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Numerical and physical modelling of pore pressure relief drains in homogeneous embankment dams

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ABSTRACT: The failure of embankments due to seepage and other water-related issues is often underestimated. Pore water pressure buildup in embankments can lead to stability issues or failure of civil infrastructure. This study explores the efficacy of pore pressure relief drains to alleviate excess pore pressure within embankments. Here, silica sand embankment dam models were constructed by means of a drainage and seepage tank to visualize seepage. Numerical simulations, based on the geometries of the physical models, were conducted to mimic and further study the behaviour of homogeneous embankments with different drainage systems. Geotechnical experiments were performed on the material used for physical modelling, and finite element analysis tool (SEEP/W) was used to model the embankment behaviour. The findings showed that strategically placed pore pressure relief drains can effectively reduce excess pore pressure and significantly lower the phreatic surface, thereby improving the stability of the downstream slope. Physical model tests demonstrated significant reductions in pore pressure for drainage types fitted with pore pressure relief drains, this was also confirmed by numerical simulations. Drain location, geometry, and material properties were shown to be crucial factors in designing efficient drainage systems. This work contributes to the stability of embankment structures, particularly in regions with high water tables or heavy rainfall. The combination of physical and numerical modelling improves the understanding of optimal drainage system design. Carefully designed pore pressure relief drain systems can significantly reduce excess pore pressure in homogeneous embankments, enhancing the stability of the downstream slope.

Keywords: Pore pressure relief drains, seepage, physical modelling, numerical simulation.

1 INTRODUCTION

Embankment dams play a critical role in water management and flood control. They are built to impound water and provide storage capacity for various purposes such as irrigation, hydroelectric power generation, and municipal water supply. The stability of embankment dams is paramount to ensure the safety and longevity of these structures. Pore pressure buildup within embankment dams can compromise their stability and lead to catastrophic failures. To mitigate the risks associated with pore pressure buildup, various measures, including the use of pore pressure relief drains, have been implemented. Pore pressure relief drains are designed to alleviate excess pore water pressure within embankments by providing a pathway for the drainage of trapped water (Luo et al., 2016).

However, this involves a comprehensive understanding of the behaviour of pore water pressure within the dam and the methods employed to mitigate potential issues. In this work, we will explore the numerical and physical modelling aspects of pore pressure relief drains in homogeneous embankment dams, drawing upon relevant research insights and experiments to highlight the importance of these critical components in embankment dams.

2 LITERATURE AND THEORY

The design and implementation of pore pressure relief drains in homogeneous embankment dams is a critical aspect of dam engineering to ensure the stability and safety of such structures and the environment (Klohn and Leonoff, 1984). Studies on the cause of dam breaches worldwide has shown that 34% of these incidents were triggered by overtopping due to insufficient spillway capacity, 30% were due to foundation defects, and 28% were due to piping and seepage issues (Lou, 1981). While this was reported several decades ago, recent studies (Torabi Haghighi et al., 2020; Rico et al., 2008) show that this is a persistent issue. A complete worldwide database for all historic failure events is practically not available, and many incidents worldwide remain unreported (mainly in developing countries), therefore, these figures could be well above the recorded ones (Azam and Li, 2010). Seepage due to upstream hydraulic head has been extensively studied over the past years, yet it is still found to be the general failure of embankments and levees today as it is frequently underestimated (El Shamy and Aydin, 2008; Serre et al., 2008).

