Experimental analysis of infiltration process and hydraulic properties in soil and rock profile in the Taihang Mountains, North China

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ABSTRACT

In this research, an experiment was conducted in the Taihang Mountains in China with a self-designed automatic soil and rock water infiltration monitoring system and a time domain reflectometry (TDR) device to analyze the infiltration process of disturbed soil and rock profile under constant head, unsaturated seepage properties and permeability coefficient of discontinuous rock masses. It was found that the infiltration process curve has an obvious fluctuation in the late stage of unsaturated seepage (after 18:00 p.m. on March 20th) which not only reflects the temporal variation of infiltration rate, but the spatial variation of rock structure. The lateral soil water of soil and rock dual-texture mainly flows in the interface of soil and rock. The infiltration rate of soil water can be as high as 2.42 × 10⁻⁴ cm/s, accounting for about 20% of the stable infiltration rate. After the water infiltrated in the lower rock layers, the water was mainly stored and flowed in the fissure network in the rocks, but did not completely fill the whole fissure network. Firstly, the local priority channel is adopted to infiltrate. With the increasing of rock saturation, the local priority channel will also expand and finally extend to the whole fissure network. The permeability coefficient of the soil and rock dual-texture in the study area is 1.26 × 10⁻³ cm/s.

HIGHLIGHTS

- A set of automatic measurement systems for the infiltration was designed.
- Infiltration process curve of heterogeneity soil has an obvious fluctuation in the late stage of unsaturated seepage.
- The permeability tensor of heterogeneity soil is 1.26 × 10⁻³ cm/s.

1. INTRODUCTION

Mountain regions are a major source of surface water and groundwater recharge in the world (Viviroli et al. 2007; Dettinger 2014). Watersheds in mountainous regions provide between 40 and 80% of the water resources available to lowland settlements (Messerli et al. 2004), therefore water resources recharge is the focus of environmental benefits in headwater catchments (Křeček et al. 2017; Ostad-Ali-Askari & Shayannejad 2021). The water balance in mountainous regions is defined by the interactions between the climate, cryospheric, and hydrological systems (De Jong et al. 2005; DeWalle & Rango 2008). The semi-humid Taihang Mountain region in the North of China is the most important groundwater recharge area of the North China Plain (Sakakibara et al. 2017). Besides, Taihang Mountain plays important roles in ecological service, water conservation and climate regulation for surrounding regions (Hu et al. 2019), especially for Xiongan New Area, ‘a strategy crucial for a millennium to come’ by the Chinese government (Song et al. 2018). One noticeable characteristic of Xiongan is that it is located in the region of slow flooding and stagnation of the Daqing River, which originates from the eastern Taihang mountain and its current flood recurrence period is only one in ten years, and it has suffered many flood disasters (Xia & Zhang 2017). Taihang Mountain is located in a region with large relief caused by limestone uplift (Wang & Li 2008) and is greatly affected by the Asian monsoon during the rainy season (Yamanaka et al. 2004; Liu et al. 2010). These factors generate...
topographical and meteorological heterogeneities (Sakakibara et al. 2017). Due to physical, chemical, biological weathering and other geological processes, the geologic formation of Taihang Mountain is comprised mainly of featured rock-masses of granitic gneiss origin. Strata with extensive weathered rock underlying thin surface soil layers are typical geologic features in this critical headwater mountain region (Cao et al. 2005). The mechanism of the water cycle and the characteristics of the water conversion in the Taihang Mountain is not yet clear (Song et al. 2007).

Previous studies have attempted to estimate the effective saturated permeability coefficient of an unsaturated soil using a constant head bore hole test (Sasidharan et al. 2019). For example, analytical solutions have been developed to determine the hydraulic properties of a homogenous soil domain using constant head data and numerical simulations have been conducted to evaluate the accuracy of these analytical solutions (Xiang et al. 1997). Moreover, a number of research advances have been made in soil preferential flow and spatial variability of soil characteristics. However, because most field soils are highly heterogeneous and the permeability coefficient may change over a short distance (Sasidharan et al. 2019), under the assumption of soil homogeneity in these analytical solutions, the estimates of the permeability coefficient were often unrealistic (Reynolds & Elrick 1985).

