Experimental Modelling of Seepage in a Sandy Slope

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Abstract

Rainfall-induced shallow landslides cause significant damage to infrastructure every year. Among the major causes of shallow landslides is an increase in degree of saturation with rainfall. Partially saturated slopes have high factors of safety due to the apparent cohesion induced by soil suction. In this study, sandy soil was used to prepare slopes with four different angles of inclination and two different void ratios. Utilizing a rain simulator, the slopes were provided with different intensities and durations of rainfall, ranging from 30 mm/h to 240 mm/h. The movement of the water front was recorded during the rainfall at an interval of 5 min. The experimentally recorded values for the depth of water front with time was used to develop relationships between the velocity of seepage, void ratio and angle of inclination of the sandy slope. The proposed equations can be utilized to evaluate the stability of sandy slopes during rainfall.

Keywords

Partially saturated soil • Suction • Water front • Finite element analysis • Rainfall intensity • Slope stability

Background

During rainy seasons, damage done by shallow landslides is reported frequently in newspapers and television channels all over the world. Potential of occurrence and possible damage by these landslides are high in areas: (a) having mountainous terrain, (b) subject to high intensity rainfall for a prolonged duration, and (c) consisting of highly weathered and loose residual soils to a significant depth. Statistical data on the distribution of such shallow landslides, their associated factors, and losses due to those landslides are periodically reported in the literature. Although shallow landslides are caused by many factors such as rainfall, earthquakes, anthropogenic disturbances, etc., rainfall is reported to be among the major causes. Rainfall-induced shallow landslides often occur in marginally stable slopes, and due to their proximity to various important infrastructure such as roads and irrigation channels, they are considered one of the most significant geo-environmental hazards that need immediate attention (Orense et al. 2004). Several countries have therefore implemented significant monitoring systems to observe the real-time change in rainfall amounts and implement warning systems based on an estimated threshold rainfall amount. The increase in the number of landslides during and slightly after heavy precipitation can be attributed to the saturation of the ground and an increase in the unit weight, as well as to

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pore water pressure in the potential sliding zone. Decoupling these triggering factors requires a detailed investigation on the behavior of slopes during seepage under both partially saturated and fully saturated conditions. However, there is little systematic research on the mechanisms associated with the infiltration of water into saturated and/or partially saturated soil and its effect on the stability of slopes.

Results of numerical and experimental studies of the seepage of rainwater into sloping ground and its effect on slope stability have been frequently reported in the literature. Orense et al. (2004) prepared slope models of silty sand material in a 2.2 m long and 0.8 m wide container and measured deformation and failure modes of soil for nine different seepage conditions, ranging from artificially prepared seepage from a side of the model tank to artificially simulated rainfall through nozzles. Intensity of rainfall varied from 80 to 262 mm/h across the model soil mass. Model tests were performed on soils having relative densities of 50 and 70 % and slope angles of 30° and 40°. They reported that slope failure occurs when the soil around the toe region becomes saturated, even though the remaining part of the slope is still in just a partially saturated condition. They also reported that water infiltration alone doesn't cause a failure of the slope if there is no seepage flow to raise the pore water pressure at the toe. They argued that prediction of slope failure is possible by monitoring the soil moisture content. Please note that, in this study, pore pressure was generated by supplying water from a side of the container using a water tank. The rainfall intensity was not uniformly applied in the model—rainfall intensity in one end was higher than four times the intensity in the other end.

Similarly, Huat et al. (2006) performed an experimental study of the mechanisms of water infiltration in unsaturated soil slopes and evaluated the stability of the slope based on the water infiltration behavior. Using a sandy soil sample, they prepared inclined soil models at different slope angles—0°, 15°, 30° and 45° (with the help of hydraulic jack) and applied a rainfall of 756 mm/h through a sprinkler-type rain simulator. They also measured soil suction at various depths. Although the presented data did not fully support the conclusion, the authors concluded that water infiltration rate in a soil mass becomes constant after some length of time of rainfall. They observed that the infiltration rate decreases with an increase in the inclination of the slope. They argued that the infiltration rate is higher on a covered slope compared to a bare slope. Some of the major issues we observed in this study were—the test results pertinent to suction were not consistent, and the rainfall that was applied in the inclined direction might have caused a non-uniform distribution of rainfall intensity throughout the model.

