

# Natural Drainage Transporter System for Rainfall-Induced Residual Soil Slope Stabilisation – a review

Nur Azlin Baharudin<sup>1</sup> Azman Kassim<sup>1</sup> Kamarudin Ahmad<sup>1</sup>

Corresponding author: azmankassim@utm.my

**Abstract.** The rainfall-induced residual soil slope stability issues constitute a major threat to both lives and property particularly in tropical country which characterized as intense and long duration rainfall. Capillary barrier system (CBS) is a well-known alternative in controlling the pore-water pressure built up and percolation. There were various studies has been done to improve the CBS performance but it shows that the performance of the conventional CBS under intense rainfall has not been particularly convincing. The application of transport layer with CBS as a cover to prevent percolation of rainfall infiltration into residual soil slope and landfill has been studied however the effectiveness was assured. This review article discusses the application of unsaturated drainage transport layer system as an intermediate layer at natural soil layer to divert rainfall infiltration laterally for residual soil slope stabilisation. A drainage transport system is a great alternative to increase lateral diversion capacity at the interface of Grade VI and Grade V soil slope layers and delay breakthrough occurrences.

## 1. Introduction

Weathering process has yield a soil heterogeneity that inherent feature common to tropical residual soil and this type of soil constitutes more than 75% of surface deposit in Peninsular Malaysia. Soil heterogeneities in tropical residual soil are consist of weaker material due to the weathering process and will affect the permeability of the soil mass thus control the mechanisms and location of slope failure [1][2]. In Malaysia, the tropical climate that represent a heavy rainfalls and high temperature facilitate rapid chemical and mechanical weathering process that result with deep residual soil profile. The deep residual soil profile of different layers which constitutes of Grade VI and Grade V soil with distinct interface in between the layers. The typical arrangement of soil layers which fine grained soil close to the ground surface compared to the soil at greater depth and form a natural capillary barrier system [3]. The stability of residual soil slope is affected by several natural and triggering factors. Soil characteristic, groundwater condition, vegetation and slope gradient are example of natural factors and the triggering factors include volcanic eruptions, earthquake and rainfall infiltration. Rainfall infiltration are one of the most triggering natural factors to slope instability in many parts of the world especially in tropical climate regions covered with residual soils [4][5]. Rainfall-induced slope failures are usually shallow which failure not exceeding three meters and likely occur on slopes with 30 to 40

<sup>1</sup> Department of Geotechnics and Transportation, School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia



degrees slope inclination. The soil matric suction decrease as the rainfall infiltrates into the soil and it is one of the failure mechanism suggested by Rahimi et al. [6]. The decreasing of matric suction would trigger a non-linear drop in soil shear strength. Hence, the matric suction of soil approaches zero indicate a nearly saturated soil that will resulting in slope stability and further inducing disasters such as landslides and debris flow.

Rainfall-induced slope failures have becoming the most damaging natural hazard in the world, with slope failure occurring every rainy season that result in devastating consequences as damage of surrounding infrastructure and loss of lives [7]. These failures are commonly occurred in natural slopes that signifies an abundant of residual soil existence. Residual slope is in unsaturated condition with deep ground water table. The rainfall-induced slope failures are generally occurred through shallow failure mechanism [8] which is depth failure less than 2m. The primary controlling factors in rainfall-induced slope failures has widely accepted to be both rainfall and soil properties [9] particularly in tropical regions where there are usually in high intensity rainfall and humid condition (low evaporation rate). Chemical weathering process and leaching of mineral form near-surface soil could happen due to rainfall and may result in open structures of soil at slope surface. The void ratio is commonly will affect the hydraulic properties of a soil which is one of the factors to determine the amount of infiltrating water that may trigger slope failures. Melchiorre et al. has stated that the intensity, duration antecedent condition, resolution and pattern of rainfall event play important role in rainfall-induced slope failure [9]. Frydman et al. (2005) and Yunusa (2015) stated that matric suction distribution decrease as the rainfall intrusion into unsaturated part of soil slope as the event significantly changes both hydraulic and shear strength properties of unsaturated soil [10][11]. Intense rainfall has often been identified by most of previous researcher as triggering factor for many slope failures around the world [12]. Rainfall resolution is usually crucial in determining the amount of rainwater infiltration that may lead to slope failure. Thus, Apip et al. has suggested a high resolution rainfall data which is hourly instead of daily rainfall data in the analysis of rainfall-induced slope stability to produce more accurate results [13]. The 70% of total rainfalls obtained from IDF curve was applied for infiltration due to the surface loss approximately 30% from total rainfalls. [14][15][16].