In a geotechnical point of view, there are generally two types of processes that can be generated by seepage within an embankment: internal erosion inside the embankment and sliding failure long the embankment slope; under certain conditions, both processes can induce embankment failure (Polemio and Lollino, 2011). Under specific seepage circumstances, water flow can initiate the internal erosion process (Fell and Fry, 2007; Adamo et al., 2020a, 2020b), and this may occur under different modes such as backward erosion, as explained by Terzaghi (1939), it occurs when the downstream area of the embankment has a high enough seepage exit gradient to mobilize soil particles and can move upstream if the hydraulic gradient remains elevated across the embankment. In addition to backward erosion, FEMA (2006) also mentioned suffusion and concentrated leakage erosion as issues that may induce internal erosion when an embankment is not equipped with a well-designed drainage system. The backbone of seepage analysis is Darcy's formula,

$$Q = kiA, \tag{1}$$

which relates the rate of flow (Q) to permeability (k), cross-sectional area (A) and hydraulic gradient ($i = \frac{\Delta h}{\Delta l}$). Numerical and physical modelling of pore pressure relief drains in homogeneous embankment dams is crucial for assessing and ensuring the stability and safety of these structures.

3 MATERIALS AND METHODS

In this section, the experimental program, consisting of laboratory tests, physical and numerical simulations will be introduced.

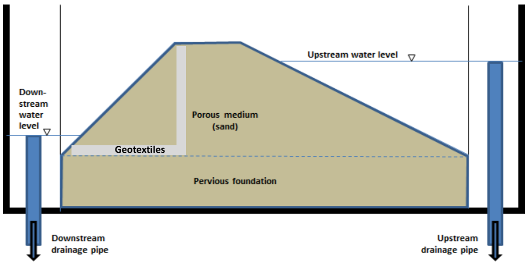

Figure 1. Schematic of a drainage and seepage tank setup.

3.1 Model materials

Hydrometer analysis was carried out in order to determine the particle distribution of the material used for constructing the embankment models, silica sand, identified as centrifuge sand. Tests were also conducted on some clay and tailings materials for comparison purposes, Figure 2 shows particle distribution curves for the materials.

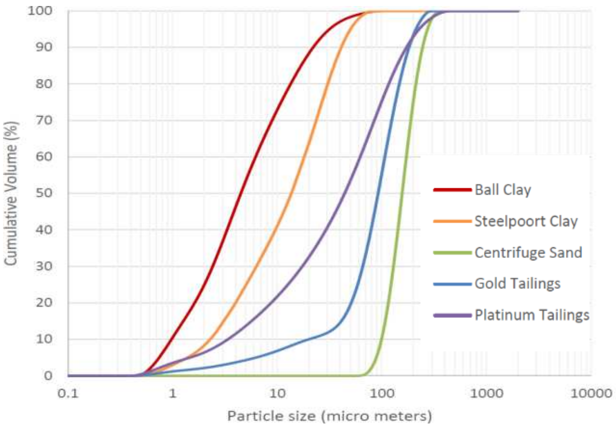

Figure 2. Particle distribution curve plot of silica sand (centrifuge sand) and other materials.

Filter material within the embankment models were geotextiles with the following hydraulic conductivity properties 4.2 x 10^{-3} m/s and 170 x 10^{-6} m for permeability (k_g) and pore size (O_{95W}), respectively. Given that the pore size of the geotextile filter material lies between 0.150 mm and 0.300 mm, it can be compared to a material with median grain size of more than 0.075 mm (d_{50} > 0.075 mm) and it would behave as a distinct drainage layer within the embankment. Furthermore, following the work done by Terzaghi and Pfletschinger on filter design criteria, noted by Fannin (2008), the filter should be 10 to 20 times more permeable than the soil. The geotextile material and the soil used in the experiments satisfies this criterion as shown in inequality equation (2).

$$k_g \geq 10k_s \ (4.2 \times 10^{-3} \ \geq \ 2 \times 10^{-3}), \tag{2}$$

where k_g is the permeability of the geotextile (m/s) and k_s is permeability of the base soil (m/s). It is important to acknowledge that the permeability of the geotextile in equation (2) reflects its measurement in isolation, which may not entirely reflect its behaviour when incorporated into the soil embankment. Further research is warranted to better understand its performance within the specific soil context of this study.

Figure 3 and Figure 4 represent the filters (fitted with a pore pressure relief drain) used for the experiments. The filters were 15 mm thick for both vertical and horizontal filters. The filter in Figure 3 was used in the experimental model with a vertical filter (chimney drain) and the filter shown in Figure 4 was used in the model with a horizontal and vertical filter (blanket and chimney drain).

