Water movement in unsaturated multi-layered slope under heavy rainfall conditions in wetting and dry process

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ABSTRACT

In 2013, a number of shallow landslides triggered by heavy rainfall affected a mountainous area which located on Izu-Oshima island (Eastern Japan). These slopes are consist of fine soil layers and coarse soil layers which have different permeability coefficient and soil water characteristic curves. To clarify the characteristics of water infiltration in such unsaturated multi-layered slope and to assess the influence of the water content distribution on slope failure, 4 groups of slope model experiments were conducted. Silica No 1(D50=3.10 mm) and silica No 7(D50=0.16 mm) were used as the slope materials. The results indicated that wetting front apparently stopped at the interface between the silica No 7 layer and silica No 1 since the capillary barrier works and then lateral water flow occurred along with the interface and infiltrate into next layer when soil approaches saturation. It was found that lower water content in fine and coarse layer, unsaturated permeability coefficient K in coarse layer (5.54E-06 cm/s) is smaller than fine layer (1.08E-04 cm/s) since matric suction is 2.5 kPa, which result that capillary barrier works. In addition, higher water zone still exists at the bottom of the fine layer after drainage for a long period which results in the failure in this zone firstly when second rainfall was applied. Piping occurred at the bottom of the model when amount of water exists inside the slope.

Keywords: unsaturated soil, water infiltration, capillary barrier, multi-layer slope, soil piping

1 INTRODUCTION

This study deal with a slope consist of fine layer and coarse layer. It has a deep influence on the process of rainfall water infiltration and volume water content distribution in slope, thus governing the failure of slope. These kinds of multilayer slopes are present in many landscapes. For example, the catastrophic landslides that occurred in May 1998, involved pyroclastic covers laying upon the slopes of Pizzo D’Alvano, in Campania Southern Italy (Mancarella et al., 2012). Another example is the multi-layer slope consists of volcanic sand and loess in Japan, which have the failure on the surface in Izu-Oshima in 2013. Rainfall infiltrating water owing to the build-up of capillary barriers (Shackelford et al., 1994) that occur at the interface between unsaturated fine and coarser soil layers. Capillary barriers can maintain a high degree of saturation in the soil above them which result into a different failure part in multi-layer (Garcia et al., 2007). These phenomena are related to capillary tension that limits the downward movement of water from a finer soil into underlying coarser soil. In some situations, capillary forces in the upper fine layer can no longer hold water, any additional infiltration is transmitted to the lower coarse layer. This situation happens at a critical distance from the top of the slope that can be estimated using a model proposed by (B.Ross, 1990).

In this paper, building up and breakthrough point of the capillary barrier has been taken into consideration and its influences on slope failure time and failure modes are discussed based on slope model experiments. The main objectives of this study are to evaluate the influence of capillary barrier and its diversion capacity on slope failure and the different failure modes between single layer and multi-layer slope. SWCC tests of fine sand and coarse layer were also conducted to estimating the different hydraulic conductivities to explain how the capillary barrier works.

2 MATERIALS AND METHODS

2.1 Basic material properties

Two soils from Japan, Silica No 1 and Silica No 7 were used in the lab experiments, which were excavated from Tono-Area Gigu Province. The sieve tests were conducted using the JGS Geotechnical Society standard test methods (JGS0131-2009). The details of the experiment properties are shown in Fig 1. The dry density of the coarse layer is 1.43 g/cm\textsuperscript{3} while
that of the fine layer is 1.33 g/cm³. In addition, Table 2 and Fig 5 show soil water characteristic curves of silica No 1 & 7 in both drying and wetting process and the fitting parameters by the VG model. It was found that saturated water content and residual water content in silica No 1 is lower than silica No 7, and volume water content is also lower under the same matric suction condition. The other basic physical properties of test materials, including specific gravity Gₛ, maximum dry density, soil grain size distribution was measured in accordance with JGS standard test methods and the result are shown in Table 1. According to the soil classification system (USCS), Silica No 1 is classified as the coarse sand while No 7 is fine sand.

Table 1 Basic properties of Silica No 1 and No 7.

| Description                  | Silica No 7 | Silica No 1 |
|------------------------------|-------------|-------------|
| Specific gravity Gₛ          | 2.63        | 2.62        |
| Gravel content (>4.75mm; %)  | 0           | 97.13       |
| Sand content (%)             | 87.31       | 2.86        |
| Fines content (<0.075mm; %)  | 11.64       | 0           |
| D10 (mm)                     | 0.043       | 2.26        |
| D50 (mm)                     | 0.152       | 3.52        |
| D60 (mm)                     | 0.165       | 4.21        |
| Maximum dry density (g/cm³)  | 1.556       | 1.52        |
| Minimum dry density (g/cm³)  | 1.271       | 1.38        |

SWCC and unsaturated permeability coefficient of sands was obtained in lab. Fig 1 shows the relationship between matric suction and volume water content. Both drying process and wetting process experiments were conducted showing a difference in both sands. In this case, permeability coefficient increased in coarse and fine sand with water content increase.