The aim of this paper is to review the current state of slope stabilisation measure particularly in application natural drainage transport system with capillary barrier effect within the natural residual soil slope mantle. In order to understand the effectiveness of capillary barrier system (CBS) in slope stabilisation, it is necessary to briefly review and understand the soil layer heterogeneity condition and capillary barrier effect in controlling rainfall infiltration. The paper will briefly discuss the various application of CBS and focus on natural unsaturated drainage transport system with capillary barrier effect within natural residual soil slope layer.

## **2. Slope Stabilisation**

Generally, slope stabilisation can be categorized into active and passive measures [17]. The utilization reinforcement or counterweight systems to resist the sliding force of soil masses are known as active measure. Geotextile reinforcement, soil nailing and retaining structures are examples of active measure residual soil slope stabilisation and the application of these method has been proven in practice but it is not cost effective. Passive measures are maintaining and controlling rain water infiltration into residual soil slope for slope stabilisation. Horizontal drain is one of the passive slope stabilization measure that has broadly applied to stabilize unsaturated residual soil slope in most country around the world. This method has been identified as the most economical existing method in practice but it requires regular maintenance and frequent replacement [18]. The effectiveness of this method is limited to divert groundwater out of the soil slope and lower the water table thus minimize slope failure risk. The effective application of horizontal drain is as low as possible in the slope and the placement in the upper regions of the slope is unnecessary in the long term. The drain type, location, number, length and spacing also play an important role for the effectiveness of horizontal

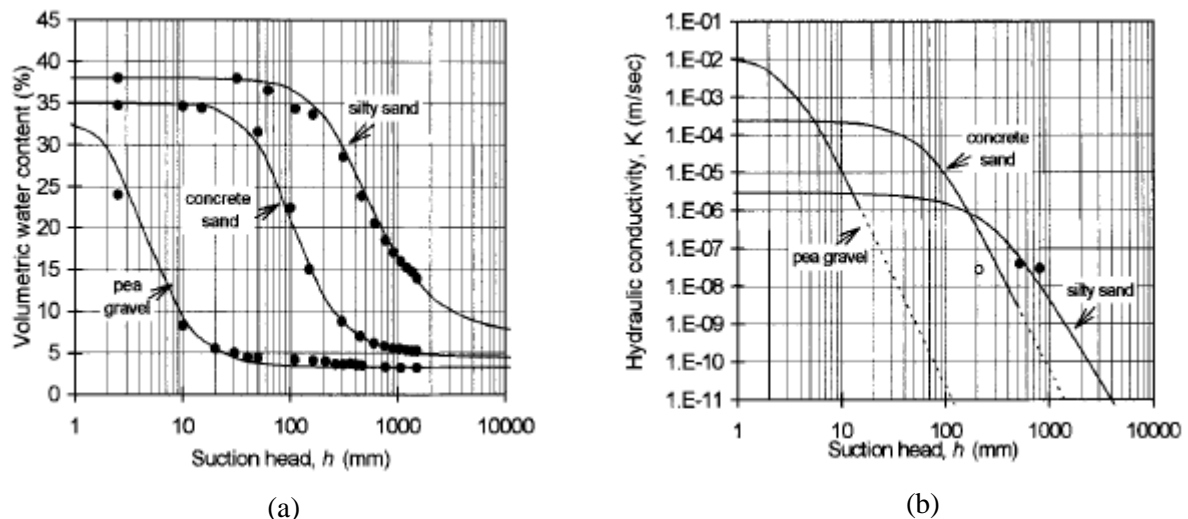
drain [19]. Siphon drain is an example of passive measure in residual soil slope stabilization that pump water by gravity without external energy input through a permanent primed siphon pipe [20]. The traditional siphon drainage is limited due to siphon lift restriction and poor reliability in long term service that prevent it from being widely used. Siphon drainage is similar with horizontal drainage which is ideal for slope groundwater control in slope stabilisation. The natural sloping ground allow the operation of the siphon system as a long term low flow rate pumping for landslide drainage and stabilization. Siphon drain and horizontal drain is effective in groundwater control proven have minimum role in minimizing infiltration and it is the main factor of rainfall induced residual soil slope. Capillary barrier system has been widely introduced as a passive hydrological method in controlling and minimising the rainfall infiltration into the residual slope.

