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Article

Toe drain size and slope stability of homogeneous embankment dam under rapid drawdown

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Abstract. The slope stability of an embankment dam has always been a serious issue of concern for any design team. Unfortunately, the information on the potential influence of a toe drain size on the slope stability of an embankment dam under rapid drawdown conditions is still scarce. This study investigated the potential effect of a toe drain size on the slope stability of a homogeneous embankment dam under rapid drawdown conditions. Three different sizes (5m, 10m, and 15m) of the toe drain were investigated under instantaneous (worst scenario) and 5 days (more realistic) drawdown rates with the help of numerical modeling in GeoStudio. From the results, it was observed that the pore-water pressures at the upstream face of the embankment decreased with the increase in the toe drain size, while the pore-water pressures at the downstream toe were increasing with the increase in the toe drain size. The factor of safety values were also observed to be affected by the changes in the toe drain size. The 5m drain size had a minimum size of 0.961, the 10m drain size had a minimum factor of safety of 0.970, while the 15m drain size had a minimum factor of safety of 0.978.
Keywords: slope stability, embankment dam, seepage, toe drain, rapid drawdown, factor of safety.

1. Introduction

Slope stability is among the serious issues of concern when designing embankment dams. This is due to the fact that the inappropriate design of embankment dams increases the risk of failure leading to catastrophic consequences [1]. A toe drain is among the features of embankment dams that have to be properly investigated during the design and operation phases under different loading conditions [2].

Among many other factors, seepage remains to be a very important factor that has to be carefully investigated and controlled when designing embankment dams [3]. The significance of controlling seepage is brought by the fact that excessive seepage through the embankment can pose a significant threat to the stability of the dam and eventually leading to its failure. Piping and sloughing are regarded to be the most prominent types of seepage failures along the downstream face of the embankment. In history, there are many cases of dam failure reported due to a lack of proper seepage management, including the Teton Dam in Idaho and Tunbridge Dam in Australia [4].

The application of drains and filters in embankment dams becomes handy as they tend to reduce seepage and loss of soil particles, which in turn improves the slope stability [5]. It has to be noted that, in the case where seepage through the embankment is blocked, then it will find a new route or build-up, leading to slope instability. Therefore, to avoid the aforementioned issues the embankment should include a well-designed internal drainage system. However, the effectiveness of the toe drain can be significantly affected by its shape, location, and most importantly the size of the toe drain. Unfortunately, the information regarding the potential effect of a toe drain size on the slope stability of an embankment dam under rapid drawdown conditions is still scarce. A rapid drawdown condition occurs when the water elevation that has reached the peak suddenly drops within a relatively short period of time [6]. The phenomenon can lead to reduced hydrostatic pressure and alteration of pore water pressure in the embankment. In this matter, estimation of velocity of flow through the embankment is also important. To achieve that, Darcy derived an equation that calculates the velocity of flow of water through porous media as illustrated in Eq. 1 [7].

$$V = Ki \quad (1)$$

Where: V stands for Darcy's velocity, K is the hydraulic conductivity of the porous medium, and i is the hydraulic gradient.

The combination of numerical modeling and finite element method is among the prominent approaches in investigating the nature of seepage through the embankments and the slope stability. GeoStudio is a widely used computer program for seepage and slope stability modeling [8].

In this study, the potential effect of a toe drain size on the slope stability of a homogeneous embankment dam under rapid drawdown conditions is investigated using numerical modeling. In the modeling process, three different sizes (5m, 10m, and 15m) of the toe drain are investigated. Also, two transient flow cases; instantaneous (worst scenario) and 5 days (more realistic) drawdown rates are investigated in GeoStudio.

2. Methods

2.1 General description of the numerical simulation

Finite element method analyses were performed to investigate the influence of the toe drain size and rapid drawdown rates on the slope stability of the embankment. Three different cases as determined by the toe drain size were taken into consideration. The numerical modeling process was achieved using the GeoStudio software (GeoStudio 2018 R2 v9.1.1.16749). Mainly SEEP/W and SLOPE/W sub-units of the GeoStudio were used for the seepage analysis and slope stability analysis respectively.

