Water shielding mechanism of a double-layered compacted earth structure and its application to conservation of tumulus mounds

Mécanisme d'étanchéité d'une double couche de terre compactée et son application dans la préservation des tumuli de terre

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ABSTRACT: Tumuli are burial mounds for ancient rulers constructed in many parts of Japan more than 1300 years ago. A tumulus usually consists of a burial chamber made of stones covered by a compacted earth mound. They should be conserved for the next generations as historical cultural heritages, but many of them have been seriously damaged by natural forces and man-caused damages. Precipitation is one of the main causes of the damage of tumuli. Infiltrating rainwater into a mound induces slope failures, which results in the deterioration of the burial chamber by poor protection from precipitation and heat. Infiltration control is hence a vital objective in the restoration of damaged tumuli. In the present paper, conservation of tumuli by controlling infiltration using a capillary barrier is proposed with an example of the restoration of the Garandoya Tumulus. A capillary barrier is a water shielding system formed at the interface between finer and coarser grained layers. The mechanism of water shielding by a capillary barrier is investigated thorough model chamber tests and simulation of the tests. It is found that water shielding by a capillary barrier is caused by the difference in unsaturated hydraulic conductivity of the finer and coarser grained layers.

RÉSUMÉ : Les Tumuli s'agissent de tertres funéraires destinés aux anciens souverains, construits dans de nombreuses régions du Japon et datant de plus de 1300 ans. Les Tumuli sont généralement composés d'une chambre funéraire en pierres, couverte par un monticule de terre compactée. Plusieurs Tumuli ont subi des dommages importants causés par des forces naturelles et humaines. La précipitation est la cause principale de ces dommages. L'eau de pluie infiltrant le monticule engendre des glissements de pentes, ceci entraine la détérioration de la chambre funéraire suite à la mauvaise protection contre la pluie et la chaleur. De ce fait, contrôler l'infiltration est primordial pour la restauration des tumuli endommagés. Le présent document propose la conservation des tumuli par contrôle d'infiltration en utilisant une barrière capillaire. La solution est accompagnée d'un exemple de restauration du Tumulus de Garandoya. Une barrière capillaire est un système d'étanchéité formé à l'interface entre les couches fines et grenues du sol. Le mécanisme d'étanchéité par barrière capillaire est examiné à travers des essais sur une chambre modèle et leur simulation. Il est constaté que l'étanchéité par une barrière capillaire est due à la différence entre les conductivités hydrauliques des couches de sol fin et grenu en milieu non saturé.

KEYWORDS: capillary barrier, unsaturated soil, model chamber test, seepage flow analysis, historical cultural heritage

1 INTRODUCTION

Tumuli are burial mounds for ancient members of the imperial family and district 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. Tumuli should be conserved for the next generation as vital compornets of Japanese history, but many of them have been seriously damaged by natural forces and man-caused distructions.

Precipitation is one of the main causes of damage of tumuli. Rainfall infiltration induces slope failures in a tumulus mound. The mound restricts rainfall infiltration and heat conduction to the stone chamber. The destruction of the mound hence results in the deterioration of the stone chamber. Infiltrating rainwater into the stone chamber promotes the deterioration of the stones due to wet-dry cyclic condition. In addition, temperature change in the stone chamber activates moisture movement and fungal growth on the stones. These damage on the stones degrades the worth as a historical cultural heritage particularly when the stones are decorated with mural paintings. Controlling rainfall infiltration into the tumulus mounds is hence a vital objective in the restoration of tumuli damaged by precipitation and the induced environment change in the chamber.

The authors have been studying the mechanism of the damage of tumuli and restoration methods supported by geotechnical engineering techniques (Sawada et al. 2015; Sawada et al. 2016; Sawada and Mimura 2016). In this study, a means for controlling rainfall infiltration into tumulus mounds using a capillary barrier is proposed with an example of the restoration of the Garandoya Tumulus. A capillary barrier is a water shielding system formed at the interface between the finer and coarser grained soil layers (Fig. 1) which has been studied as a covering for toxic waste (e.g. Ross 1990). To install it effectively to the restoration of the tumuli, the mechanism of water shielding by a capillary barrier is investigated by conducting model chamber tests and analyzing the infiltrating water in the double-layered models.

