# FEM-Based Approach To Study The Impact Of Drainage On Hydraulic Behaviour Of Earth Dams

***[a] Qazi Umar Farooq*, [a] Muhammad Tayyab Naqash,***

a: Department of Civil Engineering, Islamic University of Madinah, Saudi Arabia
umar@iu.edu.sa; tayyab@iu.edu.sa;
* Corresponding author: Email ID: umar@iu.edu.sa

***Abstract-*** Small homogenous dams are an integral part of the water resource management system yet their failures are common and result in massive life and economic losses. Piping, uplift, and porewater pressure buildup, are the primary reasons behind the hydraulic failure of the dams. The dam drainage system is of great importance in the hydraulic stability of the retaining structure. In this paper, FEM-based analysis has been done to examine the effect of drainage material's geotechnical properties on the hydraulic behavior of homogenous small-scale earthen dams. The study results reflect the extent of variation in, pore water pressure, flow net patterns, and overall seepage velocity with changes in the toe drainage characteristics. With the selection of appropriate drainage material, more than 10-m of head loss has been reported at downstream. The results can be applied for the upgrading of hydraulic and geotechnical considerations for the design of homogenous dams.

***Keywords*-** Toe Filter, Porewater Pressure, Flow Nets, Hydraulic Conductivity

## 1 Introduction

This paper presents a part of ongoing research on small-scale dams at the Islamic University of Madinah. Water resource conservation and development are key global issues under changing climatic conditions. Water resource management has been targeted by various international, regional, and national future visions such as the kingdom of Saudi Arabia vision 2030, the middle east green initiative[1], and the national water vision of Pakistan. With an estimated population of 227 million by 2025, Pakistan's current water availability of less than 1100 cubic meters per person, down from 5000 cubic meters in 1951, classifies it as a "water-stressed" country that is headed towards becoming a "water-scarce" country if action is not taken urgently [2]. According to the records of the International Commission on Large Dams, there are approximately 150 dams in Pakistan. The majority of them are located in Punjab and Khyber Pakhtunkhwa (KPK), where the River Indus and its tributaries flow from the northern hilly areas to the southern regions of Sindh and fall into the Arabian Sea [3]. Most of these dams are homogeneous and are constructed from the middle of the 1960s to 1975. Earthen or concrete dams of reasonable height are common hydraulic structures built to impound water [4]. Since large dams require huge capital, special geological and geographic conditions, and environmental consequences[5] small scale dams will be the easiest solution for Pakistan's water problems.

Small dams still withstand a reasonable quantity of water; therefore, proper investigations of dams are required to prevent downstream devastation due to any failure. These failures can range from minor to catastrophic, impairing human life and property damage [6]. Piping failures in dams are pretty common; the mechanism of ''piping associated with heaving'' was introduced by Terzaghi [7]. Piping failures are attributed to the uncontrolled seepage or unsuitable zonation of materials and filters in earthen dams. Other causes of piping that lead to the failures in earth dams can be Hydraulic, Seepage, and Structural failures [8]. The unfamous 1976 incident of Teton dam failure in Idaho, USA was primarily due to the piping[9]. Another issue with the failure of dams is the dry-wet cycle which can cause cracks in the soil structure and destabilize the dam [10]. The piping and undesirable seepage can be effectively controlled by placing an appropriate dam drainage system. Various studies have been found in the literature on the design and implementation of dam drainage systems [11][12]. The FEM analysis has also been extensively used for the structural and dynamic stability of the embankments[13]. This study particularly focuses on the hydraulic behavior of the earthen dams while considering the material characteristics of the toe drainage system. The objective of this research is to highlight the effectiveness of different economically viable geomaterials in the toe drainage system.

## 2 Materials and Method

The hydraulic behavior of the dam system has been demonstrated by three different material components. The homogenous embankment, the dam foundation, and the targeted drainage systems. The dam drainage system's main component i.e., the toe filter has been modeled by using three different geomaterials. The geotechnical property of the filter varies in terms of porosity and permeability. The details of the material properties for all the dam components and the three tested filters are tabulated in Table 1.

*Table 1: Material properties of various dam components*

| Dam Component | | Geotechnical Properties | | |
|---|---|---|---|---|
| | | Dry Unit weight ($\gamma_d$) kN/m$^3$ | Porosity ($n$) % | Hydraulic Conductivity ($k$) m/s |
| **Embankment** | | 18 | 40 | $1x10^{-9}$ |
| **Foundation** | | 17.5 | 42 | $3x10^{-8}$ |
| **Toe Filter** | **TF-1** | 16 | 36 | $3x10^{-7}$ |
| | **TF-2** | 15 | 37 | $5x10^{-6}$ |
| | **TF-3** | 14 | 38 | $1x10^{-6}$ |

The FEM analysis for the dam model has been performed by a 2-D dam system. The geomechanics module of the COMSOL Multiphysics program has been used for the analysis. The model geometry with distinguished features is shown in Figure 1.

