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# Vertical Capillary Barriers and Wick Drains to Mitigate the Rain-induced Slope Failures: Numerical Analysis

**Udesh Wijepala and Shiran Jayakody**

**Abstract:** Slope failures are catastrophic when they suddenly occur in human habitats. The stability of slopes gradually diminishes with heavy rainfall due to the increase in pore water pressure; subsequently, the shear strength of the slope soil decreases. The effect of rainwater on the instability of slopes was studied in this research with respect to factor of safety values. Accordingly, finite element analysis and limit equilibrium analysis were conducted using a 2D model of a soil slope in SEEP/W and SLOPE/W programs to observe the responses of the slope soil profile under heavy rainfall. Movement of the wetting front and the fluctuation of the groundwater table were studied to develop a drainage mechanism, thereby to control the effect of infiltrated rainwater on slope failure. A conceptual method was introduced in this study by developing a numerical model with an effective drainage system which consists of vertical capillary barriers with combination of horizontal wick drains in a cascade manner in the slope. This method exhibited high stability of the slopes even with continuous rainfall for number of days, therefore, applicable as a sustainable prevention method of slope failures.

**Keywords:** Slope stability, Wetting front, Capillary barrier, Wick drain, Slope failure

## 1. Introduction

Landslides are abrupt events of slope failures and catastrophic geotechnical hazards when they occur in populated regions [1]. The time of the occurrence of a landslide is unpredictable due to the uncertainty of behaviour of the hillslopes under different triggering factors such as intense rainfall, slope geometry and geology [2], [3]. Therefore, prevention methods are required to increase the stability of the slopes and mitigate landslides in human habitats.

Rainfall is the main triggering factor of slope failures and landslides. Researchers have investigated various approaches to develop new landslide prevention methods to manipulate the triggering effect of rainfalls. Hencher & Lee [4] revealed a detailed relationship between rainfall and landslides in Hong Kong. They observed many landslides that occurred when the rainfall exceeded 500 mm/day and low impact on failure when the rainfall around 100 mm/day. Orense et al. [5] revealed that saturation of the toe of a slope increases the vulnerability of a landslide although the rest of the slope is at a very low level of saturation; vulnerability severely increases with increase of inclination of the slopes [6]. However, many slope failures occur due to the drag force on the soil while rapid drain out of water occurs by downslope seepage after prolonged periods of rain. Seepage occurs due to the hydrostatic pressure created by the excess water in the soil after the rise of the Ground Water Table (GWT) [7].

Yamamoto et al. [8] introduced a simple and low-cost drainage system to reduce the adverse effects of GWT within a slope by effectively draining out the infiltrated water from slopes rather than constructing massive retaining structures. Pathmanadan [9] observed greater efficiency in introducing horizontal drains as subsurface drainage method for slopes. Santi et al. [10] studied wick drains, and suggested that wick drains are the most successful alternative to stabilize the slopes than conventional drainage systems, in terms of cost, ease of installation, ease of handling, clog resistance, and service life.

The infiltration of water into the slope soil profiles could be prevented by introducing capillary barriers. Satyanaga et al. [11] studied capillary barriers to estimate the efficacy in reducing infiltration, and preventing the rise of the GWT in slopes. The outcome emphasizes the use of capillary barriers as a successful mechanism for minimizing the adverse effects of infiltrated water and significantly increasing the factor of safety (FOS) of slopes during heavy rainfall.

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This study focused to investigate a mechanism of slope stabilization by controlling the infiltrated water from heavy rains without retaining structures. An effective drainage system was numerically modelled by combining vertical capillary barriers and wick drains in a cascade manner in a slope. The infiltration of rainwater was prevented by the capillary barriers and drained out by the wick drains in the drainage system. The arrangement of capillary barriers with wick drains effectively drained out the rainwater, consequently, degree of saturation of the slope due to the rainfall and the level of GWT were controlled simultaneously. Results highlighted reduction of risk of slope failure though the rainfall intensity is high.

More research on the slope stabilization is based on structural developments and rare to find non-conventional approaches. The developed slope stabilization mechanism in this research does not involve mass structures such as retaining walls; therefore, it would be a cost-effective alternative to stabilize the slopes. Hence, this would be successfully applicable as a sustainable prevention method of slope failures without harming the natural beauty of a slope where the rainwater is the major triggering factor of slope failures.

## 2. Development of Numerical Model

SEEP/W and SLOPE/W software were used for modelling the hydrodynamic behaviour and the brittle behaviour of the soil profile, respectively [12]. Saturated/unsaturated model and Mohr Coulomb model were assigned as the material models to simulate the hydrodynamic behaviour and the brittle behaviour, respectively, in the numerical model. The transient seepage analysis results from parent finite element analysis using SEEP/W were applied as input parameters in the subsequent limit equilibrium analysis in SLOPE/W.

The applied mechanism of developing the numerical model was validated by modelling a real landslide in Thong Nhat, Vietnam. The real parameters were obtained from a case study by Nguyen et al. [13]. Figure 1(a) shows the 2D profile of the Thong Nhat landslide which was reproduced by SEEP/W and SLOPE/W according to the gathered information of geometric details, material properties and boundary conditions. The model was simulated by assigning a cumulative rainfall of 320.8 mm for five days with equal intensity of rainfall each day (64.16 mm/day) as in the original study of Nguyen et al. [13].

As Figure 1(b) indicates, the failure pattern determined by the SLOPE/W software almost coincided with the actual incident. The red line shows the failure path of the actual event as per Nguyen et al. [13], and the bottom boundary of the green hatched area of Figure 1(b) is the failure path obtained by the SLOPE/W analysis of the reproduced model. The real failure path almost coincides with the failure path resulted in the numerical model. This signifies successful validation of the applied mechanism to develop the model in SEEP/W and SLOPE/W software.

