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In situ rainfall infiltration studies at a hillside in Hubei Province, China

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Abstract

Field infiltration tests were conducted at a hillside near the ship lock of the Three Gorges Dam in Hubei Province, China. The test site consists of residual soil and decomposed granite. The infiltration rate is estimated from the in situ tests to be $1.465–2.778 \times 10^{-6}$ m s^{-1}, depending on the initial water content. The rate at which the infiltration front moves down through the soil matrix within 2 m of the ground surface is estimated to be ca. 0.26 m day^{-1} on average. At the end of the in situ tests, the matric suction profiles show that the soil below a depth of 80 cm remained unsaturated, while the zone above was almost fully saturated. This finding was unexpected. The site was excavated after the test to examine the abnormal behaviour of the matric suction profiles in the depth. A relic joint was identified at a depth of 78 cm at an attitude almost parallel to the slope surface. It is surmised that the joint transmitted water laterally and limited further penetration of the wetting front. The water in the zone above the joint appeared to be 'perched'. This experiment indicates that, to describe thoroughly the infiltration process within a weathered jointed granite profile for slope engineering design purposes, a model based on the assumption of a uniform porous media is inadequate. The model should include the discontinuities. This is challenging since it requires field studies to identify the pattern and distribution of the joints. The implications of the experimental results on slope stability are discussed. The in situ tests provide important information for further studying groundwater seepage under rainfall conditions and a dewatering system design for the slope above the ship lock of the Three Gorges Dam in China.

Keywords: Groundwater; Infiltration test; Landslides; Slope failure; Soil suction; Unsaturated flow

1. Introduction

The Three Gorges Dam is located at the Yichang County, Hubei Province, P.R. China. The ship lock of the dam is excavated in granite to a depth of some 170 m. The upper some 40 m of the cut are in decomposed granite. The stability of the slope is extremely important and requires extensive studies on the mechanical, hydraulic and hydrologic properties of the saturated and unsaturated geological materials.

Rainfall is one of the most popular triggers of slope instability. The mechanisms by which rainstorms can lead to slope instability in the unsaturated zone in weathered igneous rock profiles include rainfall infiltration, percolation in the unsaturated part of a slope, and saturated ground-

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water flow resulting in rise in groundwater tables. However, the mechanisms are not yet fully understood. Experimental studies on unsaturated soils are generally costly, time-consuming and difficult to conduct (Wang and Benson, 1995). Field infiltration tests have been commonly used by many researchers to understand groundwater recharge for water supply purposes, but the field monitoring studies of matric suction (negative pore pressure) and rain infiltration in slopes in weathered igneous rock profiles for geotechnical purposes are relatively rare (Geotechnical Control Office, 1982; Krahn et al., 1989; Lim, et al., 1996).

In this paper, the result of field infiltration tests at a decomposed granite hillside near the ship lock of the Three Gorges Dam Area in Hubei Province, China, is reported. The in situ matric suction profiles are analysed and the infiltration capacity is estimated. After the test, the site was excavated in an attempt to understand the anomalous behaviour of the profiles. The implications of the experiment results on slope stability study are discussed. The in situ tests provide important information for further studying groundwater seepage under rainfall conditions and a dewatering system design for the slope above the ship lock of the Three Gorges Dam in China.

2. Site description

The test materials are residual soil and completely decomposed granite. The colour is yellow to grey. The soil consists of 95% of medium to coarse gravel. The dry unit weight of the soil is ca. 2.0 g cm^{-3} and the porosity is ca. 0.27. The hydraulic conductivity was estimated to be of the order of 10^{-7} m s^{-1} (Zhang et al., 1997). Apart from the very surficial zone which is structureless and has vegetation roots, the relic structure and texture of the granite remain in the soil. There are well-preserved joints. The horizontal linear joint density is ca 0.85–2.1 m^{-1}. The relic features will be destroyed after disturbance and thereby the mechanical and hydraulic properties will be changed. In situ experiments can avoid disturbance to the natural soil and provide data more representative of the natural soil.