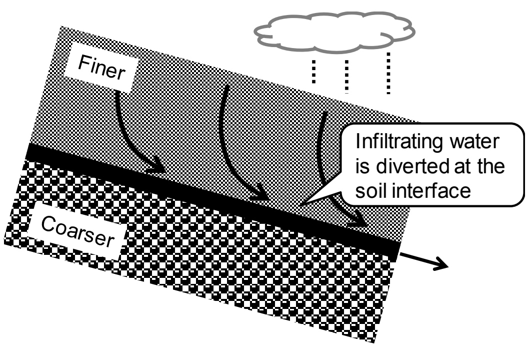

Figure 1. Water shielding by a capillary barrier.

2 THE MECHANISM OF WATER SHIELDING BY A CAPILLARY BARRIER

2 .1 *Capillary barrier*

A capillary barrier is formed at the interface between finer and coarser grained soil layers. As shown in Fig. 1, the infiltrating water into the finer grained layer cannot enter the underlying coarser grained layer and diverted at the soil interface due to the difference of the hydraulic properties of the two soils.

In the previous studies, the mechanism of water shielding by a capillary barrier is explained from three different factors, namely 1) suction, 2) total head and 3) hydraulic conductivity.

1) A capillary barrier is formed by the difference in suction of the two layers. As far as the finer grained layer has higher suction than the coarser grained layer, all the infiltrating water is retained in the finer grained layer (Kung 1990, Morii et al. 2015).
2) A capillary barrier is formed by the difference in total head of the two layers. As far as the finer grained layer has lower total head than the coarser grained layer, water moves upward and the infiltrating water cannot enter the coarser grained layer (Kitamura and Sako 2013).
3) A capillary barrier is formed by the degree of difference in hydraulic conductivity of the two layers. Downward flux into the coarser grained layer is restricted when the coarser grained layer has lower hydraulic conductivity than the finer grained layer (Miyazaki 1988; Ross 1990; Stormont et al. 1996).

Considering these conditions for the formation of a capillary barrier, the mechanism of water shielding by a capillary barrier is proven in the following sections through a series of model chamber tests and the simulation of the tests.

2 .2 *Model chamber test*

A capillary barrier was observed by the model chamber test shown in Fig. 2. A 30cm thick finer grained layer was placed on an underlying 20cm thick coarser grained layer in the chamber of 110cm in length and 12cm in width. The grain size distribution curves of the soils are shown in Fig. 3. At the end of each layer, there was an outlet from which a part of the infiltrating water drained. The drainage from each of the outlets was measured by a weighing balance. Degree of saturation was also measured by moisture sensors at 6 points in each layer. A rainfall simulator which produces water drops of constant intensity was set above the chamber. The constant precipitation was applied continuously for 45 hours. More details on the model chamber test are found in Sawada et al. (2016).

The tests were conducted on soil layers with a different combination of three factors, namely the inclination of the soil interface, the thickness of the finer grained layer and precipitation. The test conditions and the proportion of the

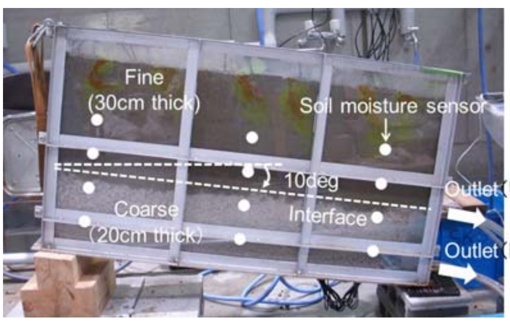

Figure 2. The model chamber test for observation of a capillary barrier (No.1 and No.4).