For this kind of ‘overlying soil and underlying rocks’ stratum, here we call it soil and rock dual-texture, the study of water movement and transformation mechanism is still relatively weak both in indoor experiment, numerical simulation and field experiment. First, in the study of hydrological processes and mountain ecosystems in mountain basins, only the upper soil layer is generally considered, while the underlying weathered rock layer is less considered, or the porous media are treated as the same layer as the upper soil layer (Yair & Raz-Yassif 2004; Frot et al. 2008; Yu et al. 2009; Zhu & Lin 2009). Such treatment not only covers up the influence of the underlying weathered fissured rock masses on the rainfall infiltration and redistribution, but also ignores the reservoir and permeability function of the underlying weathered fissured rock masses layer, so it is difficult to reflect the real situation of water movement and transformation in soil and rock dual-texture. Second, in hydrogeology, engineering geology and environment geology research, scholars mainly concentrated on the saturated seepage characteristic and seepage and stress coupling relationship of fractured rock in deep bedrock, the consideration of the unsaturated percolation flow characteristics of surface weathering rock is not enough (Shen & Wang 2002; Feng et al. 2004).

Therefore, the objective of this study is to reveal the water movement and transformation mechanism of soil and rock dual-texture in a mountain system based on a large permeameter device with a length of 2 m, a width of 1 m, a depth of 3 m and a self-designed automatic soil water infiltration monitoring system and a time domain reflectometry (TDR) device. The results of the study could add new perspectives to existing water management strategies for greater enhancement of agro-environmental and socio-economic sustainability and promote water resource management in the North China Plain. The conclusions are of great significance for the knowledge and understanding of the hydrological cycle process in mountain ecosystems and the recharge of groundwater in mountains to plains and future flood control and sustainable development of the water resources of Xiongan.

2. MATERIALS AND METHODS

2.1. Study area

The experiment was conducted in the Taihang Mountain Ecological Experimental Station of Chinese Academy of Sciences, which is located at 114°15′50″E, 37°52′44″N. The Taihang Mountain Station with an altitude of 350 m is in the middle of the eastern Taihang Mountain in Hebei Province, northern China. It is a hilly area in the transition from plain to plateau (Figure 1). This region has a semi-arid continental monsoon climate with an annual average temperature of 13.0 °C, the average annual precipitation is 560 mm and water surface evaporation is 1,200 mm. It is the central area where the east-west moisture gradient and the north-south heat gradient intersect in China, with good geographical representation and typicality. The typical vegetation type is mainly 20-year old secondary forest and scrub, the secondary forest is mainly Robinia pseudoacacia, and the shrubs are mainly Vervain Family and wild jujube. Some of their roots are distributed in the soil layer, and some of them are distributed in the fissures of the lower weathered rock. The hill slopes are composed of stratum characterized by ‘overlying soil and underlying rock’. The overlying soil layer is thin, with a thickness of 20–50 cm and mainly constituted of gravel. The thickness of the underlying rock layer, which is mainly a weathered layer of gneiss full of fissures, is 0.5–10 m. With the increase of the depth, the discontinuous texture frequency and permeability of weathered rock are reduced one after another. In addition, the surface between soil layer and weathered rock layer is uneven, and some irregularly shaped debris is interspersed (Cao et al. 2013). Due to the developed weathering fissures, rainfall redistribution is main
vertical infiltration, and the average annual surface runoff coefficient is small, seepage flow in the fissured rock mass occurs throughout the year (Han et al. 2012).

2.2. Experiment design
For this experiment, it is the most ideal and representative to dig up a large enough rock from the slope. While, because of the integrity and weakness of the rock, the difficulty of digging is increased with the increase of sample volume. When the sample size is up to a few cubic metres, the digging workload and difficulty is quite large, it is also difficult to ensure the integrity of the sample. Therefore, in this study, we use the disturbed composite rock and soil samples; that is, the experiment design includes two parts, one part is to build a suitable permeameter device, and one part is to backfill the soil and rock into the permeameter device.

