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The Effect of Horizontal Drainage Lengths on the Stability of a Homogeneous Earth-Fill Dam Under Seepage Conditions

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Abstract

Failures can occur from seepage failure in the downstream slope of an earth-fill dam. The excessive pore pressures and seepages must be controlled to achieve the desired safety level in such dams. This safety can be provided with a horizontal drainage cover design. The essential goal of drainage system design is to increase system efficiency in reducing pore water pressures and seepage. Several calculations were made with a downstream slope cover design and downstream horizontal drainage length for homogeneous earth-fill dams. The minimum and maximum effective length of the filtered drainage system was obtained after the analyses. Moreover, the factor of safety regarding the downstream slope was calculated for the drainage system with different geometries. The results showed that the horizontal drainage length affects system performance and the seepage behavior of the dam.

1.INTRODUCTION

Despite the remarkable development of the dam industry and the application of modern methods and equipment in dam constructions, homogeneous earth-fill dams are still in use thanks to their ease of application, environmental compatibility, local material usage, and availability to be built on a low-strength foundation [1]. Therefore, homogeneous earth-fill dams are one of the most common types [2].

Homogeneous earth-fill dams are hydraulic structures made of impermeable material built along a river to form an upstream reservoir to hold water for various purposes. The purposes of impoundment may include irrigation, hydropower generation, flood control, shipping, and fishing. Dams can be built to meet any of the purposes mentioned above or constructed to achieve more than one purpose [3].

The homogeneous earth-fill dam is designed with relatively fewer slopes to stay safe while being built. (Generally, 1:3 on upstream side and 1:2 on downstream side) [4]. The design differs due to dam location and the material variety in the construction. Furthermore, the building purpose of the dam also affects the design. It is not possible to present a general design criterion for earth-fill dams [5]. But each design criteria should include the following design aspects.

- Stability of embankments and foundations in critical conditions such as earthquakes and floods
- Seepage and pressure check for both filling and foundations
- Erosion control methods

Critical conditions such as earthquakes, overflows, and unexpected increases in seepage must be overcome with control structures such as filter-protected stack drains, horizontal drains, relief wells, and edge drainage [6,7].

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Figure 1 illustrates that the drains are divided into horizontal, triangular toe, chimney, and combined drain based on their location and geometry [8].

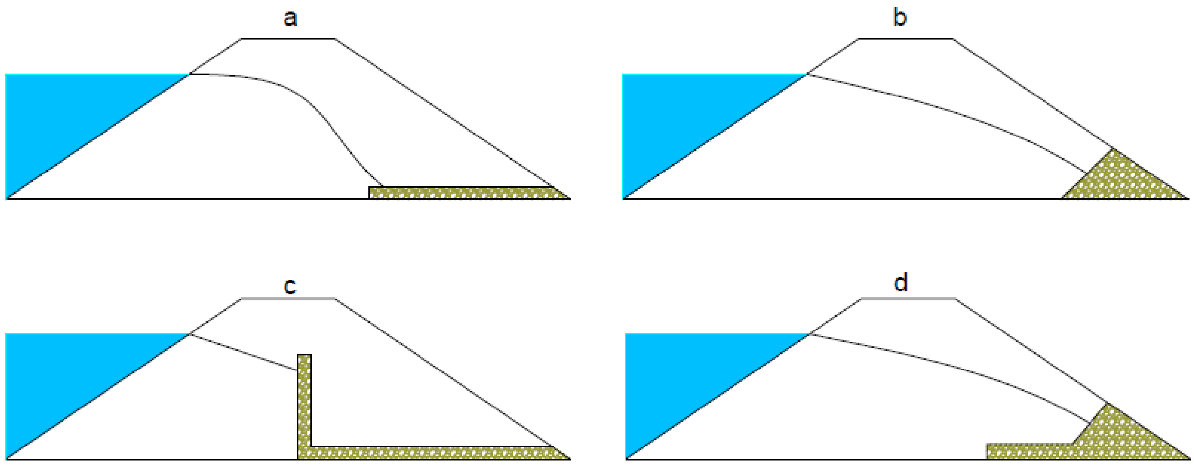

Figure 1. *Different types of drainage in homogeneous earth dams, (a) Horizontal drain, (b) Triangular toe drain, (c) Chimney drain, (d) Combined drain.*