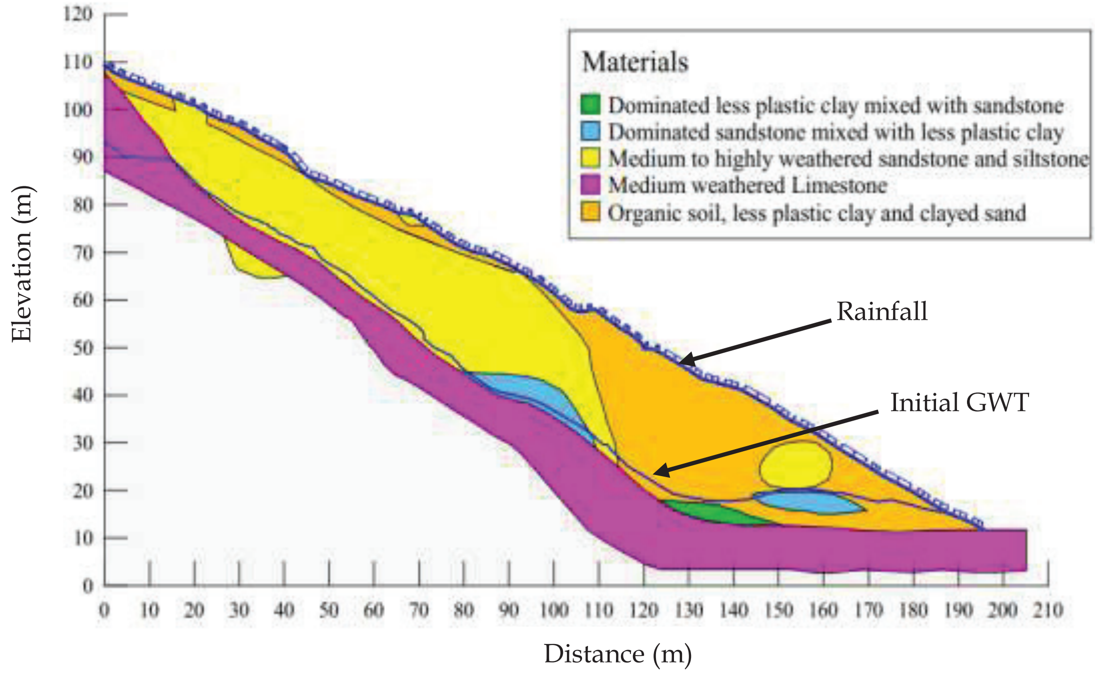
The validated slope model was slightly altered to develop the model of this study and following alterations were applied: (i) homogeneous soil profile was considered with a uniform gradient of $45^0$, (ii) Capillary Barrier Layers (CBLs) and Moisture Retention Layers (MRLs) with 0.2 m in thickness and 2.5 m in height were vertically introduced to control the infiltration, (iii) wick drains were laterally applied in the slope model to drain out the infiltrated water and they are indicated as lines within the numerical model. Boundary conditions were applied as per the standard mechanism in the developed model. Figure 2 shows the geometric 2D view of the slope profile with capillary barriers and wick drains.

### 2.1 Material Properties

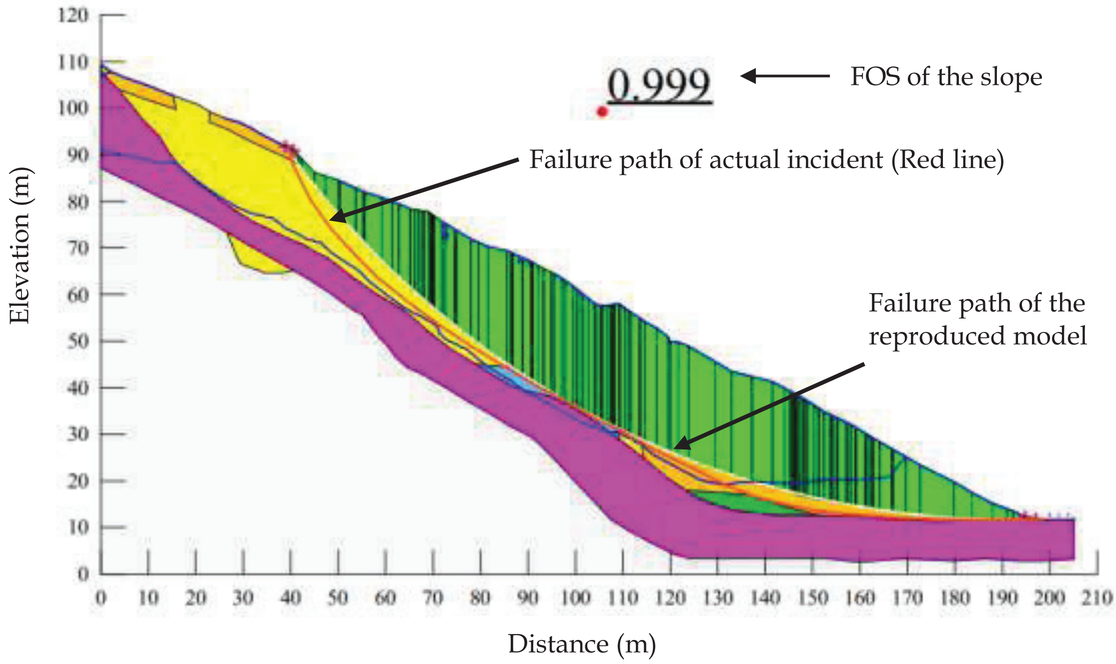
Properties of the silty sand were considered as the slope material while clay and gravel were used in the layers of the MRLs and CBLs, respectively. Table 1 shows the applied hydrological and shear strength properties of the soil types in the numerical model those acquired from literature [14]. The volumetric water content (VWC) data point function and the hydraulic conductivity data point function with corresponding matric suction for the three types of materials were developed within the SEEP/W program itself by assigning the hydrological properties presented in Table 1 [12]. The vanGenuchten SWCC (soil water characteristic curve) model was applied in SEEP/W to estimate the permeability functions of unsaturated soils which were based on the saturated hydraulic conductivity ($K_S$) of each soil.

