Agri Articles
(e-Magazine for Agricultural Articles)
Volume: 04, Issue: 04 (JULY-AUG, 2024)
Available online at http://www.agriarticles.com
©Agri Articles, ISSN: 2582-9882

Seepage Analysis in Earthen Dams: A Finite Element Approach

(*Engr. Imran Arshad)
Agriculture Engineer, SAA Technical and Specialized Services Establishment – (ADAFSA Project), Ghayathi, Abu Dhabi, United Arab Emirates
*Corresponding Author's email: engr_imran1985@yahoo.com

Abstract
This study utilized SEEP/W software to analyze the seepage behavior of the Hub Dam at a pond level of 339 feet, comparing scenarios with and without a cut-off wall. The results showed that the cut-off wall effectively mitigates seepage issues by reducing the speed of flow vectors, minimizing seepage flux (5.6064 x 10^{-4} ft³/sec/ft), and lowering the exit gradient (0.188), thereby enhancing dam stability. In contrast, the absence of the cut-off wall led to higher seepage flux (3.2517 x 10^{-3} ft³/sec/ft) and exit gradient (0.691), indicating increased risk of internal erosion and potential dam failure. The findings underscore the critical role of cut-off walls in improving dam safety by controlling seepage and internal pore water pressure.

Keywords: Non-Homogeneous Dam, Seepage Flux, Exit Gradient, Phreatic Line, SEEP/W, Geo-Slope Software.

Introduction
Most dams experience some level of seepage. Even if a dam looks stable, seepage can cause internal damage. If the seepage rate increases and the water is not clear but carries soil particles, it likely means internal erosion or piping is happening (Moayed et al., 2012). This issue usually occurs because of the difference in water pressure between the upstream and downstream sides. Water finds its way through soil pores or rock cracks, eroding fine soil particles and causing piping within the dam (Baghalian et al., 2012). The amount of water seeping through and under a dam, along with the pore water pressure distribution, can be analyzed using the theory of flow through porous media (Arshad et al., 2014). Knowing the amount of seepage helps estimate water loss from the reservoir, and the distribution of pore water pressure helps identify the hydraulic gradient trend (phreatic line) at the seepage discharge point (Al-Damluji et al., 2004). The phreatic line inside the dam is the boundary where the pressure changes from negative above the line to positive below it.

It is important to determine the phreatic line trend because it shows the division between dry and wet soil. The phreatic surface should be at or below the downstream toe to prevent piping and control the exit gradient. Properly designing a dam with a filter drain helps control the phreatic line, keeping it near the upstream side. The filter stops fine particles from entering the drain while allowing excess water to be removed, thus controlling pore water pressure within the dam (Garg, 2006). Today, engineers use the finite element method (FEM) to analyze the behavior of complex structures before building them, ensuring their stability and durability (Arshad et al., 2017). In this research, the FEM technique was used to study a non-homogeneous section of the Hub dam. The study compared two scenarios: (i) with a cut-off wall and (ii) without a cut-off wall, and examined the differences in seepage flux and exit gradient for each scenario.

Overview of the Hub Dam

The Hub Dam, located 35 km northwest of Karachi, is a rolled earth-fill structure standing 156 feet high with a crest length of 15,640 feet. The dam's top elevation is 352 feet, featuring a 28.66-foot-wide crest and a 26.5-foot-wide road. The reservoir, nestled between the Kirthar and Pub mountain ranges, covers 24,939 acres (38.96 square miles) at its maximum water level of 346 feet, with a gross storage capacity of 857,000 acre-feet. The minimum operational level is 270 feet, providing 760,000 acre-feet of live storage and 97,000 acre-feet of dead storage. The annual allocated supply is 193,000 acre-feet (Arshad et al., 2014).

