Capillary Barrier System for Resilient Slope Cover

Auckpath Sawangsuriya[1] and Apiniti Jotisankansa[2]

[1]Bureau of Road Research and Development, Department of Highways, Bangkok, Thailand
[2]Department of Civil Engineering, Faculty of Engineering, Kasetsart University, Bangkok, Thailand

ABSTRACT: Capillary barrier system (CBS) is a two-layered cover system that consists of an upper finer layer overlying a coarser layer and is designed based on the principle of unsaturated soil mechanics. An application of CBS with vegetative slope cover is becoming an attractive solution because of lower cost, higher resiliency, more nature-oriented measure as well as improved aesthetics comparing to traditional concrete-based structure. This paper explores the performance and effectiveness of CBS as a resilient nature-based solution to mitigate rainfall-induced slope failures and surface erosions under tropical climatic conditions with high rainfall intensities. Moreover, some alternative products such as biochar, reclaimed asphalt aggregate, marginal soils, local plants etc. were considered in the proposed CBS. Results of field investigation indicated that the CBS with vegetative slope cover exhibited better performance in terms of soil moisture, pore-water pressure development, and erosion controls. Its effectiveness also depended on material type and geotextile sheet inclusion. Vegetations seemed to be more effective without the geotextile sheet between finer and coarser layers. The CBS however exhibited less suction preservation, which highlighted a tradeoff between plant establishment and suction preservation, warranting further exploration.

INTRODUCTION

Residual soil and weathered rock slopes are typically found in mountainous and hilly terrains in most tropical regions. These earth slopes are often in the unsaturated condition with negative pore-water pressure or matric suction. The presence of matric suction is a favorable condition because it has beneficial effect on the shear strength of unsaturated soils and the stability of slopes. However, when the rainfall infiltrates into slope, the pore-water pressure increases, the matric suction decreases, and hence reducing the stability of the slope. This phenomenon causes the slope to become more prone to failure, which is widely known as rainfall-induced landslide and is one of the most destructive natural hazards that is usually random and sudden event that is often hard to predict.

According to Iverson (2000), Polemio and Petrucci (2000), rainfall is one of the main triggering factors of landslides and slope instability. Rainfall-induced slope failures and surface erosions have been increasingly becoming more severe in the tropics due to more frequent extreme climate conditions and potential climate impacts (severe storms, floods, violent monsoon, strong typhoon, rise in sea levels, frequent tidal surges, prolonged drought, forest fire, prolonged and heavy rainfall etc.). Such climate extremity in addition to improper urbanization and natural resource exploitation on mountainous and hilly terrains caused potential risks of landslide and surface erosion, resulting in catastrophic damage of residential and land transportation infrastructure, reduction of agricultural productivity, degradation of wildlife and natural forests, human and time losses.

With the increasing severity of landslides and surface erosions, limited funds, and global concern about environmental issues, the application of capillary barrier system (CBS) with vegetative slope cover is becoming an attractive solution because of its relatively lower cost, higher resiliency, more nature-oriented measure as well as improved aesthetics comparing to traditional concrete-based structure. Such CBS is a two-layered cover system that consists of an upper finer-grained layer overlying a coarser-grained layer and is designed based on the principle of unsaturated soil mechanics. This mitigation technique has been continuously developed and investigated in several slope stabilizations and erosion controls (Khire et al. 2000, Yang et al. 2004, Tami et al. 2004, Zornberg et al. 2010, Rahardjo et al. 2012, Rahardjo et al. 2016, Satyanaga et al. 2021). It can be effectively used to improve slope stability during rainfall by maintaining optimal values of matric suction in the underlying soil (e.g. Rahardjo et al. 2016), resulting in a stable slope, and thus mitigate rainfall-induced slope failures during the most critical rainfall events (e.g. Khire et al. 2000, Yang et al. 2004). By using this technique, it is also possible to utilize valorized waste materials and local products (e.g. biochar, reclaimed and recycled materials etc.) along with local soils and vegetations such as vetiver grass (Grimshaw 1994). Although this application for slope stabilization has been traditionally used as a landfill covers to reduce water infiltration into protected waste materials, its application to slope stability as an alternative means to effectively control suction is still limited only in relatively warm climates (Scarfone et al. 2022) and has been rarely applied in the tropics.

Therefore, this paper presents the performance and effectiveness of CBS with vegetative slope cover for resiliency and sustainable mitigation to rainfall-induced slope failure and surface erosion as well as the beneficial use of valorized waste materials and local materials, e.g. biochar, vegetation, reclaimed and recycled asphalt, in the CBSs.

