

Infiltration control using capillary barriers for conservation of historical tumulus mounds

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ABSTRACT

Tumuli were constructed more than 1300 years ago and have been conserved as historical cultural heritages but many of them are seriously damaged by rainfall infiltration. In the present paper, a capillary barrier formed at the coarser-finer soil interface under unsaturated condition is studied as a feasible means for protecting tumuli from rainfall induced damages. The mechanism of water shielding by a capillary barrier and the diversion capacity are quantitatively discussed by conducting model chamber tests and numerical analyses. A series of the model chamber tests indicates that a capillary barrier is formed when the coarser grained soil has lower hydraulic conductivity than that of the finer grained layer and the diversion capacity is controlled by the inclination of the soil interface, the thickness of the finer grained layer and the intensity of precipitation because these factors are related to the degree of the difference in hydraulic conductivity of the finer and coarser grained soils.

Keywords: capillary barrier, historical cultural heritage, unsaturated soil, model test

1 INTRODUCTION

Tumuli are burial mounds for ancient rulers constructed in many parts of Japan from the middle of 3rd century to the 7th century. A tumulus consists of a burial chamber made of stones covered by a compacted earth mound. The existence of the tumuli for more than 1300 years after construction shows that the dense compacted tumulus mounds have high durability in a natural environment but some of them have been seriously damaged by natural forces and man-caused destructions. One of the main causes of the damages in tumuli is precipitation. It causes slope failure in a tumulus mound and the infiltrating rainwater in the burial chamber deteriorates the decorated stones composing the chamber (Sawada et al., 2015). Rainwater infiltration control is hence indispensable for conservation of tumuli.

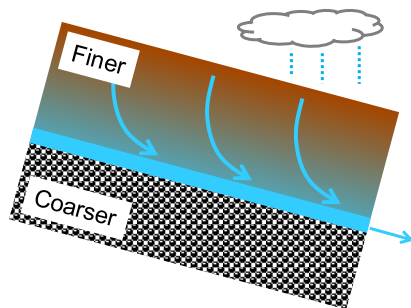


Fig. 1 A capillary barrier formed at the coarser-finer soil interface

A capillary barrier is one of the feasible options. A capillary barrier is formed at the coarser-finer soil interface under unsaturated condition. The infiltrating water is unable to enter the coarse soil and is diverted laterally at the soil interface (Fig. 1). A capillary barrier has been successfully introduced in the restoration of the Garandoya Tumulus in Oita, Japan. The tumulus is famous for its mural painting on the stone chamber but the earth mound that originally covered the stone chamber has been destroyed. To compensate for the

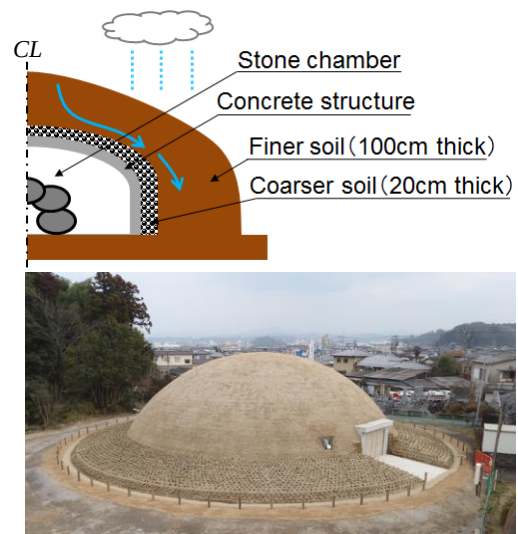


Fig. 2 The reconstructed earth mound using a capillary barrier (The Garandoya Tumulus in Oita)

poor protection from precipitation due to non-existence of the earth mound, the stone chamber had been covered by a tarpaulin until the reconstruction, which resulted in promoting dew condensation and salt crystallization on the mural painting. The local government hence decided to reconstruct the earth mound to protect the mural painting from farther deterioration. The reconstructed earth mound shown in Fig. 2 consists of a finer grained soil layer underlain by a coarser grained soil layer to control rainfall infiltration into the stone chamber by a capillary barrier. In addition to infiltration control, the earth mound with high heat insulation controls the temperature change that accompanies dew condensation and salt crystallization in the stone chamber.