The annual rainfall in Yichang County is ca. 1150 mm and most rainfall occurs from May to August. The maximum calendar daily rainfall was 386 mm. In order to avoid the uncertainty of the natural rainfall, artificial rainfall was used for the tests and the test period was chosen to be in the dry season (March to April). A canvas-covered shelter was built over the site to protect the infiltration apparatus system from natural rainfall. The regional water table is >24 m below the ground surface and the tested soil is far above the regional water table.

3. Infiltration apparatus and field measuring system

The emphasis of this preliminary study is to understand the infiltration rate and the hydraulic features of the highly decomposed unsaturated granitic materials. The vegetation changes significantly over the hillslope. The influence of vegetation and slope angle on infiltration is complicated. For this preliminary study, the effect of vegetation and slope angle is avoided by selecting a relatively flat area on the hillside and removing the top part (ca. 5 cm) of the vegetation and root zone. Considering the difficulties in finding a large flat area at the hillside and providing a large amount of water supply to the infiltration system, the test area was chosen to be 1×1 m^2 (Fig. 1).

The main body of the artificial rain apparatus is a box of Plexiglas reinforced with a steel sheeting. Columns and rows of outlets are arranged on the box bottom at a uniform spacing of 5 cm. A small plastic cap is fixed at each outlet, so that a syringe needle can be easily put in and taken off. Various rain intensities can be simulated by adjusting water pressure in the box and using different types of syringe needle. The box can be turned over, which makes it convenient to exchange syringe needles if necessary. The four supporters can be screwed up and down to set the box in a horizontal position. Before testing, the water pressure in the box and the flow rate out of the syringe needles were carefully adjusted until the desirable rain intensity is achieved.

This experiment was designed to measure the two vertical suction profiles (Profiles A and B)

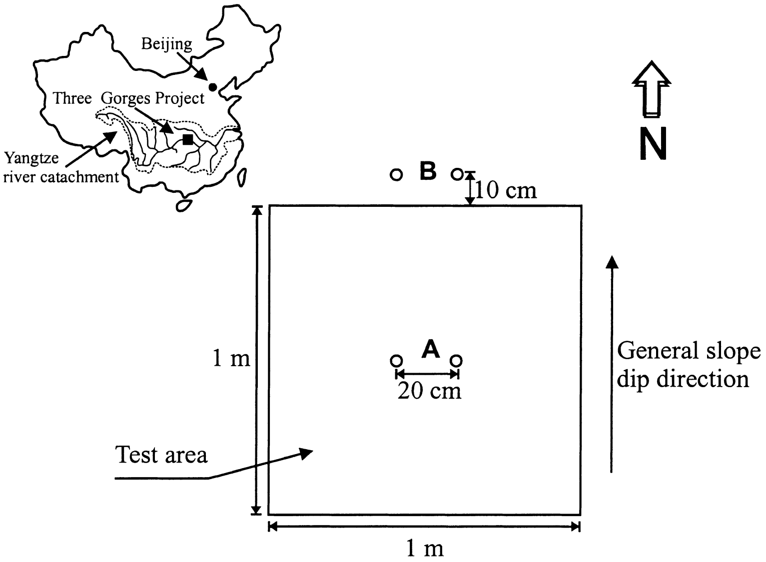

Fig. 1. Schematic plan view of the test site.

inside and near the test area (Fig. 1). At each profile, two holes of 3 cm diameter were drilled to install tensiometers. In each hole six tensiometers were installed, so one profile consists of 12 tensiometers. The vertical distance between the tensiometers in the two holes was 15 cm. The deepest tensiometer was installed at a depth of ca. 1.80 m below the surface. The horizontal distance between the two holes is small (ca. 20 cm) and at a given time during the test the difference in suction at a given depth is assumed to be negligible. There are plastic pipes connecting the tensiometers and the reading board on the ground surface. Each time after a tensiometer was installed, the hole immediately above the tensiometer was first refilled using the soil originally dug from the hole and then some grouting (cement) was added. The grouting between two tensiometers was ca. 10 cm thick. The purposes of the grouting were to fix the plastic pipes of the tensiometers and avoid any infiltration ‘short cut’ between the two tensiometers. The aim of the tensiometers outside the rainfall area was to monitor the lateral dispersion of the infiltration.