CAPILLARY BARRIER SYSTEM (CBS)

A capillary barrier develops when an unsaturated fine-grained soil or finer layer (e.g. silt, clay etc.) is underlain by another unsaturated coarse-grained soil or coarser layer (e.g. sand, gravel etc.). The CBS works based on the contrast between the unsaturated hydraulic properties of the finer and coarser layers. Given a relatively light rainfall event, the coarser layer is typically at very low degree of saturation and hence the corresponding unsaturated hydraulic conductivity, which decrease many orders of magnitude with decreasing degree of saturation. Since the unsaturated hydraulic conductivity of the coarser layer is typically very low and can be many orders of magnitude lower than that of the finer layer, the coarser layer acts as an almost impermeable barrier. This is in contrast to what would happen under fully saturated condition when the hydraulic conductivity of the coarser layer would be much higher than that of the finer layer. Fig. 1 illustrates the mechanism of capillary barrier which describes the interaction between materials with contrasting hydraulic conductivity (e.g. sand and low plasticity clay) under unsaturated conditions (Zornberg and McCartney 2007).

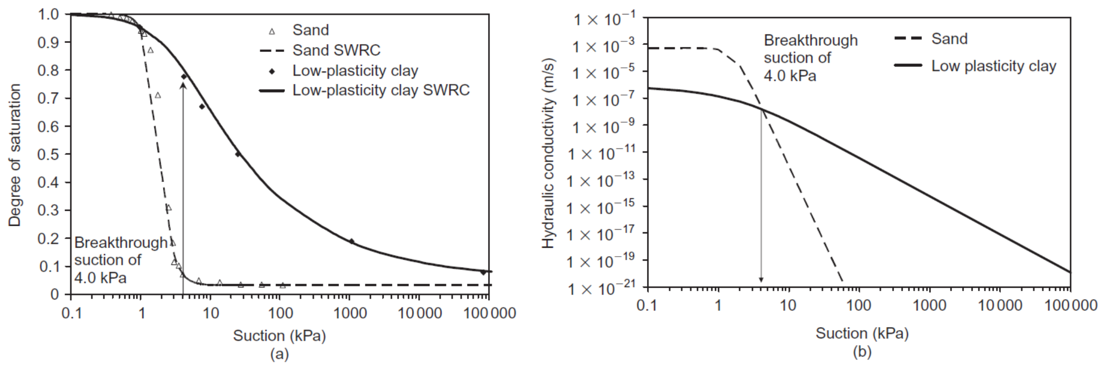

Fig. 1. Soil-water characteristic curve and soil hydraulic conductivity curve for a sand (coarser material) and a low-plasticity clay (finer material) (Zornberg and McCartney 2007).

In the case of the slope cover, infiltrating water starts entering the finer layer at the top of the slope. Suction at the interface between finer and coarser layers is relatively high since the water content is still low at the beginning of rainy season. The coarser layer behaves as an impermeable layer and water is diverted laterally down the slope within the finer layer because of gravity. At the middle of the slope, the amount of water flowing laterally within the finer layer increases, the degree of saturation at the base of the layer is greater than that further up the slope, and the corresponding suction at the interface is lower. If the suction at the interface decreases down to a point where the degree of saturation of the coarser layer increases until continuous water channels are formed within the coarser layer, the coarser layer becomes highly hydraulically conductive, and breakthrough occurs into the coarser layer and eventually into the underlying soil. Beyond this point on the slope, no more water can be diverted laterally, and infiltration water becomes percolation into the coarser layer. In accordance to lateral drainage, rainwater can also be removed from the CBS by evaporation and evapotranspiration.

INSTRUMENTED CBS WITH VEGETATIVE SLOPE COVER

Unsaturated characteristics of CBS with vegetative slope covers were comprehensively investigated along the highway's cut slopes in the Northern Thailand. They include: (1) highway No. 1192 at km post 11+500 (namely DOH 1), (2) highway No. 118 at km post 46+700 (namely DOH 2), (3) highway No. 21 at km post 329+700 (namely DOH 4). Additionally, highway No. 21 at km post 324+151 (namely DOH 3) involved slope stabilization using flapped soil bag and screw pile only without CBS. Description of slope stabilization in each section is summarized in Table 1. For all sites, a series of screw pile (76 mm in diameter, 1 m spacing and 1.6 m deep) was installed either at the slope toe (DOH 1, DOH 2, and DOH 4), which acted as a retaining structure for flapped soil bag with vegetation (Bougainvillea) or just below the slope fill (DOH 3). Such slope strengthening using screw pile with flapped soil bag was an essential of slope stabilization as indicated by the high seepage zone and severe erosion at this location. Different types of slope cover included vetiver system (VS), erosion control blanket (ECB), and capillary barrier system (CBS). It is noted that only at DOH 1, the recycled asphalt aggregate (RAA) was used as coarser layer with geotextile sheet, while at DOH 2 and DOH 4, the coarse-grained biochar was used as coarser layer without the geotextile sheet. The reason for excluding the geotextile sheet between coarser and finer layers at Sites DOH 2 and DOH 4 were to allow the plant roots to penetrate through the coarser layer into the existing soil slope to further stabilize the cut slope. For finer layer of the CBS, biochar with planting organic soil was used at DOH 1 and DOH 2, while the biochar mixed with original clayey soil was used at DOH 4.