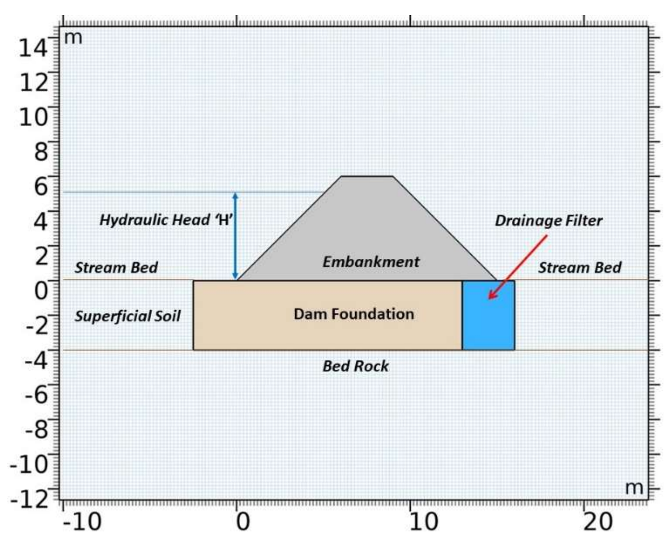
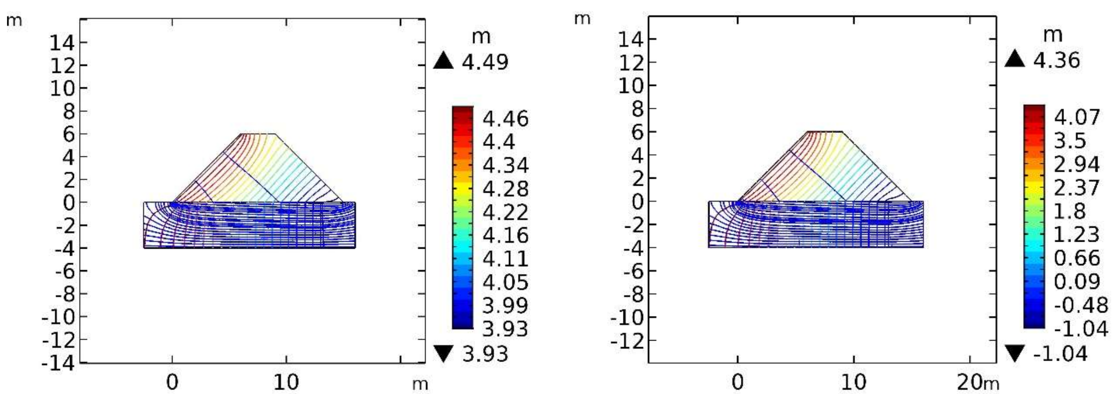



*Figure 1: Cross-section of the dam and boundary conditions*

The small-scale earth dam system comprises a homogeneous trapezoidal embankment. The main dam embankment has a 6-m long base with a 2-m wide crown, while the dam height is assumed as 6-m. Considering a 1-m freeboard the maximum hydraulic head that can be applied to the dam is 5-m. The dam system is overlaying on the bedrock with very low permeability. The foundation is 4-m deep and comprises the same soil as that of the main embankment, however, it is more porous than the embankment. The more porous foundation creates a longer seepage path and avoids the concentration of flow nets in the main dam body. The study cases are differentiated by the material properties of the toe drainage filter. Three drainage filters namely TF-1, TF-2, and TF-3 were considered in this analysis, where '*TF-1'* was the least permeable filter. The density, porosity, and hydraulic conductivity of the filters can be controlled by field compaction. In this study, the porosity of filters varies from 36 to 38 %, while the coefficient of permeability of the least permeable filter is three times less than the maximum one.