2.2.1. Permeameter device
Considering the completed permeameter device can be used in the mathematical model of fissured rock mass, the representative elementary volume (REV) of fissured rock mass should be smaller enough (generally for 1/20–1/50 times) the size of

![Figure 1 | Location of the study area.](image)
the permeameter device. The volume of a single piece of weathered rock from the natural hillslope is generally about 0.025 m$^3$ (0.4 m $\times$ 0.25 m $\times$ 0.25 m). Therefore, the permeameter device volume should be larger than 1 m$^3$. Considering the requirements of surface runoff on hillslope length and evaporation from groundwater on the depth of groundwater, the length, width and depth of the permeameter device were determined to be 2 m $\times$ 1 m $\times$ 3 m, respectively.

2.2.2. Backfilling soil and rock

The backfilling process of soil and rock include three steps. First, in the bottom of the permeameter device, a layer of sand and gravel with a thickness of 5 cm was laid as the filter layer (Figure 2(a)), and then the rock layer was backfilled. We used the method ‘one layer of rock, one filling of mud’ to ensure all the gaps between rocks could be filled with the mud (Figure 2(b) and 2(c)). The thickness of the rock layer is 2.5 m (Figure 2(a)). Finally, the soil layer was backfilled. The thickness of the soil layer is 0.5 m. During backfilling, five cross-pointer soil-rock water sensor (CS616) soil water sensors (Campbell Scientific, Inc., USA) (one in soil, three in gap filler and another in rock) and draft tubes were buried at different soil depths, including 30 cm, 60, 100 and 200 cm, and there are two sensors at the 200 cm depth (Figure 2(a)).

The experiment equipment consists of six components, including a permeameter device, constant head water supply device, tipping-bucket flow meter, water reservoir, pump and funnel (Figure 2(a)).

We conducted three experiments from March 20th to March 21st, 2009. The first experiment was to study the variation of flow in the permeameter device and to analyze the infiltration process. Under the basis of steady infiltration rate, we conducted the second and third experiments to estimate the permeability coefficient of soil and rock dual-texture.

Different from the first infiltration test, we conducted the last two infiltration tests in the case that the outflow of the permeameter device ($Q_2$) is zero. Above the upper soil layer and below the outlet of the permeameter device, there is 10 cm

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Figure 2 | A sketch of the experiment equipment, permeameter device listing the general information on the soil and rock backfilling process, the automatic infiltration monitoring system (a), (b) depicting the rock of the backfill; and (c) denoting the gap filler between rocks. 1- permeameter device; 2- constant head water supply device; 3- tipping-bucket flow meter; 4- water reservoir; 5- pump; 6- funnel.
depth of water (Figure 2(a)). Through controlling the 10 cm depth of water constantly, the infiltration processes are also carried out under a constant head.

2.3. Soil and rock masses basic properties

The rock masses were constituted of rocks and gap fillers. The backfilled rocks in the permeameter device were dug from the natural hillslope. The gap fillers are mud and they were made through placing the wet mud in a bucket where gravity water could be discharged at the bottom, and then air-dried naturally in the laboratory. The basic properties of soil and rock masses include physical properties and grain size composition, which were measured by us in the laboratory.

For the physical properties (Table 1), the bulk density of rock masses can be obtained by volume weighted average according to the bulk density of rocks and gap fillers under the assumption that there is no individual difference between rocks and that the fillers are evenly distributed in the gaps between rocks. As shown in Table 1, it is 1.96 g/cm³. The gap rate of rock masses, considered as the ratio of the volume of gap fillers to the total volume of rock masses, is 35.1%.

For the grain size composition of the soil in the upper soil layer, it mainly concentrated below 1 mm, accounting for about 62% (Table 2). The grain size above 5 mm is less than 10%.

The grain size composition of the gap filler in the lower rock mass layer mainly concentrated below 0.5 mm, accounting for 61.39% (Table 3).

2.4. Infiltration process measurement

The soil and rock infiltration process was monitored under constant head with the depth of 0.15 m. The equipment consists of a pump, a water supply device with constant head, and a tipping-bucket flow meter (Figure 2(a)). Based on the principle of dynamic water balance, the infiltration rate at any specific time can be calculated as follows:

\[
v = Q_1 - Q_2 = \frac{Q_3}{A}
\]

where \(v\) is the infiltration rate, in cm/s; \(Q_1\) is the flow of the water supply device, in ml/s; \(Q_2\) is the outflow of the permeameter device, in ml/s; \(Q_3\) is the infiltration flow into the soil and rock mass, in ml/s; and \(A\) is the cross section area of the permeameter device, in cm².