Table 1. Description of CBS used in the study

Component	DOH 1	DOH 2	DOH 3	DOH 4
Original Soil	Silty Sand (SM)	Clayey Sand (SC)	Sandy Clay (CL)	Sandy Clay (CL)
Finer Layer	Biochar with Planting Organic Soil	Biochar with Planting Organic Soil	NA	Biochar with Original Clay
Coarser Layer	SM with Recycled Asphalt Aggregate (RAA)	Coarse Biochar (max size 19 mm)	NA	Coarse Biochar (max size 19 mm)
Geotextile between Finer and Coarser Layer	Yes	No	NA	No
Average Slope Angle (degree)	60	50	35	40
Height of Slope Stabilization (m)	8.5	7.5	3.5	4.0

*NA: Not Applicable

The topographical conditions of these sites are typically mountainous and hilly terrains, which are prone to rainfall-induced slope instability under natural and engineered systems due to their slope composition of decomposed granite and colluvium deposits. The slope composition at DOH 1 and DOH 2 consisted of silty sand (SM) and clayey sand (SC) respectively, both derived from granitic rock, while

DOH 3 and DOH 4 consisted of sandy clay (CL) derived from colluvium soil in sedimentary rock setting (siltstone and claystone). The residual soil at DOH 1 was highly erodible and severe rills, sheets and gully erosion were frequent in the area, often leading to shallow slope failure (<1 m). DOH 3 and DOH 4 were suffered from recurrent erosion and failure problem. The average annual rainfall of these sites was ranged from 1,200 to 1,300 mm. To demonstrate the performance and effectiveness of CBS with vegetative slope cover and other nature-based approaches, various slope cover sections were constructed and completed in 2022. Typically, each site consisted of three types of slope cover e.g. vetiver system (VS), erosion control blanket (ECB), and capillary barrier system (CBS). Most slope cover sections had the gradient approximately 35 to 60 degrees with the height ranging from 3.5 to 8.5 m.

The instrumented slope cover sections at four sites aforementioned were installed with a series of field instrumentation consisting of 3 to 6 soil moisture sensors, 2 to 3 piezometers, 3 to 5 tensiometers, 1 inclinometer, 6 to 8 tiltmeters, 1 rain gauge, and 6 settlement points. The instrumentation was located near the crest, middle, and toe of the slope cover at each site. A schematic diagram of instrumented CBS with vegetative slope cover is illustrated in Fig. 2. Fig. 3 illustrates some photos of the instrumented sections.

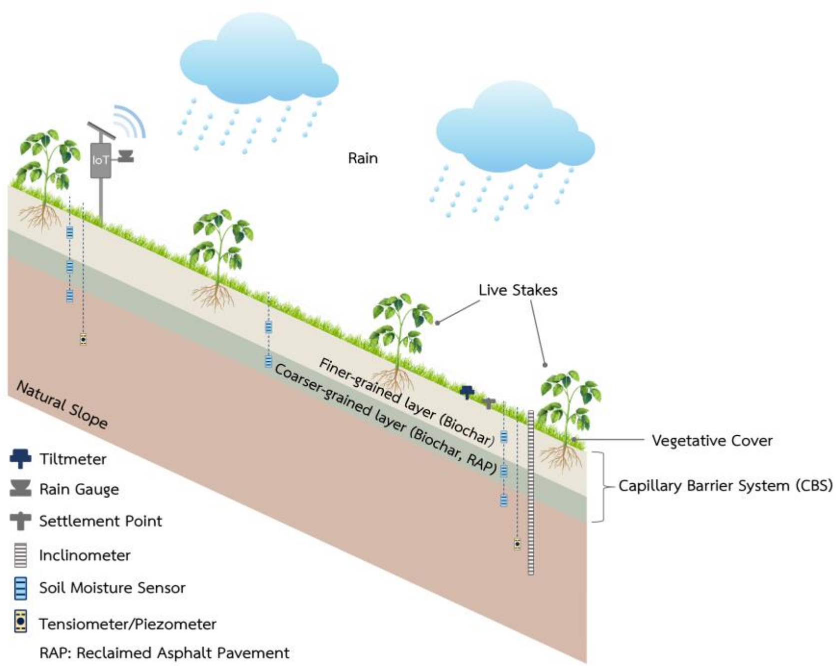

Fig. 2. Schematic of CBS with vegetative slope cover.