### **3. Capillary Barrier System (CBS)**

The conventional CBS is comprises of fine-grained soil layer overlying a coarse-grained soil layer [21] and can occur naturally or engineered using selected material. Kassim (2011) stated that the contrast of hydraulic conductivity greatly affect the suction distribution and movement of water flow in tropical residual soil slope which create unstable areas with elevated pore-water pressures [14]. The result of weathering profile is soil with fine grained content decrease with depth then produce the typical arrangement of Grade VI and Grade V soil layer. Soil layer with lower permeability overlain a higher permeability soil layer could develop excess pore-water pressure in the weathered slopes parallel to a slope surface that would trigger slope failure [22]. The excess pore-water pressure is cause by the impeded water infiltration at the fine layer that act as a water storage layer. The downward movement of infiltrating water restricts with capillary break and facilitate lateral flow of water above the interface of soil layers. CBS is effective in minimizing rainfall infiltration by diverting it above the interface of unsaturated residual soil slope. Figure 1 is an example of infiltration test to examine the capillary barrier effect of underlying coarser material [23]. The breakthrough of rainfall infiltration across the interface into lower soil layers is occurred when the suction head at the interface reached the breakthrough head of the lower soil layer. It is known as suction head when the coarser soil layer became conductive and not influence by the rate of rainfall infiltration and soil properties of finer soil layer. The study stated that the coarser lower soil layer control the breakthrough of rainfall infiltration in the residual soil slope thus influence the effectiveness of the capillary barrier [23]. The upper layer of soil and rainfall infiltration control the suction head profile before the breakthrough process. The percolation of water at the interface before the breakthrough occur would trigger the shallow rainfall-induced slope failure. Suction head decrease below the breakthrough head is the response of the increase of water content near the interface. The coarser layer hydraulic conductivity increase rapidly and the coarse layer will not act as a barrier. The decrease of water content will increase the suction head until it reached restoration head, the coarse layer would form a barrier again.

There are several performance of the CBS has been investigated by numerous researchers including physical performance using one-dimensional soil column tests, two-dimensional slope model and field monitoring. Physical laboratory modelling, numerical analysis and field monitoring approaches has been applied by previous researches to study effect of rainfall infiltration on the suction distribution and slope stability. These approaches is similarly applied to utilise the capillary barrier effect to prevent rainfall infiltration into residual soil slope layer. The one-dimensional soil columns model simulated only as flat cover system and unable to investigate the lateral flow of water in the capillary barrier effect cover (CCBEs) system. There are study on one-dimensional with different material as coarse grained layer which is gravelly sand and geosynthetic material and it shows that geosynthetic material is more effective than gravelly sand [24]. The other research approaches on CBS is the dual capillary barrier (DCB) and it has been compared with traditional single capillary barrier (SCB) [25]. They has found that DCB stores more water compared to SCB and fined-grained layers of DCB have higher volumetric water content during drainage than fine grained layer of SCB. The capillary cover (CBC) has been tested at Jiangcungou landfill in Xi'an China. Zhan et al.(2017) stated that loess-

gravel CBC has increase the ability to store water by 41% at the completion of percolation and vegetation had a significant influence on water storage capacity [26]. The most recent study on CBS is known as “biomediated capillary barrier system” (B-CBS) and the study shows that it is effective to control the infiltration by taking advantages of less-permeable biomediated soil cover and minimize water infiltration into residual soil slope [17].



**Figure 1.** Graf of (a) Measured Moisture Characteristic Curve for Wetting and Calculated Moisture Characteristic Curves (b) Hydraulic Conductivity vs soil suction for three type of soil.

The theoretical and experimental studies on the behaviour and design of CCBs has been conducted for over fifteen years. Generally, the system with CCBs has been applied as a measure to reduce infiltration due to the long durability, ease of construction, cost effective and minimum maintenance if carefully constructed. Hence, it can be an alternative to prevent rainfall infiltration and reduce risk of rainfall-induced residual soil slope failure. There are various extensive studies of CBS as soil cover to control infiltration into waste containment system such as landfill and mining waste [27][28]. Recently, the principle of CBS has been extended and utilised as slope stabilisation method by preventing the rainfall infiltration into unsaturated residual soil slope. [29][30][31][32] However, breakthrough occur especially during wet period when residual soil slope experienced high moisture content hence minimum suction condition and has become the major setback of using capillary barrier in humid climates with high rainfall infiltration. The breakthrough of water infiltration from fine-grained soil layer into coarse layer occur when the rate of infiltration is greater than the storage capacity of the upper fine-grained soil layer. Therefore, transport layer or unsaturated drainage layer is introduced to enhance the performance of CBS. Table 1 shows the previous study on development CBS and the improvement of the system [28].

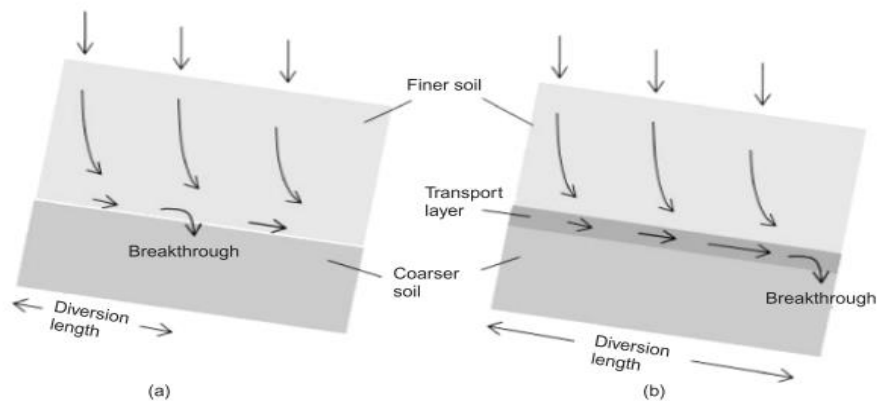
**Table 1.** Historical Development of Capillary Barrier System.