Table 1 | Physical properties of the soil and rock-mass in the permeameter device

| Layer            | Medium   | Volume (m³) | Bulk density (g/cm³) | Specific gravity | Saturated water content (%) | Permeability coefficient (cm/s) | Specific yield (%) | Gap rate (%) |
|------------------|----------|-------------|----------------------|------------------|----------------------------|---------------------------------|-------------------|--------------|
| Soil layer       | Soil     | 1.0         | 1.43                 | 2.65             | 45.6                       | 6.94 × 10⁻⁴                    | 5.2               |              |
| Rock mass layer  | Gap filler | 1.75       | 1.34                 | 2.65             | 46.9                       | 5.83 × 10⁻⁴                    | 4.1               | 35.1         |
|                  | Single rock | 3.25       | 2.31                 | 2.68             | 8.26                       | 2.64 × 10⁻⁵                    | 0.92              |              |
|                  |          | 5.00        | 1.96                 | 2.67             |                            |                                 |                   |              |

Table 2 | Grain size composition of the soil in the upper soil layer (%)

| Grain size | 0.1 mm | 0.1-0.2 mm | 0.2-0.5 mm | 0.5-1 mm | 1-2 mm | 2-3 mm | 3-5 mm | 5-7 mm | 7-10 mm | > 10 mm |
|------------|--------|------------|------------|----------|--------|--------|--------|--------|---------|---------|
| 20.25      | 10.81  | 11.87      | 19.41      | 15.79    | 3.41   | 9.89   | 3.14   | 2.25   | 3.18    |         |

Table 3 | Grain size composition of the gap filler in the lower rock mass layer (%)

| Grain size | 0.1 mm | 0.1-0.2 mm | 0.2-0.5 mm | 0.5-1 mm | 1-2 mm | 2-3 mm |
|------------|--------|------------|------------|----------|--------|--------|
| 30.14      | 19.38  | 11.87      | 19.41      | 15.79    | 3.41   |        |
\[ Q_1 \] is obtained directly from the water meter at the outlet of the water supply device, \[ Q_2 \] (surface runoff), \[ Q_4 \] (groundwater runoff) and \[ Q_5 \] (interflow at different soil depths) are measured by the tipping-bucket flow meter (Figure 2(a)). And \[ Q_3 \] is calculated by \( (Q_1 - Q_2) \).

### 2.5. Soil and rock masses water measurement

The five water sensors were connected to the CR10X data collector for automatic data collection and the data were collected at 20 min intervals. According to the volume of the soil, gap filler and rock (Table 1), the calculation formula of soil and rock masses water content of the permeameter device is as follows:

\[
W = \frac{1}{100} \sum_{i=1}^{n} V_i W_i
\]  

where \( W \) is the total water content of soil and rock at a certain time, in m³; \( n \) is the number of the soil and rock parts, in this study, \( n = 3 \); \( V_i \) is the volume of part \( i \), in m³; and \( W_i \) is the water content of part \( i \) at the corresponding time, in %. In this paper, formula (2) should be as follows:

\[
W = \frac{1}{100} \times [1 \times W_{30} + 1.75 \times (3W_{60} + 7W_{100} + 15W_{200})/25 + 3.25 \times W_{200}^r]
\]  

where \( W_{30}, W_{60}, W_{100} \) and \( W_{200} \) are the water content of soil and gap filler at the depths of 30 cm, 60, 100 and 200 cm, in %; \( W_{200}^r \) is water content of rock at the depth of 200 cm, in %.

The soil and rock water increment of the permeameter device in a certain period is as follows:

\[
\Delta W = W_e - W_s
\]  

where \( \Delta W \) is the total water variation content of the permeameter device in a certain period, in m³; \( W_e \) is the total water variation content of the permeameter device at the end of this period, in m³; \( W_s \) is the total water variation content of the permeameter device at the beginning of this period, in m³.