The soil-water characteristic curves of the soil have been modeled with the van Genuchten-Mualem model (van Genuchten, 1980), namely:

\[
S_r = \left[1 + \left(-\alpha h\right)^n \right]^{-m} \\
S_v = \frac{\theta - \theta_r}{\theta_s - \theta_r} \\
m = 1 - \frac{1}{n}
\]  

(1)

In the above equation, the water retention curve has been expressed in terms of effective degree saturation. Where \( \theta \) is the volumetric water content; \( \theta_r \) and \( \theta_s \) indicate residual and saturated values of the water content; \( \alpha, m \) and \( n \) are the fitting parameters. \( h \) is the matric suction. \( \alpha \) is a scaling parameter (units of \( m^{-1} \)) and the exponents \( n \) and \( m \) are parameters that determine the shape of the retention curve. The hydraulic parameters are given in Table 2.

Table 2 Hydraulic properties of the silica No 1 and silica No 7.

| Description                  | Symbol (unit) | Soil No 7 | Soil No 1 |
|------------------------------|---------------|-----------|-----------|
| Drying curve                 |               |           |           |
| Saturated volume water content | \( \theta_s \) | 0.44      | 0.42      |
| Air-entry value              | \( \psi_e \)  (kPa) | 2.44      | 0.62      |
| Residual volume water content | \( \theta_r \) | 0.12      | 0.05      |
| van Genuchten model          | \( a \)       | 0.41      | 1.59      |
| Fitting parameter            | \( n \)       | 4.07      | 3.11      |
| Wetting curve                |               |           |           |
| van Genuchten model          | \( a \)       | 0.42      | 0.03      |
| Fitting parameter            | \( m \)       | 4.51      | 1.42      |

Fig. 1. Permeability coefficient of Silica No 1 & No 7 in drying process and wetting process.

The results shows that the volume water content in silica No 7 is higher than No 1 when under the same suction, which could explain how the capillary barrier works. Suction in fine layer decrease as the water content increase, capillary will breakthrough and rainwater start to infiltrate into the next layer.

Fig. 2. Relationship between permeability coefficient and volume water content of Silica No 7 in both Drying and Wetting process.
2.2. 2D flow and slope failure in Multi-layer Slope Models

In this paper, a 2D multi-layer flume model have been set up to evaluate the effect of capillary barrier acting on a slope resembling. This model system built to show the advance of wetting front, monitor volumetric water content, pore water pressure, slope displacement of each layer. In addition, failure process in were directly recorded by cameras to have a better understanding of failure modes and the effect of capillary barrier. Besides, numerical analysis was carried out to comparing with the results of model experiments.

Figure 4 (a) shows the apparatus for model experiments consisted of an inclined steel box, a rainfall simulation system, a set of pore water pressure and volumetric water content sensors (Fig 5). Details pertaining to each subsystem are as follows; (i) the inclined steel box has a dimensions of 1.0 m (length) X 0.3m (width) X 0.5m (height); (ii) the sidewalls of the box were made of acrylic plate to observe the advance of the wetting front and failure process during rainfall infiltration. The gap between the steel plates and the acrylic plate was sealed with epoxy adhesive.; (iii) A total of 12 holes were drilled into the bottom and backwall for pore pressure sensors and water content sensors.

2.2.1. Rainfall simulation system

A rainfall simulator was placed 60cm above the model box to create rainfall with a constant intensity. The intensity and duration of rainfall were controlled by control value and air pressure gauge. Rainfall intensity by air pressure to create a constant which range from 35mm/h to 100mm/h. The system consisted of a nozzles, an air pressure tank and pressure gauge, two control value and two water tank (one is the red water while another is normal water).

Fig. 5. Nozzle body and spray pattern and distribution for rainfall simulation

2.2.2. Calibration of measurement devices

The instruments used in the model experiments were calibrated before installation, including the pore water pressure, water content sensors, tilt sensor (Figure 4) and rainfall simulator. Intensity and uniformity of artificial rainfalls by simulator was calculated based on the weight of sampled at a certain time.

2.2.3. Testing procedure

Soil preparation. The silica No 1 and silica No 7 used to make the slope was dried in an oven for 48 hours. Then, the amount of water was added to the soil to achieve the initial water content.