The horizontal drainage method is a cost-effective and widespread method for seepage design. These drains dissipate excess pore water pressure, causing equipotential lines to become closer to the ground surface and more horizontal. They also have a very substantial effect on the stability of the upstream slope during a rapid drawdown. The efficiency of the horizontal drainage system is a function provided by several factors such as soil properties, slope geometry, drainage location, length, and spacing [8].

There is limited scholarship to describe several parameters that control horizontal drainage design or evaluate the feasibility of using a horizontal drainage system to reduce groundwater levels [9-11]. Moreover, Rahardjo et al. (2002) analyzed the effectiveness of horizontal drainage for slope stability in dams [12,13].

Properly designed horizontal drainage can provide dam safety by shortening the seepage flow length [14]. Therefore, it is essential to design a drainage system long enough to hold the water surface within the dam structure and short enough to prevent excessive seepage volume [15].

Horizontal drains are commonly used in medium-height homogeneous dams up to 50 m high [16]. This drainage should have adequate length and thickness to channel the water safely from the dam body. The recommended drain thickness is at least 1 meter [17]. The upper limit for the length of the drain is defined in the USBR (1987). The limitations indicate that the distance between the dam's centerline and the upstream end of its horizontal drainage should not be less than H+1.55 m, where H is the height of the dam. Furthermore, the drain should be placed in such a way that no capillary rise above the waterline is visible on the downstream slope [18-20].

This study includes an analysis on horizontal drainage systems applied in homogeneous earth-fill dams. The data from the literature, drainages of different lengths were designed, and the stability and pore water pressures on the downstream side of the dam were detailed.

2.MATERIAL AND METHODS

2.1. Materials

The slope stability and pore water pressures varying along the slip surface were examined under the conditions of drainage systems with different geometry of a homogeneous earth-fill dam. The sample dam considered from the literature data was defined according to the USBR (1987) criteria.

Since the properties of the dam material largely determine the seepage and stability behavior of the dam, these properties were collected from sources containing actual data in the literature. Therefore, the soil properties of the homogeneous earth-fill dam investigated are available in Table 1, while the dam model used in the analysis is detailed in Figure 2 [21,22].

Table 1. *Properties of materials used in seepage and stability analyses*

	c (kPa)	Φ (degree)	ψ (degree)	γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)	ν	*E* (kPa)	k (m/s)
Homogeneous Earth-fill Dam	20	30	0	18	19.2	0.30	6000	10^{-7}
Impervious Foundation	25	40	10	19	22	0.32	73200	10^{-10}
Horizontal Filter Drain	0	35	5	17.8	20.9	0.25	12250	$4x10^{-3}$

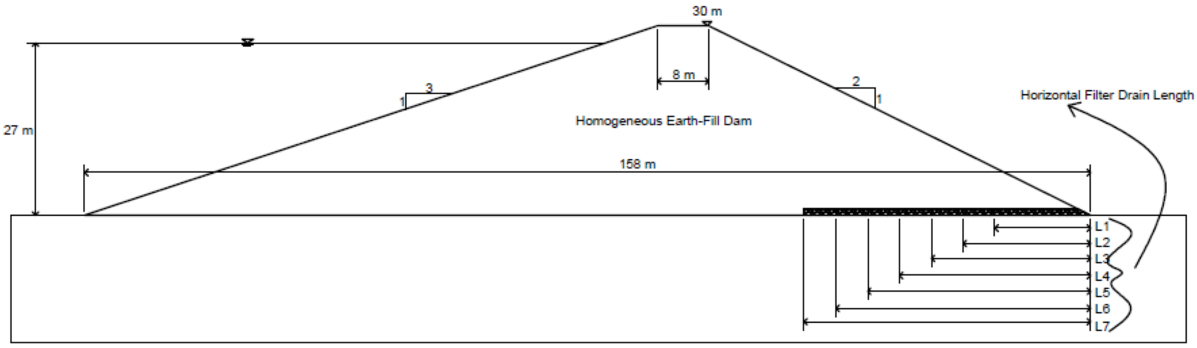

Figure 2. *The general section of a homogenous earth dam with a horizontal filter drain*