### 2.6. Permeability coefficient measurement

The permeability coefficient of the soil and rock dual-texture \( k \) (in cm/s) was determined as follows:

\[
k = \frac{1}{6} \times 10^{-5} \times \frac{Q}{A} \times \frac{L}{H}
\]  

where \( Q \) is the infiltration flow, in ml/min, in this paper, it is \( Q_3 \); \( A \) is the cross section area of the permeameter device, in this study, \( A = 2 \text{ m}^2 \); \( L \) is the infiltration path length, in m, in this paper, \( L = 3 \text{ m} \); \( H \) is the head difference, in this study, \( H = 3.15 \text{ m} \).

If there are several hydraulic connected aquifers with different permeabilities, the permeability coefficient can be calculated by the weighted average value of the permeability coefficient of each aquifer and the thickness of the aquifer. Therefore, the calculation formula of the permeability coefficient of the rock mass layer \( k_r \) (in cm/s) is as follows:

\[
k_r = \frac{h_r}{h_e} \times \left( k - k_s \times \frac{h_s}{H} \right)
\]  

where \( k_s \) is the permeability coefficient of the upper soil layer, in this paper, it is \( 6.94 \times 10^{-4} \text{ cm/s} \); \( k \) is the permeability coefficient of soil and rock dual-texture, in cm/s; \( h \) is the depth of soil and rock dual-texture, in this paper, it is 3.0 m; \( h_r \) is the depth of the rock mass layer, in this paper, it is 2.5 m; \( h_s \) is the depth of the soil layer, in this paper, it is 0.5 m.

### 3. Results and Analysis

Three infiltration experiments with constant head were conducted and the results are shown in Table 4, including the amount of surface runoff, infiltration flow, total interflow at the soil and rock interface, the total groundwater runoff, maximum
groundwater runoff, outflow time from infiltration and groundwater runoff coefficient, and the soil and rock water increment of the permeameter device. As shown in Table 4, the total infiltration flow, water increment, and groundwater runoff of those three infiltration processes (from 12:35, March 20th to 20:00, March 25th) was 1,197.2 mm, 618.65 mm and 476.15, respectively.

The first infiltration test was set as the example, which started at 12:35 p.m. on March 20th and ended at 4:00 a.m. on March 21st, 2009.

3.1. Infiltration process of soil and rock

As shown in Figure 3, the initial infiltration rate was 5.0 mm/min, and decreased about 75.7% in the first two hours (from 12:35 to 14:40). The infiltration tracked an obvious inflection curve at 14:35 with the rate of 1.2 mm/min, and then followed by a slow decline. The rate stabilized at 0.8 mm/min (1.33 × 10⁻³ cm/s) after 3:30 a.m. on March 21st. It takes about 15 hours to achieve steady infiltration in the soil and rock dual-texture. A function of infiltration rate and time is

\[ y_{\text{infiltration rate}} = 4.338t^{-0.395} \quad (R^2 = 0.91, \quad N = 94, \quad P < 0.01) \]

In addition, in the late stage of the infiltration (from 18:00 on March 20th to 4:00 a.m. on March 21st), the infiltration process curve has an obvious fluctuation (Figure 4), which belongs to a pulse flow, this should be related to the characteristics of the fracture network in the lower rock layer and the water exchange between fracture and rock.

3.2. Soil and rock interflow

The experimental results show that the lateral interflow of rock and soil mainly occurs at the rock-soil interface. Interflow occurred at 14:09 p.m., which was 2 hours later than the infiltration (Figure 5). In the initial stage, the rock-soil interface flow rapidly increased and reached the maximum value of 290 ml/min (2.42 × 10⁻⁴ cm/s) at about 15:30 p.m., and was then followed by a steady flow. At about 21:30 p.m., the total interflow runoff was 58.4 mm (Table 4).

3.3. Groundwater runoff

Figure 6(a)–6(c) plot the process curves of groundwater runoff during the three infiltration processes. Groundwater runoff occurred in those three infiltration processes, suggesting that water infiltrated the soil layer with a depth of 300 cm. However, the total groundwater runoff, maximum groundwater runoff, outflow time from infiltration and groundwater runoff coefficient were significantly different for the three infiltration processes (Table 4).

