Performance of Capillary Barrier System Included in Test Shallow Land Waste Repository

Toshihiro MORII[1, 2*], Tetsuya SUZUKI[1, 2], Takayuki KAWAI[2], Kaoru KOBAYASHI[3] and Kazunobu MATSUMOTO[3]

(Received February 7, 2013)

Summary

ABSTRACT: Capillary barrier (CB) is a soil layer system which is composed of sand layer underlain by gravel layer. Water infiltrating from soil surface is well diverted along an interface between the soil layers due to a physical difference in unsaturated hydraulic properties of soil. A shallow land waste repository, in which a top CB and a bottom CB are included to reduce infiltration due to rainfall and to divert water percolating through the protected waste material respectively, was proposed to isolate safely a hazardous waste material or a very low level radioactive waste. The diversion length of the CB which could be applied to structural design of the shallow land waste repository was determined based on the laboratory soil box test. Long-term measurements of soil moisture content in the test land waste repository showed an excellent and stable water diversion of the CB in the field.

Bull.Facul.Agric.Niigata Univ., 65(2):179-186, 2013

Key words : Capillary barrier of soil, Shallow land waste repository, Test construction, Diversion length

Capillary barrier (CB) is a tilting soil layer system which is composed of a finer soil (usually sand) layer underlain by a coarser soil (usually gravel) layer. Water which infiltrates into the soil is suspended just above an interface between the soil layers and diverted downward along the interface, with the result that a vertical movement of water into deeper soil layers below the interface stops within some length along the interface. Because of this excellent diversion of infiltration water, the CB has been employed in a top cover of waste landfills and mining wastes to reduce water infiltration into the protected waste materials (Stormont and Anderson, 1999; Yanful *et al.*, 1999). The CB has also been proposed to be used as a soil cover for slope stabilization purpose against rainfall-induced slope failure (Tami *et al.*, 2004; Rahardjo *et al.*, 2007). Water flow downward along the interface between finer and coarser soil layers accumulates gradually its mass of flow due to continuous infiltration from the soil surface, and, at some length along the interface, water percolates into the coarser soil layer (Ross, 1990; Walter *et al.*, 2000) as shown schematically in Figure 1. A horizontal length or distance from the beginning of water flow to this percolation into the coarser soil layer (breakthrough) is called a diversion length of the CB, and is one of important parameters in designing structural configuration of the CB system and selecting a suitable combination of the finer and coarser soils. It is well known that the diversion length can theoretically be estimated based on the infiltration flux, saturated and unsaturated hydraulic properties of the finer and coarser soils, and the slope of the interface (Steenhuis *et al.*, 1991). Although Ross (1990) discussed that the diversion length might be theoretically as much as 50 m in a dryer climate with an order of magnitude less infiltration, only 1 to 2 meters of the diversion length has been observed and published (Walter *et al.*, 2000) . These values are so small that it may be difficult to employ the capillary barrier of soil in

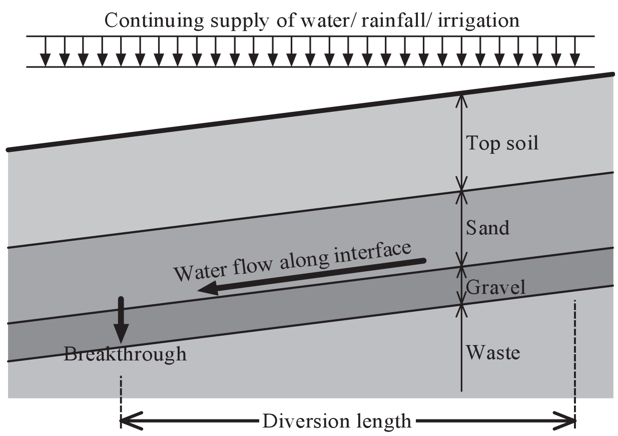


Fig. 1. Schematic layout of the capillary barrier of soil. Water infiltrating from top soil moves downward along an inter-face between the soil layers.

