Fundamental laboratory experiments of siphon drain for slope stabilization

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Abstract. Controlling the groundwater level in the slope can prevent the occurrence of landslides and maintain the stability of soil slopes. This paper aims to present the results of laboratory siphon drain experiments to evaluate the siphon drain effectiveness in lowering the water table in a model slope under different experimental conditions. The objective of the experiments was to observe and document the effect of the siphon well location, the siphon well spacing, and the initial groundwater level on the discharge and groundwater level. Five siphon pipes connected to five flushing units were used to extract the water from the slope. Several plastic manometer tubes were installed to monitor the water table. The laboratory experiments demonstrate that the siphon drains decreased the water level in the slope under different siphon well locations. The water seeping out of the slope toe decreased as the water extracted by the siphon drains increased. However, the siphon drains are useful to decrease the water level in the wells with a high-pressure head. Under high water due to rapid water level rise, the siphon drain can reduce the water table level within the slope up to 10 cm at the steady-state condition. In contrast, the siphon drain can effectively prevent the increase of the water table and further development of the seepage face area at the slope toe under low water level associated with a slow increase of water level.

1. Introduction
Landslides are natural disasters that have a high incidence during the rainy season with high intensity and long duration. This rainfall pattern causes an increase in the groundwater table in the hillslope and a decrease in the shear strength of the soil layer, which consequently triggers landslides. Many occurrences of rainfall-induced landslides have claimed significant deaths and property losses every year in Indonesia. Many efforts to stabilize rainfall-induced landslides have mainly focused on slope reinforcement, such as ground piling, rock gabion, and retaining wall [1-15]. Some reinforcement works may be costly and ineffective to prevent re-activation because the groundwater rise may still be the main causative factor of the hillslope instability during a long heavy rainfall period [1]. Therefore, preventing an increase in the groundwater table in a hillslope during heavy rainfall is necessary to mitigate this landslide hazard.
Many drainage methods for landslide stabilization are available nowadays. Amongst others, sub-horizontal drains are the most common groundwater drainage method used in landslide stabilization. However, the application of this method has some technical limitations, such as difficulties in reaching all aquifers, drilling length, and site access [6]. Thus, these drawbacks obviously hinder the effectiveness of this method to stabilize landslides with a deep groundwater level.

The siphon drain method is an alternative method commonly used to lower the groundwater level in landslide areas in Europe [7-10]. This siphon drainage consists of a vertical well, a siphon tube, and a flushing unit (figure 1). This drainage method has some advantages owing to its simplicity of operation and no need for power to operate. The siphon drain can facilitate drawdowns of up to 12 m, without the need for any additional energy [6]. Some previous studies have focused on tube diameters and flow rate on siphon drainage [11]. Another study by [12] suggests that the outlet should be kept about 4.1 m lower than the inlet to guarantee that the released air will be gathered in the descending tubes. Other studies have shown the field application of a newly designed siphon drain with inclined boreholes [13-15]. In a recent study, [16] has investigated the factors controlling the effectiveness of siphon drains in a field experimental program. However, this field study still did not indicate how well location and the initial groundwater level would affect the performance of siphon drains. Thus, implementation of this sub-drainage method requires a comprehensive knowledge of factors affecting its efficiency to lower the groundwater, such as well spacing, well location, and rate of groundwater rise. This knowledge can be gained by a series of laboratory experiments.

This paper presents the results of a series of laboratory experiments on siphon drainage to lower the water table in a model slope. The experiments aim to clarify factors controlling the effectiveness of the siphon drains method for different experimental conditions. The objective of the experiments was to evaluate the effect of well locations, the initial water level, and different rates of water table rise on the performance of the siphon drain. Plastic manometers stand-pipe were used to observe and measure the water level.