### Table 4 | Water balance and groundwater runoff of the permeameter device

| Experiment | Time period          | Infiltration flow (mm) | Surface runoff (mm) | Total interflow (mm) | Water increment (mm) | Total flow (mm) | Maximum runoff (ml/min) | Outflow time (h) | Runoff coefficient (%) |
|------------|----------------------|------------------------|---------------------|----------------------|----------------------|-------------------|--------------------------|-------------------|------------------------|
| 1          | 12:35, 03/20–04:00, 03/21 | 529.5                  | 451.5               | 58.4                 | 469                  | 2.1               | 15.29                    | 5                 | 0.397                  |
| 2          | 13:00–19:30, 03/21     | 192.5                  | 0                    | 0                    | 186.3                | 6.2               | 22.8                     | 14                | 3.22                   |
| 3          | 9:19–21:37, 03/24      | 475.2                  | 0                    | 0                    | 7.35                 | 467.85            | 1,582                    | 34                | 98.45                  |
| 4          | 12:35, 03/20–20:00, 03/25 | 1,197.2               | 451.5                | 58.4                 | 618.65               | 476.15            | –                        | –                 | –                      |

### Figure 3 | Infiltration curve of the soil and rock dual-texture.
For the first infiltration process, the groundwater runoff occurred at 2:50 a.m. on March 21st, which was about 13.5 hours later than the infiltration (Figure 6(a)). It takes 2.5 hours for the runoff to reach the maximum value, at about 5:15 a.m., and the maximum value maintained for 1.5 hours. The groundwater runoff started to decrease rapidly at 6:50 a.m. and eventually stopped at about 7:55 a.m. on March 21st. The total outflow time was 5 hours with a total outflow of 2.1 mm, runoff coefficient is 0.397% and maximum groundwater runoff flow is 15.29 ml/min (1.28 x 10^{-5} cm/s) (Table 4), which is much smaller than the stable infiltration rate (1.33 x 10^{-3} cm/s). It can be concluded the soil and rock dual-texture was highly unsaturated.

For the second infiltration process, the groundwater runoff occurred at 14:40 p.m. on March 21st; which was about 1.7 hours later than the infiltration (Figure 6(b)). It takes 1.6 hours for the runoff to reach the maximum value, at about 16:20 p.m., and the maximum value maintained for 9 hours. The groundwater runoff started to decrease rapidly at 1:40 a.m. on March 22nd and eventually stopped at about 4:40 a.m. on March 22nd. The total outflow time was 14 hours with a total outflow of 6.2 mm, runoff coefficient is 3.22% and maximum groundwater runoff flow is 22.8 ml/min (1.9 x 10^{-5} cm/s) (Table 4), which is still much smaller than the stable infiltration rate (1.33 x 10^{-3} cm/s), indicating the soil and rock dual-texture was still highly unsaturated.

For the third infiltration process, the groundwater runoff occurred at 10:40 a.m. on March 24th; which was about 1.3 hours later than the infiltration (Figure 6(c)). It takes 1.3 hours for the runoff to reach the maximum value, at about 12:00 p.m., and the maximum value maintained for 7.6 hours. The groundwater runoff started to decrease rapidly at 19:40 p.m. on March 25th and eventually stopped at about 20:40 a.m. on March 25th. The total outflow time was 34 hours with a total outflow of 467.85 mm, runoff coefficient is 98.45% and maximum groundwater runoff flow is 1,582 ml/min (1.32 x 10^{-3} cm/s), which is very close to the stable infiltration rate (1.33 x 10^{-3} cm/s), indicating the soil and rock dual-texture was almost saturated. We can conclude that the saturation of soil and rock dual-texture depends on the outflow time of underground runoff. We attempted to establish the relationship between the maximum groundwater runoff flow and outflow time in the soil and rock dual-texture and it can be described as an exponent function (Figure 7). However, three points are too few to prove it.
Figure 6 | Process curves of the groundwater runoff in three infiltration experiments, (a) the first time; (b) the second time; (c) the third time.

Figure 7 | The relationship between the maximum groundwater runoff flow and outflow time.
3.4. Soil and rock water dynamics

The soil and rock water curves for different depths of the three infiltration processes are plotted in Figure 8, including the depth of 30 cm, 60 cm, 100 cm, and 200 cm. The data were collected with an interval of 20 minutes. For the soil and rock, during the whole process from unsaturated to saturated, the soil and rock water shows obvious spatial and temporal variability.