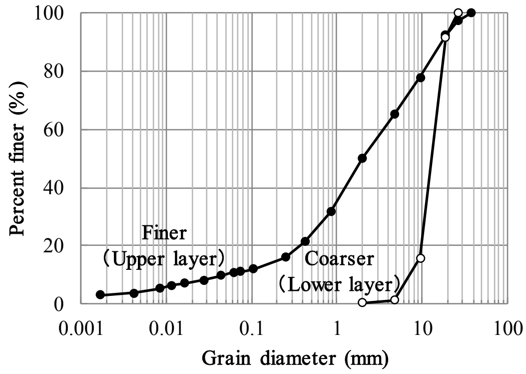

Figure 3. The grain size distribution of the soils.

amount of drainage from the upper outlet to the total amount of

Table 1. The test conditions and measured drainage from the outlets.

No.	Inclination (deg)	Thickness (cm)	Precipitation (mm/h)	Drainage upper/total (%)
1	10	30	4.09	100
2	5	30	4.07	0
3	10	15	4.26	91
4	10	30	8.55	52

infiltration in a steady state are summarized in Table. 1. The drainage from each outlet was continuously measured during the test and it reached a steady state in about 10 hours. The proportion of the upper drainage to the total means the diversion capacity of the capillary barrier. The results show that the diversion capacity is controlled by the inclination and thickness of the soil layers and precipitation.

2 .3 *Simulation of the model chamber tests and discussion on the mechanism of water shielding by a capillary barrier*

The model chamber tests were analyzed with a saturate-unsaturated seepage flow analysis. In each test, the calculated amount of drainage from the outlets and degree of saturation in the soil layers quantitatively agreed with those measured in the model chamber tests (Sawada et al. 2016).

Fig. 4 shows the distribution of the suction, total head and hydraulic conductivity in the soil layers in a steady state. The suction of the finer grained layer is higher than that of the coarser grained layer in all the tests. The condition for formation of a capillary barrier described in 2.1-1) is hence satisfied, but No.2 and No.4 observe significant amount of drainage from the coarser grained layer. On the other hand, the total head of the finer grained layer is higher than that of the coarser grained layer and 2) is not satisfied in all the tests, but No.1 shows almost perfect water shielding. These inconsistencies indicate that suction and total head are not direct causes of water shielding by a capillary barrier although they are related to water flow in the soil layers.

Compared to 1) and 2), 3) is a more feasible explanation for the results. The coarser grained layer has lower hydraulic conductivity hence a part of the infiltrating water is diverted at the soil interface and drained from the upper outlet although all the infiltrating water is drained from the lower outlet in No.2 because the inclination is less than the threshold for drainage (Sawada et al., 2016). The amount of upper drainage corresponds to the degree of difference in hydraulic conductivity of the two layers. In No.1, the capillary barrier with high diversion capacity is formed on the coarser grained layer of which hydraulic conductivity is about 10000 times lower than that of the finer grained layer. This suggests that water shielding by a capillary barrier is caused by the mechanism shown in 3) and it is effective when the hydraulic conductivity of the two soils are contrasting.