2.2. Methods

Numerical models were used to analyze how the dam stability is affected under seepage conditions. It is possible to mathematically model the physical process of water flowing through the environment with numerical modeling by creating a mathematical simulation of an actual physical process. It is also purely mathematical, in this regard, and very different from scale physical modeling in the laboratory or full-scale field modeling [23]. Limit equilibrium approach modeling is a well-known method regarding stability analysis problems. This method considers the force or moment balance of the soil mass above a possible failure surface.

Figure 3 shows the simulation steps. This process includes creating geometric models and mesh, defining material properties and boundary conditions, solving boundary conditions and governing equations, and finally, visualizing and interpreting the results.

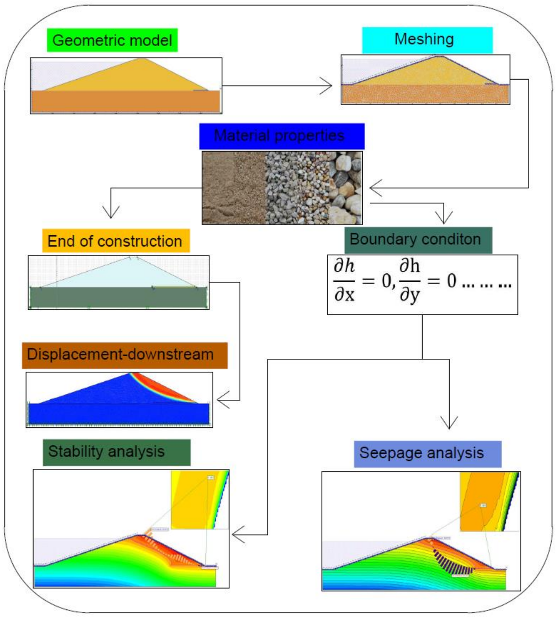

Figure 3. *Simulation process of the study*

2.3. Governing equation

The equations are two-dimensional diffusion equations in the unstable state. The general partial differential water flow equation for seepage, derived from the combination of Darcy's law and the mass conservation equation, can be detailed as follows [24].

$$(k.h) = S_s \frac{\partial h}{\partial t} (1)$$

The sum of elevation head (z) and pressure head is called piezometric head.

k: the hydraulic conductivity

h: the piezometric head

S_s: specific storage and t is time

The two-dimensional form of equation (1) can be formulated as [1]

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial h}{\partial z}\right) = S_S \frac{\partial h}{\partial t} (2)$$

2.4. Seepage and Stability Solutions

The purpose of the analysis is to define the pore water pressures in the dam-downstream system needed for slope stability and calculations. The analyzes were performed through the SLIDE module of the Rocscience geotechnical software package.

Figure 3 shows the boundary conditions and mesh at the dam and around the horizontal drainage system. A tight mesh was applied around the drainage system and in the dam body.