2.1.2 Embankment geometry

The geometry of the embankment was kept constant in all three main investigations while changing the toe drain size. The width of the embankment is approximately 59m at the base as well as 7m at the top, while the height of the embankment is 13m as shown in Fig. 1. The toe drain located at the downstream toe of the embankment varied from 5m, 10m to 15m. The maximum water level in the reservoir is 10m. Table 1 provides a summary of the embankment geometry parameters.

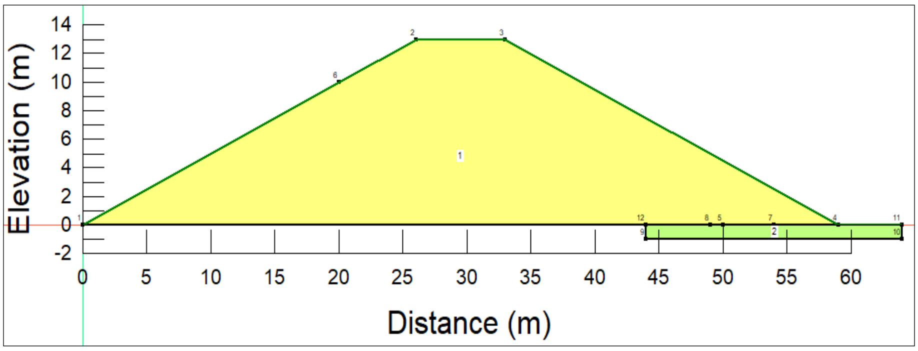


Figure 1 – General embankment geometry

Table 1 – Summary of the embankment geometry parameters

Parameter	Unit	Value
Bottom width	m	59
Top width	m	7
Embankment height	m	13
Maximum water level	m	10
Slope, H:V	-	2:1
Toe drain	m	5, 10, 15

2.2 Seepage and slope stability analyses

In general, the SEEP/W water transfer-based analyses were used to assess changing pore-water pressure conditions. The instantaneous drawdown case was taken as the worst drawdown scenario and then the rate was increased to 5 days (Fig. 2). To simulate the drawdown behavior of the slope in this study, initially, the transient seepage analysis was performed to obtain seepage-induced pore pressures and free groundwater-surface for different drawdown rates.

On the other hand, the slope stability analyses were performed using the SLOPE/W sub-unit of the GeoStudio based on the Spencer method. Generally, the Spencer method allows for unconstrained slip plains which in turn can determine the factor of safety along any slip surface [9].

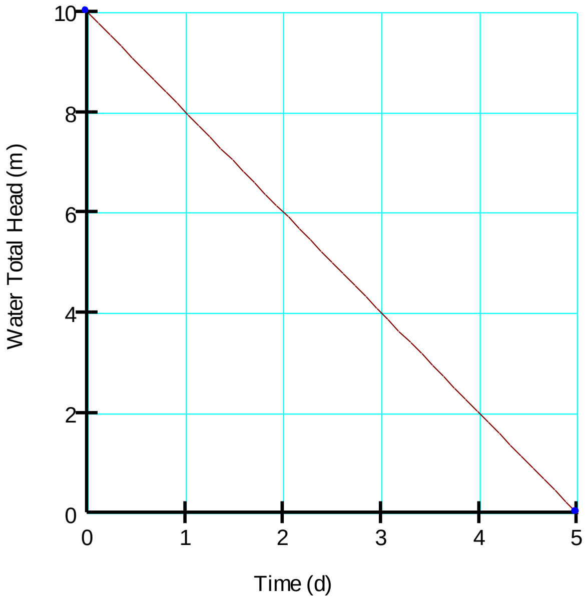


Figure 2 – Water total head function for 5 days drawdown rate

2.3 Soil material characteristics

The soil material properties for the embankment were kept constant for all the cases investigated to avoid any variability and capture the effect of the changes in the toe drain sizes. Table 2 provides a summary of the soil material properties used in the seepage and slope stability analyses. The saturated water content, coefficient of compressibility, saturated conductivity, residual water content, soil unit weight, cohesion, internal friction angle, young's modulus as well as Poisson's ratio were the main soil parameters to the model.