The tensiometer can sense the change of suction via the porous ceramic cup. After filled with de-aired water inside the cup, the surface of it will generate a film of water. When the suction is between 1 and 760 mm Hg height, water can pass through the cup but not air. After a tensiometer is installed, air-bubble-free water is filled into the tensiometer. Some water will pass through the cup, seep into the soil nearby, which influences the reading of the natural soil suction. To ensure the tensiometer to provide the correct reading, the tensiometers were installed 1 week before the test was started. It was believed that, by the time of the actual testing, the suction of the soil near the cup reached the equilibrium with the natural soil nearby. At equilibrium, the water in the tensiometer has the same negative pressure as the pore water in the soil.

4. Infiltration test

The tensiometers were installed on 31 March. The infiltration test was conducted between 5 April and 9 April 1997. Before the test started, readings of the matric suction of the tensiometers were taken. They are presented in Figs. 2 and 3. The two plots show the change of suction with depth at the two profiles. As can be seen, ca. 6 days after the tensiometers were installed, a few tensiometers

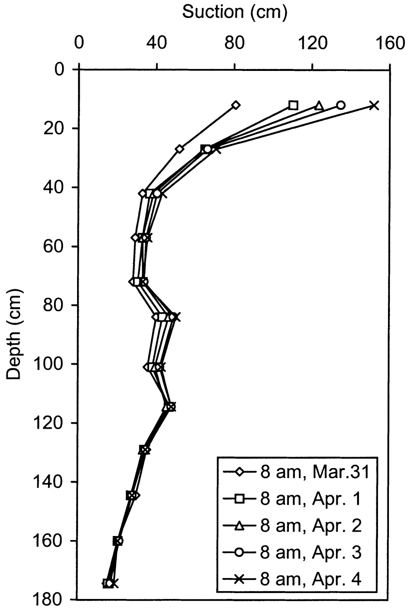

Fig. 2. Matric suction profile inside the test area (Profile A) before the 1997 test.

near the ground surface indicated a temporal increase in suction. This could be attributed to evaporation. Readings of tensiometers below 40 cm were stable and reflected the natural distribution of soil suction at this site.

Two rainfall intensities were used for the test. The test actually had three periods with 'low rain intensity', 'no rain' and 'high rain intensity' (Table 1). The high rainfall period had an intensity of 2.778×10^{-6} m s^{-1}, which was close to the maximum daily rain intensity in the Dam area during 1960–1968. The low rain intensity was $1.389–1.465 \times 10^{-6}$ m s^{-1}, equal to about half of the high intensity. The three periods lasted 64, 32 and 6.2 h, respectively.

4.1. *Analysis of the infiltration test in Period I*

During Period I, no surface water was ponded. Figs. 4 and 5 show the profile of suction distribution near the centre (Profile A) and the area beyond the boundary (Profile B) of the test area, respectively. As expected, the wetting front near the centre moved much faster than the area beyond the boundary. The profile in Fig. 4 shows that the

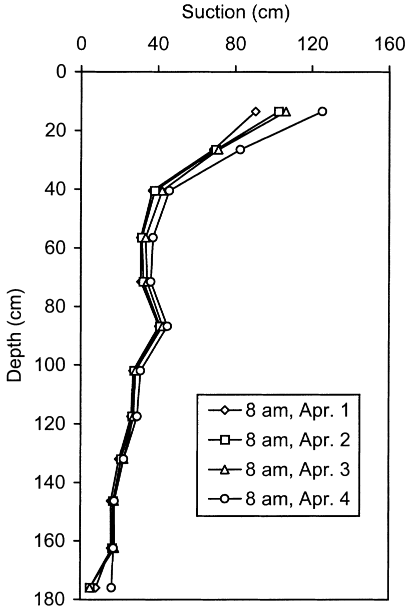

Fig. 3. Matric suction profile outside the test area (Profile B) before the 1997 test.