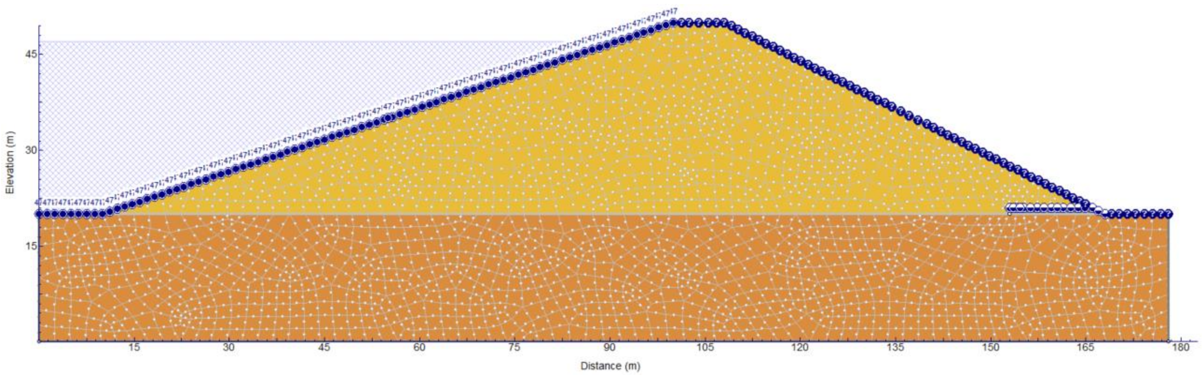

Figure 4. *Initial conditions for the dam as it is designed in Rocscience Slide* [25].

The upstream and downstream boundaries are defined as the water height behind the reservoir and the water height in the tail-water region. It should be noted that the boundary condition is assumed to be load-free since there is no water downstream of the dam.

The Bishop method, one of the limit equilibrium methods, was applied to analyze the slope safety in the downstream region of drainage systems with different geometries. The Bishop method is prevalent in practice for circular cutting surfaces. It uses the interslice normal forces while omitting the interslice shear forces [26-27].

3.ANALYSES

It is critical to evaluate the embankment body, upstream and downstream slope at the end of construction before analyzing the pore water pressures that may occur in seepage cases. Therefore, displacements that may occur on the downstream side of the drainage system were examined through FEM-based PLAXIS 2D software after the construction of the homogeneous earth-fill dam (Fig. 7 (28)

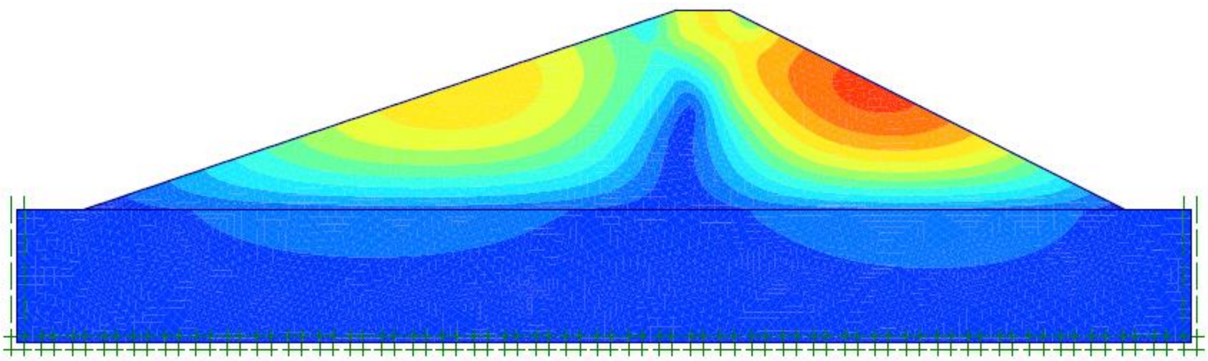

Figure 5. *Total displacements during the end of construction using FEM (downstream-45 m drain)*

The geological section was placed in the Rockscience Slide 6.0 software. Moreover, the stability analysis and the maximum and minimum pore water pressure values varying along the slip surface were calculated.

Horizontal drainage lengths of 15, 20, 25, 30, 35, 40, and 45 meters were included and applied to the dam geometry, respectively. Factors of safety on the downstream side were calculated for each drainage length. In contrast, the minimum and maximum pore water pressures after the seepage along the slip surfaces were calculated (Figure 6).