Table 2 – Soil properties

Soil material properties	Symbol	Unit	Value
Saturated water content	θ_s	%	43
Coefficient of volume compressibility	M_v	m^2/kN	2×10^{-4}
Saturated conductivity	K_{sat}	m/s	1×10^{-6}
Residual water content	θ_r	%	5.5
Soil unit weight	γ	kN/m^3	20
Cohesion	c'	kN/m^2	5
Internal friction angle	$\emptyset'$	degrees	25

3. Results and Discussion

The seepage and slope stability analyses were successfully executed using the combination of the finite element method and numerical modeling. From the seepage analysis, the water pressure at the downstream toe of the embankment was observed to increase with the increase in the toe-drain size. From Fig. 3, it can be observed that the 15m length drain size has higher pore-pressures than the 10m and 5m. In general, in the literature drains have been observed to be important features in the stability of embankments [10–12].

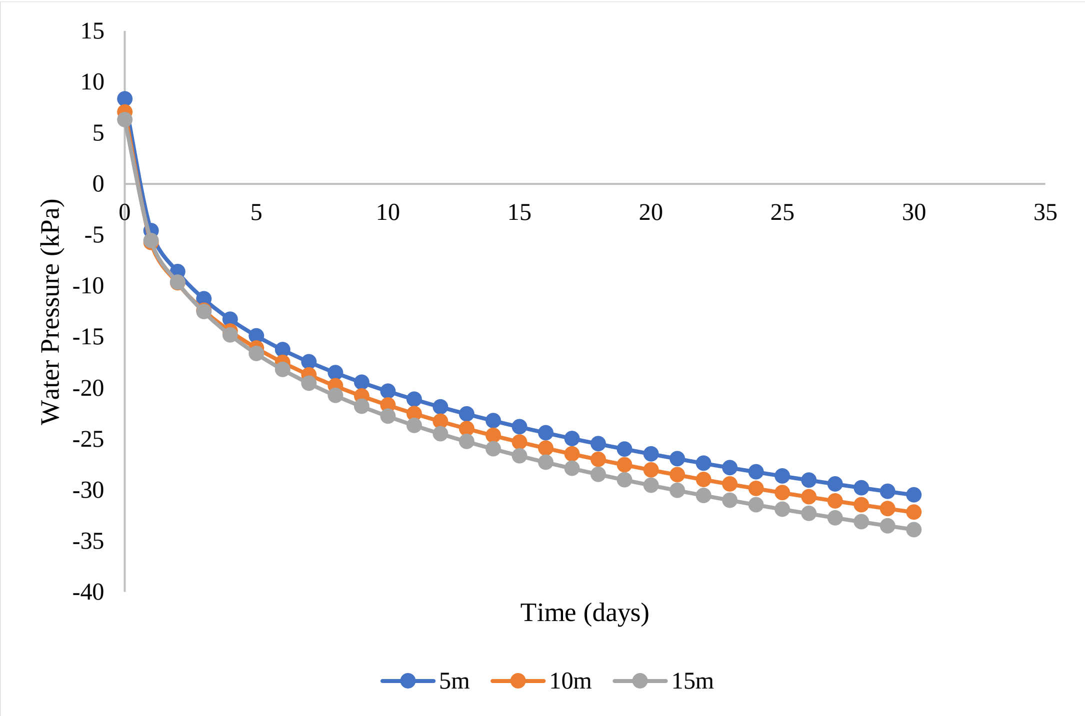


Figure 3 – Pore-water pressure at the upstream face

Contrary to the downstream toe, the pore water pressures at the upstream face of the embankment were observed to be decreasing with the increase in the toe-drain size. From Fig. 4, it can be observed that the pore-water pressures from the 15m length drain size were slightly higher than those from the 10m and 5m. The phenomenon suggests that, as the size of the toe drain increases, the seepage is more conveniently carried through the embankment allowing easy dissipation of pore-water pressures in the embankment after the drawdown.