### 2.2 Boundary Conditions

The boundary conditions applied in the numerical model are illustrated in Figure 3, which include the initial groundwater level, rainfall, and water flow through the wick drains. The initial groundwater table was established at a depth of 15 meters from the crest of the slope as a moderate value as per the past studies [15] and it runs parallel to the slope surface.




(a)




(b)

**Figure 1 - Soil profile of Thong Nhat landslide, Vietnam; (a) Reproduced landslide profile in SEEP/W and SLOPE/W programs, (b) Failure path and FOS of the soil profile given by the SLOPE/W program**

The applied rainfall intensity, which was a moderate magnitude, was selected as 25 mm/hr (0.6 m/day). This value was chosen based on prior research studies that have documented rainfall intensities ranging from 10 mm/hr to 200 mm/hr [16],[17],[18].

The boundary conditions for the wick drains were defined with the maximum flow rate of 594 l/hr/m to remove all shedding water as it is higher than the applied rainfall [19].

The impervious areas (light blue lines in Figure 3) illustrate the vertical and horizontal boundary conditions for the right, left and the bottom ends of the model. Square meshing pattern was created for the evaluation of the model, and an element size of 1 m was decided by performing a mesh convergence study.

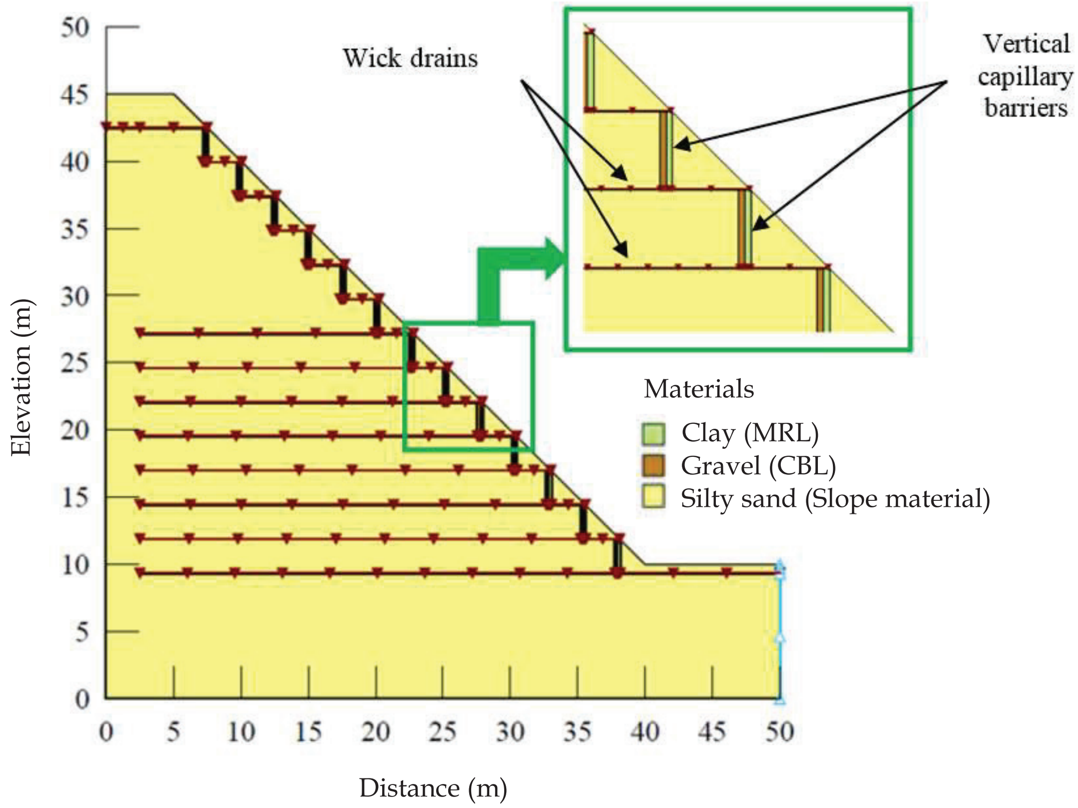



**Figure 2 - Geometric 2D view of the Slope Profile with Capillary Barriers and Wick Drains**

**Table 1 - Hydraulic and Shear Strength Parameters of the Âoils in Numerical Model [14]**

| Soil type | Hydrological properties | | | Shear strength properties | | |
|---|---|---|---|---|---|---|
| | Saturated hydraulic conductivity ($K_S$) (m/sec) | Saturated VWC | Residual water content | Cohesion (kPa) | Friction angel ($^0$) | Unit weight (kN/m$^3$) |
| Silty sand | $5 \times 10^{-6}$ | 0.5 | 0.05 | 15 | 34 | 17.7 |
| Gravel | $5 \times 10^{-3}$ | 0.5 | 0.05 | 0.0 | 38 | 20.0 |
| Clay | $5.56 \times 10^{-7}$ | 0.5 | 0.05 | 22 | 32 | 17.1 |

### 2.3 Numerical Simulation

In order to numerically analyse the effectiveness of controlling rainwater infiltration, two hypothesized combinations of lateral wick drains in conjunction with vertical capillary barriers were considered: "short wick drains with capillary barriers" and "long wick drains with capillary barriers". Accordingly, the model was run for a period of 10 days under four scenarios as follows.

1. Initial slope model without rainfall

Homogeneous slope model was initially analysed with only the GWT for 10 days to verify the stability of the slope profile before the rain.

2. Initial slope model with rainfall

The initial homogeneous slope model was analysed under the rainfall with an intensity of 25 mm/hr to understand the failure mechanism of the slope.

3. Modified slope model with capillary barriers and short wick drains with rainfall

The slope model was modified by introducing the vertical capillary barriers and short horizontal wick drains, to analyse the effectiveness on the stability under rainfall.