Although a capillary barrier is expected to be widely applied to earth structures as a water shielding system, it is difficult to design a capillary barrier with required diversion capacity because the diversion capacity fluctuates depending on many factors, namely the intensity of precipitation, the hydraulic properties of the soils, the inclination of the soil interface and the thickness of the finer grained layer. In the present paper, the mechanism of water shielding by a capillary barrier and the diversion capacity are quantitatively discussed by conducting model chamber tests with a different combination of the controlling factors of diversion capacity. In addition to the model chamber tests, a series of numerical analyses was also conducted for detail observation of the water flow in the soil layers.

2 MODEL CHAMBER TEST

The model chamber test apparatus is shown in Fig. 3 and Fig. 4. It consisted of a chamber and a rainfall simulator. The chamber measured 110cm in width, 60cm in height and 12cm in depth and dipped at 10 degrees. A 30cm thick finer grained layer was placed on an underlying 20cm thick coarser grained layer in the chamber. Six moisture sensors (EC-5, Decagon Devices, Inc.) were installed in each layer to monitor degree of saturation. At the end of each layer, there was

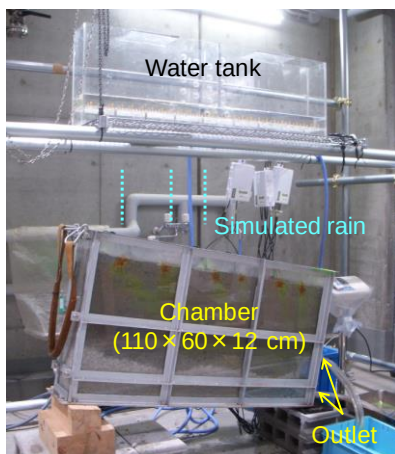


Fig. 3 The model chamber test apparatus

an outlet from which a part of the infiltrating water drained. The drainage from each of the outlets was measured by a weighing balance. The rainfall simulator set above the chamber produced water drops of constant intensity controlled by water head in the water tank. The constant precipitation was applied continuously for 45 hours.

The coarser and finer grained soils were the same with those used for the reconstruction of the Garandoya Tumulus. The basic properties and grain size distribution of the soils are shown in Table. 1 and Fig. 5, respectively. The difference in grain size distribution results in the sharply contrasting soil water characteristic curves (SWCCs) illustrated in Fig. 6. The

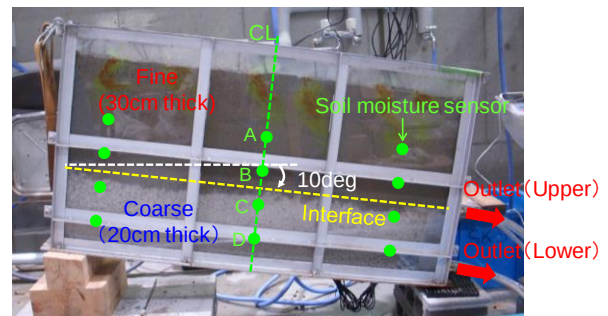


Fig. 4 The coarser and finer grained layers (Test No.1)