Specifically, for the first infiltration process, the soil and rock water at the depths of 50, 60 and 100 cm had obvious response to the infiltration process, while the soil and rock water at the depths of 200 cm had no response to the infiltration process, no matter the fissure or rock.

In the second infiltration process, because of the short interval time with the first infiltration process, the soil and rock water at the depths of 50, 60 and 100 cm decreased little, especially at depths of 60 and 100 cm, there is no clear response to the infiltration process, while the soil and rock water at the depths of 200 cm, both in the fissure and rock, had an obvious response. As for the third infiltration process, the soil and rock water at each depth all had obvious response to the infiltration process.

In those three processes of infiltration, the rock water at 200-cm depth showed the same change trend with gap filler of 200-cm depth, but their water increment and the infiltration process showed obvious differences. The water increment of the rock surface is less than the gap filler and the response time of the rock water is also later than the gap filler. It can be shown that in the process of infiltration, the rock surface not only absorbs water, but also conducts water, infiltrated water mainly being stored and flowed in the fissure network in the rocks. There exists a water exchange process between rock and fissure; in the increasing stage of soil and rock water, the rock is recharged by the fissure. And in the decreasing stage, the fissure is recharged by the rock.

According to the principle of water balance, we calculated the soil and rock increment ($\Delta W$) of the permeameter device at different periods (Table 4). $\Delta W$ was 618.65 mm during the period of 12:35 p.m. on March 20th and 20:00 p.m. on March 25th, 2009. With the measured values of soil and rock water and formula (4), $\Delta W$ was calculated again, and was 575.1 mm. It can be seen that the calculated result based on the measured value of soil water is very close to that of the water balance of the permeameter device, with a difference of only about 7.0%.

3.5. Permeability coefficient

As shown in Table 4, the amount of infiltration water (475.2 mm) was very close to the total outflow of groundwater runoff (467.85 mm) during the third infiltration process, which indicates the soil and rock dual-texture of the permeameter device.
was almost saturated. At this time, the maximum groundwater runoff flow is 1.582 ml/min (Figure 5(c)). With Formula (5), the saturated permeability coefficient of the soil and rock dual-texture is $1.26 \times 10^{-3}$ cm/s. And the permeability coefficient of the rock mass layer is $1.37 \times 10^{-3}$ cm/s. The results were consistent with the previously reported permeability coefficient of granitic gneiss, ranging from $1.2 \times 10^{-3}$ cm/s to $1.9 \times 10^{-3}$ cm/s (Zhou & Wang 2004).

4. DISCUSSIONS

1. The combination of constant head water supply device and tipping-bucket flow meter can realize the automatic measurement of the soil and rock infiltration process, especially the automatic measurement of the soil and rock permeability coefficient. The amount and stability of outlet flow of constant head water supply device and the resolution of the tipping-bucket flow meter will directly affect the measurement accuracy of the infiltration rate. Due to the large volume of soil and rock, the infiltration process takes a long time, and the water consumption is large, while the principle of the Mariotte bottle is mainly applicable to the case of small water consumption and flow (Zhang et al. 2001; Lei et al. 2005; Mao et al. 2011). Therefore, on the basis of soil and rock infiltration characteristics and actual needs, we designed a set of constant head pressure water supply device that can provide larger flow and continuous water supply, and through the multiple regulations on the outflow of this water supply device, we can ensure the outflow of the permeameter device is in the measurement range of the tipping-bucket flow meter.

2. There is a fluctuation phenomenon in the curve of the rock and soil infiltration process. Whether it is caused by error or is real is worth further study. In fact, as in the late stage of the infiltration process, the measurement has tended to be stable, the influence of error should be small. Therefore, we think the fluctuation exists in the actual situation. When the water infiltrates through the upper soil layer into the rock layer, it will mainly store and flow in the fissure network (Nativ et al. 1995). However, the vertical fissures and horizontal fissures have differences in aspects of morphology, fissure width, roughness, and the ability of water storage and conductivity. If the water flowed in the vertical fissures, the infiltration rate will show an upward trend due to the strong ability for water storage and conductivity of the vertical fissures. While, with the weak ability in water storage and conductivity of the horizontal fissures, the infiltration rate will show a downward trend in the flow of the horizontal fissures. This fluctuation not only reflects the temporal variation of the infiltration rate, but the spatial variation of the rock structure. It should be related to the characteristics of the fissure network in rock masses and water exchange between fissures and rock masses.