[1] Faculty of Agriculture, Niigata University
[2] Research Institute for Natural Hazards and Disaster Recovery, Niigata University
[3] Research Institute of Technology, Tobishima Corporation
* Corresponding author: morii@agr.niigata-u.ac.jp

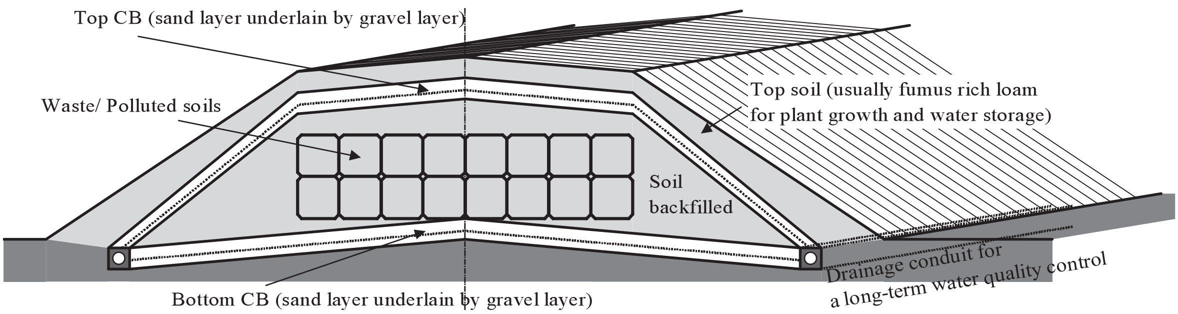


Fig. 2. Proposal of shallow land waste repository covered with a top CB layer and placed with a bottom CB layer.

the top cover of waste landfills or the slope stabilization.

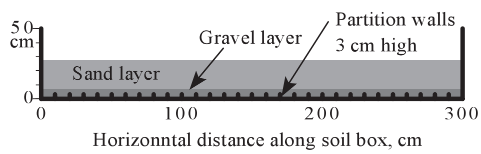
In this study, a shallow land waste repository shown in Figure 2 is proposed to isolate effectively a hazardous waste material or a very low level radioactive waste. A top CB and a bottom CB are placed in the shallow land waste repository to reduce infiltration due to rainfall and to divert percolating water through the protected waste material, respectively. As the shallow land waste repository is constructed on ground surface, there may be no risk that groundwater enters the waste and diffuses pollutants into a surrounding environment. It should be also emphasized that the CB can maintain its function of water diversion for an extremely long duration because it consists of natural materials such as sand and gravel. The diversion length of the CB which can be applied to structural design of the shallow land waste repository is determined based on a laboratory soil box test, and some innovative and feasible proposition will be given for construction of the shallow land waste repository. Observations of soil water movement in a test shallow land waste repository are also discussed to show an effectiveness of the CB.

ESTIMATION OF DIVERSION LENGTH

Soil box test

In order to observe directly the breakthrough of water flowing along the interface, and to determine the diversion length, a series of laboratory soil box test was carried out. Figure 3a shows an acrylic soil box, 300 cm in length, 20 cm in width and 50 cm in height, built in a steel frame. The soil box was placed horizontally, and the gravel was compacted into the layer of 7.5 cm thickness, then the sand into 20 cm thickness as shown in Figure 3b. A completely-permeable polypropylene net was placed over the compacted gravel layer so that the sand particles did not fall into voids formed in the gravel layer. After a gauze sheet was spread over the soil surface to protect soil erosion due to rainfall droplet, one side of the soil box was jacked up to obtain the tilting interface of the CB. The infiltration water was supplied on the surface of the upper sand layer by a rainfall simulator which had emitting needles (syringe needles), 0.3 mm in an

a. Soil box (lower set) and rainfall simulator (upper set).



b. Partition walls attached to the bottom of the soil box.

Fig. 3. Test equipment prepared for the soil box test to measure diversion length of the CB.

inner diameter, attached to the base plate of water reservoir with constant head of water. To keep the acrylic front panel clean, the emitting needles were placed so that the rainfall droplet did not fall along the front panel. Intensity of rainfall was simulated by adjusting the head of constant water in the water reservoir. Uniformity of the rainfall intensity over the soil surface was examined by measuring the water mass collected into a glass beaker during 10 minutes.