The upstream face has two berms at elevations 270 and 318 feet. The slope varies from 4.5:1 up to 270 feet, 3:1 up to 318 feet, 2.5:1 up to 342 feet, and 2:1 up to 352 feet. The downstream face slopes 2:1 from the crest to 318 feet, 2.5:1 to the berm at 270 feet, and 3:1 below that. Slope protection consists of river sand and gravel. The dam features a zoned earth-fill section in the river portion with a central impervious core and pervious fill on both sides, while the flanks have a semi-impervious section. Downstream embankment drains are located at the toe parallel to the dam axis (WAPDA, 2009). This study focuses on the non-homogenous zoned embankment section with a 28.5-foot-wide cut-off wall at chainage 56+00, with a foundation at elevation 220 feet and a crest at 352 feet.

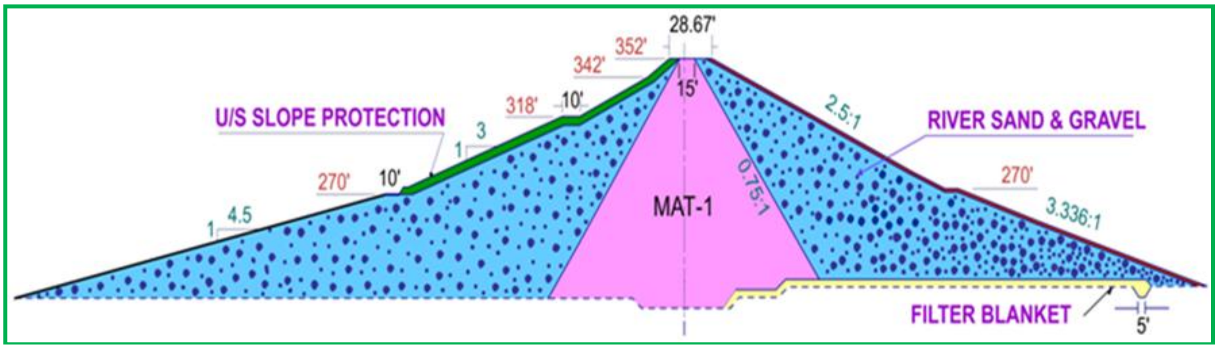

Fig 1. Geometry of Non-Homogeneous Section.

Model Development and Verification

To develop the FEM mesh for a non-homogeneous section of the Hub Dam, SEEP/W was used. The drawing units and scale were set in imperial units. Based on coordinates from AutoCAD, the model was sketched, and the domain was created with distinct colors for the dam foundation, shell, core, and filter (toe drain) (Nasim, 2007). Material properties were calibrated and applied using the key-In command, with hydraulic conductivities adjusted through trial and error using observed hydraulic heads as a reference (Table 1). Boundary conditions were assigned similarly, with a Dirichlet boundary on the upstream face, a Neumann boundary on the downstream face, and zero pressure on the toe drain (Arshad et al., 2017).

The final FEM mesh was verified, analyzed, and solved using the solve manager option to compute seepage flux, exit gradient, and phreatic line trends for various water levels. For verification, Geo-Slope software (SEEP/W) was used to develop cross-sections for two cases: (i) with a cut-off wall and (ii) without a cut-off wall. The mesh elements included triangular, square, rectangular, and trapezoidal shapes (Arshad et al., 2015). The mesh for case (i) had 2,512 nodes and 2,489 elements, while case (ii) had 2,421 nodes and 2,403 elements. Computations were performed for maximum (346 ft), minimum (270 ft), and normal pond levels (339 ft). Figures 2a and 2b illustrate the mesh formation for both cases.

Table 1. Guess and Calibrated Values of Material Properties for Non-Homogeneous Section

S. No	Material type	Hydraulic conductivity (ft/sec)	
		* Guess Values	Calibrated Values
01	Foundation	10^{-4} to 10^{-6}	3.000×10^{-6}
02	Shell	10^{-5} to 10^{-6}	2.385×10^{-5}
03	Core	10^{-8} to 10^{-7}	2.000×10^{-8}
04	Filter Drain	10^{-2}	3.280×10^{-2}