## 3 Results and Discussions

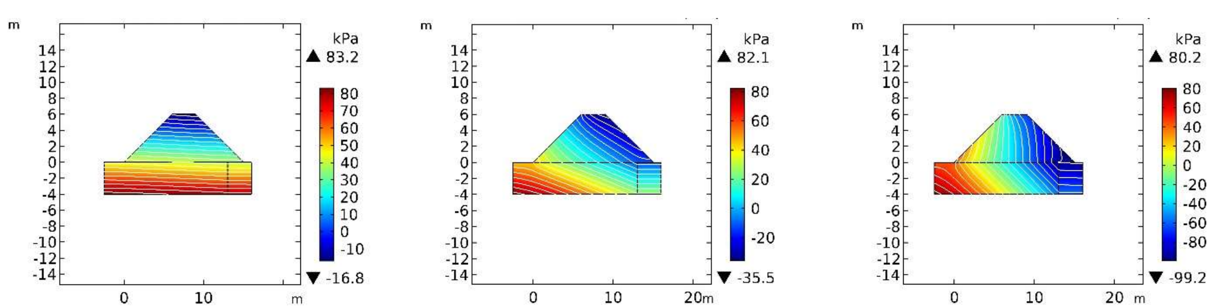
The FEM analysis presented in this section is based on Richard's equation for flow through porous media under partially saturated conditions. The flow nets for the dam system under the hydraulic head of 5-m at equilibrium with TF-1 and TF-2 filters are respectively shown in Figure 2a, and Figure 2b. The flow net pattern for both cases is quite similar with flow lines concentrated in a more permeable foundation and relatively high permeable drainage filter. Nevertheless, the hydraulic head at different dam sections is diverse in the two figures and more porous filter TF-2 has better head loss at downstream.




a) TF-1 b) TF-2

*Figure 2: Flow net patterns with different filters, the legend shows the hydraulic head.*

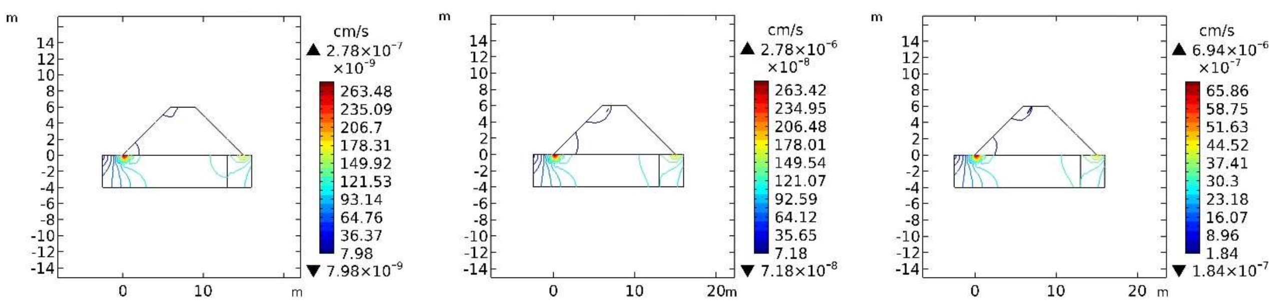
The effectiveness of the filter can be better reflected by comparing the water pressure diagram. The porewater pressure situation at equilibrium under the 5-m hydraulic head for the three filters is shown in Figure 3. The dam system with the least permeable TF-1 filter has a very limited partially saturated zone, near the dam crown, (Figure 3a). With an increase in drainage the partly saturated zone increases this can be seen in Figures 3a to 3c.




a) TF-1 b) TF-2 c) TF-3

*Figure 3 Pressure Distribution concerning Filter Properties*

The improved drainage also increases the seepage velocity across the dam sections which is not an encouraging indication. The seepage velocities for the three considered cases are compared in Figure 4. With drainage improvement the minimum and the maximum seepage velocities in the system increase. The widespread velocity lines with an increase in higher velocity red zone at the embankment foundation junction on the upstream side can be seen in the figure. The seepage velocities at some locations can reach the critical value and cause scoring which can lead to piping.




a) TF-1 b) TF-2 c) TF-3

*Figure 4: Net Seepage velocity (cm/s) Patterns*

The summary of the FEM analysis is presented in Figure 5. With the increase in outflow seepage velocity, the overall system head loss (*hl*) enhances almost exponentially, however, more data sets are required to establish an allowable range and an appropriate mathematical relation. The head loss reflects the pore pressure drop at various dam sections and hence an increase in hydraulic stability. However, the higher seepage velocities can lead to internal erosion and effects long-term stability therefore, a reasonable maximum allowable seepage velocity is required to be determined for each dam element. The maximum allowable seepage velocity through a porous media mostly depends on the critical hydraulic gradient, material porosity, and soil gradation.

The study results show that the drainage filter characteristics greatly affect the hydraulic stability of an embankment dam. The filter placement shall be strictly monitored during the construction. In situ compaction and permeability tests must be done at greater frequency and any misalignment with the filter design shall be referred to the geotechnical engineer.