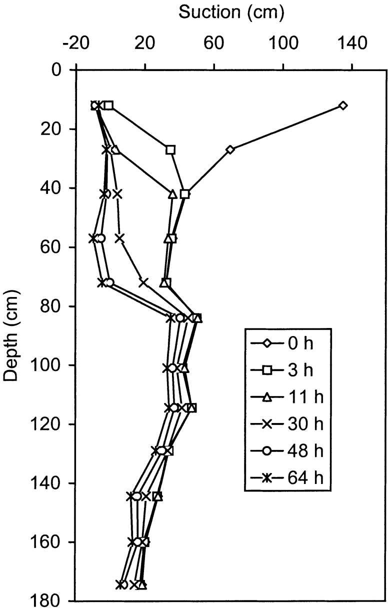

Fig. 4. Matric suction profile inside the test area (Profile A) during infiltration period I.

Table 1
Test periods, time duration and rain intensity

Test period	Period I		No rainfall	Period II
Time duration (h)	64		32	6.2
Starting time of different periods	5 April, 14:00 pm	6 April, 1:00 am	8 April, 6:00 am	9 April, 14:00 pm
Accumulative time (h)	11	64	96	102.2
Rain intensity (10^{-6} m s^{-1})	1.465	1.389	0.0	2.778

suction at the centre area decreased significantly at time = 3 h. The significant change of the suction at a depth indicated that the infiltration front had reached the depth. At 3 h, the profile shows that the front reached somewhere between the second and the third tensiometers. The suction of the Profile B, however, did not show any change at this time. This indicates that the lateral dispersion of infiltration did not reach this location yet. At Profile A, after 30 h, the soil above 60 cm became almost fully saturated. However, some tensiometers above 60 cm at Profile B still showed negative pressure. Even after 64 h, the soil suction below 80 cm did not change much.

Fig. 6 is the water content profile calculated based on the suction distribution at Profile A and water characteristic curves obtained from laboratory testing of the same kind of soil. Details of the calculation and laboratory testing can be found in Zhang, et al. (1997). Fig. 6 shows the advance of the infiltration front with time. The front reached the depth of 70 cm after 63.5 h. The rate at which the front moved was ca 0.26 m day^{-1}.

On basis of Fig. 6, the net increase of water amount in the soil near the centre area with time can be calculated. This net increase should equal the infiltration. Fig. 7 shows how the calculated cumulative infiltration (I_{centre}) at the centre of the site and observed cumulative rainfall (R) change with time. As shown in Fig. 7, I_{centre} calculated from this experiment is much less than R. For example, when $t = 20$ h, R is ca. 2.5 times greater

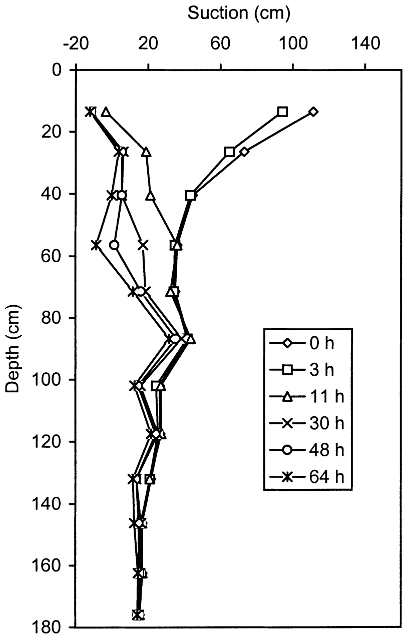

Fig. 5. Matric suction profile outside the test area (Profile B) during infiltration period I.

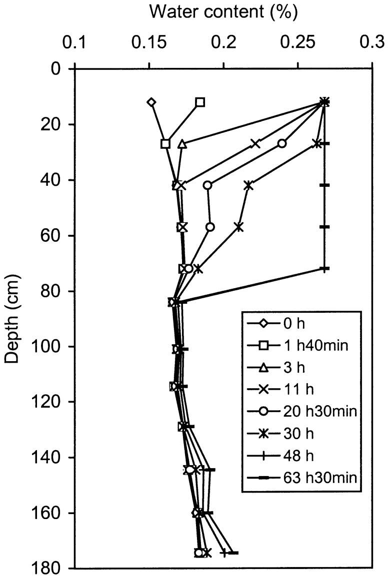

Fig. 6. Water content profile inside the test area (Profile A) during infiltration period I.