* Source: WAPDA

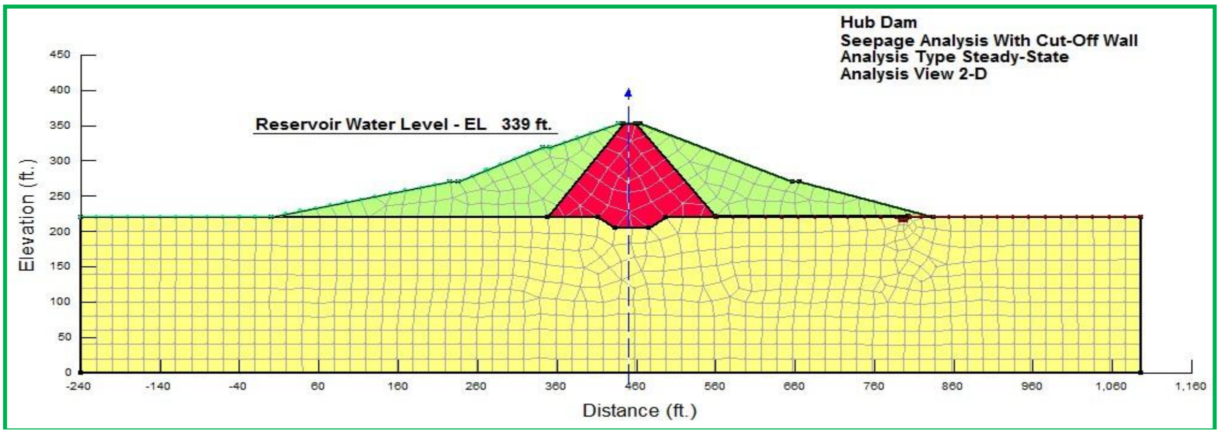

Fig. 2a. Mesh formation for non-homogeneous section with cut-off wall

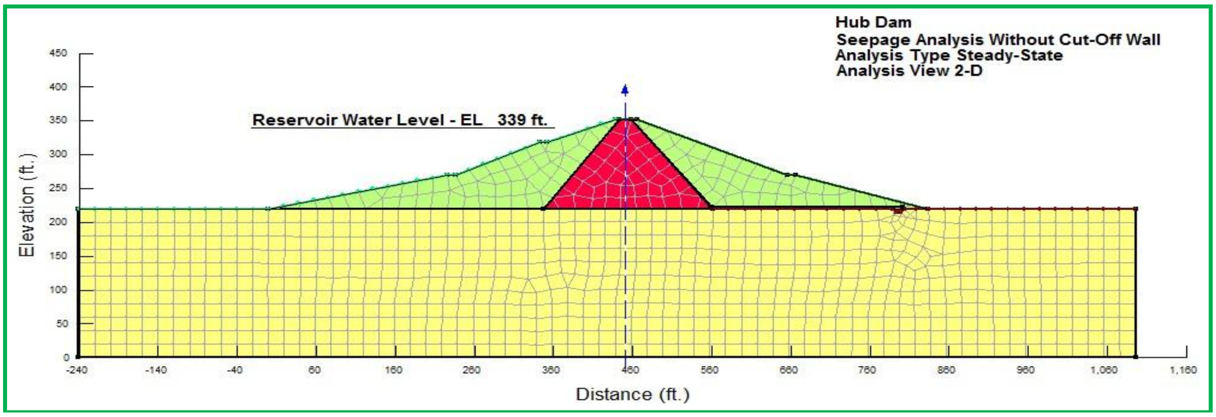

Fig. 2b. Mesh Formation for Non-Homogeneous Section without cut-off wall

Finite Element Analysis of Seepage at Pond Level 339 ft

The SEEP/W software was used to evaluate the seepage characteristics of the Hub Dam at a pond level of 339 feet for two scenarios: (i) with a cut-off wall and (ii) without a cut-off wall.