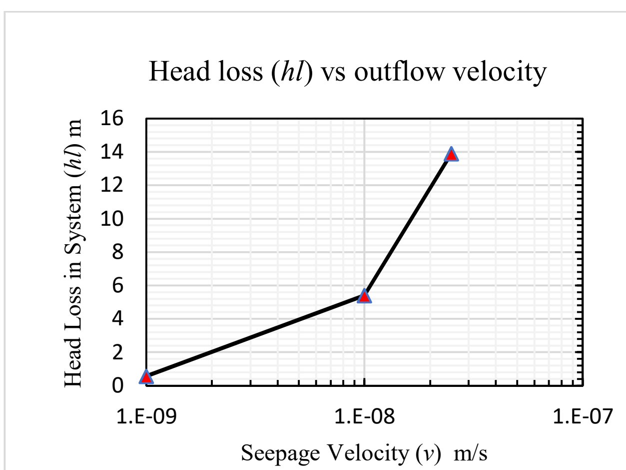



*Figure 5: Filter Drainage and Dam performance*

## 4 Conclusion

Richards's approach for partially saturated flow in soils can be utilized in FEM-based models to economically study the hydraulic behavior of small-scale homogeneous embankment dams. The study results can be concluded as follows:

1. The efficacy of the toe drainage is critical in terms of dam stability and can alter the pore water pressure distribution, and seepage velocity patterns in the dam system.
2. The increase in system outflow velocity remarkably decreases the water pressure at various dam sections however, it also results in higher seepage velocities which may lead to scoring. Therefore, an optimal solution is required for the specific site conditions and available materials.
3. The dam design engineers are encouraged to utilize FEM-based tools through industry-academia linkage for the optimal selection of design parameters and geomaterials.

## Acknowledgment

The authors would like to acknowledge the technical support and other facilities provided by the department of civil engineering, Islamic University of Madinah.

## References

[1] Q. U. Farooq, M. T. Naqash, and A. T. Ahmed, "Numerical Evaluation of Embedded Smart Irrigation System for Deep-Rooted Desert Trees," *Civil Engineering and Architecture*, vol. 10, no. 2, pp. 470–476, Mar. 2022, doi: 10.13189/cea.2022.100207.
[2] Planning Commission, "Pakistan Vision 2025," *Goverment of Pakistan*, 2014. .
[3] T. Hussain, A. Basit, and M. N. Javed, "Climate Change Effects on Water Resources and Need of Dams in Pakistan," *Global Mass Communication Review*, 2021, doi: 10.31703/gmcr.2021(vi-i).24.
[4] Y. Li, A. Chen, L. Wen, P. Bu, and K. Li, "Numerical simulation of non-cohesive homogeneous dam breaching due to overtopping considering the seepage effect," *European Journal of Environmental and Civil Engineering*. 2022, doi: 10.1080/19648189.2020.1744481.
[5] S.-Y. Han, S.-J. Kwak, and S.-H. Yoo, "Valuing environmental impacts of large dam construction in Korea: An application of choice experiments," *Environmental Impact Assessment Review*, vol. 28, no. 4–5, pp. 256–266, May 2008, doi: 10.1016/j.eiar.2007.07.001.
[6] J. D. Pisaniello, T. T. Dam, and J. L. Tingey-Holyoak, "International small dam safety assurance policy benchmarks to avoid dam failure flood disasters in developing countries," *Journal of Hydrology*, vol. 531, pp. 1141–1153, Dec. 2015, doi: 10.1016/j.jhydrol.2015.09.077.
[7] K. Terzaghi, *Theoretical Soil Mechanics*. 1943.
[8] I. Singh Saluja ZHCET, A. Mohammad Athar ZHCET, and A. A. Sarfaraz Ansari ZHCET, "Causes of Failure of Earthen Dams and Suggested Remedial Measures," *Prof. Sarfaraz A. Ansari International Journal of Computer & Mathematical Sciences IJCMS*, 2018.
[9] "Teton Dam failure - at last the complete story.," *CONSTR. NEWS*, no. 5501, Mar. 10, 1977. 1977.
[10] W. Ye and F. H. Ma, "Study on the effect of dry-wet cycle on the dam slope stability," *MATEC Web of Conferences*, 2019, doi: 10.1051/matecconf/201927201050.
[11] M. M. Aboelela, "Control of Seepage through Earth Dams Based on Pervious Foundation Using Toe Drainage Systems," *Journal of Water Resource and Protection*, vol. 08, no. 12, pp. 1158–1174, 2016, doi: 10.4236/jwarp.2016.812090.
[12] A. Pak and M. Nabipour, "Numerical Study of the Effects of Drainage Systems on Saturated/Unsaturated Seepage and Stability of Tailings Dams," *Mine Water and the Environment*, vol. 36, no. 3, 2017, doi: 10.1007/s10230-017-0468-y.
[13] K. Fuławka, A. Kwietniak, V. Lay, and I. Jaśkiewicz-Proć, "Importance of seismic wave frequency in FEM-based dynamic stress and displacement calculations of the earth slope," *Studia Geotechnica et Mechanica*, vol. 44, no. 1, 2022, doi: 10.2478/sgem-2022-0002.