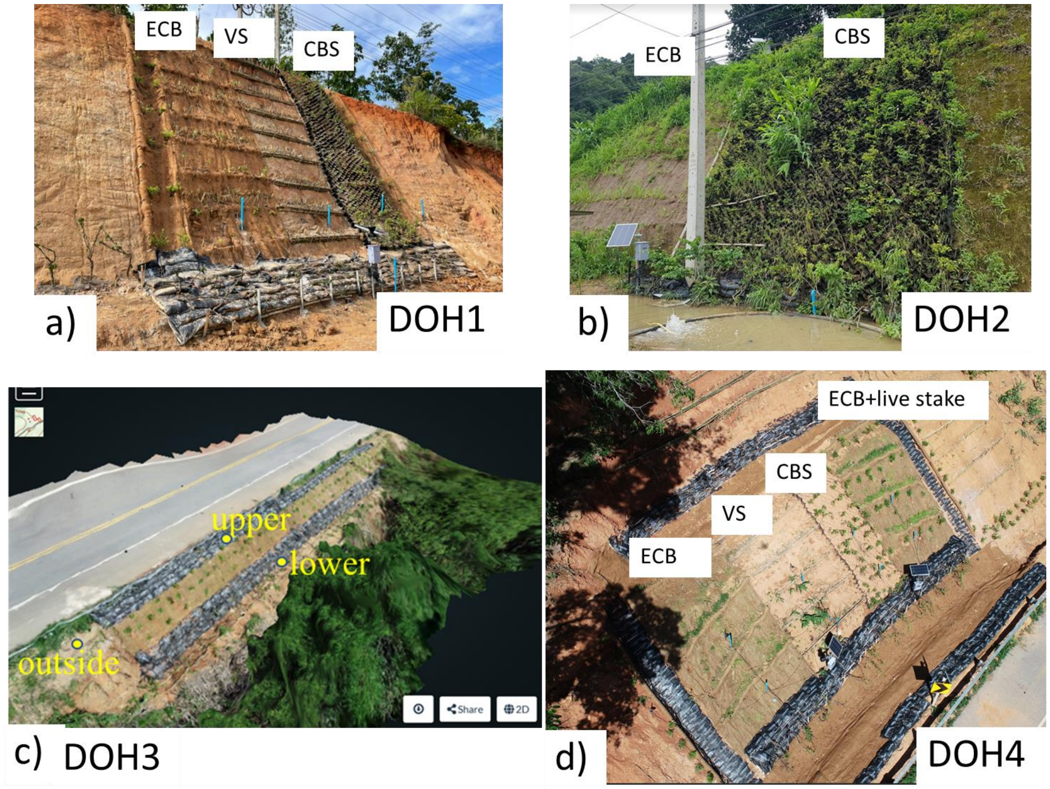

Fig. 3. Photos of the instrumented sections.

In addition to the pore-water pressure, soil moisture, and soil movement data taken from the sites, the fundamental properties of materials and local products used at these sites were also determined in the laboratory for the unsaturated soil's hydraulic and mechanical behavior. A comprehensive field investigation e.g. UAV surveys, geophysical surveys, groundwater aeration sound surveys, Kunzelstab penetration tests etc. was made at the site. Their typical results are presented in Fig.4. In general, the loose soil mantle thickness varied across the slope, measuring approximately 1.0 - 1.5 m. In addition, the field investigation also suggested that there existed the concentration of groundwater and seepage around the slope toe, which aligned with the visual observations of soil erosion.

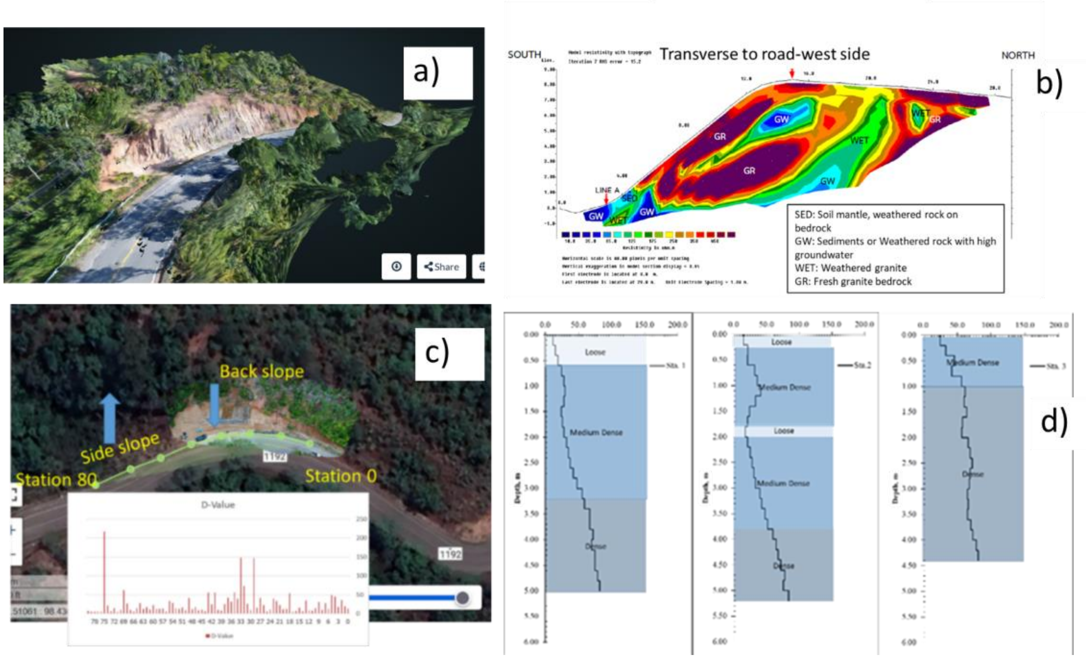

Fig. 4. Typical field investigation results at DOH 1.