1. **With Cut-Off Wall:** At this pond level, the cut-off wall effectively mitigates seepage issues. Flow lines and equipotential lines are well-aligned, indicating stable flow conditions. The flow vectors are relatively slower and more controlled, moving steadily towards the filter drain. The seepage flux is 5.6064×10^{-4} ft³/sec/ft (57.152 LPH), and the exit gradient at the downstream toe is 0.188. The cut-off wall's presence reduces the speed of velocity vectors, thereby minimizing the internal pore water pressure and controlling the movement of seepage flow. The phreatic line within the dam shows a consistent trend, staying well within safe limits, which helps in preventing potential erosion. Figures 3a – 3c illustrate the behavior of the dam with cut-off wall.

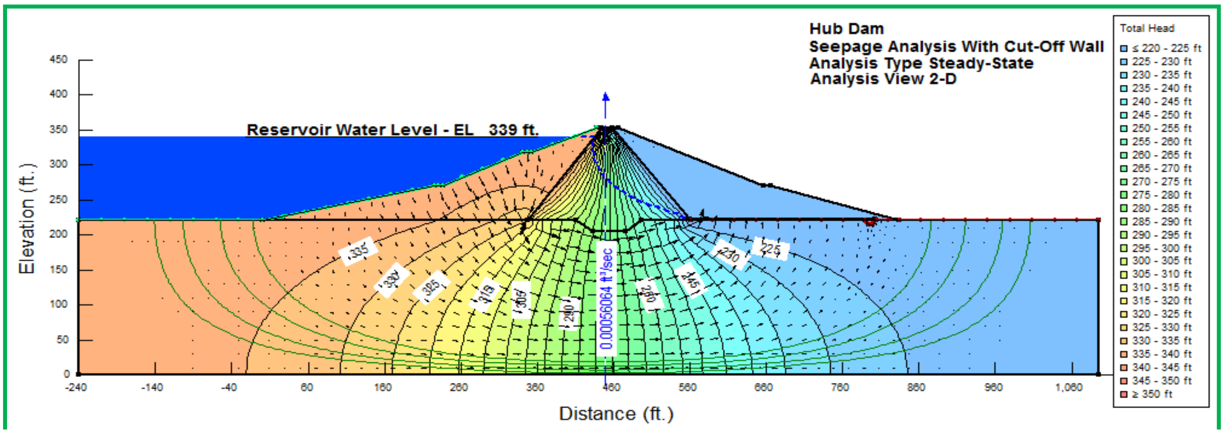

Fig. 3a. Flow-net for Non-Homogeneous Section with Cut-off Wall (Pond level = 339 ft)

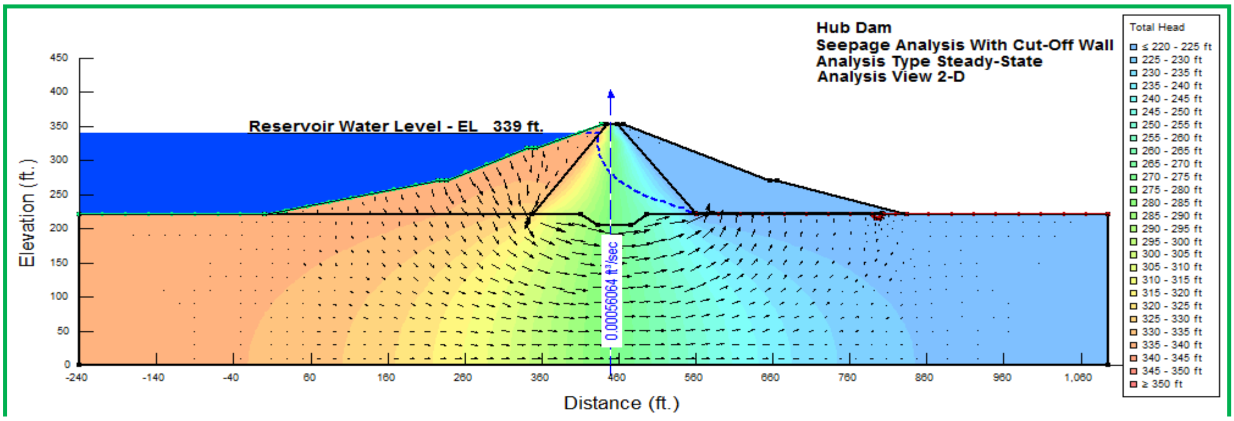

Fig. 3b. Flow Vectors for Non-Homogeneous Section with Cut-off Wall (Pond level = 339 ft)