Year	Work	Reference
1993	1D Column to study the infiltration characteristic of CBS	Yang et al.,2004
2000	Mechanism of sloping CBS under high rainfall condition	Tami et al.,2004
2003	Use of modified residual soil for fine-grained layer in CBS	Indrawan et al.,2006
2004	Potential use of residual soil and geosynthetic material in CBS	Krisdani et al., 2006
2005-2015	CBS for slope repair in Bedok (2006), Ang Mo Kio (2009), Tampines (2010), Matilda (2015)	Rahrdjo et al.,2007, 2012, 2013
2010	Development of dual capillary barrier (DCB) system using recycled materials	Hamas et al.,2014
2012	Joint Patent for Medular Cover System (NTU-HDB)	
2013	DCB for landfill cover system	Rahardjo et al., 2013
2015	Development of GeoBarrier system for slope protection and retaining structure	Rahardjo et al.,2015

#### 4. Transport Layer in Capillary Barrier System

A transport layer or unsaturated drainage layer (UDL) is an intermediate layer that constructed between fine and course soil layer so that the infiltrating water can flow above and within this layer due sloping surface. The application of UDL is effective to improve the performance of capillary barrier system by preventing the development of positive pore water pressure in response to rainfall infiltration [11]. Furthermore, UDL is able to increase the lateral diversion and delay breakthrough occurrence in CBS. There a several study on application of capillary barrier cover with transport layer and it has been proven that it performed much better than the conventional capillary barrier cover [30]. The prior research on capillary barrier effect with UDL generally suggest unsaturated sands as transport layer material [30] [33] stated that particle size plays a significant role in promoting lateral diversion of a system with capillary barrier effect. Studies has found that underlying coarse material approximately 2.5 times coarser than the overlying fine material would achieve about 80% of maximum diversion. In other case, the similar outcome with 90% of maximum diversion with 5 times coarser of course material than the overlying fine material.

There are studies on the long-term performance of capillary barrier cover with an unsaturated sand layer in humid climate in China [33]. The UDL is layer of 10cm sand within 20cm silt layer and 10cm gravel. The monitoring result for 2 years has been identified lateral drainage successfully divert 16.87% of total precipitation and it shows the possibility of successful application in China's humid climate [33]. The most recent study on the improvement of CCBEs is vegetated three-layer landfill cover that consist of crushed concrete as the transport layer or intermediate layer between decomposed granite as top and lowest layer. The study conclude that grass-covered landfill cover has significant effect on the cumulative precolation with more sustainable material [34].The selection of transport layer transport layer should have sufficient moisture and thickness to be conductive enough to divert water laterally downward to preserve capillary break within the underlying courser material as shown in Figure 2 [35]. The development of positive pore-water pressure results in slope failure that is shallow in nature. Therefore, the poor drainage characteristics of the residual soil mantle can be improved significantly by introducing a transport layer.



**Figure 2.** Lateral drainage in unsaturated soil with (a) a capillary barrier, (b) a transport layer above a capillary barrier.

## 5. Conclusion and Future Perspectives

The residual soil slope stabilisation have been widely studied to prevent the rainfall-induced residual soil slope and give negative impact to lives and surrounding infrastructure. The cumulative effort of academic and industrial scientist over the past few years has led to many improvement of residual soil slope stabilisation method including the advance capillary barrier system with various improvement. Probably the best known alternatives is the application of transport layer with capillary barrier system which include a method as a slope cover to prevent rainfall infiltration and waste containment cover to prevent leachate that would trigger underground water pollution. The study of long term performance of the system should be explore due to the cyclic environmental changes and not limited to assessment for wet period only.

At this point of time, although the UDL is reliable to enhance the capillary barriers due to engineered material, there is no systematic study and application on the unsaturated drainage transport system in natural residual soil mantle. The application of capillary barrier as slope stabilization measure was very limited or even yet to be exploited in Malaysia. In addition, the usage of natural material as the intermediate layer is introduced instead of geotextile material or drainage cell material. It is a great effort for sustainability measure which is the usage of more natural material for unsaturated drainage layer. With advances in understanding of the heterogeneity of soil profile, capillary barrier effect mechanism and engineering design principle used for fabrication of UDL, there is great hope that effective natural drainage transport system within the soil layers would be developed. The risk of rainfall-induced residual slope failure problem would be minimised.

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