In addition to the above mentioned experimental model testing, Tohari et al. (2007) performed experimental studies on a 2.0 × 1.0 × 1.5 m size metal tank to understand the mechanism of slope failure on river sand as well as residual granite at angles of inclination of 45° and 32°. This research utilized three different relative densities of soil; a rainfall intensity of 100 mm/h was utilized throughout the study. They also studied the effect of seepage on slope stability by supplying water from the head of the slope using a constant head water tank. The variation in the degrees of saturation with time was measured with moisture sensors. They concluded that the permeability of the soil and antecedent soil moisture conditions control the slope stability. In this study, time to initiate the failure was observed experimentally without measuring the soil suction and the depth of the water front with time. Moreover, analysis of partially saturated condition was loosely described.

Among the studies available in the literature, none of the studies incorporated the combined effect of soil suction, rainfall intensity, and angle of inclination of slopes in triggering shallow landslides. Moreover, either the rainfall intensities were non-uniform throughout the slope or were much higher than the reported rainfall intensities in various parts of the world. In our study, experimental studies were performed in a systematic manner to observe the infiltration of water in sandy soil, variation in suction with intensity and duration of rainfall and the effect of water infiltration as well as change in suction on slope stability.

Materials and Methods

Experimental Modeling

Experimental models were prepared with double washed sand. The proportion of sand was approximately 90 %, with approximately 5 % fines. The soil was classified as SW material according to USCS. Specific gravity of the sand was 2.65. Horizontal and vertical coefficients of permeability of the sand were 8.0×10^{-3} cm/s and 4.3×10^{-3} cm/s, respectively. A 1.22 × 1.22 × 1.22 m sized Plexiglas container was used to prepare the models. The Plexiglas container provides visibility to mark the depth of water front at various durations of rainfall. The rain simulator that was used in this study was made of 16 special sprinkler heads arranged in such a way that flow of water could be controlled in the sprinkler system in order to vary the intensity of rainfall from 18 to 360 mm/h. Separate slope models were prepared at angles of inclination of 0°, 30°, 40°, 45° and 50° by compacting soil in the container at the void ratio of 0.6 (40° slope) and 0.7. The experimental set-up is presented in Fig. 1. Four tensiometers were installed in the slopes, as presented in Fig. 2, in order to measure the spatial variation in suction with the duration of rainfall. The

Fig. 1 Plexiglas container with slope made of the double washed sand at 45 and 50° inclinations, and rain simulator used in this study

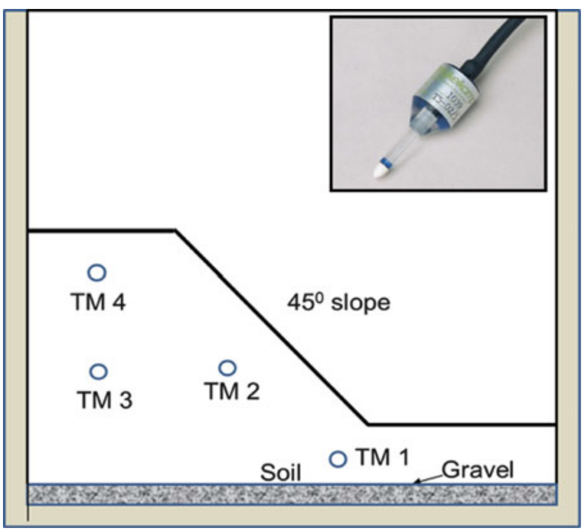

Fig. 2 Location of tensiometers within slope. A tensiometer is shown on the *top right* corner