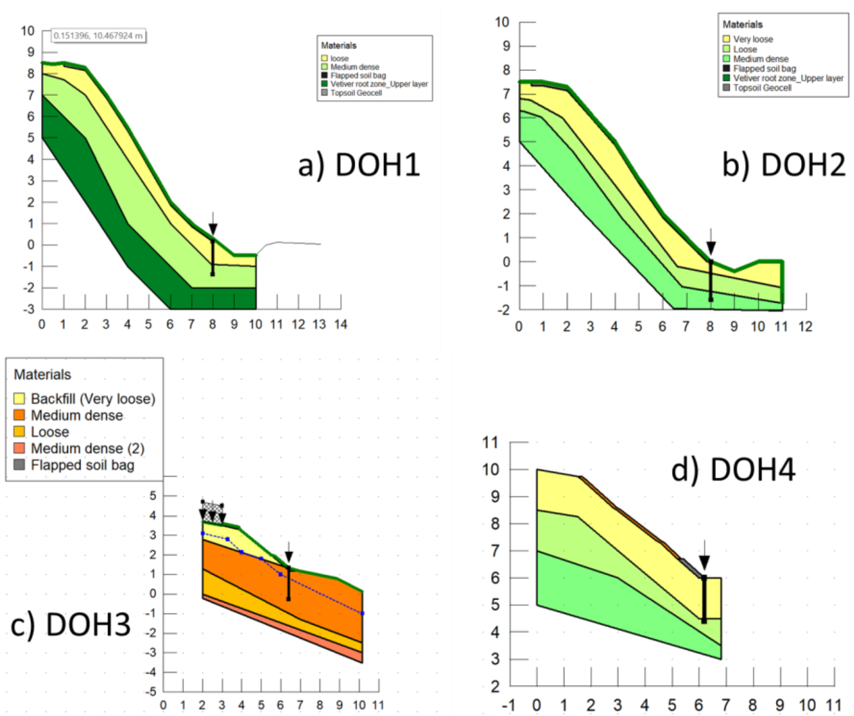

Fig. 5. Cross-sections of four sites (unit of the axis in meter).

PERFORMANCE OF CBS WITH VEGETATIVE SLOPE COVER

The performance and effectiveness of CBS with vegetative slope cover in minimizing rainwater infiltration into the slope and increasing stability against rainfall-induced slope failure and surface erosion were investigated based on the field monitoring results. Fig. 5 presents the monitoring results obtained from the field instrumentation installed at DOH 1.

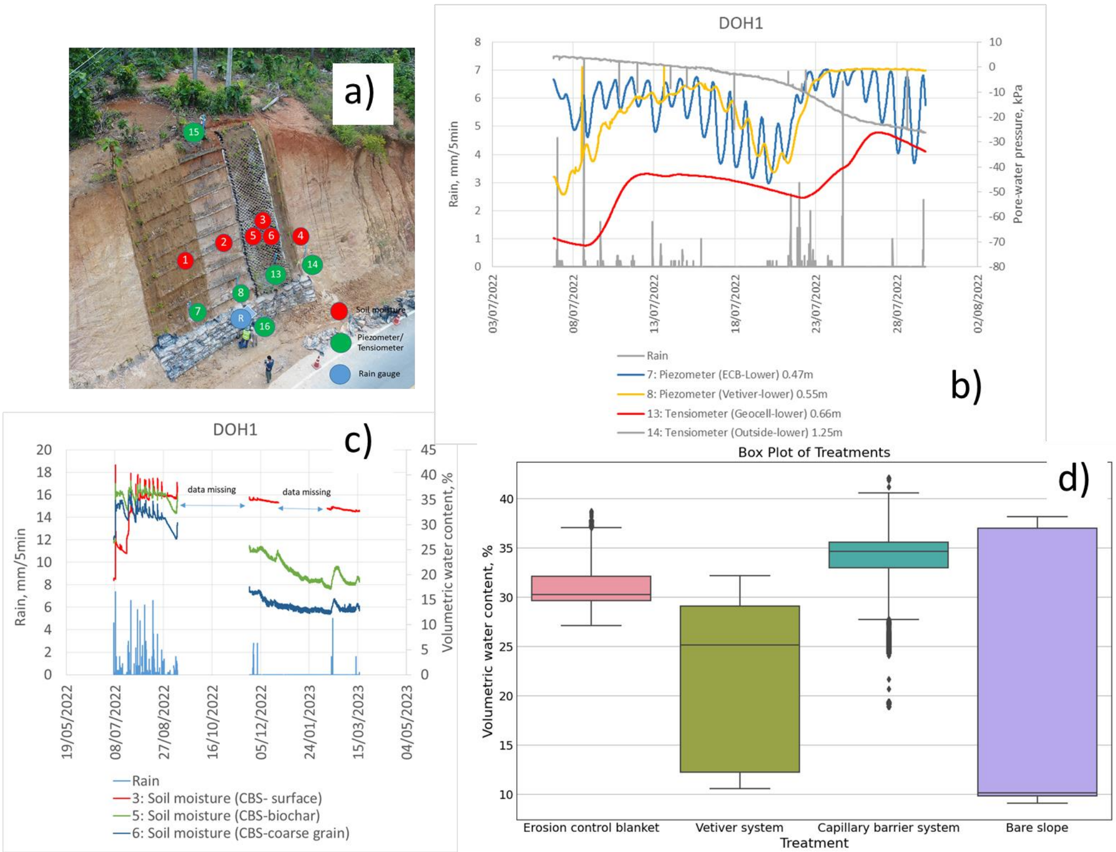

Fig. 5. Field monitoring results from DOH 1.