4. Modified slope model with capillary barriers and long wick drains with the rainfall

The slope model was modified by introducing the vertical capillary barriers with long horizontal wick drains and studied the effectiveness on stability under rainfall.

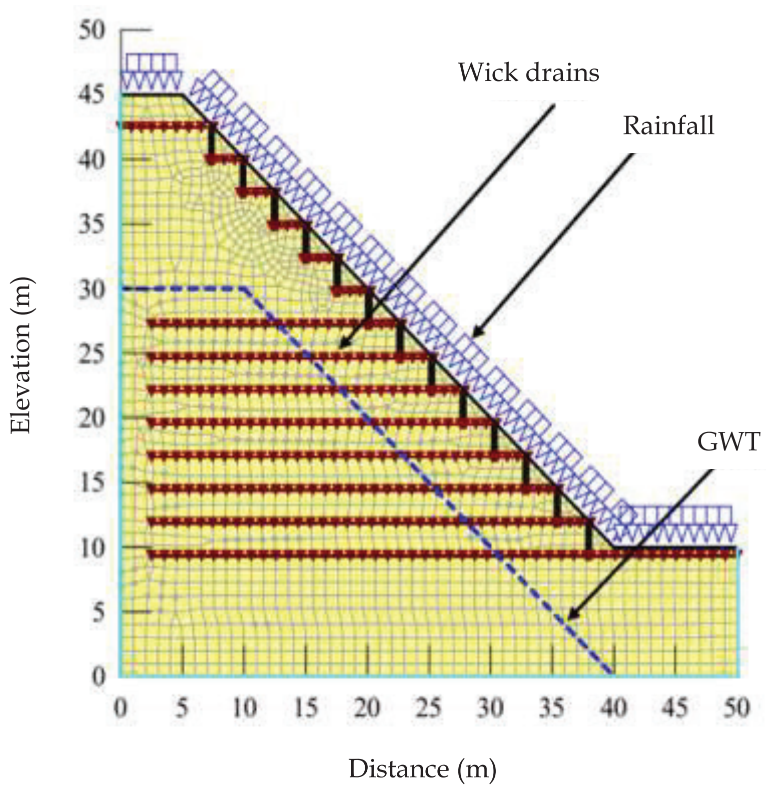



**Figure 3 - Boundary Conditions in the Model**

## 3. Results and Discussion

### 3.1 Simulation of the Initial Slope Model without Rainfall

This simulation was carried out for 10 days to verify the stability of the developed conceptual model before rainfall without any stabilization method. FOS of the slope at day 1 was obtained as 1.22 from SLOPE/W analysis and a slight increase was observed in each day as shown in Figure 4. The adverse effect of the GWT gradually decreased due to the dropping down of GWT throughout the period of 10 days; consequently, the slope stability was increased. Therefore, the stability of the initial model before the rainfall was confirmed since the FOS was greater than 1.0.

### 3.2 Simulation of the Initial Slope Model with Rainfall

Variation of the FOS was obtained under the rainfall and is presented in Figure 4. A gradual decrease of FOS was observed with the increase of rainwater infiltration. A concave downward shape can be observed from day 1 to day 5 and a concave upward shape can be observed from day 5 to day 10 in the FOS variation with the rainfall and the bending starts at the value of the FOS around 1.0. However, the FOS on the 5$^{th}$ day is 0.99 which implies the occurrence of the slope failure under the applied rainfall of 0.6 m/day.

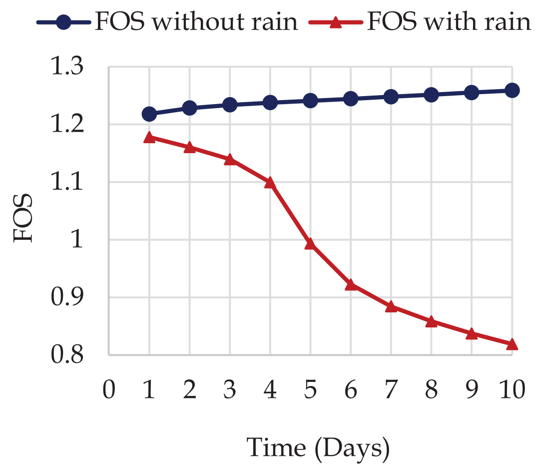



**Figure 4 - Variation of FOS of the Slope with and without Rainfall**

Figure 5 shows the behaviour analysis of both wetting front and GWT with the pore water pressure distribution under continuous rainfall up to the day of slope failure. The GWT gradually increased while the wetting front lowered due to the rainwater infiltration, and they collided on the day 4. Consequently, the GWT was rapidly increased, and the failure occurred on day 5.

A vertical slice of the slope was selected as shown in Figure 6(a) to analyse the variations of pore water pressure, shear resistance, and the weight of the soil domain due to rainwater infiltration. Obtained results are presented in