Figure 4 shows grain size distribution curves of sand and gravel used in the soil box test. The sand has less-5% fine and coarse fractions; the gravel, commercially available, is siliceous with a mean particle size of 5 to 6mm. Relationships of negative pore pressure, *h*, with volumetric moisture content of sand and gravel were measured by a laboratory soil column test, and are plotted in Figure 5a. Soil-water characteristic curves are determined by using van Genuchten equation (Stephens, 1996). Figure 5b gives unsaturated hydraulic conductivity, K, of sand and gravel estimated from Figure 5a by using van Genuchten equation. It is seen that, when the negative pressure head just above the interface between sand and gravel decreases to 3 to 4cm due to accumulation of water, the hydraulic conductivity of gravel becomes larger than that of sand and the accumulated water will begin to percolate into the gravel layer. But, because nearly 100% saturation within the sand layer as estimated from Figure 5a rarely occurs under evaporation condition with a restricted supply of water, the breakthrough of accumulated water into the lower gravel layer would not either.

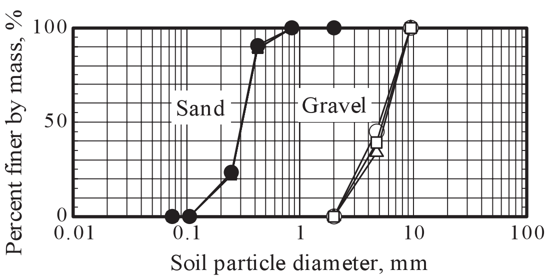


Fig. 4. Grain size distribution of sand and gravel used in the soil box test.

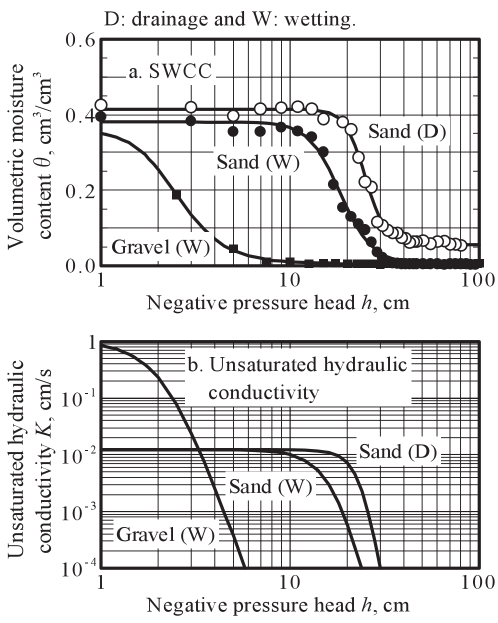


Fig. 5. Soil-water characteristic curves (SWCC) of sand and gravel measured by laboratory soil column tests in a. Unsaturated hydraulic conductivities of sand and gravel are estimated by using van Genuchten's equation in b.

Measurement of diversion length

Totally 12 tests were conducted by combining two interface angles, 5 and 10 degrees, with three infiltration rate, 5, 10 and 20 mm/h, in two soil boxes. The sand layer in one of two soil boxes was compacted into 90 % of a maximum dry density, 1.616 Mg/m^3, and 85 % in another soil box. Water which percolated into the lower gravel layer was collected along a partition wall 3 cm high attached transversely every 10 cm intervals onto the bottom plate of the soil box as shown in Figure 3b, and led to a collecting beaker through a silicon tube connected to the lowest position of the side wall of the soil box as shown in Figure 3a. The diversion length was determined by observing and measuring a volume of water collected into the collecting beaker along the bottom of the soil box. Figure 6 shows a typical measurement of the water volume collected along the distance of the bottom of the soil box in the case of 90 % compaction of the sand layer, 10 degrees in slope and 10 mm/h of infiltration rate (rainfall intensity). As a mean total amount of the water volume, 1077.4 cm^3/10 min., is converted into 10.8 mm/h of the infiltration rate, it is found that a mass balance between infiltration and drainage of water is kept. In this case, the diversion length of 170 cm was determined from Figure 6.