tensiometers used in this study were miniature tensiometers with a 0.5 cm^2 surface area and 5 mm tip size (T5 type), supplied by the Decagon Devices. The tensiometer can measure pore pressures ranging from −100 to +85 kPa with an accuracy of ±0.5 kPa. Slopes with angles of inclination of 0°, 40°, and 45° were first subjected to a rainfall with an intensity of 240 mm/h. Then, slopes with angles of inclination of 30, 45, and 50 were subjected to the rainfall with an intensity of 30 mm/h for 3 h. The movement of the water front was marked at the boundary of slope around the Plexiglas container every 15 min and the values of suctions were recorded every minute.

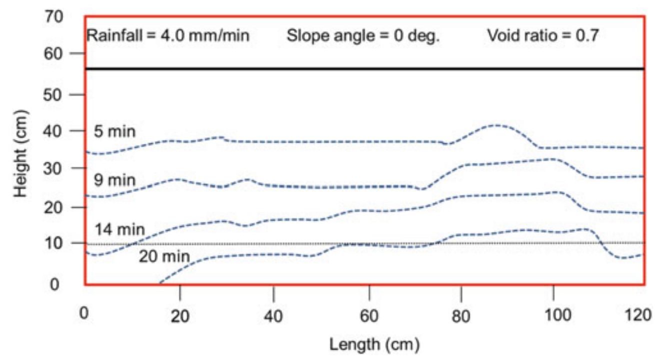

Fig. 3 Depth of water front on a flat slope subjected to 240 mm/h of rainfall, recorded at different periods

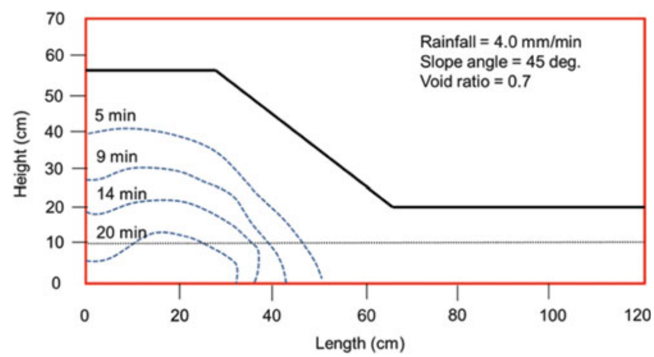

Fig. 4 Depth of water front on 45° slope having 240 mm/h of rainfall, recorded at different periods

Results of the Study

The depth of water front with time can approximately reveal the rate of infiltration of water into the soil mass. Depth of the water front is an approximate indicator that illustrates nearly saturation of soil as the soil above the water front (in case of rain water percolating downwards) is considered to be close to saturation, although it may not be fully saturated. Presented in Figs. 3, 4, and 5 are the depth of water front in those models prepared at 0°, 45° and 40° slopes, respectively with a void ratio of 0.7. As could be observed in Fig. 3, the water front reached a 10 cm height (equivalent to 46 cm depth) in 20 min. As the slope was flat, the depth of the water front was expected to be uniform throughout the model. However, there were small spatial variations in the depth of the water front at different locations. This can be attributed to several factors, including a slight spatial variation in compaction densities of soil and in rainfall amount. As the variation was not unacceptably high, the experimental results were considered reasonable. As observed in these figures, the water front traveled an approximately 46 cm vertical distance in 20 min in all slopes. In slopes (Figs. 4 and 5), the advance of the water front was approximately

