collapsibility. In addition to the above-mentioned similar conclusions, the paper found that the water infiltration line was bent, this phenomenon was rarely mentioned in the above literature. However, the specific reasons for this phenomenon, for example, differences in porosity, water content, permeability coefficient, or matrix suction, require further theory and experimentation to verify.

There are few field tests on rainfall infiltration of backfills. In the previous literature, the infiltration depth of undisturbed loess during rainfall was studied, and it was found that its infiltration depth was only about 3 m, which was similar to the results of this paper. Although the loess parameters had a certain influence on the calculation results, the difference was not obvious. Under the influence
of rainfall, because there was no influence of water pressure, the driving force of water was mainly gravity and matrix suction. The undisturbed loess and backfilled loess showed the same test results, indicating that the depth of water accumulation had a greater impact on water infiltration in the loess.

The lower permeability coefficient of compacted loess and destruction of original loess structure made it difficult for surface water to infiltrate filling area in a short time. Although the water storage test generated water pressure due to the gravity of the water, when the suction and air pressure resistance reached equilibrium, the water penetration would stagnate again. Compared with the infiltration depth of 3 m in the rainy period, the infiltration depth of the field water storage test was only 7 m, which was much smaller than the infiltration depth of the original loess. There are few field tests on compacting and reshaping loess, but comparing this article with field tests on undisturbed loesses around the world, the infiltration depth was very shallow. For specific test results, please refer to the references cited in this article.

Through the test results of this article, it can be found that in actual engineering problems, the infiltration rate and depth of water in loess can be effectively reduced by means of dynamic compaction and rolling. However, if uneven dynamic compaction causes a part of the area not to become dense, the water infiltration in the area will be very fast, and the strength of the area will be significantly reduced, which will cause engineering problems or geological disasters. This is worthy of further study and discussion.

6. Conclusions

In this paper, water immersion test of an undisturbed loess foundation pit, water content test in rainy season, and water storage test of backfill loess site were carried out, and the infiltration law of water in undisturbed loess and remolded loess was compared and analyzed. The following conclusions were drawn:

Infiltration rate of undisturbed loess was very fast and water would always infiltrate in the in situ water immersion test, after 9 days of water storage, the infiltration depth of water was close to 25 m, which was closely related to the macro porous structure of loess. In the in situ test, although underwater infiltration experienced areas with large difference in loess parameters, such as new loess, paleosol, and old loess, among which the permeability coefficient of paleosol and old loess was very low, water could still infiltrate downward through the pore between loess grains, and finally reached the phreatic layer. Furthermore, because of the differences of density, permeability coefficient, porosity, and water content among the new loess, paleosol, and old loess, refraction occurred in the water infiltration line.

The seasonal rainfall test and the surface water storage test in filling area on the loess plateau showed that, the water infiltrated only about 3 m in 25 days and 7 m in 50 days, respectively, it was obviously different from the in situ immersion test. After the backfill loess had experienced the vibration load such as rolling and compaction, porosity decreased and compactness increased, the permeability coefficient was reduced by 1–2 orders of magnitude, the original structure of the loess had also been destroyed, the pore channel between the loess particles was blocked, the sealing gas in the loess was also difficult to be discharged, the rate of water infiltration was very slow. The research results of this paper provide a reference for engineering construction on loess.

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