Estimation of diversion length

Some theoretical equations have been proposed to estimate the diversion length of the CB by several researchers (Ross, 1990; Steenhuis *et al*., 1991; Kung, 1990). Among these, the equation by Steenhuis *et al*. (1991) is effectively adaptable (Walter *et al*., 2000; Smesrud and Selker, 2001). In the case where an infiltration rate, q, is much smaller than a saturated hydraulic conductivity of sand (the upper finer soil), K_S, the equation of the diversion length, L, is given by

$$L \leq \frac{K_s}{q} \tan\phi \left[\alpha^{-1} + (h_a - h_w) \right], \tag{1}$$

where ϕ is the slope angle of the interface; h_a and h_w are the

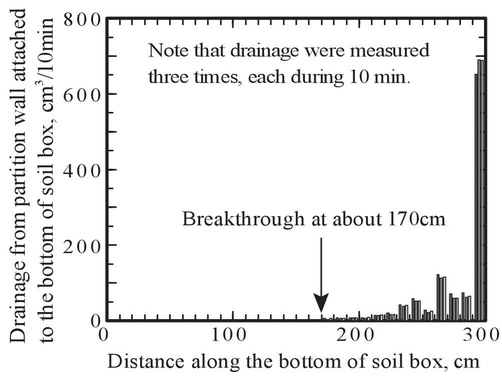


Fig. 6. Typical measurement of water volume collected along the bottom of the soil box to determine the diversion length.

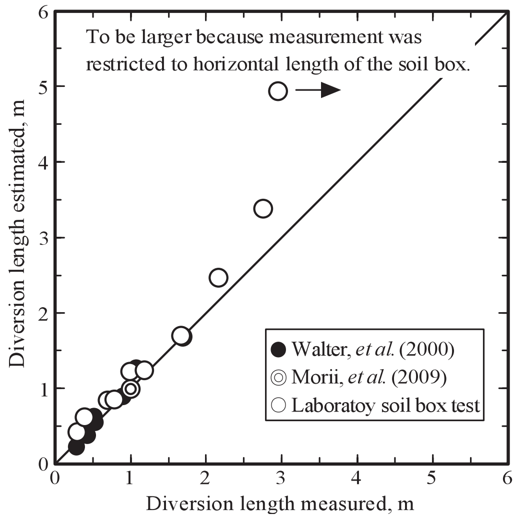


Fig. 7. Comparison of the diversion length between measurements and estimations.

air entry value of sand and the water entry value of gravel, respectively. α is an exponential constant describing the relationship between h and K of sand near saturation:

$$K = K_s \qquad |h| < h_a\,; \\ K = K_s \exp[\,\alpha^{-1} + (h - h_a)] \qquad |h| \geq h_a\,; \tag{2}$$

In Equation 1, q may depend on a thickness of the top soil layer above the sand layer as well as rainfall intensity and duration.

All the diversion lengths measured in the soil box test are given in Figure 7 and compared well with the estimations calculated by Equations 1 and 2. K_s of 90 %-compacted sand is 1.31×10^{-4} m/s, and 85 %-compacted sand 1.91×10^{-4} m/s. The unsaturated hydraulic properties of the sand, h_a, h_w and α, are determined to be 13 cm, 1 cm and 0.12/cm, respectively, based on the laboratory soil column tests (Nakafusa *et al*., 2012). Some experiment data published by Walter *et al*. (2000) and the observed data by Morii *et al*. (2009) are also plotted in Figure 7. Be sure that the measured value of the data denoted by a small arrow would be larger because the measurement was restricted to the length of the soil box, 300 cm. A fairly good comparison of the diversion length between the measurements/ observations and the estimations can be found in Figure 7. It is thought from Figure 7 that Equations 1 and 2 proposed by Steenhuis *et al*. (1991) can be practically employed to estimate the diversion length of the CB.