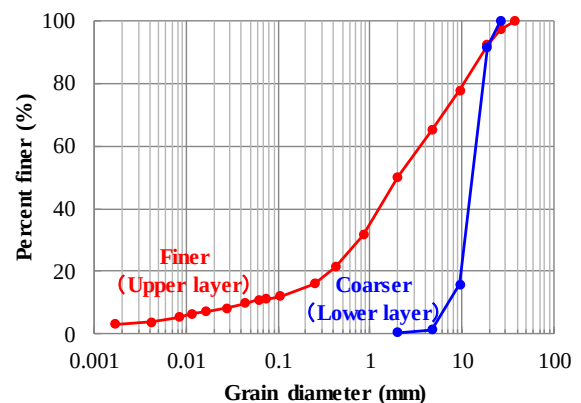


Fig. 5 Grain size distribution of the soils

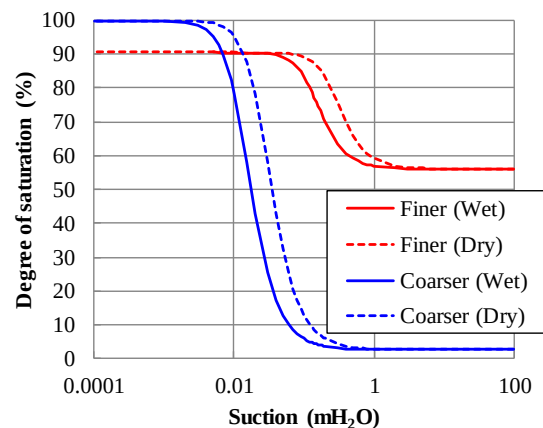


Fig. 6 The SWCCs of the soils

Table. 1 The basic properties of the soils

	Upper layer (Finer)	Lower layer (Coarse)
Specific gravity (g/cm ³)	2.67	2.67
Dry density (g/cm ³)	1.74	1.52
Water content (%)	11.4	2.0
Degree of saturation (%)	57.11	7.07
Void ratio	0.53	0.75
Saturated hydraulic conductivity (m/s)	3.94×10^{-5} $\sim 1.18 \times 10^{-4}$	4.21×10^{-3}
SWCC model parameters	$\alpha=0.038$ (Dry) $\alpha=0.075$ (Wet) $n=2.816$, $m=0.645$ $\theta_r=0.195$, $\theta_s=0.315$	$\alpha=0.386$ (Dry) $\alpha=0.771$ (Wet) $n=2.654$, $m=0.623$ $\theta_r=0.011$, $\theta_s=0.430$

Table. 2 The factors of the model chamber test

No.	Inclination (deg)	Thickness (cm)	Intensity of rain (mm/h)
1	10	30	4.09
2	5	30	4.07
3	10	15	4.26
4	10	30	8.55

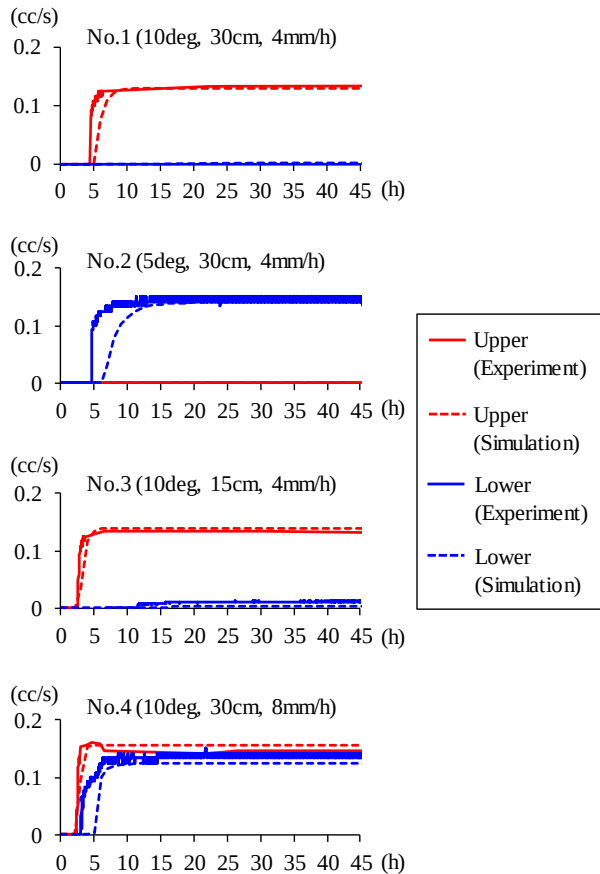


Fig. 7 Drainage from the outlets

SWCCs were obtained by laboratory tests and the results were fitted by van Genuchten's model (van Genuchten, 1980) of which parameters are shown in Table. 1.