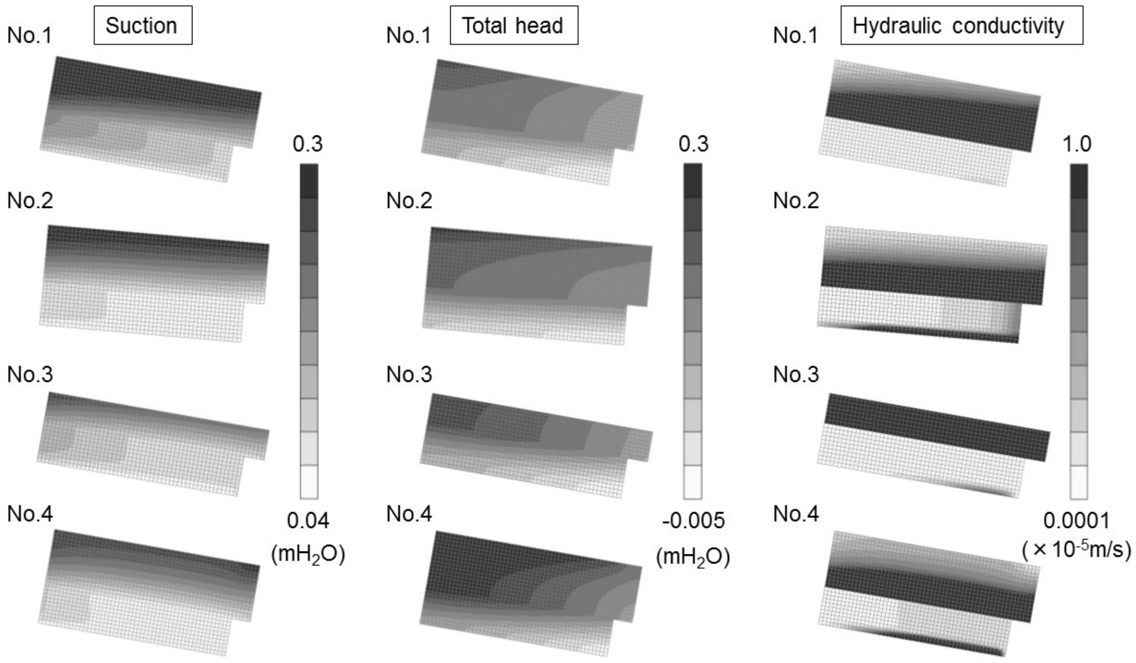

Figure 4. The distribution of suction, total head and hydraulic conductivity in a steady state.

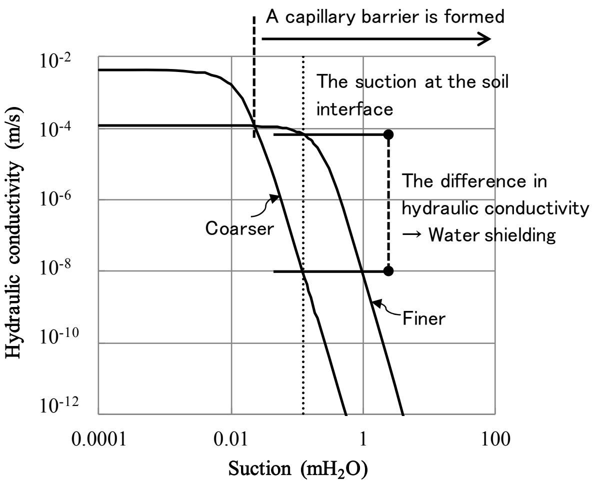

Figure 5. The mechanism of water shielding by a capillary barrier.

The mechanism of water shielding by a capillary barrier is illustrated by relations between suction and hydraulic conductivity of the finer and coarser grained soils shown in Fig. 5. The unsaturated hydraulic conductivity of the soils is determined by experimentally obtained soil water characteristic curves and Mualem's model (Mualem 1976). A capillary barrier is formed as far as the suction at the soil interface is located to the right of the intersection shown in Fig. 5, and the diversion capacity degrades as the suction moves toward the intersection.

3 THE APPLICATION OF A CAPILLARY BARRIER TO CONSERVATION OF TUMULUS MOUNDS

3 .1 *The Garandoya Tumulus*

A capillary barrier was successfully introduced to conservation of the Garandoya Tumulus in Hita City, Japan. The tumulus was constructed in the 6^{th} century and the burial chamber decorated with a mural painting was originally covered by an

Figure 6. The Garandoya Tumulus before the restoration (Mimura and Yoshimura 2011).

earth mound of 30m in diameter. As shown in Fig. 6, the mound was, however, completely destroyed and the burial chamber had been exposed to natural environment for several decades. Due to the destruction of the mound, the mural painting had been deteriorated by dew condensation and salt crystallization promoted by temperature change in the chamber.