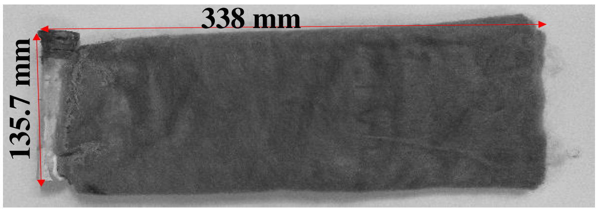

Figure 3. Vertical filter with a relief drain.

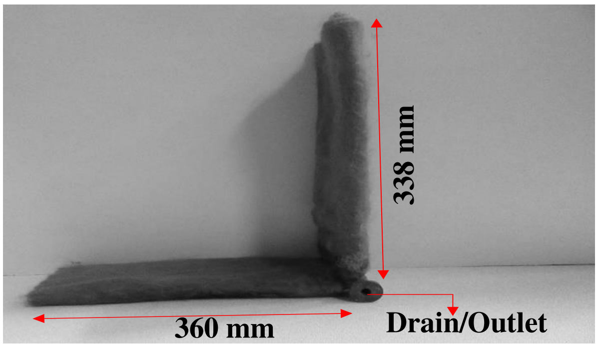

Figure 4. Drainage system consisting of horizontal, vertical filter and relief drain (outlet).

3.2 Physical model construction

Four homogeneous embankment models with identical dimensions but varying drainage conditions were constructed by means of a seepage and drainage tank filled with silica sand. Figure 1 depicts a generalized model, while the geometry of the embankment model is illustrated in Figure 5.

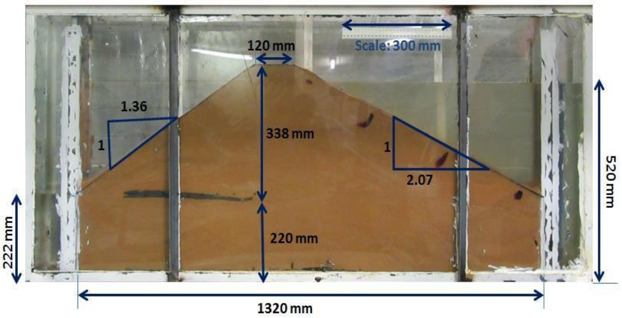

Figure 5. Illustration of the embankment model geometry.

The drainage and seepage tank was equipped with a pumping system ensuring a stable water level in the upstream side of the dam model. It is also worth noting that the soil used in the construction of the embankment models for all experiments was not recycled, this was done to retain consistency and avoid introducing any variability.

3.3 Numerical modelling

To ensure control of seepage, which is crucial for the safety and stability of embankments, an analysis can be carried out to gather information on embankment seepage estimates which can also provide some information on stability. This can be achieved through simulations in a GeoStudio tool, SEEP/W, which was used in this study. The purpose was to identify the phreatic surface, determine seepage direction and velocity, analyse pressure head and total head, as well as to evaluate pore water distribution under different drainage conditions during “normal” conditions. Each embankment underwent a steady-state analysis to establish a distinct steady-state seepage process across the embankment, while also examining how the flow is influenced by filter configuration.

Simulations and seepage calculations were conducted based on the saturated/unsaturated assumption and stable soil conditions. Moreover, different boundary conditions for the models were established, with the boundary condition set to a value of pressure equal to zero for the relief drain, while the residual water content and hydraulic conductivity for each material were set in accordance with Table 1.

Further assumptions comprised a liquid limit of 31.3%, a minimum matric suction set at 0 kPa (the software default), and an accepted maximum matric suction value set up to 1000 kPa.