The four tests with a different combination of the inclination of the chamber, the thickness of the fine soil layer and precipitation were conducted (Table. 2). The diversion capacity of the capillary barrier is reflected in the time history of drainage from the outlets shown in Fig. 7. Less drainage from the lower outlet means higher diversion capacity. Water drained from the coarser grained layer in No.2, No.3 and No.4 but not in No.1. In No.1, seepage surface went down into the coarser grained layer as time elapsed but the infiltrating speed was slow and the seepage surface was still above the bottom of the chamber even at 45 hours after the rainfall started. These results suggest that the diversion capacity decreases with decrease in inclination and/or the thickness of the finer grained layer and/or with increase in precipitation, but there was not significant difference in degree of saturation between the four tests. In each test, the degree of saturation in a steady state tends to become 15-25% in the coarser grained layer and 70-80% in the finer grained layer and increase in the down dip direction. Fig. 8 shows the time history of degree of saturation at the four measurement points on

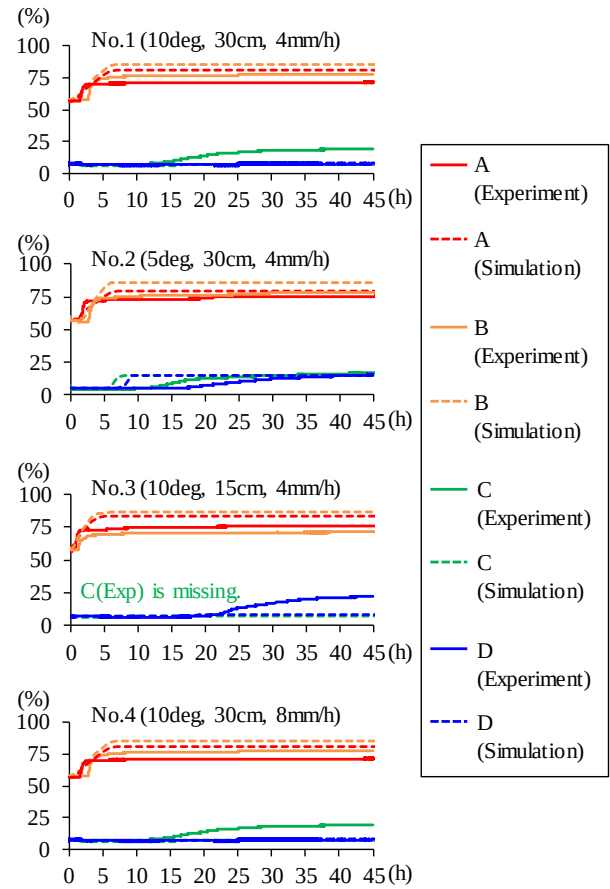


Fig. 8 Degree of saturation at the measurement points on the center line of the chamber

the center line of the chamber indicated in Fig. 4.

3 NUMERICAL ANALYSIS ON THE MODEL CHAMBER TEST

The model chamber tests were numerically simulated by the saturate-unsaturated seepage flow analysis (Akai et al., 1977) to observe the water flow in the soil layers. The setup parameters for each test are summarized in Table. 3. The parameters were determined based on the experimental results shown in Table. 1 and Fig. 6 so that the calculated drainage from the outlets is consistent with the measured one as shown in Fig. 7. Here, $H_{seepage}$ in Table. 3 is a parameter that controls the drainage from the outlet. The boundary condition of the outlet switches from an impermeable boundary to a seepage boundary when the pressure head reaches $H_{seepage}$. More details on the assessment of the parameters is obtained from Sawada et al. (2016).