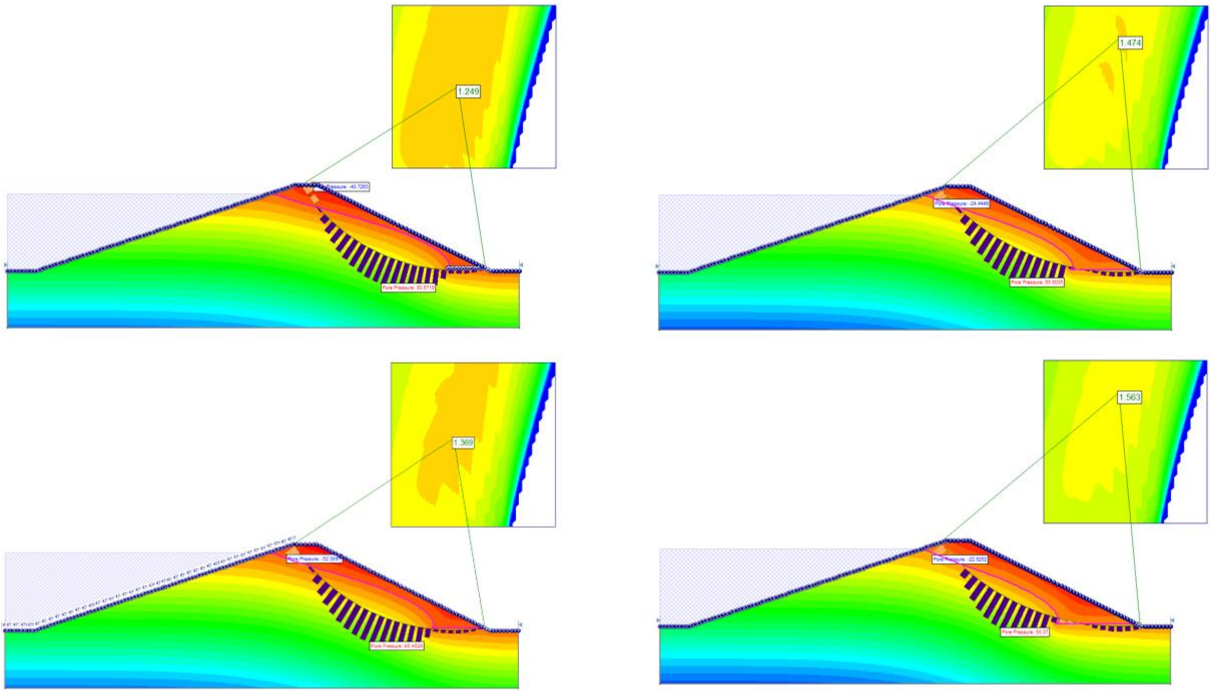

Figure 6*. FoS and pore-water pressure for various lengths of the drain (15-20-25-30 m)*

The results obtained showed that the lowest factor of safety belonged to the 15-meter horizontal drainage system. A linear correlation was observed between the horizontal increase in drainage lengths and the factor of safety. However, after a certain length (35-40-45 m), it was found that the factor of safety did not change much (Table 2). This might be rooted in the idea that exceeding the horizontal drainage length specified in the design at certain levels will not affect the safety of the dam.

Table 2. *The Pore water pressures and factor of safety for various lengths of the blanket drain.*

Horizontal Filter Drain Lengths (m)	Factor of Safety	Along Surface Minimum and Maximum Pore Water Pressure	
		Minimum	Maximum
15	1.249	-40,720	93,671
20	1.369	-32.309	85.452
25	1,474	-24,444	65.603
30	1.563	-22.525	50.070
35	1.637	-36.501	24.643
40	1.673	-60.400	8.269
45	1.673	-64.728	8.270

Figure 7 shows the pore water pressure variation along the slip surface beside the correlation between the horizontal drainage length and downstream stability. Considering the length variation of the horizontal drainage system, it was found that the drainage geometry affects the reduction of pore water pressure after 25-30 meters for both combinations.