TEST CONSTRUCTION OF SHALLOW LAND WASTE REPOSITORY

Construction of test shallow land waste repository

Structural dimensions of the CB depend on the diversion length determined by the hydraulic properties of sand and gravel, the inclination of the CB layer, and the infiltration rate from the upper soil. Based on the results in the previous section, about four meters of the diversion length can be practically employed to design the CB in the shallow land waste repository. A test shallow land waste repository was constructed in order to monitor the soil water movement in the field and to examine an excellent water diversion by the CB. The original ground soil was compacted with the surface inclination of 5 degrees. The gravel was placed over the compacted ground surface and compacted statically by using the plate-type bucket in 10 cm thickness and in 4 m horizontal length (Figures 8a, b), then the sand over it in 15 cm thickness. After constructing the CB layer, sandy soil, polypropylene soil-bags which simulated containers for waste storage, and sandy soil were placed and compacted successively higher (Figure 8c). Uniformity in density of the compacted sand layer is an important property which guarantees the water diversion in the CB system because the diversion length directly relates to the saturated hydraulic conductivity of sand as shown in Equation 1. After constructing the CB layer, 19 cylindrical sand cores, 100 cm^3 in volume and 5 cm in height, were sampled, and the densities of the sand cores were measured in laboratory. Figure 9a shows a mean value and a standard deviation of the dry density of sand cores on a normal distribution curve, together with the saturated hydraulic conductivity of sand measured by laboratory permeability test in Figure 9b. It can be seen from Figures 9a and 9b that the saturated hydraulic conductivity corresponding to a maximum density expected with 95% confidence is about 65 % lower than that corresponding to a minimum density along an average line between K_s and ρ_d in Figure 9b, with the result that the diversion length varies largely.

Figure 10 shows the schematic diagram of the test shallow land waste repository which has half the structural section of Figure 2. The top CB was not included because it was planned only to observe the diversion of infiltration water. The depth of the CB layer was 1.1 m from the top surface of the test shallow land waste repository. Width of the section shown in Figure 10 is about 2 m, and another 2-m-width section without the CB layer was constructed as a reference plot to monitor the soil water movement. Two rectangular soil surfaces under construction in Figure 8d show these plots in which the back side is the CB layer plot and the front side the reference plot without CB layer. Nine painted circles in Figure 10 show positions in which dielectric soil moisture sensors EC-5 (Decagon Devices, Inc.) were embedded to measure volumetric moisture content of soil. Numerals before and in parenthesis are numbers of the sensor embedded in the CB layer plot and in the reference plot without the CB layer, respectively.

Soil water movement

The volumetric moisture contents measured in the test shallow land waste repository from June to September are given in Figure 11. The left and right rows in Figure 11 show

a. Gravel layer compacted statically by the plate-type bucket.

b. Another gravel placed and spread by the plate-type bucket.

c. Test shallow land waste repository constructed, about 8 m wide, 6 m deep and 2 m high including surrounding soil slope.

d. CB layer plot (the back side) and the reference plot without the CB layer (the front side) under construction. Some black lines placed transversely on the soil surface are connection cables of EC-5.

Fig. 8. Construction of the test shallow land waste repository.

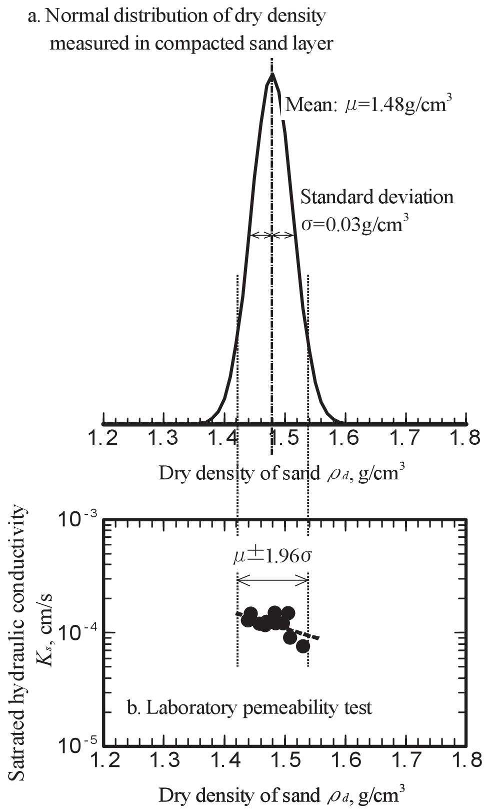


Fig. 9. Frequency distribution of dry density measured in the compacted sand layer and the saturated hydraulic conductivity measured in laboratory.