Compaction of soils. Slope model was constructed in the model box when the soil has been prepared. The prepared soil was compacted and placed in a series of horizontal layers. Silica No 7 and No 1 were placed
into the model box in layers and compacted to achieve the dry density of 1.33 g/cm³ and 1.43 g/cm³, respectively. Each layer was tamped equally rod to a thickness of 5cm and repeat the procedures until the height of slope was achieved. Fig 4 (b) shows the information about slope completed. Layers of Silica No 1 was placed as the coarse layer in multi-layer slope.

**Positions of sensors and cameras.** During the soil placement, 11 volumetric water content sensors and 5 tilt sensors were placed at the specific locations in three different layers and time of recording the quantity of water content was 10 seconds. Cameras were put in 6 different locations to record the failure condition of the slope every 30 seconds.

**Rainfall Simulation.** When the initial values of all sensors and camera were stable, the rainfall simulation commenced. The nozzles were used to simulate artificial rainfall at different intensities from 30 mm/h to 100 mm/h. At the beginning of rainfall, red water was applied for 5 minutes and then adjusted switch to normal water continuously under the same air pressure. During the rainfall, 4 hours was applied with intensity was 75 mm/h. Then the slope model was subjected to a drying process without rainfall for 72 hours; The experiment was stopped with the assumption that seepage had reached a steady-state condition.

### 3 RESULTS

**Fig. 7.** Volumetric water content during rainfall and drying process in case I, II, III and VI

Figs. 7 shows the time histories of volumetric water content (VWC) during and after rainfall in different locations (i.e., surface, middle and toe) of case I, II, III and VI, respectively. The time histories recorded by the VWC sensors as well as the sensor locations are shown in Fig 2 (b). As in Case I (Fig 7 (a)), the advance of the wetting front is evident from the time history of the volumetric water content (VWC) sensors. Initially, the rise in the VWC was rapid then became gradual as the ground approached full saturation. When the volumetric water content at point B reached 32%, the wetting front infiltrated into next layer in case I.

**Fig. 8.** Profile of volumetric water content in case I, II, III and VI (The VWC distribution after slope failure was verified by obtaining soil samples from various locations at the end of the tests).

#### 3.1. Profile of volumetric water content in slope

- **(a) Case I.** Volumetric water content in multi-layer slope.
- **(b) Case II.** Volumetric water content in single layer slope.
- **(c) Case III.** Volumetric water content in multi-layer slope in inclined group.
- **(d) Case VI.** Volumetric water content in multi-layer slope in inclined group.
was about 3% before capillary barrier breakthrough at the beginning of rainfall. This indicates that wetting front was stopped above the interface for a while and rainfall water was stored in the upper fine layer since influence of capillary barrier. The upper fine layer had the potential to prevent water infiltrate into coarse sand layer which had a much lower volumetric water content. In the lower section I which height was from 0 cm to 20 cm, volumetric water content kept a constant condition. In case II and VI, the volumetric water content increased gradually along the section while wetting front arrived.

3.1.2. Breakthrough of capillary barrier (t = 0-0.6h in case I & III)

During the first 0.8h of rainfall, as shown in case I & case II in Fig 8, the volumetric water content in section I above interface increased to 34% in case I whereas VWC (volumetric water content) in coarse changed 3% to 5% in case I at the depth of 0.22 m while VWC was from 4% to 22% in case II at same depth in case II. In this stage, the coarse sand layer acted as a capillary barrier and broke gradually when bottom of upper fine layer was almost to saturated. This indicates that little water infiltrated the coarse sand layer. In case II and case VI, the VWC in section I above interface increased from 6% to 32% while coarse sand layer was from 3% to 4%. A lateral diversion flow occurred along the inclined interface, which resulted capillary barrier breakthrough later in section I compared with case I.

3.1.3. After the breakthrough of capillary barrier (t = 0.6h-0.78h in case I & III)

After 0.6h of rainfall, the VWC of the upper layer kept a constant value in section I along the depth in case I and III. In section I, the VWC of the coarse sand layer increased to 12% at 0.83 h and to 13% at 1.2h (see Fig 8) in case I and the VWC of the coarse sand layer increased to 7% at 0.78h in case III. A VWC of 21% at 0.7h in case II was observed in sections II and III. In the gravelly sand layer, pore water pressures of 1.3 kPa and 2.6 kPa were recorded in sections II and III, respectively. Besides, the VWC of bottom of finer layer increased to 36% at 0.8h in case I and to 8% at 0.78h in case III, respectively. In case II and VI, its VWC remained 11% and 13% at the bottom of section I around 0.7h, respectively.