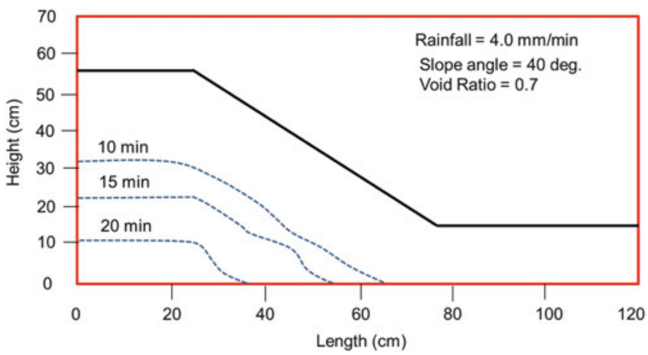

Fig. 5 Depth of water front on 40° slope having 240 mm/h of rainfall, recorded at different periods

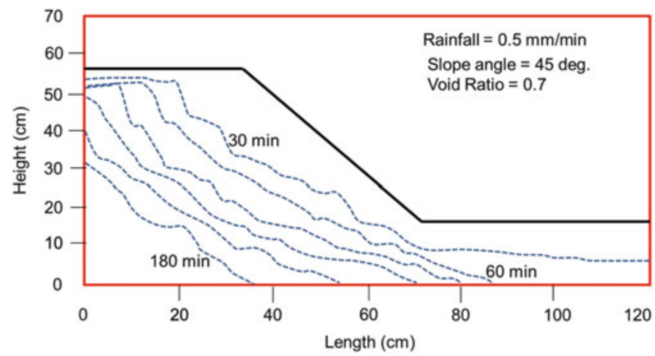

Fig. 7 Depth of water front on 45° slope having 30 mm/h of rainfall, recorded at different periods

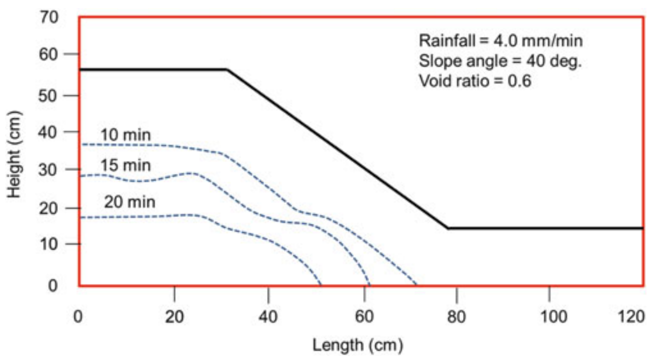

Fig. 6 Depth of water front on 40° slope and void ratio of 0.6 having 240 mm/h of rainfall, recorded at different periods

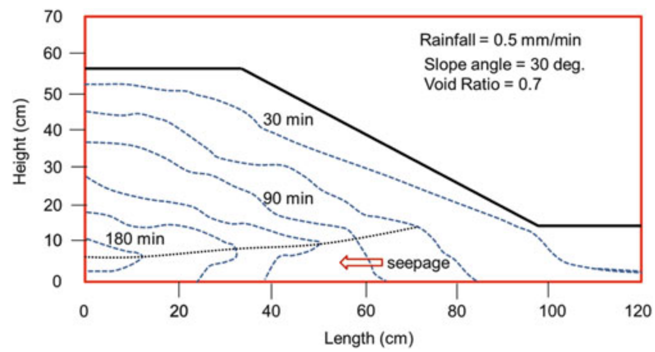

Fig. 8 Depth of water front on 30° slope having 30 mm/h of rainfall, recorded at different periods

parallel to the slope. This is inconsistent with the reports available in the literature (Pradel and Raad 1993). Figure 6 also illustrates the depth of water front in the 40° slope model prepared at the void ratio of 0.6. Figure 6 shows that although the depth of the water front was parallel to the slope, the rate of infiltration (i.e., the rate of movement of the water front) is lower in the soil compacted at the void ratio of 0.6 (denser soil) compared to the soil compacted at the void ratio of 0.7 (looser soil). This is reasonable as the hydraulic conductivity of soil decreases with the decrease in void ratio.