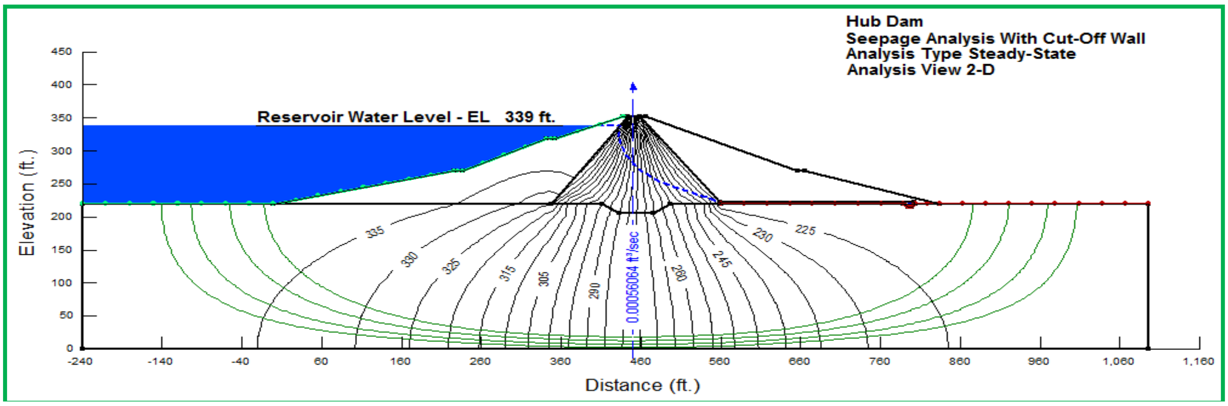

Fig. 3c. Phreatic Line Behaviour for Non-Homogeneous Section with Cut-off Wall (Pond level = 339 ft)

2. **Without Cut-Off Wall:** In contrast, the absence of a cut-off wall at the same pond level results in noticeably different seepage behavior. Flow lines and equipotential lines are misaligned, suggesting irregular seepage patterns. The flow vectors exhibit higher velocities and are less controlled, leading to an increased risk of internal erosion. The seepage flux is significantly higher at 3.2517 x 10^{-3} ft³/sec/ft (359.004 LPH), and the exit gradient reaches 0.691. The absence of the cut-off wall leads to a higher speed of velocity vectors, which increases the pore water pressure and can potentially compromise the dam's stability. The phreatic line shows a more erratic behavior, indicating a higher risk of seepage-related issues. Figures 4a – 4c illustrate the behavior of the dam without cut-off wall.

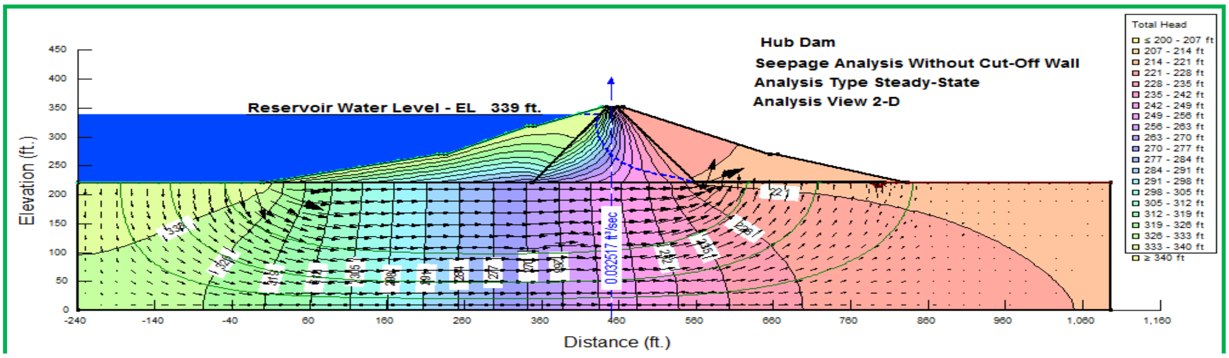

Fig. 4a. Flow-net for Non-Homogeneous Section with Cut-off Wall (Pond level = 339 ft)