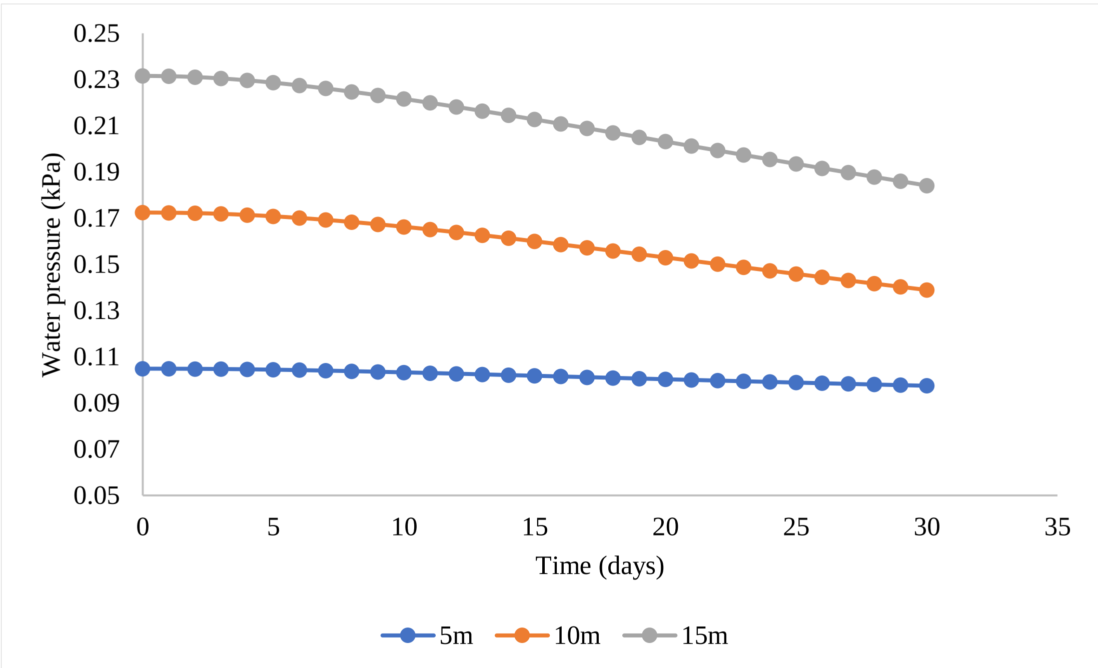
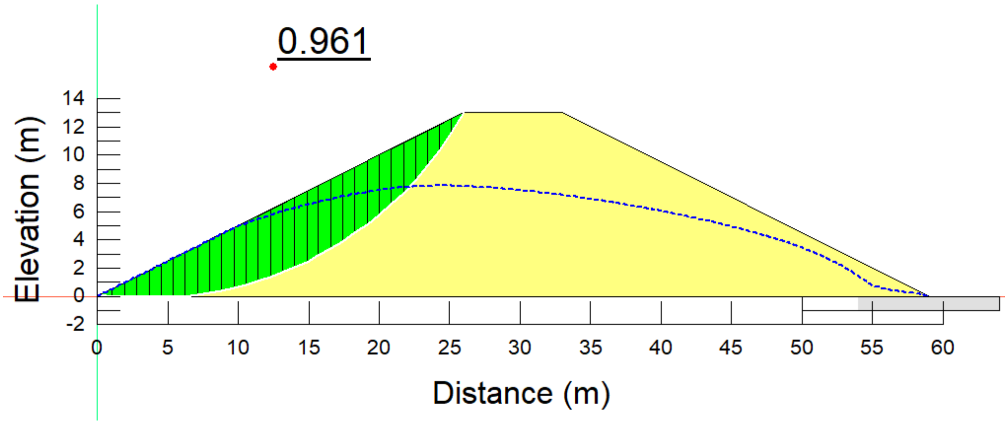
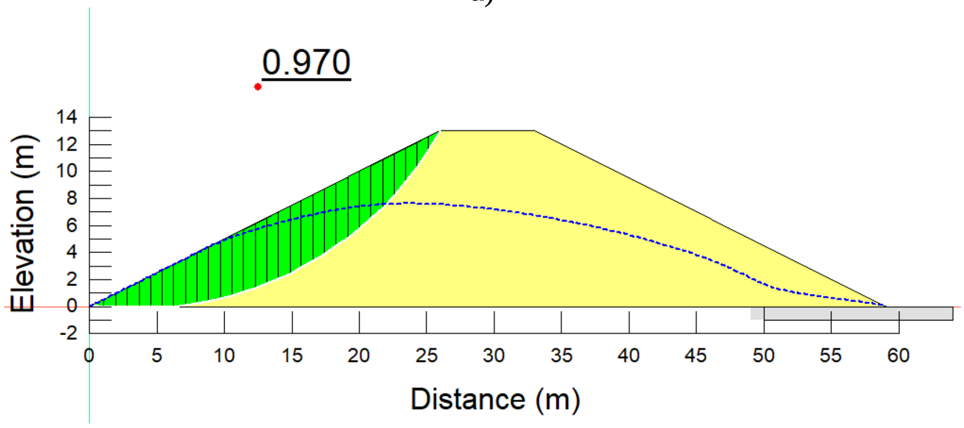