3.1.4. Failure occurred (t=0.78h-1.2h) tilt sensor Breakthrough of capillary barrier (After the breakthrough of capillary barrier (t = 0.6h-0.78h in case I & III))

During around 1 hours of rainfall, the failure occurred at the toe of slope recorded by the tilt sensor which were inserted on slope surface at different locations. In flat group, failure occurred at 1.2h and 0.92h in multi-layer and single layer, respectively. The results suggest that multi-layer slope was safer under same rainfall condition since failure occurred late in flat group. On the contrary, the later failure was at 0.84h observed in single layer slope while it was at 0.78h in multi-layer slope which proved inclined multi-layer was more dangerous under same condition. Comparison of the results for Cases I and II, the results show that the slope under the same condition with an inclined angle failed first and more rapidly.

3.1.5. Drying process after rainfall (t = 3.5h-36h)

The VWC in soil decreased once the rainfall stopped in case II and VI. However, the bottom of upper fine layer still kept a higher water content condition at 31% comparing with single layer which was 20% in flat group.

3.2. Water movement in single and multi-layer model experiments

In order to clear the water movement across the interface, more sensors were put in the coarse layer (Point H, M, C, N and O) in slope experiments.

![Figure 9](image_url)  
(a) Volume water content variation with time at different locations along the coarse layer in multi-layer slope in flat group (case I); (b) Volume water content variation with time at different locations along the coarse layer in multi-layer slope in inclined slope in (case III).

![Figure 10](image_url)  
(a)Case I. Multi-layer slope, 0 deg, 75mm/h.  
(b)Case II. Single layer slope, 0 deg, 75mm/h.  
(c)Case III. Multi-layer slope, 15 deg, 75mm/h.  
(d)Case VI. Single layer slope, 15 deg, 75mm/h.

Figure 10. Volumetric water content changes with time in Cases I, II, III and VI. (The VWC distribution after slope failure was verified by obtaining soil samples from various locations at the end of the test).
Fig 9 (b) (case III) shows the water content at point H, M, C, N, and O which at different locations in the coarse layer. The graph shows that when rainfall was applied, the water content at point O and M increased firstly since the location was closest to surface, then N, C and M increased when wetting front arrived the interface and have a small flux before capillary barrier breakthrough. Meanwhile, water content at point H increased quickly and showed a higher water content in Silica No 1 since the capillary barrier didn’t work. When rainfall was stopped and the dry process started, water drained down easily with a rapid reduction in water content in the coarse layer.

Fig 10 shows the VWC history of whole slope which in three different soil layers. This graph shows that water content above the coarse layer (point B and G) remain wetter than the soil below the coarse layer (point D and I). The sand above coarse layer showed 30% of volume water content all the time, suggesting that water didn’t drain down through the coarse layer when first rainfall was stopped while the below showed a sharp reduction in the dry process.

In Figure 7 (a) and (b), Comparing the water content at toe (point L) in the flat group, the toe reached to the saturated condition later (see Fig 7 (a) and (b)) in multi-layer since capillary barrier prevents the water infiltrate into the bottom of slope which makes the slope more stable and caused a time delay in failure time. Comparing the water content at point L in the inclined group (see Fig 7 (c) and (d)), point L reached to saturated condition still later but the failure time is earlier (about 20 minutes) than single layer slope which means the multi-layer slope is more dangerous under rainfall situation. It was proved that lateral diversion occurred along the interface in inclined slope, which resulted in a higher water content near toe of the slope and water could not infiltrate into lower finer layer in Fig7 (c). This result may be associated with the sloping of the cover system (Zhan et al., 2014). The lateral diversion in the coarse layer was around 40cm, possibly because of the inclined angle, material properties and rainfall intensity used in the test. Afterwards, water could infiltrate into deepest finer layer at the end of lateral diversion.

3.3. Failure modes in different group model experiment

In Fig 11, compared with failure in case I, the images recorded by cameras in case II showed erosion failure involving and more rapid progression of movement in whole slope since the lower slope surface was almost fully saturated and therefore had a lower strength. As the red line shown in Figure 8, non-circular retrogressive failure surfaces were present in both slope which caused by seepage of rainfall water.

From Fig 12, different failure modes were observed during the slope experiments. In case I and case II, the start of mass movement occurred at the toe of slope after the seepage of rainfall water. Collapse began near the bottom half of the slope adjacent to the wall and propagated upward to other parts of the slope. It is interesting that failure of the ground in case VI was not with erosion but piping occurred at the toe of the slope. In comparison, collapse of the slope in Case VI is extremely rapid since mass were taken away by piping.