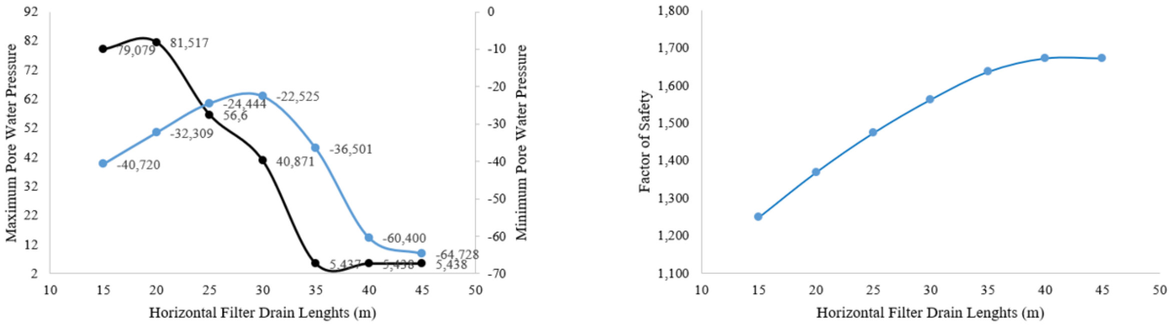

Figure 7. *Pore water pressure distribution and factor of safety*

However, it cannot be asserted that increasing the length beyond 35 meters significantly affects pore water pressure. This might be rooted in the fact that the horizontal drain length should be increased in length to reduce pore water pressure, and the design length should be considered.

The analyses for the critical loading situation revealed that the drainage systems of different lengths do not meet all the requirements of the United States Army Corps of Engineers (USACE), British Dam Society (BDS), and Canadian Dam Association (CDA) recommendations. This is detailed in Table 3 [21].

Table 3. *Summary slope stability analysis results*

Condition	FoS (USACE)	FoS (BDS)	FoS (CDA)	Length (m)	FoS	Status
Steady-State	1.5	1.3-1.5	1.5	15	1.249	x
				20	1.369	x
				25	1.474	x
				30	1.563	✓
				35	1.637	✓
				40	1.673	✓
				45	1.673	✓

The data obtained from the SLIDE program was used in the analysis through the SEEP/W software with the design system of the maximum drainage length (45 m). SEEP/W software is a finite element program that can simulate groundwater flow in soils. Different materials and boundary conditions can be modeled two-dimensionally under saturated or unsaturated conditions for steady-state or transient analysis. It is widely used for groundwater flow modeling by several scholars.

Graphic data showing the variation of soil permeability and volumetric water content with matric suction pressure in the seepage analyses made according to soil mechanics principles are available in Figure 8.