Presented in Figs. 7 and 8 are the depths of water fronts at different periods on 45° and 30° slopes, respectively when those slopes were subjected to 30 mm/h of rainfall. The rate of movement of water front was much slower than that with 4 mm/min of rainfall. As it can be observed in Figs. 7 and 8, the rate of movement of the water front within the slope (location b) is much faster than the rate of movement of the water front in the flat portion on top of the slope (location a). This can be attributed to the movement of water in an inclined direction, especially for the saturated soil above the water front. However, the angle of inclination of the water front was less than the angle of inclination of the slopes. In the case of the slope with a 30° angle of inclination, it was observed that once the flat portion near the toe (location c) became saturated, it completely filled the drainage layer and started to supply water in the horizontal direction as well. Therefore, the data below the dotted line (indicated as seepage) is not considered for further analysis.

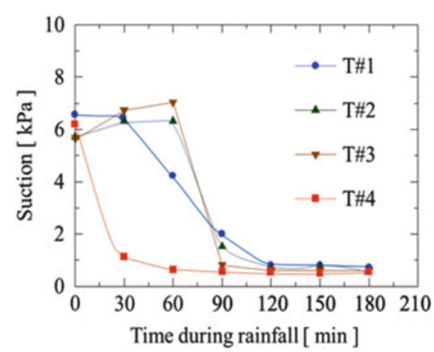

Fig. 9 Variation in suction with duration of rainfall at locations described in Fig. 2 for a 45° slope

Figure 9 illustrates the values of suction observed at four locations, described in Fig. 2. The initial suction at four locations prior to rainfall ranged from 5.5 to 6.5 kPa. The soil at the top (near tensiometer #4) required approximately 60 min to reduce the suction close to 0 kPa, whereas the soil near the