The local government decided to restore the damaged tumuli and conserve the area as a historical site. The objectives in the restoration is to protect the mural painting from precipitation and heat. To achieve these objectives, the burial chamber was covered by double-layered earth mound which forms a capillary barrier. A capillary barrier controls rainfall infiltration into the burial chamber, in addition, heat conduction is also restricted by covering the chamber with soil layers with high heat insulation (Sawada and Mimura 2016).

3 .2 *Conservation of the damaged tumulus using a capillary barrier*

Fig. 7 shows the Garandoya Tumulus restored by constructing a double-layered earth mound. The earth mound has been applied to cover around the concrete building that stores the burial chamber. The coarser grained soil was packed in netted bags and placed on the building. Then, the finer grained soil layer was compacted on the coarser grained layer using a lightweight compaction machine. The soils used for the restoration were the same with those used in the model chamber tests. They were obtained close to the tumulus where volcanic ash deposits are

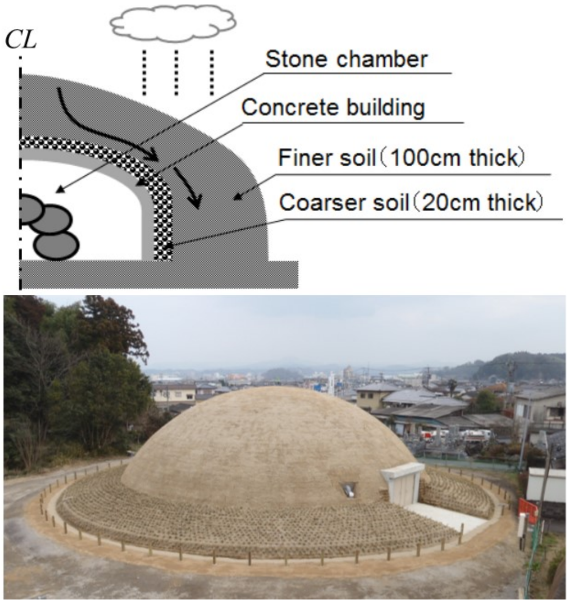

Figure 7. The restored tumulus using a double-layered earth cover and its structure (March, 2015).

Figure 8. The construction of the double-layered earth mound (September, 2014).

spread and divided into finer and coarser grained soils by sieving.

As described in above, a capillary barrier is caused by the difference in hydraulic conductivity of the finer and coarser grained soils, and the diversion capacity is largely controlled by precipitation. As precipitation increases, the suction at the soil interface moves toward the intersection in Fig. 5 so that the infiltrating water equals to the sum of the lateral flux in the finer grained layer and the vertical flux into the coarser grained layer. A capillary barrier is not effective anymore for heavy rain. In the restoration of the Garandoya Tumulus, the burial chamber is hence designed to be protected by both the capillary barrier and the concrete building. The capillary barrier is expected to perform as the first water shielding layer. The water infiltrating through the capillary barrier is diverted at the surface of the concrete building.

4 CONCLUSION

In the present paper, the mechanism of water shielding by a capillary barrier was discussed and a successful application of a capillary barrier to the restoration of a damaged tumulus was described.

The mechanism of a capillary barrier was investigated by conducting model chamber tests and simulating them. A series of model chamber tests showed 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 precipitation. The distributions of suction, total head and hydraulic conductivity of the soil layers were evaluated with a seepage flow analysis, which concluded that water shielding by a capillary barrier is caused by the difference in hydraulic conductivity of the finer and coarser grained soils. The downward flux into the coarser soil layer is limited when the suction at the soil interface is sufficiently large and hydraulic conductivity of the coarser grained layer is negligible low compared to that of the finer grained layer.

A capillary barrier was successfully introduced to the restoration of the Garandoya Tumulus of which original mound was destroyed. The burial chamber was stored away in the concrete building covered with a double-layered earth mound to protect the decorated burial chamber from precipitation and heat. The diversion capacity of a capillary barrier is controlled by precipitation and it is impossible to protect the burial chamber from heavy rain. The burial chamber is hence designed to be protected both by the capillary barrier and the concrete building, and the capillary barrier is expected to perform as the first water shielding layer.

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