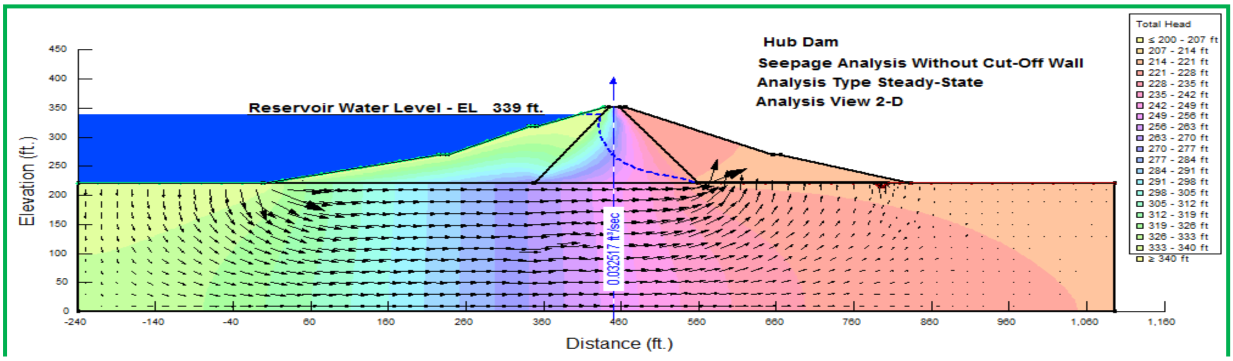

Fig. 4b. Flow Vectors for Non-Homogeneous Section with Cut-off Wall (Pond level = 339 ft)

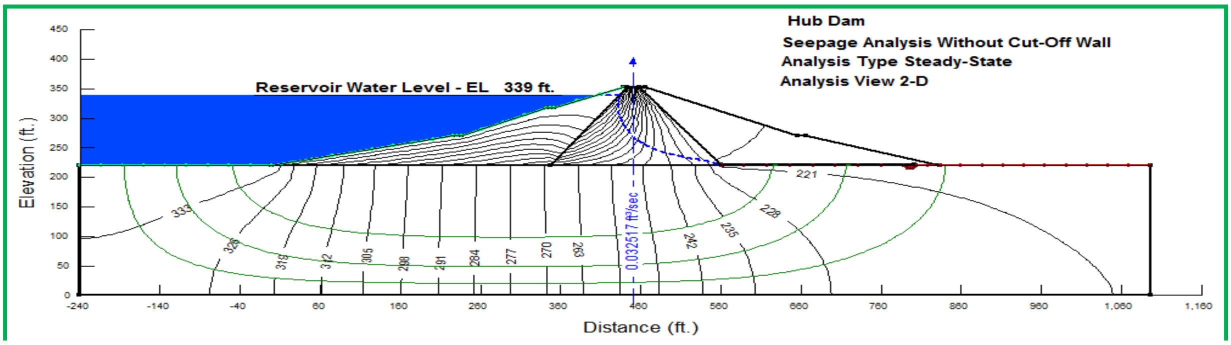

Fig. 4c. Phreatic Line Behaviour for Non-Homogeneous Section without Cut-off Wall (Pond level = 339 ft)

Conclusion

In conclusion, the analysis using SEEP/W software for the Hub Dam revealed that while the dam is generally safe from piping in both scenarios, the absence of a cut-off wall results in increased seepage flux and a higher risk of failure during extreme flood events. The presence of a cut-off wall significantly reduces seepage flux and exit gradients by lowering internal pore water pressure, thereby improving the dam's stability and safety.

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