The numerical analyses almost successfully simulate the model chamber tests. The calculated drainage from the outlets and degree of saturation in the soil layers in each test are compared with the measured ones in Fig. 7 and Fig. 8, respectively. In addition to a good agreement in drainage, the calculated degree of saturation is also quantitatively consistent with the measured one although disagreements probably due to local flows associated with the heterogeneity in compaction of the finer grained layer are observed at a few measurement points.

Table. 3 The formation of parameters

No.		1	2	3	4
SWCC model parameters	Upper	$\alpha=0.037$	$\alpha=0.056$	$\alpha=0.037$	$\alpha=0.056$
	Lower	$n=2.816, m=0.645, \theta_r=0.195, \theta_s=0.315$			
Saturated hydraulic conductivity (m/s)	Upper	1.18×10^{-4}	1.18×10^{-4}	7.89×10^{-5}	9.86×10^{-5}
	Lower	4.21×10^{-3}			
Initial suction (mH ₂ O)	Upper	-1.848	-1.538	-1.558	-1.743
	Lower	-0.115	-0.164	-0.117	-0.114
Controlling factor of drainage $H_{seepage}$ (mH ₂ O)	Upper	-0.100	-0.013	-0.100	-0.100
	Lower	-0.100	-0.013	-0.100	-0.100

4 DISCUSSION ON THE MECHANISM OF WATER SHIELDING BY A CAPILLARY BARRIER

In the previous studies, the mechanism of water shielding by a capillary barrier is explained from three different factors, namely suction, total head and hydraulic conductivity. Kung (1990), Kitamura et al. (2008) and Morii et al. (2015) report that a capillary barrier is formed as far as the finer grained layer has higher suction than the coarser grained layer. On the other hand, Kitamura et al. (2013) explains the formation of a capillary barrier in terms of total head instead of suction. The infiltrating water cannot enter the coarser grained layer as far as the finer grained layer has higher total head than the coarser grained layer. Hydraulic conductivity as well as suction and total head is considered as a controlling factor for water shielding by a capillary barrier (Miyazaki, 1988; Ross, 1990; Stormont et al., 1996). Downward flux into the coarser grained layer is limited when the coarser grained layer has lower hydraulic conductivity than that of the finer grained layer.

The model chamber tests are analyzed considering the above-mentioned three factors. Fig. 9, Fig. 10, Fig. 11 are the distribution of suction, total head and hydraulic conductivity at 45 hours after the rainfall started, respectively. The suction of the finer grained layer is higher than that of the coarser grained layer in