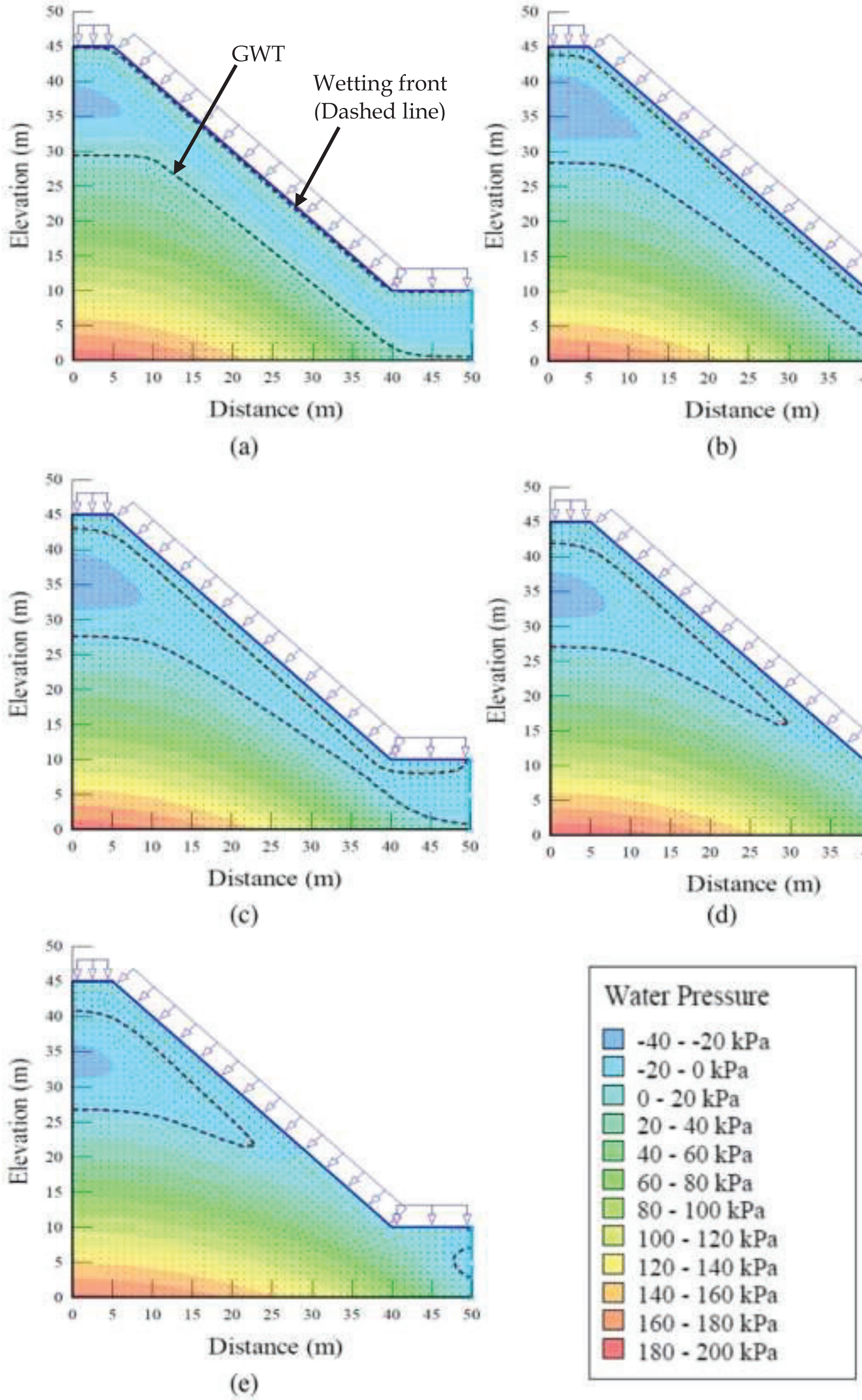



**Figure 5 - Variation of the Wetting Front and GWT at the end of each Rainy day; (a) Day 1, (b) Day 2, (c) Day 3, (d) Day 4, (e) Day 5**

Figures 6(b), (c), and (d). The results show sudden increase of the porewater pressure and drop of shear resistance from day 4 which triggered the failure of the slope under continuous rainfall.

Figure 7 presents the corresponding average vertical depths of the wetting front in the soil profile obtained from the slope surface at the end of each day.