As shown in Fig. 5, the inclusion of geotextile sheet between finer and coarser layers in the CBS helped enhancing the performance of CBS. Fig. 5b shows the pore-water pressure during the first month after installation in the rainy season. Results suggested that the pore-water pressure in the CBS was preserved, while that in other slope covers was not. However, when visualizing the long-term monitoring data over a one-year period in Fig. 5c and Fig. 5d, the finer layer exhibited higher soil moisture (e.g. higher degree of saturation and unsaturated hydraulic conductivity), while the coarser layer exhibited lower soil moisture (e.g. lower degree of saturation and unsaturated hydraulic conductivity). This resulted in the development of a capillary barrier, e.g. the contrast between the unsaturated hydraulic properties of the finer and coarser layers. The visual observations in Fig. 6, in conjunction with the field monitoring results, clearly demonstrated the superior performance of CBS (with biochar topsoil) compared to other slope covers e.g. erosion control blanket and vetiver glass.

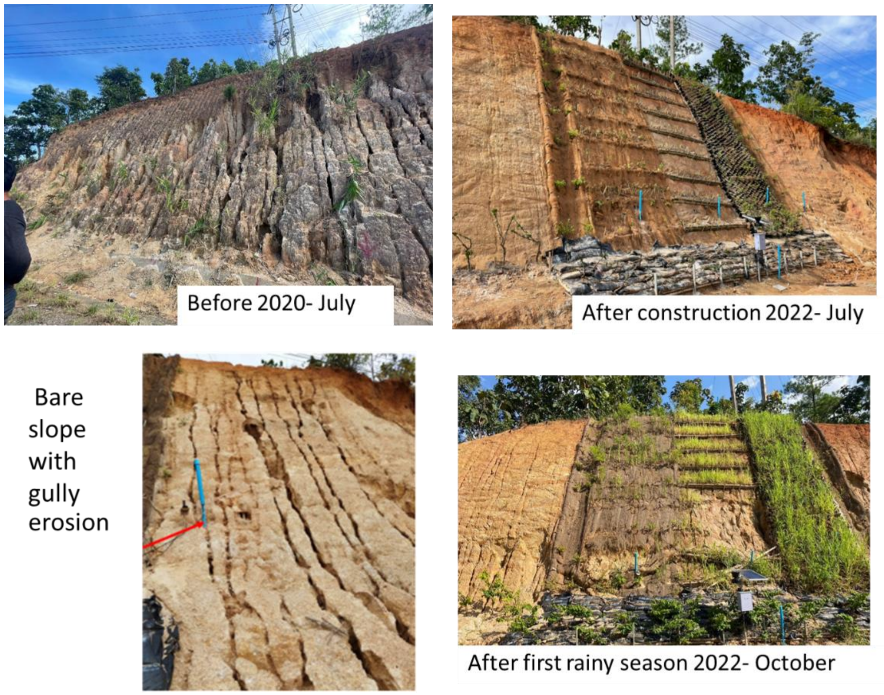

Fig. 6. Visual appearance of different slope covers at DOH 1.