Table 1. Settings and material parameters used in SEEP/W

	Hydraulic conductivity (m/s)	**Residual water content (m^3/m^3)**	**Estimation method**
Soil	2×10^{-4}	0.36	Van Genuchten
Filter	4.2×10^{-3}	0.45	Van Genuchten

4 RESULTS

Physical modelling findings, along with their respective simulation output from SEEP/W, are displayed in Figure 6 to Figure 9. The small dark arrows in the simulation output depict velocity vectors, and understanding these is crucial for interpreting the results presented in this work as seepage volumes/flux were of no importance, but how water flows in the embankment.

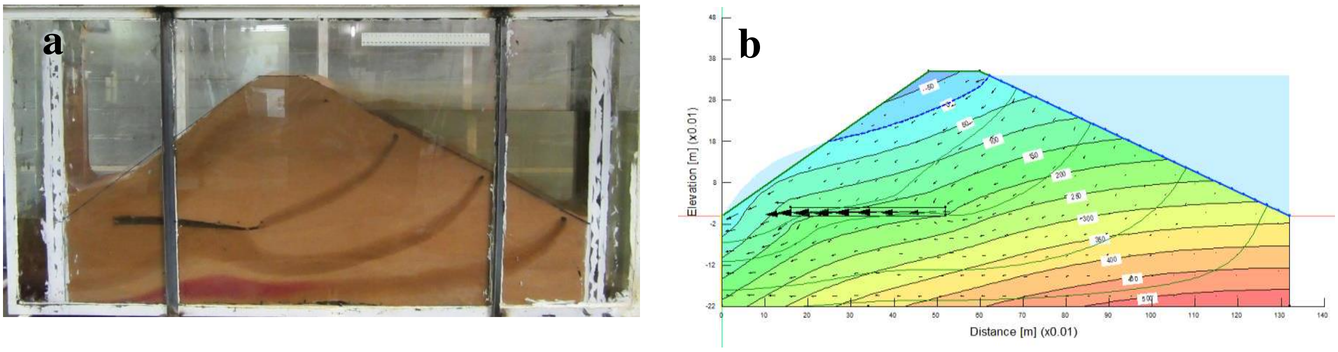

Figure 6. Physical model (a) and a numerical model (b) of an embankment with a horizontal filter (no relief drain).

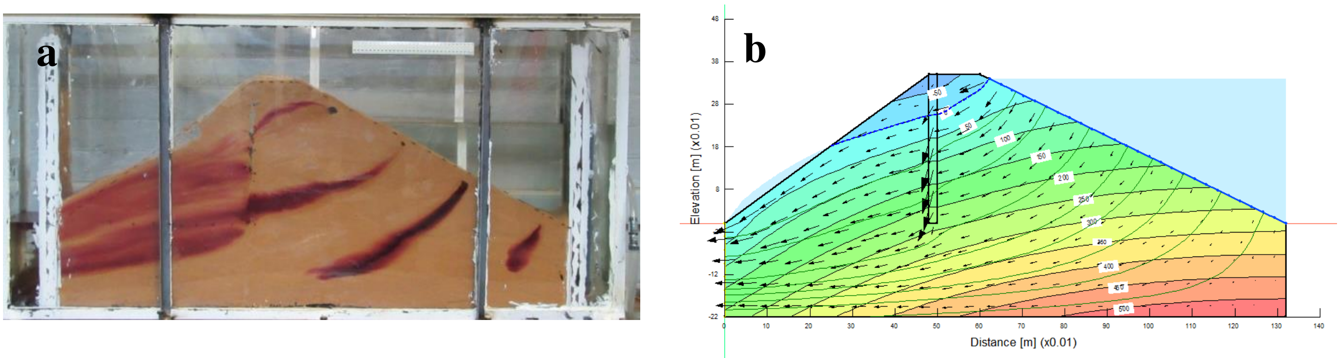

Figure 7. Physical model (a) and a numerical model (b) of an embankment with a vertical filter (no relief drain).