3. It takes about an hour and a half for flow to be found at the soil and rock interface, which indicates the lateral soil water of soil and rock dual-texture mainly flows in the interface of soil and rock at the soil and rock dual-texture. Therefore, reasonable measures should be taken to optimize and regulate the preferential flow at the soil and rock interface to avoid disadvantages, utilize the positive effect on the formation of water resources, and minimize the negative impact on the stability of soil and rock hillslope.

In addition, for the last two experiments, the total interflow is zero (Table 4), which means there is no interflow at each soil depth. Generally, the two basic conditions for the generation of lateral soil flow are that the soil water content reaches a certain size and the permeability of the lower soil and rock layer is lower than that of the upper soil and rock layer (Hewlett & Hibbert 1965; Liu et al. 2002; Kienzler & Naef 2008). Therefore, it can be assumed that under conditions of continuous rainfall, when the water content of the soil reaches a certain value, its preference is vertical flow in the stratum characterized by ‘overlying soil and underlying rock’, which exists widely in the Earth-Rocky Mountain Area of North China.

4. The seepage paths of rock and soil dual-texture are significantly differentiated in space. The analysis results of rock and soil moisture change show that, in the first infiltration process, the rock and soil moisture change at the depth of 30, 60 and 100 cm has a relatively obvious response to the infiltration process, while the rock and soil moisture change at the depth of 200 cm has no change. However, the analysis results of the dynamic process of underground runoff show that the infiltration water has not only passed through the depth of 200 cm, but also reached the bottom of 300-cm depth and flowed out of the permeameter device. It seems a contradictory result with these two infiltration processes. The only explanation is that TDR just represents the soil water change at the point where the probe is at the 200-cm depth, it cannot explain the water change on the plane of the 200-cm depth. The water of the point has not changed, just indicating the water does not flow through this point. We cannot judge whether the water flows through other points on the plane of the 200-cm depth. The measured results of groundwater runoff indicate the average water change of the whole plane. The groundwater runoff indicates that the water infiltrated exceeded the depth of 200 cm and reached the depth of 300 cm.
However, at 200-cm depth, it is impossible to know the specific path. In the infiltration process of unsaturated seepage flow in soil and rock dual-texture, because of the complexity, heterogeneity and anisotropy of the rock mass structure, water mainly stored and flowed in the fissure network in the rocks, but did not completely fill the whole fissure network. Firstly, the local preferential path is adopted to infiltrate. With the increasing of seepage time, the local preferential path will expand and finally extend to the whole fissure network. This is consistent with the research results of Nicholl & Wheatcraft (1994) and Dahan et al. (1998, 1999).

5. CONCLUSIONS

In this study, a soil and rock dual-texture model with upper soil layer of 1 m³, lower rock mass layer of 5 m³, gap rate of 35% and gap filler was constructed. Based on the principle of dynamic water balance, we designed a set of automatic measurement system for the infiltration of soil and rock under constant head, and the system was well used to complete the automatic measurement of the infiltration process and permeability coefficient of the disturbed combination soil and rock. The measured permeability coefficient of soil and rock dual-texture was 1.26 × 10⁻³ cm/s; the permeability coefficient of undisturbed soil and rock can be estimated in situ according to the steady infiltration rate, but the estimated result may be large in general, because it takes at least 2 h for the infiltration process to be basically stable.

Due to the heterogeneity and anisotropy of soil and rock, the influence of the lower rock mass on water transport is much greater than that of the upper soil layer. Therefore, in the study and analysis of the hydrological process of the soil and rock mountain areas, the influence of the lower weathered and fissured rock mass on rainfall infiltration and redistribution in drainage must be considered. The characteristics of soil and rock interface, fissure network and water exchange between fissure and rock are the main factors influencing the unsaturated seepage of soil and rock dual-texture. The results of this study are helpful to explain the significance of the soil layer for improving the water conservation function in mountainous areas; for example, storing rainfall and replenish runoff and further exploring the recharge mechanism of groundwater from the mountain area to the plain and the possible ways of artificial regulation.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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