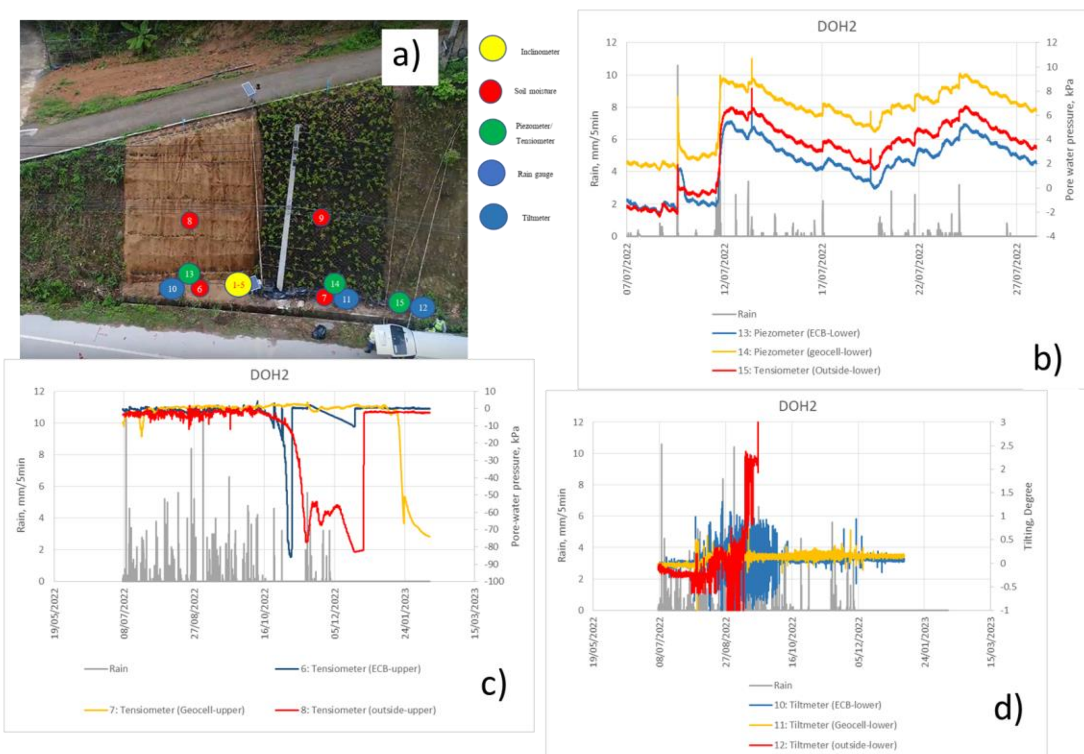

Fig. 7. Field monitoring results from DOH 2.

Fig. 8. Visual appearance of different slope covers at DOH 2.

In the case of DOH 2, without the geotextile sheet in the CBS and allowing plant root penetration aforementioned, there was no preservation of negative pore-water pressure as in DOH 1 (see Fig. 7). However, the vegetative cover seemed to work well without the geotextile sheet as shown in Fig. 8. The plants could effectively absorb available water stored in both fine and coarse biochar layers. Interestingly, the tiltmeter results (Fig.7d) showed that despite the higher pore-water pressure beneath the CBS, its movement was smaller than that in the bare slope. This could be due to the root reinforcement effect that would be higher in the fully vegetated section (Fig. 8). The fact that, the biochar could retain the moisture in the coarser layer and degraded its performance of CBS might be offset by the influence of root reinforcement. This finding warrants further exploration in this aspect.

For DOH 3 and 4 which were associated with fine-grained soils, e.g. sandy clay (CL), their typical results are shown in Fig. 9. It was found that this type of fine-grained soils in the slope also affected the performance and effectiveness of CBS. There was no clear preservation of the negative pore-water pressure and reduction of soil moisture underneath the CBS. However, due to its relatively milder slope, there was no clear distinction in terms of slope movement between different slope covers.

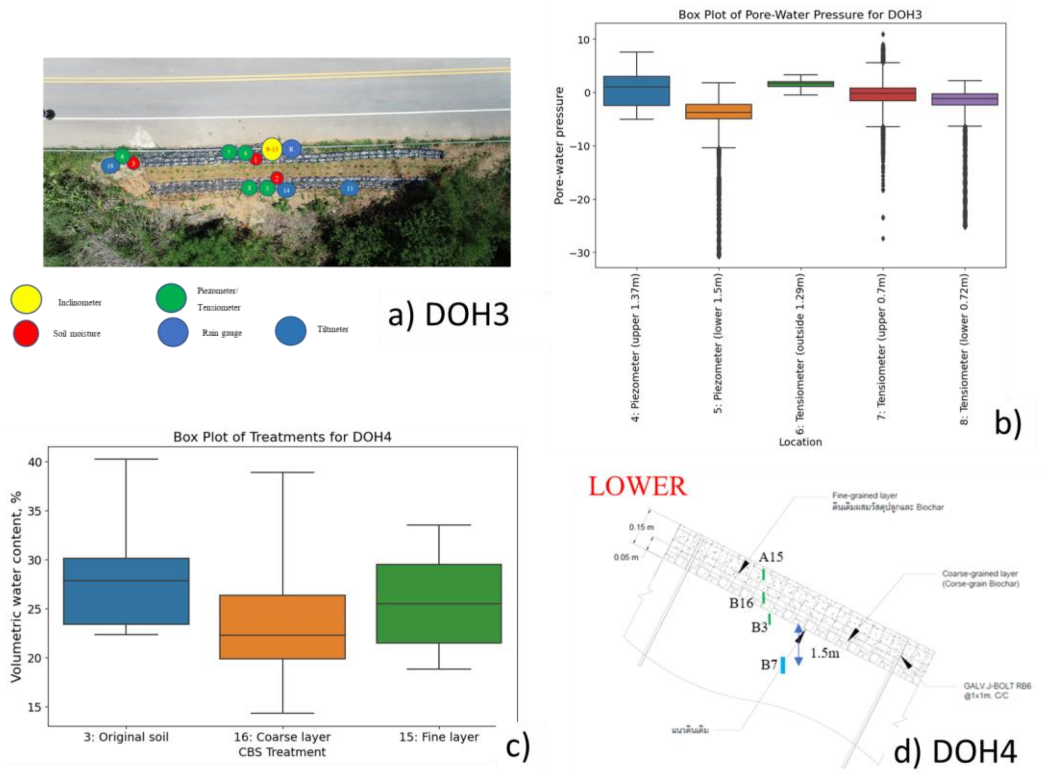

Fig. 9. Typical monitoring results of a) and b) DOH 3, c) and d) DOH 4.