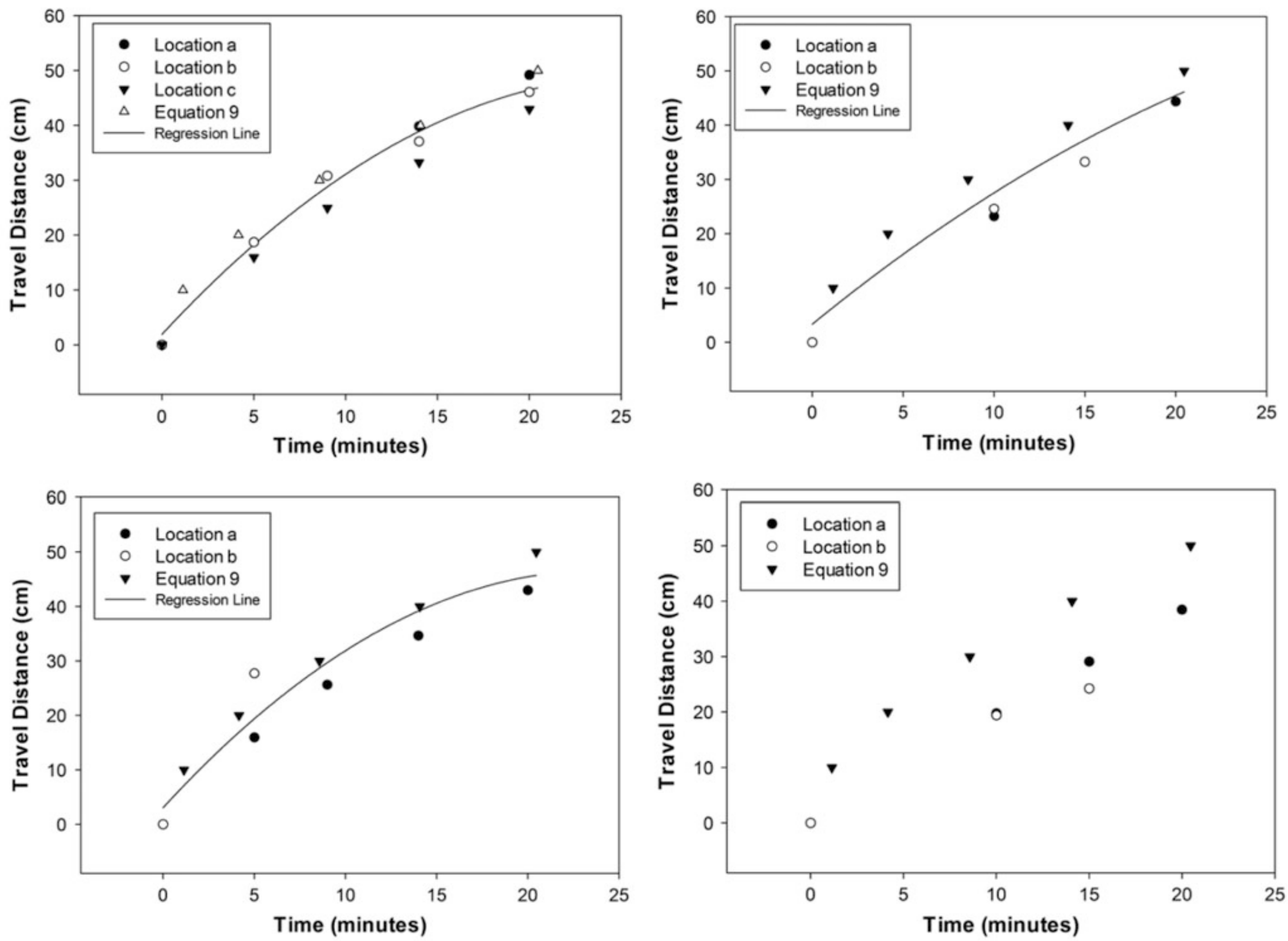

Fig. 10 Variation in travel distance of water front with duration of rainfall at locations a, b, and c in slopes with inclinations of 0, 40 (void ratio of 0.7), 45, and 40 (void ratio of 0.6) degrees, respectively

bottom of the slope (near tensiometer #1) required almost 120 min to drop the suction to 0 kPa. Please note that due to the sensitivity of the tensiometer used in this study (i.e. ±0.5 kPa), measured suction may give an error of up to 0.5 kPa. The tensiometers installed at other two locations within the slope also needed more than 60 min to become saturated. The rates of change in suction with time at all four locations were different. Locations near tensiometers 2 and 3 showed similar pattern in the reduction of suction with time. Results presented in Fig. 9 show that the water fronts were not able to progress to tensiometer #1 in 30 min and to tensiometers #s 2 and 3 in 60 min, after the initiation of rainfall.

Analysis of Test Results and Discussion

The main objective of this study was to identify a method that can be used to calculate the velocity of the movement of the water front in a sandy slope based on the intensity of rainfall. Such relationships are beneficial in predicting the movement of water front at different intensities and durations of rainfall and evaluating the stability of slopes. Presented in Fig. 10 are the travel distances of the water front plotted with time at locations a, b, and c, for 0°, 40° and 45° slopes, respectively when they were subjected to a rainfall of 240 mm/h. The movement of the water front showed a parabolic correlation with time, as presented in (1), (2), and (3). These equations are utilized later to develop the relationships between velocity of movement of the water front with the intensity of rainfall. As can be observed in Fig. 10, the movements of the water front at location b were faster than that at location a, although they are not significantly different for such a high intensity of rainfall. The velocity of the water front for a saturated soil mass can be calculated theoretically with (4) (Pradel and Raad 1993). The depth of the water front with time was also calculated using (4). For durations larger than 5 min of rainfall, the values calculated with the Eq. (4) were similar to the values