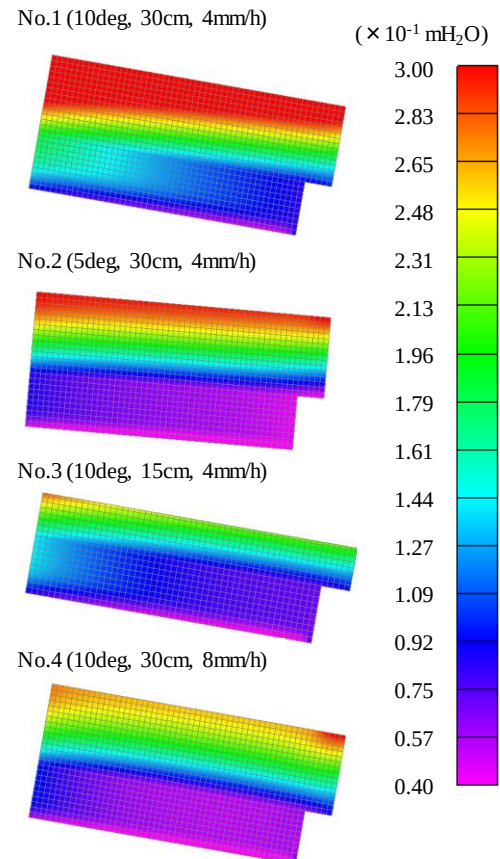


Fig. 9 The distribution of suction

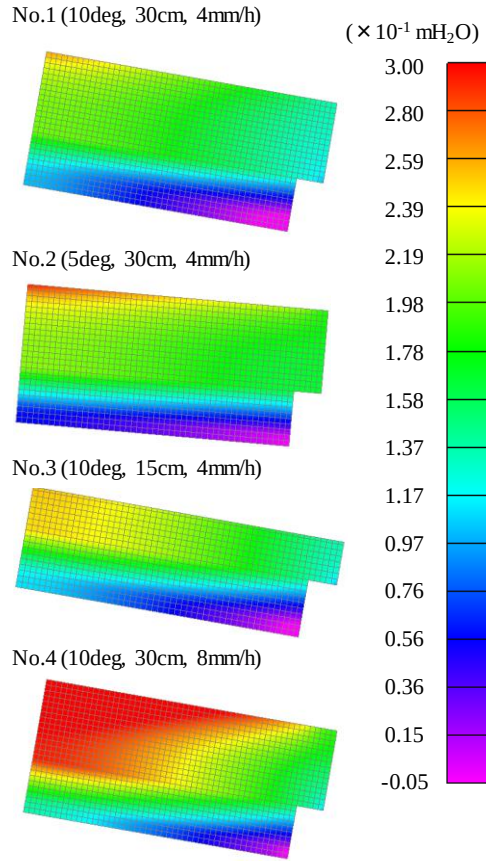


Fig. 10 The distribution of total head

all the tests as shown in Fig. 9. The condition for formation of a capillary barrier described in the previous studies is hence satisfied but No.2 and No.4 shows significant amount of drainage from the coarser grained layer. Also, the total head of the finer grained layer is lower than that of the coarser grained layer in all the tests as shown in Fig. 10 although No.1 shows almost perfect water shielding at the soil interface. These inconsistencies indicate that suction and total head are not direct controlling factors of water shielding by a capillary barrier although they are related to water flow in the soil layers. Compared to suction and total head, hydraulic conductivity is a more feasible controlling factor. As shown in Fig. 11, the coarser grained layer has lower hydraulic conductivity in all the tests but there is a difference in the degree of the difference in hydraulic conductivity of the coarser and finer grained soils corresponding to the degree of water diversion at the soil interface. The capillary barrier with high diversion capacity in No.1 is formed on the coarser grained layer of which hydraulic conductivity at the soil interface is about 10000 times lower than that of the finer grained layer. This suggests that the diversion capacity is controlled by the degree of the difference in hydraulic conductivity of the two soils and a capillary barrier is effective when the hydraulic conductivity difference is significant and the downward flux into the coarser grained layer is negligible. Fig. 12