The field monitoring data clearly suggested that the implementation of CBS with vegetative cover and the use of biochar in the finer layer and RAA in the coarser layer with geotextile sheet between them successfully prevented the accumulation of pore-water pressure, while protecting the slope surface. The visual observations along with the field monitoring data demonstrated the superior performance and effectiveness of CBS, comparing with other slope covers, e.g. VS and ECB, depending on the type of material, type of marginal soil, amount of moisture in the slope. When excluding the geotextile sheet between the finer and coarser layers of CBS (e.g. DOH 2 and DOH 4), the vegetation appeared to be well established but less suction preservation. There is a tradeoff between the plant establishment and suction preservation and hence an interesting topic for further exploration. It should be also noted that the numerical analysis, the laboratory column test, and the long-term monitoring are required to support the finding in this study.

CONCLUSIONS

Capillary barrier system (CBS) is a dual-layered protective structure comprising a fine-grained upper layer overlying a coarse-grained lower layer, designed based on the principle of unsaturated soil mechanics. The application of CBS with vegetative slope cover is gaining attraction due to its cost-effectiveness, increasing resilience, nature-based approach, and improved aesthetics compared to a traditional concrete structure. This paper explores the performance and effectiveness of CBS as a resilient nature-based solution to mitigate slope failures and surface erosions induced by rainfall under tropical climatic conditions with high rainfall intensities. In addition, alternative products e.g. biochar, reclaimed asphalt aggregate, marginal soils, and local plants were considered in the CBS design.

Field investigations revealed that CBS with vegetative slope cover demonstrated superior performance in terms of soil moisture, pore-water pressure management, and erosion control. The effectiveness was influenced by factors like material type and the inclusion of a geotextile sheet. When the geotextile sheet between the finer and coarser layers of CBS was excluded, the vegetation appeared to be well established and the CBS exhibited less suction preservation. This highlighted a tradeoff between plant establishment and suction preservation, warranting the need for further exploration.

REFERENCES

Grimshaw, R.G. (1994). "Vetiver grass-its use for slope and structure stabilization under tropical and semitropical conditions." *Vegetation and Slopes*, Institution of Civil Engineers, London: 26-35.

Iverson, R.M. (2000). "Landslide triggering by rain infiltration." *Water Resources Research*, Vol. 36 (7): 1897-1910.

Khire, M., Benson, C., and Bosscher, P. (2000). "Capillary barriers: design variables and water balance." *J. Geotechnical & Geoenv. Engrg.*, Vol. 126 (8): 695-708.

Polemio, M. and Petrucci, O. (2000). "Rainfall as a landslide triggering factor: an overview of recent international research." Landslides in Research, Theory and Practice, *Proc. 8th Int. Sym. on Landslides*, Cardiff, UK.

Rahardjo, H., Krisnanto, S., and Leong, E.C. (2016). "Effectiveness of capillary barrier and vegetative slope covers in maintaining soil suction." *Soils and Rocks*, Vol. 39 (1): 51-69.

Rahardjo, H., Santoso, V.A., Leong, E.C., Ng, Y.S., and Hua, C.J. (2012). "Performance of an instrumented slope covered by a capillary barrier system." *J. Geotechnical & Geoenv. Engrg.*, ASCE, Vol. 138, No. 4, pp. 481-490.

Satyanaga, A., Zhai, Q, Rahardjo, H., Gitirana, G.F.N., Moon, S.-W., and Kim, J. (2021). "Performance of capillary barrier as a sustainable slope protection." *PanAm-UNSAT 2021*, https://doi.org/10.1051/matecconf/202133703021

Scarfone, R., Wheeler, S.J., and Smith, C.C. (2022). "Capillary barrier systems for prevention of rainfall-induced slope instability." *Ground Engineering*, https://www.geplus.co.uk/technical-paper/technical-paper-capillary-barrier-systems-for-prevention-of-rainfall-induced-slope-instability-22-03-2022/

Tami, D., Raharjo, H., Leong, E.C., and Fredlund, D.G. (2004). "A physical model for sloping capillary barriers." *Geotech. Testing J.*, Vol. 27 (2,): 173-183.

Yang H., Rahardo, H., Leong, E.C., and Fredlund, D.G. (2004). "A study of infiltration on three sand capillary barriers." *Can. Geotech. J.*, Vol. 41 (4): 629-643.

Zornberg, J.G., Bouazza, A., and McCartney, J.S. (2010). "Geosynthetic capillary barriers: current state of knowledge." *Geosyn. Int.*, Vol. 17 (5): 273-300.

Zornberg, J.G. and McCartney, J.S. (2007). *Chapter 34: Evapotranspirative cover systems for waste containment*. The Handbook of Groundwater Engineering, 2nd edition, Jacques W. Delleur, Editor, CRC Press, Taylor & Francis Group, FL.