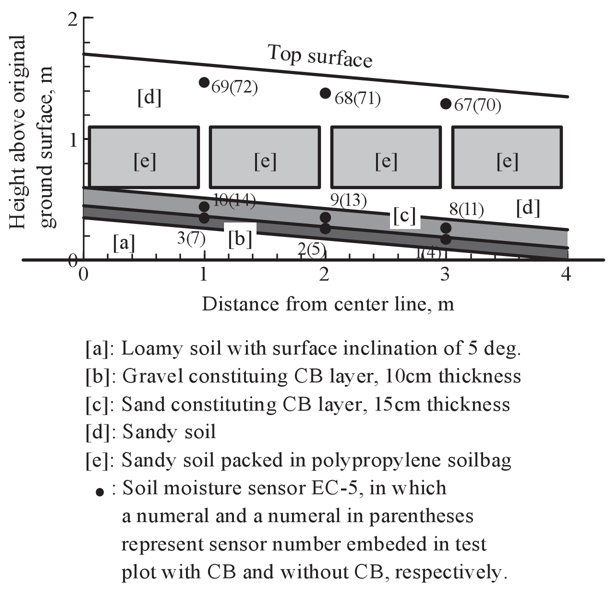


Fig. 10. Sectional layout of the test shallow land waste repository.