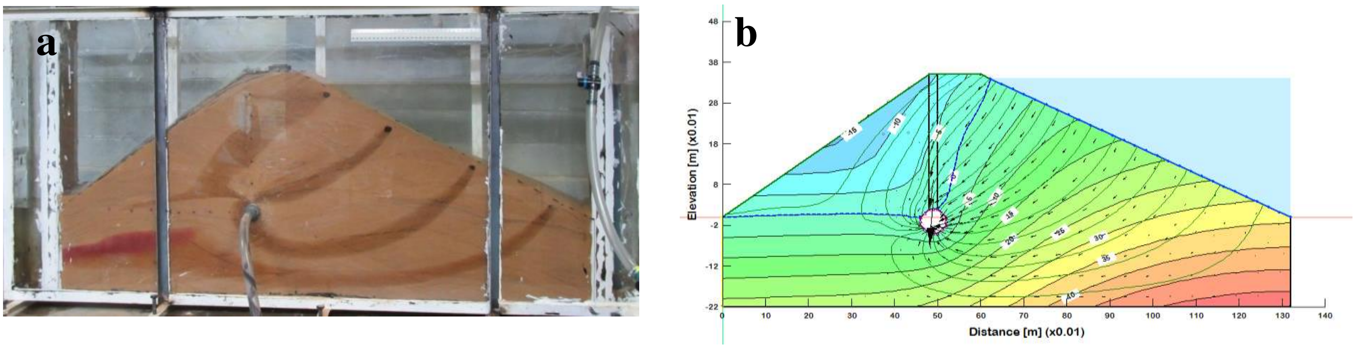

Figure 8. Physical model (a) and a numerical model (b) of an embankment with a vertical filter and a relief drain.

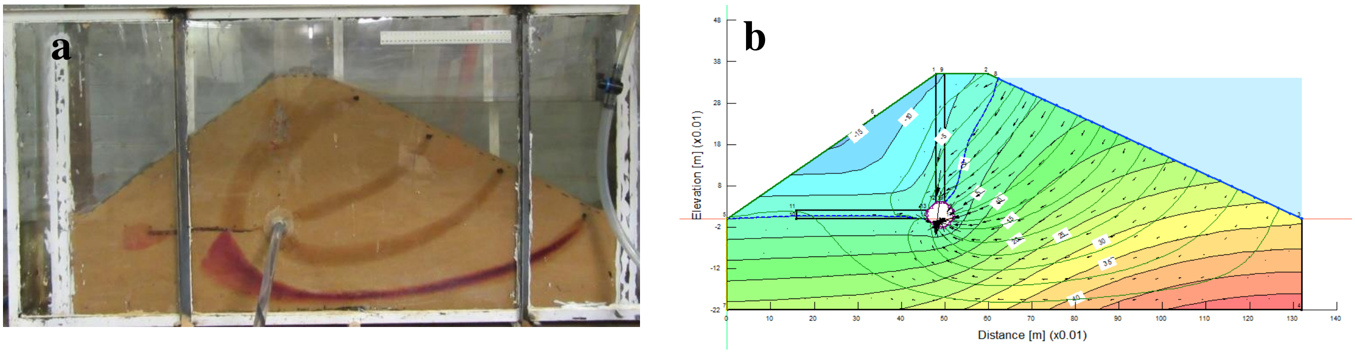

Figure 9. Physical model (a) and a numerical model (b) of an embankment with a horizontal, vertical filter and a relief drain.

5 DISCUSSIONS

The results presented offer insights into the effectiveness of different drainage conditions in maintaining the stability of embankment slopes. Several critical factors, including the relief drain (outlet), filter type, and its position, are critical in ensuring the stability of the embankment. While the physical and computer models in this study share the same dimensions, it is important to acknowledge that differences in modeling techniques and limitations may still influence the observed behavior of the drainage system. However, the discussion focuses primarily on the observed behaviours of the drainage systems and their implications on the embankment's stability without considering seepage volumes.