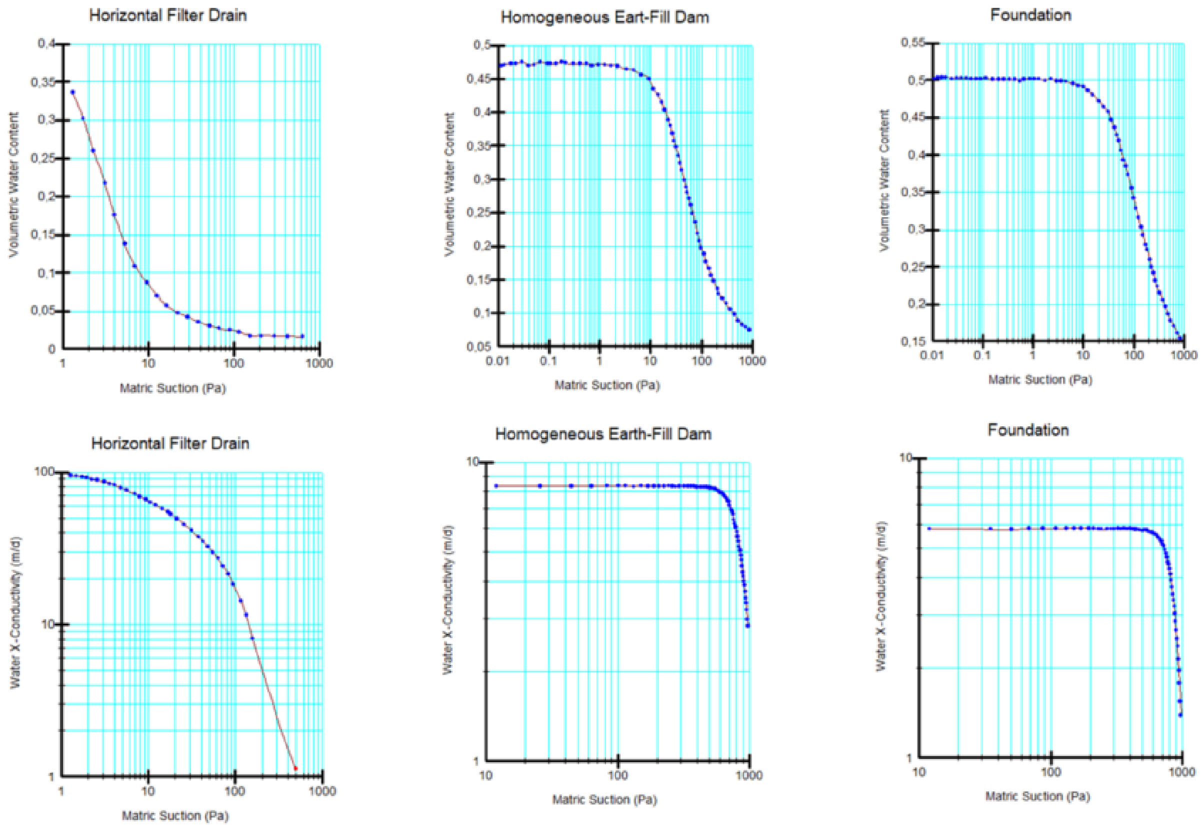

Figure 8. *Soil–water characteristic curve and permeability function for soil materials*

The analysis performed in the SEEP/W program was applied to the design with a horizontal drainage length of 45 meters [29]. As in the Rocscience Slide analysis, the seepage analysis was performed, while the maximum water was assumed to be 27 m above the foundation level. The pore water pressure distribution in the downstream region of the dam was obtained (Figure 9) through the seepage analysis.

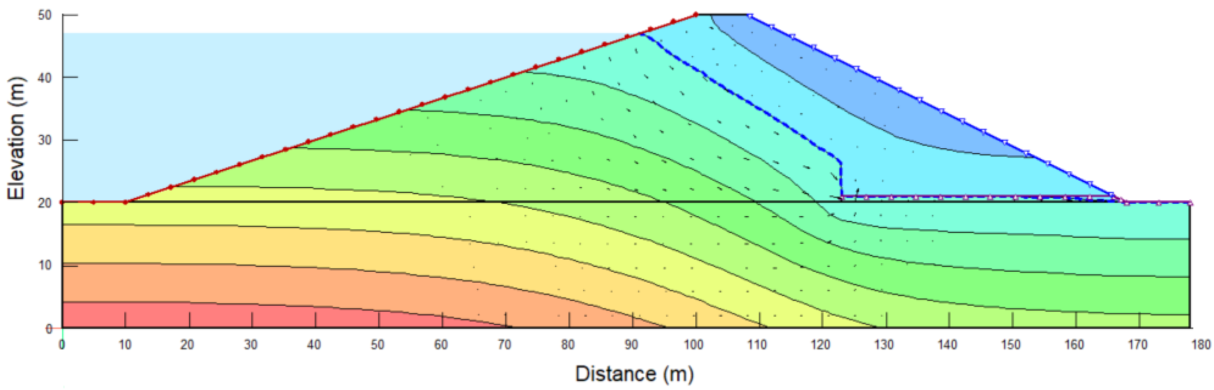

Figure 9. *Pore water pressure contours of the Dam (45 m)*

Figure 10 shows the variation of pore water pressure by the distance along the critical slip circle in the downstream slope. The graph shows that the pore water pressure is negative due to suction at the heel of the downstream slope, increasing towards the phreatic line. The critical sliding surface is zero when it intersects the phreatic line. The pore water pressure rises to the maximum ordinate of the slices from the phreatic line and begins to decrease towards the end of the downstream slope.