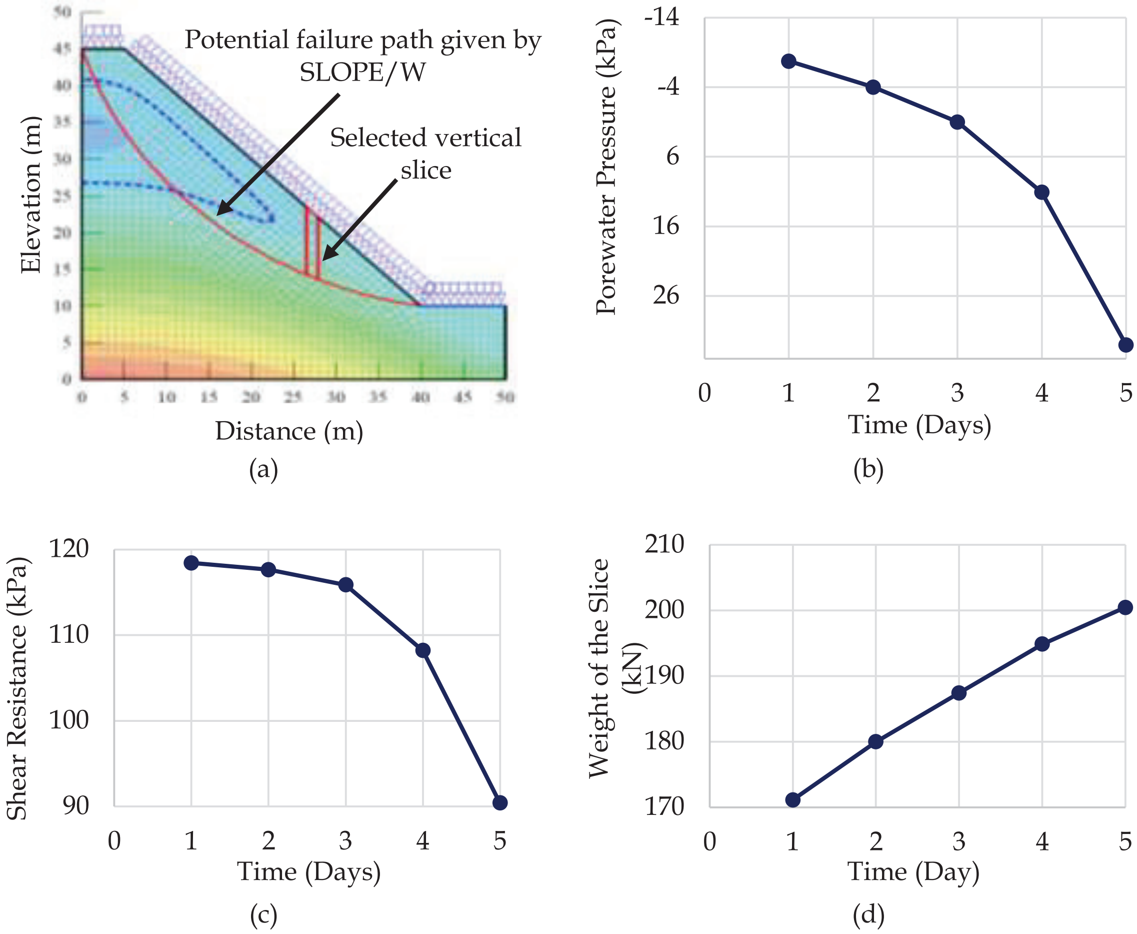



**Figure 6 - Details of a Vertical Slice at Toe Area Under Rainfall; (a) Location of the Slice with Potential Failure Path of the Â Slope, (b) Variation of Pore Water Pressure, (c) Variation of Â Shear Resistance, (d) Variation of Weight of the Slice**

Critical depth of the wetting front was 3.17 m, since it is the depth on 4th day when the collision of the wetting front with the GWT occurred.

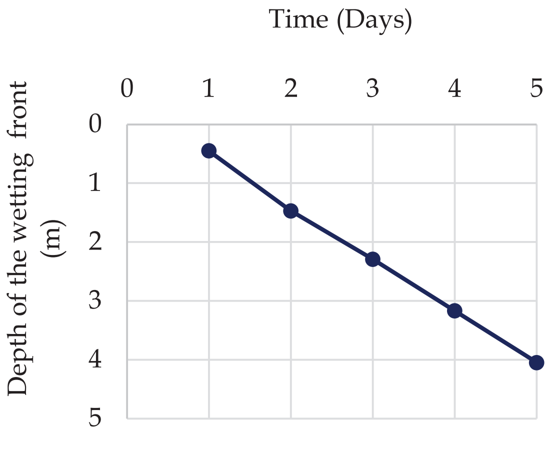


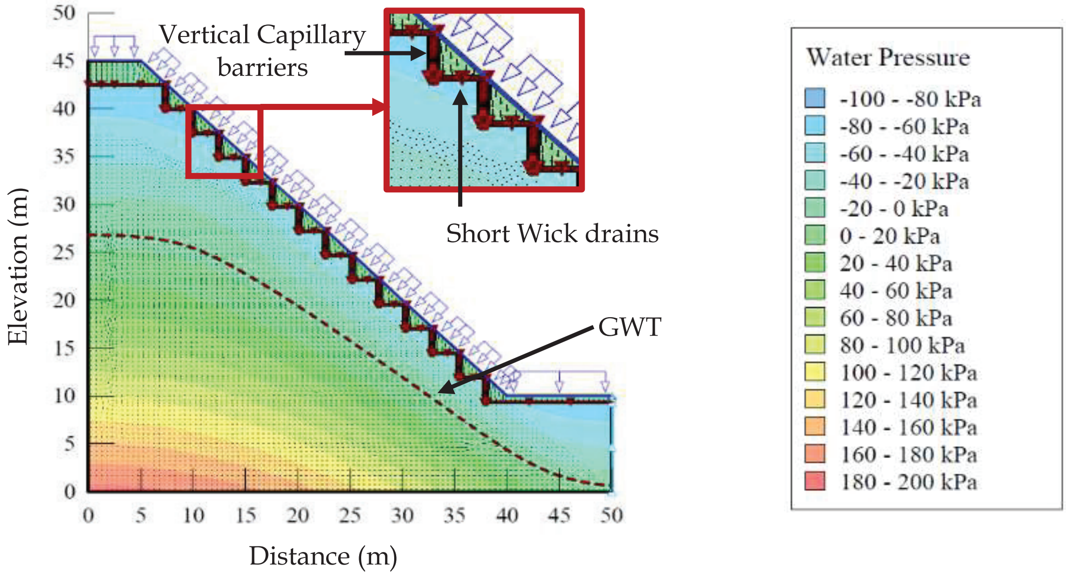

**Figure 7 - Depth Variation of the Wetting Front from Slope Surface at Each end of the Day**

The analysis reflected that the failure of the slope occurred when the wetting front collided with GWT under continuous rainfall the wetting front down the slope could be controlled by avoiding infiltration. Therefore, this study focused to introduce an effective drainage system with capillary barriers and wick drains to minimize the rainwater infiltration through the slope surface.

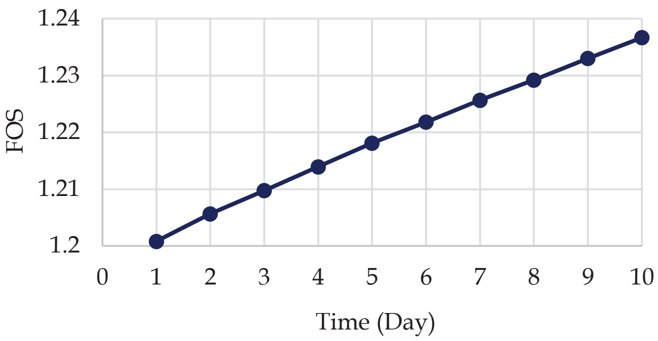
### 3.3 Simulation of the Model with Vertical Capillary Barriers and Short wick Drains

Short wick drains with a length of 2.5 m were horizontally driven into the slope from the slope surface and the CBL were attached at the inner edge of the wick drains as shown in Figure 8(a). Figure 8(a) further illustrates the behaviour of wetting front and the GWT at the end of day 4 under continuous rainfall with the effect of drainage system. The analysis depicts that the downward movement of the wetting front has been restrained at the level of 2.5 m by the capillary barriers and wick drains, therefore, there was no collision with the GWT. Figure 8(b) shows the effect of drainage system in terms of the FOS results. The stability of the slope has slightly increased with the new drainage system even though the effect of rainfall has been continuously applied for 10 days.