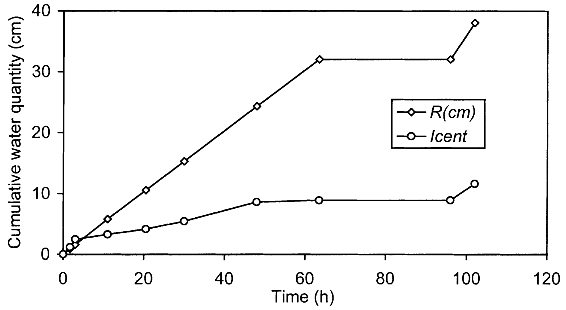

Fig. 7. Observed cumulative rainfall (R) and calculated cumulative infiltration at the centre (I_{centre}) via time in Period I.

than I_{centre}. It appears that a large portion of infiltrated water somehow disappeared from the system. Another interesting point is that, even after 64 h infiltration, matric suction below 80 cm did not indicate much change, as shown in Figs. 4 and 5. It seems that the infiltration front stopped for some reasons at the depth of ca. 80 cm.

4.2. Analysis of the infiltration test in Period II

After Period I, the infiltration stopped for 32 h before Period II started. The rain intensity in Period II was $2.778\times10^{-6}\,\mathrm{m\,s^{-1}}$. Figs. 8 and 9 show the matric suction profile before and during Period II. It can be seen that suction increased slightly at the end of 'no rain' period (see the curve at time = 95 h 51 min), which indicates the redistribution of soil moisture. However, suction of below 80 cm depth again did not show any visible change.

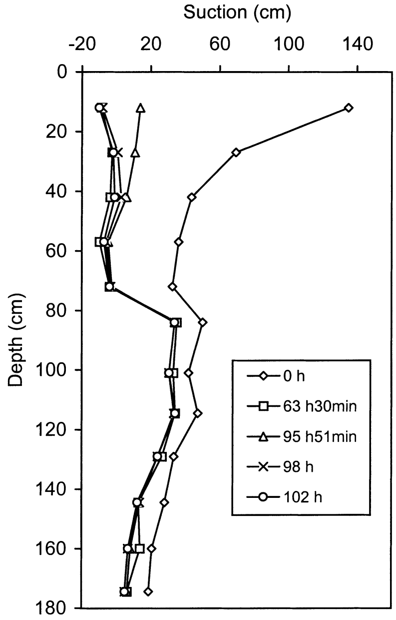

Fig. 8. Matric suction profile inside the test area (Profile A) during infiltration period II.

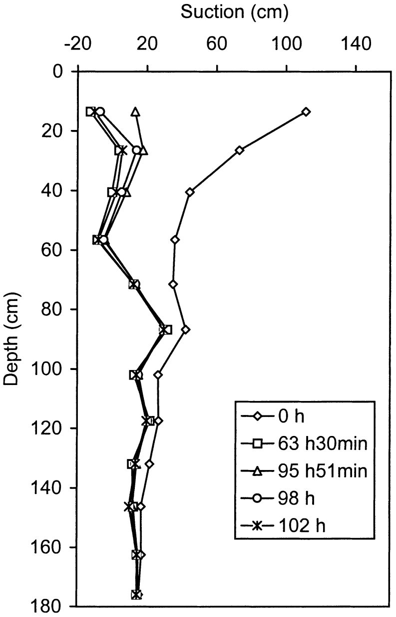

Fig. 9. Matric suction profile outside the test area (Profile B) during infiltration period II.

About 10 min after the infiltration in Period II, surface water ponding was generated, but the ponding was not significant even after 6 h of infiltration and the thickness of the water on the surface was <1 cm. The matric suction in the shallow zone responded to rainfall quickly and the soil became saturated soon, but the matric suction in the deep zone remained almost unchanged.