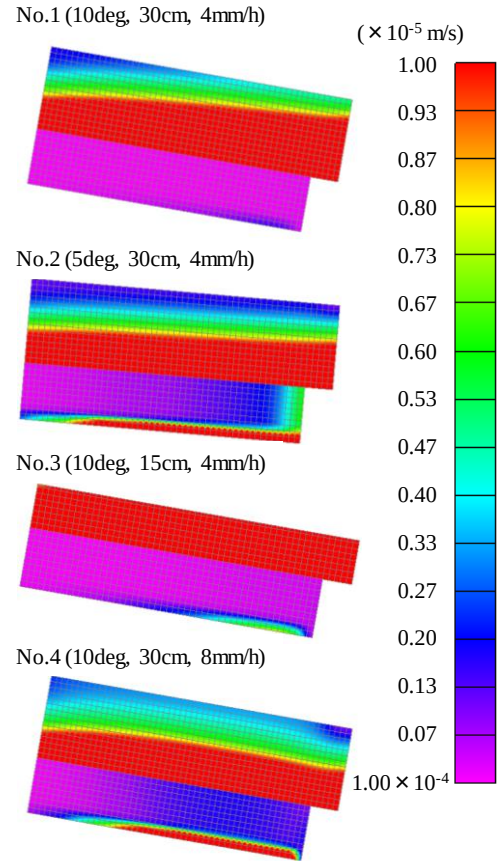


Fig. 11 The distribution of hydraulic conductivity

shows the relations between hydraulic conductivity and suction of the soils estimated from the SWCCs in Fig. 6 (Mualem, 1976). A capillary barrier is formed as far as the suction at the soil interface is located to the right of the intersection of the hydraulic conductivity curves but the diversion capacity degrades as the suction moves toward the intersection.

The fact that the inclination of the soil interface, the thickness of the finer grained layer and the intensity of precipitation affect the diversion capacity suggests that these factors control hydraulic conductivity of the soils. The relation between the three factors and hydraulic conductivity is discussed by analyzing the flows in the finer grained layer shown in Fig. 13, where the coordinates are aligned with the soil interface and the depth is unit. l , i and h are the distance from the top of the chamber, the inclination of the soil interface and the thickness of the finer grained layer, respectively. The infiltrating water is divided into horizontal and vertical flows at the soil interface. The equation for the steady state flow in the finer grained soil layer is

$$Q = Q_h + Q_v \quad (1)$$

where Q , Q_h and Q_v are the volume of the infiltrating water, horizontal flow and vertical flow, respectively. Assuming Darcy's law, Q_h and Q_v are expressed as

$$Q_h = \int_0^h k_f(z) dz \cdot \sin i \quad (2)$$

$$Q_v = k_c(0) \cdot l \cdot \cos i \quad (3)$$

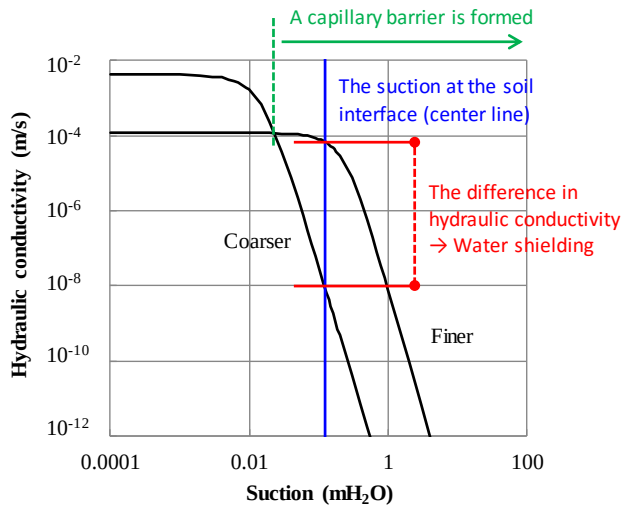


Fig. 12 The mechanism of water shielding by a capillary barrier

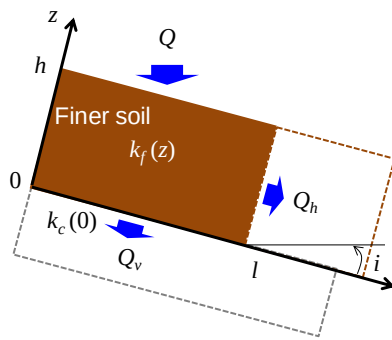


Fig. 13 The water flow in the soil layers

where k_f and k_c are hydraulic conductivity of the finer and coarser grained soils respectively that are expressed as functions of the vertical axis. Hydraulic conductivity of the soils changes to satisfy Eq. (1) depending on the controlling factors, namely i , h and Q . For example, k_f and k_c decrease when i or h increases, also when Q decreases.