Figure 4 – Pore-water pressure at the downstream toe

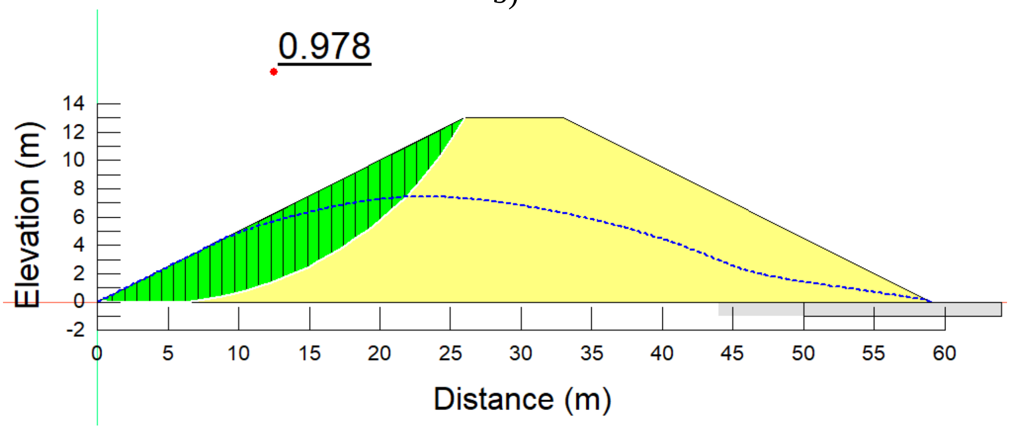
Similarly, from the slope stability analysis, it was observed that the change in the toe drain size affected the factor of safety. From Fig. 5 it can be observed that the 15m length toe drain size showed to have a bit higher factor of safety in comparison to the 10m and 5m toe drain sizes. The 5m drain size had a minimum size of 0.961, the 10m drain size had a minimum factor of safety of 0.970, while the 15m drain size had a minimum factor of safety of 0.978.



a)



b)



c)

Figure 5 – The factor of safety with slip surfaces from 5 days drawdown rate: a) 5m drain size; b) 10m drain size; c) 15m drain size

From Fig. 6, it can be observed that the lowest factor of safety values was obtained somewhere close to the last day of the drawdown. The factor of safety values dropped rapidly during the drawdown period with a gradual increase after the drawdown.