5. Excavation of the site after the test

After the test, the site was excavated in an attempt to understand the anomalous behaviour of the suction profiles and to check if the tensiometers were installed properly. The excavation started from the downhill side of the test area and gradually advanced to the centre of the site. At the distance of 85 cm from the northern boundary of the test area and at a depth of 1.2–1.3 m, there was a horizontal seepage zone and it was quite obvious that the seepage came from the infiltrated water. After a careful examination, the water was found to seep out along a relic joint. Further excavation toward the centre of the test site indicated that the joint had a gentle dip angle ($<20°$) with roughly the same dip direction as the slope. The joint extended all the way beyond the southern side of the test area and cut through the centre of the test site at a depth of 78 cm. It is suggested that the discontinuity is a controlling factor in the process of infiltration. The existence of the joint explained abnormal behaviour of the vertical suction distribution. Rainfall penetrated down until it reached the joint at 78 cm. After that a large portion of water flowed laterally along the more-permeable joint zone. Consequently, the suction and water content below that joint did not change much. This also explained why the infiltration rate (I_{centre}) calculated from a model based on a continuous soil medium was much lower than the actual infiltration rate (R).

In addition, excavation showed that all the tensiometers were installed properly, but the bore holes were not quite vertical and the depth of some tensiometers was slightly different from expected. The vertical location of the tensiometers was then corrected before the data were used for analysis. The excavation also showed that the lateral penetration of the cement was limited and it is believed that the influence of the cement on the overall permeability of the soil was insignificant.

6. Discussion and summary

The in situ experiments showed that, during the test periods, the initial infiltration rate of the surface soil is $>1.465\times10^{-6}\,\text{m s}^{-1}$. When the infiltration increased to $2.778\times10^{-6}\,\text{m s}^{-1}$, surface water ponding was generated. It can be seen that the infiltration rate depends on the initial water content in the soil. This experiment also indicates that, to describe thoroughly the infiltration process, a model based on the assumption of a uniform porous media is inadequate and should include the discontinuities. This is challenging since it requires field studies to identify the pattern and distribution of the joints.

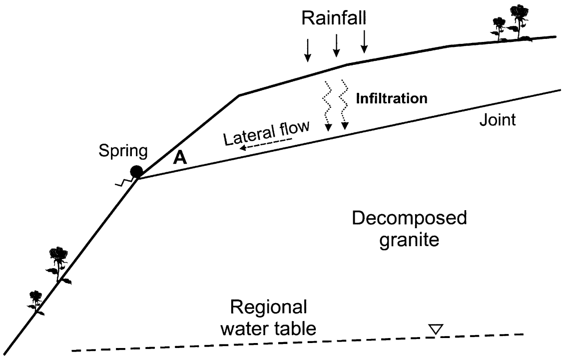

Fig. 10. Schematic diagram showing the influence of a joint on infiltration.

The infiltration pattern can be significantly disturbed by the presence of geological discontinuities. On the basis of this infiltration test, the influence of the joint on infiltration can be shown schematically in Fig. 10. Due to presence of the relic joint, at the end of both test periods, the soil below 80 cm remained unsaturated, while the shallow zone was almost fully saturated. This locally saturated zone may behave like a ‘perched aquifer’ to some degree, although it is conceptually very different from the conventional perched aquifer which requires a relatively low permeability layer (Todd, 1980). The lateral flow due to the joint can improve the stability of the slope since it reduces significantly the supply of rainwater to the regional groundwater. If the structure of the joint is vertical, there is direct access of rain to the ground water which may lead to a direct failure during or just after rain.

Although the lateral flow due to such a joint can improve the stability of the slope as a whole, it may cause small scale increase in pressure near the crest of the slope. A large amount of the rainwater may be directed toward the area around point A (see Fig. 10) if the joint is persistent. In the case where the lateral flow is greater than the spring can discharge (the worst case is that the spring area is blocked), then pore pressure may be built up locally in the area around the point A and a landslide may occur while the slope is still generally unsaturated as a whole. The failure of this kind is usually of a small scale but may occur rather quickly in response to rainfall.

While rainwater will flow laterally, there is still a portion of water which will infiltrate further down to join the regional ground water in the form of matrix flow. Based on the suction change in the first 70 cm, the infiltration rate through the matrix is estimated to be ca. 0.26 m day^{-1}. The rate may be greater near the water table since the material is at higher water content and the hydraulic conductivity is therefore greater, but still it may take many days for the infiltration to reach the water table if the original water table is at a depth of many meters. Based on the rate of descent of the infiltration front estimated from this field experiment, it is quite reasonable to believe that there may be a significant time lag between the slope failure and rainstorms if the water table response is delayed by several days.

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