The water flux through the wick drains were analysed to evaluate the efficiency, and the results are shown in Figure 9. At the end of each day, the removal of water flux through the wick




(a)




(b)

**Figure 8 - Response of the Slope Under Rainfall with Capillary Barriers and Short Wick Drains; (a)Behaviour of the Wetting Front and GWT at the End of Day 4, (b) Variation of FOS of the Slope After Introducing Capillary Barriers and Short Wick Drains**

drains has increased up to the value of 0.51 m/day until the 3rd day and remained constant thereafter under continuous rainfall of 0.6 m/day. This implies only 0.51 m/day of rainfall causes slope failures at the applied conditions. This analysis therefore can be applied to evaluate the magnitude of critical rainfall intensity which trigger the failure of specific slopes.

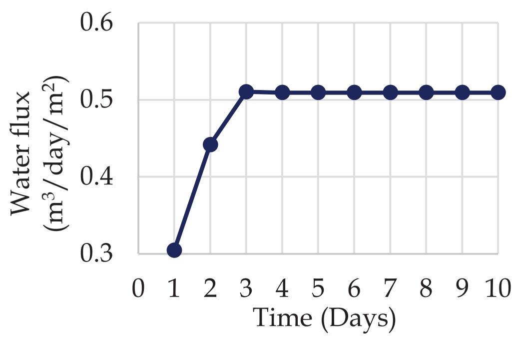



**Figure 9 - Water Flux Through a Wick Drain Under Rainfall**

### 3.4 Simulation of the Model with Vertical Capillary Barriers and Long Wick Drains

The simulation involved extending the wick drains horizontally to reach the area where the groundwater table was present, while keeping the capillary barriers in the same positions as in the previous simulation (section 3.3). The degree of saturation of the slope material was analysed at the end of each day under the continuous rainfall. The arrangement of the wick drains and the obtained results are shown in Figure 10.

The GWT (yellow dashed line) is significantly lowered by the long wick drains while restraining the moving of the wetting front downward by capillary barriers within the 2.5 m level from the slope surface. This method effectively controlled the collision of the GWT and wetting front, thereby avoiding the increase of degree of saturation of the slope profile.

A vertical slice at the toe area of the slope model, as shown in Figure 11(a), was analysed to evaluate the pore water pressure and shear resistance. Figure 11(b) illustrates a significant

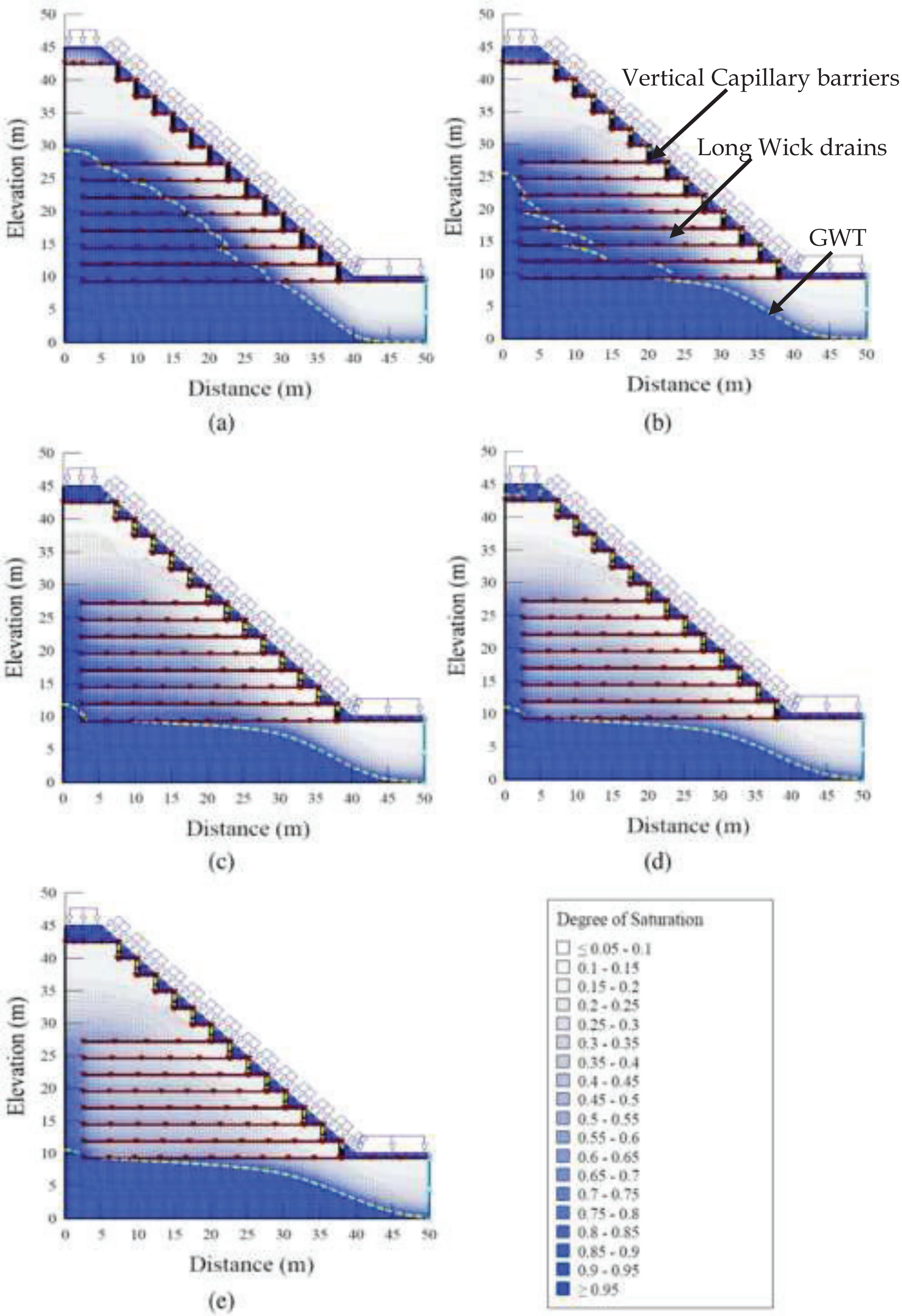
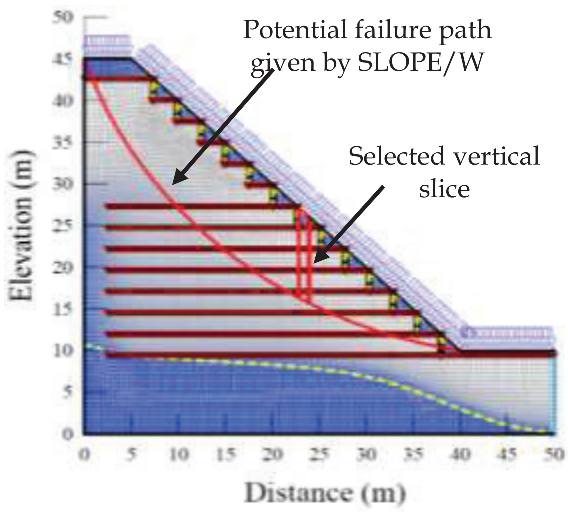