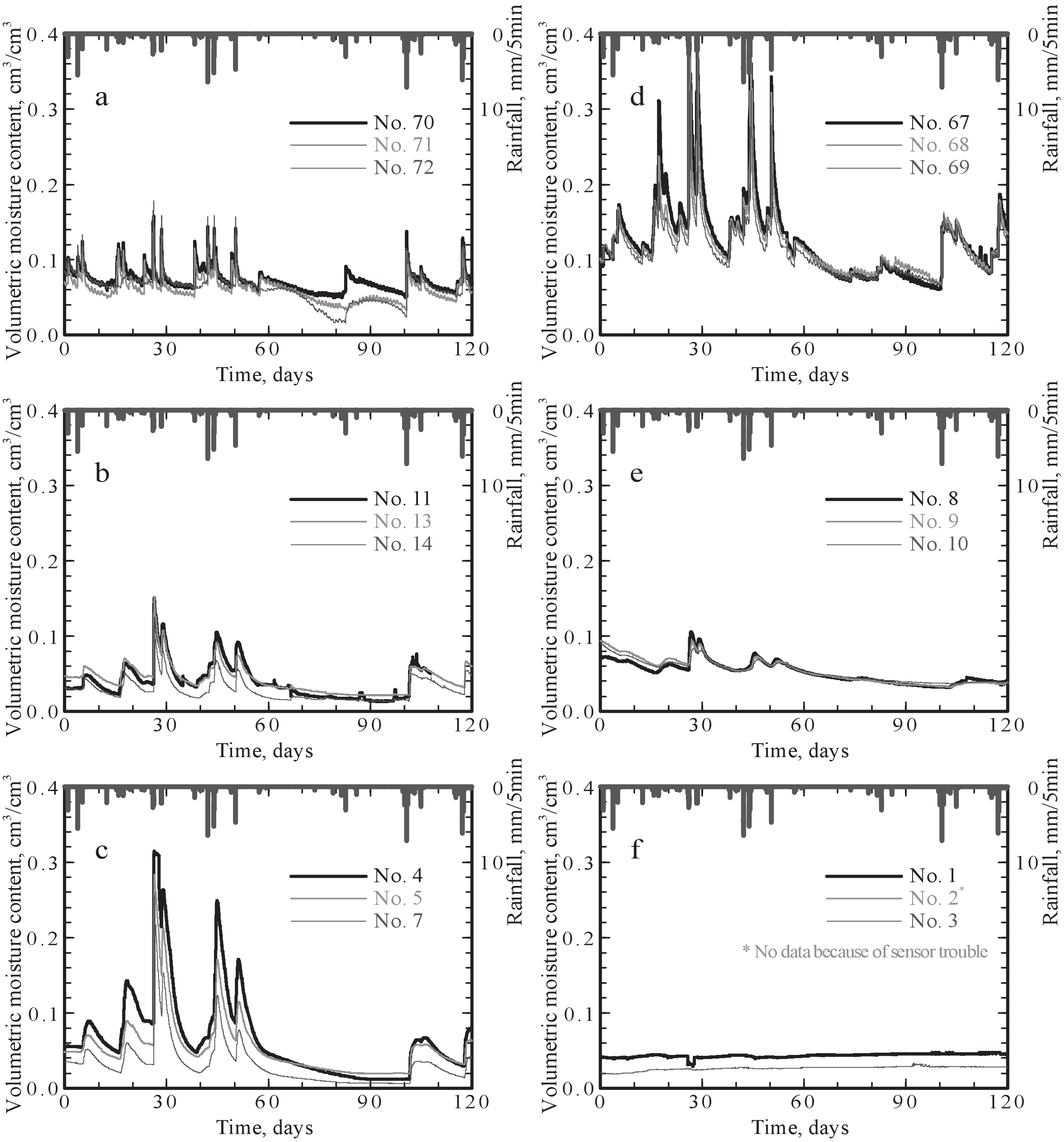


Fig. 11. Volumetric moisture content measured in the test shallow land waste repository. Position of the sensor numbered is given in Figure 10.

the volumetric moisture contents measured in the CB layer plot and in the reference plot without the CB layer, respectively, and the upper, central and lower lines near the top surface, in the sand layer and in the gravel layer, respectively. Rainfall intensity measured 5-minute intervals is given by an inverse bar with the right vertical axis of each figure. Comparing Figure 11f with 11e and 11c, it is found that the soil water which infiltrates from the top surface of the test repository enters into the sand layer, but does not into the gravel layer underling the sand layer. This is exactly due to the excellent water diversion by the CB.

CONCLUSIONS

Shallow land waste repository, in which the top CB and bottom CB are placed to reduce infiltration due to rainfall and to divert percolating water through the protected waste material respectively, was proposed to isolate effectively a hazardous waste material or a very low level radioactive waste. As the shallow land waste repository is constructed on ground surface, there would be no risk that groundwater enters the waste and dif-fuses pollutants into a surrounding environment. It should be also emphasized that the CB can maintain its function of water diversion for an extremely long duration because it consists of natural materials such as sand and gravel. The laboratory soil box test and the test shallow land waste repository constructed in the field reveal that:

1) The diversion length which determines the structural dimensions of the shallow land waste repository can be estimated well based on the hydraulic properties of sand and gravel employed in the CB, the inclination of the CB interface and the infiltration rate expected in the field. Equations 1 and 2 proposed by Steenhuis et al. (1991) is recommended to estimate the diversion length of the CB.
2) The test shallow land waste repository showed the excellent and stable diversion of infiltration water provided by the CB. A continuing observation of soil water movement may be required to evaluate the CB performance for a long duration.

ACKNOLEDGEMENTS

The present study is supported by the Grant-in-Aids for Scientific Research (B), No. 22380127, and Challenging Exploratory Research (C), No. 24658201, made by the Ministry of Education, Science, Sports and Culture of Japan. Messrs. K. Taguchi and N. Someya, TNS Co., Ltd., Japan, are sincerely grateful for their help in conducting the laboratory soil box test and in constructing the test shallow land waste repository. Their efforts done by Mr. K. Takahashi and Miss Y. Nakano, the undergraduates of Faculty of Agriculture, Niigata University, to calculate the volumetric moisture contents in the test shallow land waste repository are gratefully acknowledged.