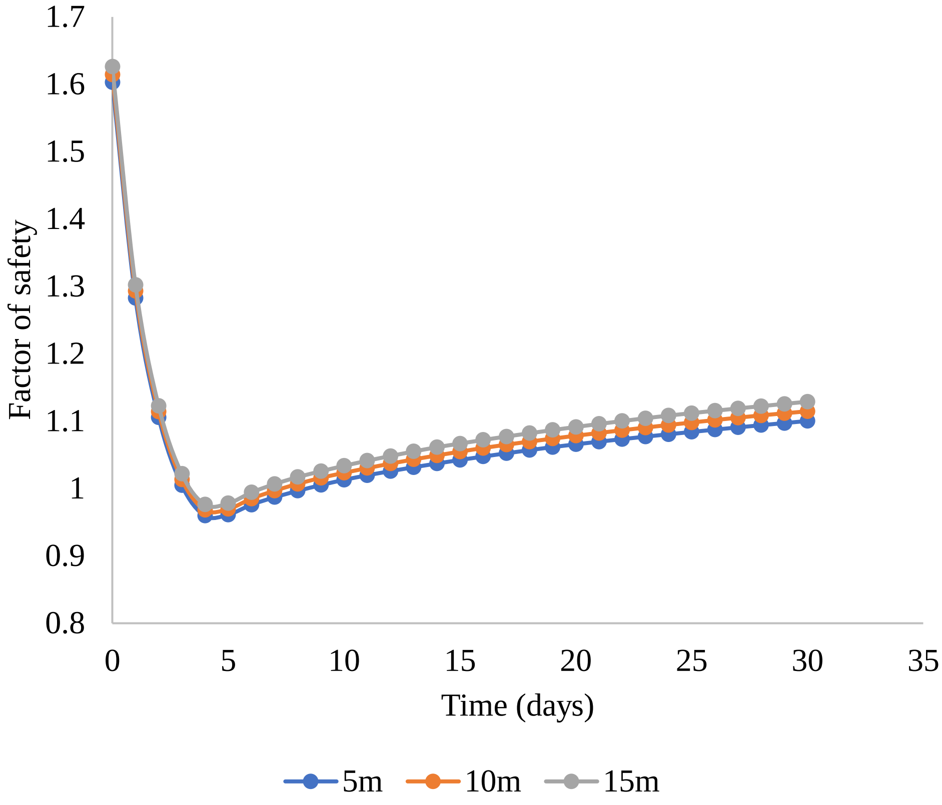


Figure 6 – The trend of the factor of safety values with time

Table 3 provides a summary of the maximum and minimum values of the factor of safety from the instantaneous and 5 days drawdown rates. From both drawdown cases, it can be observed that the factor of safety values was increasing with the increase in the toe drain size.

Table 3 – A maximum and a minimum factor of safety values from the instantaneous and 5 days drawdown rates

Drawdown rate	Toe drain size	Factor of safety	
		Maximum	Minimum
Instantaneous	5m	1.603	0.799
	10m	1.614	0.805
	15m	1.626	0.811
5 days	5m	1.603	0.959
	10m	1.614	0.968
	15m	1.626	0.976

4. Conclusions

The potential influence of a toe drain size on the slope stability of an embankment dam under rapid drawdown conditions has been investigated. From the results, it was observed that the pore-water pressures at the upstream face of the embankment were decreasing with the increase in the toe drain size, while the pore-water pressures at the downstream toe were increasing with the increase in the toe drain size. The factor of safety values were also observed to be affected by the changes in the toe drain size. Therefore, the results from this study revealed further that, there is a significant potential relationship between toe drain size and factor of safety when an embankment is subjected to a rapid drawdown condition.

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