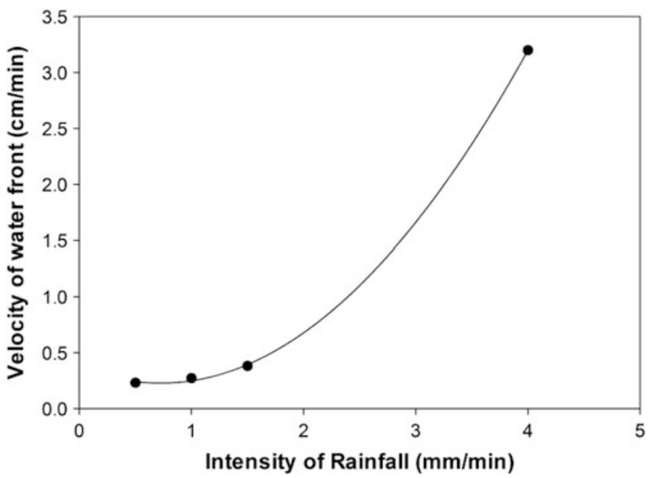

Fig. 11 Change in the velocity of the water front with the intensity of rainfall for a shorter duration of rainfall

obtained from the experimental modeling on the flat surface. Calculated values using (4) were slightly higher than the experimentally observed values at location a in the sloped models. However, the calculated values were similar to the observed values at location b, irrespective of the angle of inclination of the slope. As can be observed in Fig. 10, the rate of movement of the water front in soil with a void ratio of 0.6 was approximately 15 % slower than the movement in soil with a void ratio of 0.7.

$$Z_w = -0.091T^2 + 4.079T \quad (1)$$

Where, Z_w = Depth of water front in cm.; T = Time duration in minutes.

$$Z_w = -0.008T^2 + 2.366T \quad (2)$$

$$Z_w = -0.063T^2 + 3.406T \quad (3)$$

$$T_w = \frac{\mu}{K_w}\left[Z_w - S.\ln\left(\frac{S + Z_w}{S}\right)\right] \quad (4)$$

where T_w = Time required for water front to move a distance Z_w; μ = difference in volumetric water content before and after wetting; K_w = Saturated hydraulic conductivity; and S = Suction head at the water front.

Among the various objectives of this study was developing a relationship between the velocity of movement of the water front in a slope with the intensity of rainfall. The relationship was exponential for durations of rainfall shorter than 10 min. For durations of rainfall longer than 20 min, a second-order parabolic correlation was observed between the velocity of movement of the water front with the intensity of rainfall, as presented in Fig. 11. The corresponding regression equation is presented in (5). Please note that the velocity of the water front remains constant when the intensity of rainfall is higher than the rate of infiltration in a soil mass. The rate of infiltration (V_{is}) for saturated flow can be calculated using the Green and Ampt (1911) model, as presented in (6). For the soil slopes presented in this study, the calculated rate of infiltration for saturated soil is approximately 5 mm/min. However, it should be noted that the hydraulic conductivity of the soil changes with the degree of saturation. The seepage velocity calculated with (6) applies to saturated soil. For partially saturated soil, the velocity of flow could be as low as 10 % of this velocity. This is the subject of separate research.

$$V_i = 0.191I^2 + 0.033I \quad (5)$$

$$V_{is} = K_w\frac{Z_w + S}{Z_w} \quad (6)$$

The experimentally observed values showed that the velocities of movement of water front were higher when the angle of inclination of slope was higher at locations b and c. This justifies that once gets close to saturation, water moves in an inclined direction as well.

Summary and Conclusion

Experimental modelling was conducted in order to investigate the variation in the depth of the water front and spatial distribution of suction in sandy slopes for slopes ranging from 0° to 50° and intensities of rainfall of 30 and 240 mm/h. The results obtained from the experimental studies show that infiltration velocity increases with the intensity of rainfall. The infiltration velocity depends on the angle of inclination of the slope and initial degree of saturation. For soils with a high degree of saturation and a high intensity of rainfall, the movement of the water front is parallel to the slope.

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