REFERENCES

Kung, K.J.S. 1990. Preferential flow in a sandy vadose soil, 2, Mechanism and implications. *Geoderma* **46**: 59-71.

Morii, T., Takeshita, Y., Inoue, M. and Matsumoto, S. 2009. Alternative measures for soil slope stability using capillary barrier of soil. *Proceedings of the 4th Asia-Pacific Conference on Unsaturated Soils, Newcastle, Australia*: 319-324.

Nakafusa, S., Kobayashi, K., Morii, T. and Takeshita, Y. 2012. Estimation of water diversion provided by capillary barrier of soils. *Proceedings of the 5th Asia-Pacific Conference on Unsaturated Soils, Pattaya, Thailand*, **2**: 773-777.

Rahardjo, H., Krisdani, H. and Leong, E.C. 2007. Application of unsaturated soil mechanics in capillary barrier system. *Proceedings of the 3rd Asian Conference on Unsaturated Soils, Nanjin, China*: 127-137.

Ross, B. 1990. The diversion capacity of capillary barriers. *Water Resources Research*, **26**(10): 2625-2629.

Smesrud, J.K. and Selker, J.S. 2001. Effect of soil-particle size contrast on capillary barrier performance. *Journal of Geotechnical and Geoenvironmental Engineering*, **127**(10): 885-888.

Steenhuis, T. S., Parlange, J.Y. and Kung, K.J. 1991. Comment on "The Diversion Capacity of Capillary Barriers" by Benjamin Ross. *Water Resources Research*, **27**(8): 2155-2156.

Stephens, D.B. 1996. *Vadose Zone Hydrology*. CRC Press, Florida.

Stormont, J.C. and Anderson, C.E. 1999. Capillary barrier effect from underlying coarser soil layer. *Journal of Geotechnical and Geoenvironmental Engineering*, **125**(8): 641-648.

Tami, D., Rahardjo, H., Leong, E.C. and Fredlund, D.G. 2004. A physical model for sloping capillary barriers. *Geotechnical Testing Journal*, **27**(2): 173-183.

Walter, M.T., Kim, J.S., Steenhuis, T.S., Parlange, J.Y., Heilig, A., Braddock, R.D., Selker, J.S. and Boll, J. 2000. Funneled flow mechanisms in a sloping layered soil: Laboratory investigation. *Water Resources Research*, **36**(4): 841-849.

Yanful, E.K., Simms, P.H., Rowe, R.K. and Stratfoed, G. 1999. Monitoring an experimental soil waste cover near London, Ontario, Canada. *Geotechnical and Geological Engineering*, **17**: 65-84.

キャピラリー・バリアシステムを試験導入した盛土式廃棄物貯蔵施設の性能

森井俊広[1, 2*]・鈴木哲也[1, 2]・河合隆行[2]・小林薫[3]・松元和伸[3]

（平成25年２月７日受付）

要　約

キャピラリー・バリア(CB)は、砂層とその下に礫層を敷設した単純な土層システムをいう。地表面から浸潤してきた土中水は、土の不飽和水分特性の違いにより、両土層の境界面に沿ってうまく遮断される。危険な廃棄物、あるいは低レベルの放射性廃棄物を安全に隔離するための盛土式廃棄物貯蔵施設を提案した。この施設は、降雨による浸潤水を低減するとともに、貯蔵廃棄物を浸潤してくる土中水を排水するために、上部CB被覆層と底部CB排水層を敷設する構造となっている。盛土式廃棄物貯蔵施設の構造設計に必要となるCBの限界長を室内土槽試験で決定し、この貯蔵施設を試験施工した。長期にわたって盛土内の土中水分量を測定し、野外条件下におけるＣＢの優れたかつ安定した水分遮断機能を確認した。

新大農研報, 65(2):179-186, 2013

キーワード：土のキャピラリー・バリア、盛土式廃棄物貯蔵施設、試験施工、限界長

[1] 新潟大学農学部
[2] 新潟大学災害・復興科学研究所
[3] 飛島建設株式会社技術研究所
* 代表著者 : morii@agr.niigata-u.ac.jp