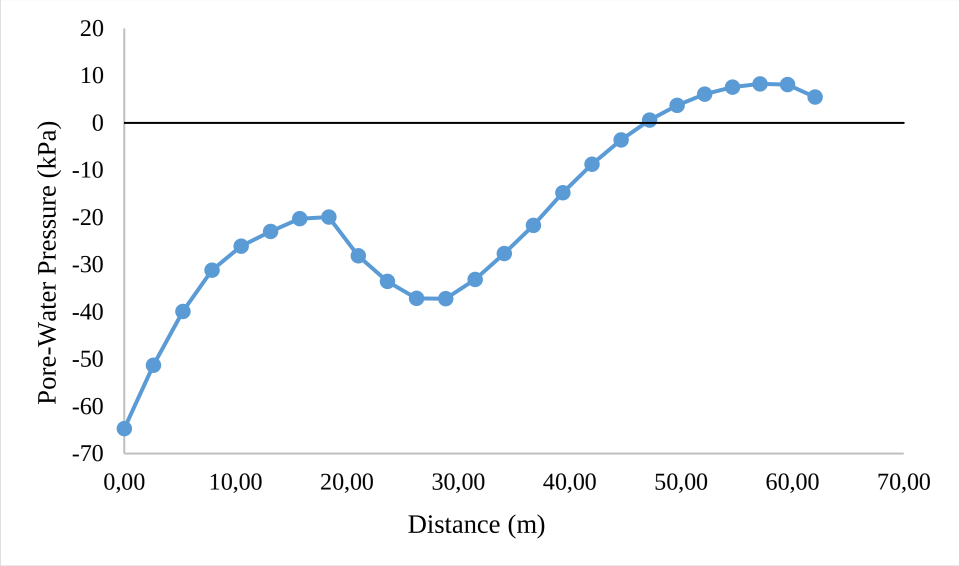

Figure 10. *Pore-water pressure and distance for the 45-meter drainage system.*

4.RESULTS

Seepage control in earth-fill dams is crucial for the safe and sustainable operation of constructed dams. The effects of horizontal drainage systems with various lengths on stability and seepage properties were analyzed with the Geotechnical software. The length of the downstream drainage on the seepage in homogeneous earth-fill dams was evaluated for seven different cases.

The main findings of this study can be summarized below:

1- It was observed that the increases in drainage length caused decreases in the pore water pressures passing through the body. Downstream slope protection is essential to the safety of the dam, but the use of drainage provides improved safety against seepage effects.
2- The downstream drainage system shifts the waterline away from the downstream slope, thereby preventing downstream slope failure. It also quickly removes the seeping water and reduces the pore water pressure inside the dam.
3- The drain length extending beyond the point of intersection with the critical failure surface does not provide a significant change in the factor of safety.
4- It was found that the maximum length has a more significant effect on the safety factor for the overall length combination when different horizontal drainage length combinations are applied for the full reservoir level and the steady-state condition regarding the fill dams.
5- The water discharged by the horizontal drain is impeded to rise in the filling on the drain. Suppose the horizontal drain does not have sufficient capacity. In that case, the upstream line will reach the downstream embankment, reducing the stability of the downstream slope and also potentially causing pipe collapse in the downstream fill.
6- The basic guidelines for drainage design were also provided, and particular suggestions were propounded on evaluating their performance by the seepage properties.

In the study, the effect of climatic conditions on the dam was ignored. These effects can be included in a future analysis. In addition, the effect of the water level change that may occur on the upstream side of the dam model used in this study (eg rapid drawndown) on the drainage filter and dam stability can be examined and can be an example for future studies.

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