2. Material and methodology
This experimental study was performed using a laboratory-scale model slope constructed using river sand. The observations were mainly focused on the water level changes within the model slope before and after the activation of the installed siphon drains.
2.1. Properties of experimental soil

This study used river sand to construct the slope model. The sand is classified as well-graded sand with an effective particle size ($D_{10}$), and the uniformity coefficient ($D_{60}/D_{10}$) of the river sand are 0.23 mm and 5.96, respectively. The maximum dry density ($\rho_{\text{dmax}}$) of the sand, according to proctor tests, is 1.24 kg/m$^3$ at an optimum water content of 22.77%. The constant head permeability tests, using a rigid wall permeameter, resulted in the saturated hydraulic conductivity ($k_s$) of $5.19 \times 10^{-5}$ m/s at a void ratio of 1.12. The direct shearing tests indicated that the river sand has a low cohesion ($c$) of 5.76 kPa and a high internal friction angle ($\phi$) of 41.4°.

2.2. Experiment apparatuses

A metal tank with maximum dimensions of 2.4×0.8×1.2 m was rigidly constructed to conduct this experimental study, as shown schematically in figure 2. The tank structure was rigidly constructed to minimize deflection. An acrylic board of 10 mm thick was installed at one side of the tank to allow observation of water level during the experiment. A thin layer of sand was glued to the tank floor to prevent direct sliding of the slope base on the soil/floor interface to create friction on the floor surface. Meanwhile, no artificial friction was created on the sidewall surface to prevent the model slope from sliding along the wall.

![Figure 2. The metal tank used in the experiment.](image)

A detachable coarse gravel-filled tank of 300 mm wide with a porous sheet outlet was constructed in the tank to generate the lateral inflow of water from a constant head tank into the model slope (figures 2 and 3). The gravel-filled tank also prevented internal erosion within the soil due to scouring during the water level increase. Twenty plastic manometer tubes were installed using metal connectors into the observation window and the tank base at designated points to monitor the water table changes with time (figure 3). A water level in the slope model was generated using a constant head tank was connected to the tank (figure 3).
To introduce drawdown of the water table in the model slope for a specific experiment condition, three rows of five siphon wells, made up of PVC pipes of 42 mm in diameter, were constructed about 15, 40, and 100 cm from the outlet of the gravel tank. A pneumatic tube with an inner diameter of 8 mm was inserted into each well to facilitate the water flow out of each siphon well. The other end of each tube was connected to the flushing unit installed at the other end of the tank (figure 3).

2.3. Experiment program
A series of siphon drain experiments were conducted under different conditions to achieve the objective of this study. The first experimental program was focused on the effect of siphon well locations on the water level. The experiment was conducted using five siphon wells in each row to produce the water extraction, and the water level at the constant head tank was raised to 60 cm. The second experimental program was conducted to investigate the effect of the initial water level in the siphon drain on the water level. For these experimental programs, the initial water levels at the constant head tank were set at 30 cm and 60 cm, and the siphon drain was executed at five siphon wells in row 2. The third experiment program investigated the effect of the rate of water level rise. The experiment program consisted of two experiments. In the first experiment, the water table raised at a rate of 0.02 cm/s. Meanwhile, the water table was increased at a rate of 0.002 cm/s in the second experiment. In these two experiments, the constant head tank was raised to 80 cm, and the siphon drains were activated after the seepage face was observed to develop at the slope toe.

3. Results and Discussions

3.1. Effect of siphon well location
The water levels at a steady-state condition before and after the activation of siphon drains for different well locations based on the water level measurements at the tank base are shown in figure 4. In all experiment conditions, the siphon drain activation resulted in lowering the water table in the model slope, consequently reducing the seepage face area at the slope toe. It is clearly shown in figure 4 that the water table decreased more significantly in all siphon wells located at row two than those in rows 2 and 1. Thus, the effect of the siphon drain is much significant when the siphon drain was performed at the slope portion with a high-water head. Thus, this suggests that applying the siphon drain method requires a good knowledge of groundwater level within the slope to assist in determining the location of siphon well construction in a hillslope.
Figure 4. The steady-state water table within the slope model for each experiment condition.