4 DISCUSSION

The diversion capacity is the maximum flow that a capillary barrier can divert water flux and the diversion length is the horizontal length from the top of the slope to the breakthrough. In order to evaluate the diversion length of a capillary barrier, following assumptions are made: (1) suction profile in the fine layer could be estimated using the linear method; (2) upper fine layers are thick enough; (3) the interface is inclined and longer
than the diversion length; (4) continuous rainfall is applied on the top of the slope.

Based on these situations, diversion capacity and diversion length of capillary could be calculated, as the equation:

$$Q_{\text{max}} = \int_{z_0}^{z_{\text{conc}}} v_h(z)dz$$  \hspace{1cm} (2)

Where, $Q_{\text{max}}$ is the maximum unsaturated lateral diversion capacity ($cm^2/s$); $v_h(z)$ - velocity profile as the function of elevation ($cm/s$); $z_0$ - elevation of base of the upper fine layer (cm); $z_{\text{conc}}$ - elevation where the maximum suction in the upper coarse layer (cm);

According to the linear method, elevation can be transformed into suction, and matric suction $\psi$ at the contact interface between two layers must be continuous across the boundary:

$$z_{\text{conc}} = z_\text{0}$$

$$\psi_{\text{conc}} = \psi_{\text{0}}$$  \hspace{1cm} (3)

According to the equation (2) and (3), equation (4) can be obtained and can be deduced via Darcy’s law.

$$Q_{\text{max}} = \int_{\psi_{\text{conc}}}^{\psi_{\text{0}}} v_h(\psi)d\psi = \int_{\psi_{\text{conc}}}^{\psi_{\text{0}}} i_h(k(\psi))d\psi$$  \hspace{1cm} (4)

Where, $i_h$ - the lateral hydraulic gradient, which equals to the tangent of slope tan $\beta$; $k(\psi)$- k function; $\beta$ -inclined angle of slope (°).

The maximum lateral diversion flux is

$$Q_{\text{max}} = k_{\text{sat}} \tan \beta \int_{\psi_{\text{conc}}}^{\psi_{\text{0}}} k_r(\psi)d\psi$$

$$k_r(\psi) = \frac{\left[1 - (\alpha \psi)^m\right]^{1/2}}{[1 + (\alpha \psi)^m]^{1/2}}  \hspace{1cm} (5)$$

According to the formulas (5), the lateral diversion capacity of the inclined capillary barrier can be diverted downsip per unit time per unit length along with the interface. Assuming the water lateral diversion length is $L_1$, the water lateral flux $Q(x)$ can be calculated by

$$Q(x) = r * L_1 < Q_{\text{max}}$$  \hspace{1cm} (6)

Substituting the equation (6) into equation (5), Equation (7) can be

$$r \cdot L_1 < k_{\text{sat}} \tan \beta \int_{\psi_{\text{conc}}}^{\psi_{\text{0}}} k_r(\psi)d\psi$$  \hspace{1cm} (7)

Diversion length is bounded by

$$L_1 < \frac{k_{\text{sat}} \tan \beta \int_{\psi_{\text{conc}}}^{\psi_{\text{0}}} k_r(\psi)d\psi}{r} \approx 0.4m$$  \hspace{1cm} (8)

According to the calculation of diversion length by simplified model, length of capillary area (Fig 14) of this case is smaller than the length of interface. As a result, infiltrating water accumulated above the coarse layer and lateral water flow occurred along with the interface and capillary barrier breakthrough in the middle part of interface which results that water starts to infiltrate into the lower coarse layer at this location. A large amount of rainfall water will pass across the coarse layer and exist in the middle part of the lower fine layer, with rainfall event continued, soil pipes contribute to the quick discharge of rainfall water which results in slope stability.

5 CONCLUSIONS

A series of laboratory tests were performed on small-scale model slopes to investigate failure time and modes in multi-layer and single slopes caused by rainwater infiltration. In addition, unsaturated permeability coefficient and SWCC were measured in lab to clarify the how the capillary barrier works under different conditions.

The following conclusions are drawn from the present study. Different failure modes occurred in under rainfall condition in inclined multi-layer slope and single layer slope.

In the flat group, multi-layer slope was safer since capillary barrier works which prevent the rainwater infiltrate into coarse layer. Failure occurred at the bottom of slope, the toe of slope reach to saturated condition is later while failure time is also late. In inclined group, failure occurred at the same location,
Although toe of slope reach to saturated condition is still later, the failure time is earlier. According to calculate the length of capillary area and compared with experiment pictures, the diversion length is smaller in this case which allows the accumulated rainfall water infiltrate at the middle part of slope, which causes the soil piping and has an influence on the slope stability.

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