5.1 Physical modelling

The initial analysis, shown in Figure 6(a), evaluated the functionality of the blanket filter, which should theoretically prevent seepage surface formation on the slope but instead leads to undesired phreatic surface exit point in the downstream slope rather than at the dam toe. Majority of the seepage water within the embankment body bypasses the filter, leading to an increased risk of failure as downstream embankment slope degradation may occur, as observed by Stirling et al. (2021). Nevertheless, it appears that the filter is efficient in capturing seepage within the foundation.

In an attempt to address bypass issues in the initial model, the filter was positioned vertically, referred to as a chimney filter without an outlet pipe, depicted in Figure 7(a). Considering the upstream water level maintained at 300 mm from the foundation, the water head at the exit of the chimney drains would correspond to this elevation. The model exhibited chimney drain dysfunctionality, leading to downstream collapse due to filter saturation and pore pressure buildup. Based on the outcome, it was clear that a relief drain was required, and this underscores the importance of an effective drainage for maintaining embankment stability. It is also evident from the incomplete flow lines that the experiment was terminated prematurely due to a failure, suggesting the possibility of an even more significant failure.

Introducing a relief drain with a chimney filter, Figure 8, demonstrated improved drainage efficiency when addressing issues from previous attempts. It can be observed that the downstream slope was not compromised, but there are indications of seepage in the foundation. This could pose a significant issue if it is substantial, potentially leading to piping or foundation failure, as noted by Adamo et al. (2020a, 2020b). Therefore, the combination of blanket and chimney filter, along with a relief drain was explored (Figure 9). This design aimed to leverage the advantages of both drainage systems, mitigating potential drawbacks. The results showed favourable seepage conditions with both vertical and horizontal filters working together to control seepage in the embankment body and the foundation, respectively. The presence of the relief drain, positioned where both filters meet, also ensures an effective function for both filters.

5.2 Numerical modelling

The SEEP/W results confirmed the observations made on the physical models and provided additional insights into the phreatic surface and distribution of pore-water pressure. Similarities can be observed between Figure 6(b) and Figure 7(b), as well as Figure 8 and Figure 9. The incorporation of a relief drain within the models led to a significant alteration in the phreatic surface. With the phreatic surface lowered to exit the dam by the embankment toe in Figure 8(b) and Figure 9(b), this eliminated the issue in Figure 6 and Figure 7, where the development of a downstream seepage face is observed, resulting in a larger zone with negative pore-water pressure that prevented downstream collapse.

Furthermore, it is apparent that embankment models incorporating a relief drain exhibit lower pore-water pressure in comparison to those without. The type of filter (whether blanket or chimney) appears to have minimal impact on the phreatic surface when the filters are poorly designed, as indicated by Figure 6 and Figure 7. However, their effectiveness varies significantly in terms of mitigating the risk of failure. The presence and placement of relief drains appear to exert a notable influence on filter performance, especially when they are prone to clogging. While blanket and chimney filters lacking relief drains may contribute to instability, a vertical filter with an outlet pipe or a combination of blanket and chimney filters with a relief drain can improve stability by effectively draining seepage water and alleviating pore-water pressure within the embankment.

6 CONCLUSIONS

This work presented different embankment models with different drainage systems. While Sachpazis (2014) demonstrated that flow nets, despite not being rigorous, offer a method for predicting water flow quantities within an embankment or the ground, this work highlights how inadequate seepage control can lead to failure in the downstream of the embankment. The computer simulation yielded consistent results comparable to laboratory experiments, providing valuable insights for optimal drainage system design and a better understanding of seepage issues.

It was revealed through experimentation that effective seepage control is essential for embankments as complete avoidance of seepage is practically impossible; therefore, it is crucial for proper embankment design. The design of the filter should efficiently guide seepage water out of an embankment while minimizing risks associated with slope instability due to piping and other seepage-related problems. Moreover, findings suggest that a chimney drain equipped with a relief drain performs similarly to a blanket and chimney filter with a relief drain, thus making it potentially more cost-effective to opt for a chimney filter with a relief drain.

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