Figure 5 shows the comparison of water discharge rate at each flushing unit for each experiment condition. The discharge rates are roughly about 18 to 22 ml/s. However, the discharge rate at rows 2 and 3 was slightly higher than that in row 1. As seen in figure 4, the different discharge rates correlated well with the different levels of the water table in the model slope. These data suggest that the pressure head at each siphon well controls the discharge rate. In other words, the highest the pressure head, the highest the discharge rate. Thus, these experimental results show that the well location will affect the effectiveness of the siphon drain method to lower the groundwater table in a hillslope.

Figure 5. The measured discharge rates from each flushing unit for each experiment condition.

3.2. Effect of initial water level

The effect of siphon drain on the water level in the slope model for different initial water levels is shown in figure 6. At a high initial water table, the siphon drains reduced the water table depth by about 17 cm. However, the seepage face area was still developed at the slope toe. At a low initial water level, the siphon drains could lower the water table by about 8 cm to a steady-state condition. In contrast, the seepage face area did not develop at the slope toe area and consequently increased the stability of the model slope. This evidence suggests that installing siphon drains at a low water table
can significantly maintain the groundwater at a low level. Thus, hillslopes will remain stable during the rainfall period.

![Figure 6](image)

**Figure 6.** The steady-state water table within the slope model for each experiment condition.

Figure 7 shows the comparison of the measured discharge rates for each experiment condition. As indicated in figure 7, the discharge rates for the experiment with an initially-high water table condition were 2.5 times higher than that of an initially-low water table condition. The averaged discharge rates for the high- and the low-water tables are about 27 ml/s and 10 ml/s, respectively. This ratio is similar to that of the final water table level after the siphon (see figure 6). Hence, the discharge rates are influenced by the initial groundwater level in a hillslope.

![Figure 7](image)

**Figure 7.** The measured discharge rates from flushing units for each experiment condition.

3.3. *Effect of the rate of water level rise*

Figures 8 and 9 show the steady-state water level condition based on the manometer measurement for every experiment condition. Figure 8 shows the observed change of the water table with the slope model during the first experiment with the rate of water table rise of 0.02 cm/s. The water table drawdown occurred up to 1.5 m from the front side of the gravel tank. The siphon drains resulted in a decrease of the water table up to 10 cm at the well location. However, the seepage area still unchanged.
Figure 9 shows the observed change of the water table with the slope model during the second experiment with the rate of water table rise of 0.002 cm/s. It is also clear that the siphon drain maintained the water table at a lower level than that in the first experiment. Thus, the siphon drain has a significant effect on lowering the groundwater table under a slow rise of the groundwater table during rainfall.

![Figure 8](image1.png)

**Figure 8.** The water table within the slope before and after the activation of siphon drains under the water level rise at the rate of 0.02 cm/s.

![Figure 9](image2.png)

**Figure 9.** The water table within the slope before and after the activation of the siphon drains when the water table rises at a rate of 0.002 cm/s.

Figure 10 shows the graph of total discharges measured in all experiments. As seen in this figure, the discharge rates in siphon S2 are higher than the other siphons. Moreover, the discharge rates measured in the first experiment are higher than those of the second experiment. Thus, it is evident from these experiments that the rate of groundwater rise in a hillslope controls the discharge rate of the siphon drain.

![Figure 10](image3.png)
4. Conclusions
Based on the laboratory siphon drain experiments, the well location, the initial water table, and the rate of water table rise control the effectiveness of the siphon drain method. The siphon drain method has a significant effect when installed on the slope with a high-water pressure head. Furthermore, a significant discharge rate occurs at an initially high groundwater level in a soil layer with low permeability. Further research is still required to determine the optimum well spacing through laboratory experiments and numerical analysis.

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