5 CONCLUSIONS

In the present paper, a capillary barrier was studied as a feasible means for protecting historical tumuli from rainfall induced damages. The mechanism of water shielding by a capillary barrier and the diversion capacity were quantitatively discussed based on both model chamber tests and numerical analyses.

A series of model chamber tests indicated that the diversion capacity of a capillary barrier is controlled by the inclination of the soil interface, the thickness of the finer grained layer and the intensity of precipitation. Then numerical analyses for detail observation of the water flows in the soil layers were successfully conducted. Using the calculated results, the mechanism of water shielding by a capillary barrier was discussed from the viewpoints of suction, total head and hydraulic conductivity. The distributions of these three factors in

the soil layers revealed that hydraulic conductivity is the most feasible controlling factors of water shielding by a capillary barrier. A capillary barrier is hence formed when the coarser grained layer has lower hydraulic conductivity and the diversion capacity is controlled by the degree of the difference in hydraulic conductivity of the finer and coarser grained soils. Hydraulic conductivity of the soils is adjusted to keep the total volume of the flows in the soil layers equal to the infiltration volume depending on the inclination of the soil interface, the thickness of the finer grained layer and the intensity of precipitation.

REFERENCES

- 1) Akai, K., Onishi, Y., Nishigaki, M. (1977): Finite element analysis of saturated-unsaturated seepage in soil, *Proceedings of the Japan Society of Civil Engineers*, 264, 87-96 (in Japanese).
- 2) Kitamura, R., Sako, K. and Takehara, S. (2008): Application of capillary barrier to maintenance and management of slopes around heritages, *Journal of Disaster Mitigation for Historical Cities*, 2, 127-132 (in Japanese).
- 3) Kitamura, R. and Sako, K. (2013): Capillary barrier in unsaturated soils, *Proceedings of the 7th International Joint Symposium on Problematic Soils and Geoenvironment in Asia*, Okinawa, Japan, 3-8.
- 4) Kung, K-J. S. (1990): Preferential flow in a sandy vadose zone: 2. Mechanism and implications, *Geoderma*, 46(1), 59-71.
- 5) Miyazaki, T. (1988): Water flow in unsaturated soil in layered slopes, *Journal of Hydrology*, 102(1), 201-214.
- 6) Morii, T., Suzuki, K., Suzuki, T. and Kawai, T. (2015): Feasible applications of capillary barrier system of soil in geotechnical and agricultural fields, *Memoirs of the Faculty of Agriculture, Niigata University*, 67(2), 125-132 (in Japanese).
- 7) Mualem, Y. (1976): A new model for predicting the hydraulic conductivity of unsaturated porous media, *Water Resources Research*, 22(3), 513-522.
- 8) Ross, B. (1990): The diversion capacity of capillary barriers, *Water Resources Research*, 26(10), 2625-2629.
- 9) Sawada, M., Mimura, M. and Yoshimura, M. (2015): Evaluation of rainfall induced slope failure in tumulus mounds and conservation of the damaged tumuli, *Japanese Geotechnical Society Special Publication*, 2(78), 2684-2689.
- 10) Sawada, M., Mimura, M. and Yoshimura, M. (2016): Infiltration control in historical tumulus mounds using capillary barriers -Experimental and analytical study on the mechanism of capillary barriers-, *Journal of Japan Society of Civil Engineers, Ser. C*, 72(2), 101-116 (in Japanese).
- 11) Stormont, J. C. (1996): The effectiveness of two capillary barriers on a 10% slope, *Geotechnical & Geological Engineering*, 14(4), 243-267.
- 12) van Genuchten, M. Th. (1980): A Closed-form-equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Sci. Soc. Am. J.*, 44(5), 892-898.
- 13) Yang, H., Rahardjo, H., Leong, E. C. and Fredlund, D. G. (2004): A study of infiltration on three sand capillary barriers, *Canadian Geotechnical Journal*, 41(4), 629-643.