**Figure 10 - Variation of Ground Water Level and the Degree of Saturation with the Capillary Barriers and Long Horizontal Wick Drains in the Slope; (a) Day 1, (b) Day 2, (c) Day 3, (d) Day 4, (e) Day 5**

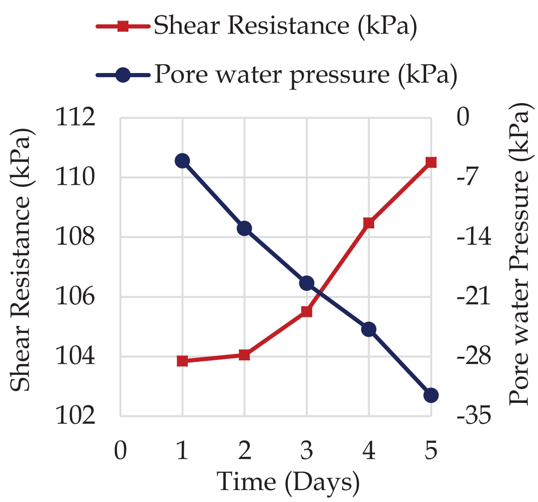
drop of pore water pressure while increase of shear resistance at the bottom of the selected slice, consequently enhancing the stability of the slope even under a rainfall with an intensity of 0.6 m/day.

The analysed results of FOS values further reflect the stability of the slope (Figure 12). The FOS value on the first day was 1.25 and, was improved to 1.50 before the end of 10 days. Originally the FOS of the slope on the 10$^{th}$ day was 1.26 without rain (Figure 4) and it has been enhanced up to 1.52 by day 10 under the effect of rain but with the introduced drainage system.

An effective drainage system mitigates the vulnerability of rainfall triggered slope failures. The numerical analysis in this study introduced capillary barriers and wick drains to drain out the rainwater effectively and efficiently for




(a)




(b)

**Figure 11 - Details of a Vertical Slice at Toe Area After Introducing the Long Wick Drains; (a) Location of the Selected Slice with Potential Failure Path, (b) Variation of Pore Water Pressure and the Shear Resistance of the Selected Slice**

controlling the infiltration. The system avoids the saturation of the slope, thereby, pore water pressure was reduced while the shear strength was increased. Therefore, the developed method would be a successful application to avoid the rainfall triggered slope failures specifically in embankments. However, the method of long wick drains is the most effective mechanism for draining man-made slopes as it lowers the GWT to the toe level.

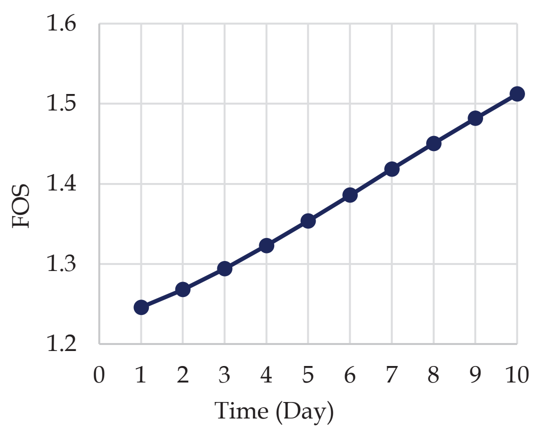



**Figure 12 - Variation of FOS of the Slope with Capillary Barriers and Long Wick Drains**

## 4. Conclusions

The ultimate objective of the study was to propose an effective drainage system with capillary barriers to increase the slope stabilization under continuous rainfall. According to the obtained results from the comprehensive 2D transient finite element and limit equilibrium analysis, the following conclusions were drawn.

The stability of a slope under continuous rainfall conditions can be maintained by avoiding the collision of wetting front and the GWT. An effective drainage system was introduced with the combination of wick drains and capillary barriers to reduce the rainwater infiltration, thereby avoiding the collision of wetting front and GWT.

The drainage system with short wick drains is the best method to increase the stability of vulnerable slopes as it does not harm the average level of GWT.

The critical magnitude of rainfall which triggers a slope failure was examined in this analysis and the results indicate that this method is applicable to evaluate the critical rainfall intensity in specific slope geometries in different conditions.

The method with long wick drains drops the GWT to the toe level and is best for the stabilization of man-made slopes.

However, most critical triggering factors of slope failures such as various dimensions (slope geometries), hydrological properties of the layers of vertical capillary barrier system and the hydrological properties of the slope materials should be studied with respect to different rainfall intensities and intermittent rainfall, to optimize the effectiveness of the introduced methods in this study [20]. The optimum horizontal spacing of the capillary barrier systems within the slope should be investigated considering the shape of wetting front between two capillary barriers by a 3D numerical model analysis and those results should be validated by a physical model.

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