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***Corresponding Author:**
Imran Arshad

Email:
engr_imran1985@yahoo.com

Finite Element Analysis of Seepage and Exit Gradient through a Homogeneous Earth Dam without Cut-Off Walls and Filter Drain by using Geo-Slope (SEEP/W) Software

Imran Arshad[1*], Muhammed Muneer Babar[2]

[1]SAA Technical & Specialized Services Establishment, Abu Dhabi, United Arab Emirates.
[2]Institute of Water Resources Engineering & Management (USPCASW), MUET, Sindh, Pakistan.

Abstract:
All dams experience seepage to some degree. While the dam experiencing seepage may appear in sound condition there may be damage occurring to the internal structure of the dam. A key factor to stability is the location of the phreatic line or the fully saturated zone of the soils within the embankment. In safe dams, this level is well confined below the surface. Since soils that are fully saturated are not as strong a higher phreatic line can reduce the ability of the embankment to resist sliding. This is often noted by seepage exiting on the downstream face of the dam. Weak or poorly compacted soils can increase both seepage and the phreatic level as well as weaken the embankment contributing to a sliding failure of the dam. In this study, a homogeneous section of an earthen dam (Hub dam) with and without cut-off wall and filter drain was analyzed by using FEM based software SEEP/W. The FEM model was run to compute the behavior of the dam in terms of seepage flux and exit gradient for three different scenarios i.e. maximum (346 ft), minimum (270 ft), and normal pool level (339 ft) respectively. The simulated results for case (i) with cut-off wall and filter drain showed that the dam is safe against piping, at its original design with overall minimum seepage flux of (2.513 x 10^{-4} ft^3/sec/ft) and exit gradient (0.351) at downstream toe respectively. However, for case (ii) without cut-off wall and filter drain, the dam showed abnormal behavior as overall extremely high exit gradient (3.112) along with the maximum overall seepage flux of order 165.81 x 10^{-4} ft^3/sec/ft respectively. The comparison showed that seepage flux (90.176% – 97.611%) and exit gradient (78.880% – 83.386%) through the dam and its foundation was found more when there are no cut-off wall and filter drain. Which is the result of continuous movement of the water within the dam especially in the foundation, as there is no any barrier installed to control internal pore water pressure, due to which the water seeping from the upstream and foundation finds its way moving towards the downstream and cuts the toe to make its way out respectively.
Keywords: Homogeneous Dam, Cut-Off Wall, Filter Drain, Seepage Flux, Exit Gradient, Phreatic Line, SEEP/W, Geo-Slope Software.

INTRODUCTION

One of the most serious dam safety concerns is the stability of the earthen embankment. Unsafe conditions could lead to a major slide that threatens the safety of the dam. Excessive seepage in any type of dam is one of the basic root causes to destabilize the dam structure and thereby bring economic havoc (Baghalian *et al.,* 2012). This mainly happens due to the potential head difference between the upstream face and downstream face, as water through soil pores or rock fissures finds its way by eroding the fine soil particles and cause piping within the dam. The amount of water seeps through and under the foundation of a dam, along with the distribution of pore water pressure, can be analyzed by using a theory of flow through a porous medium (Arshad *et al.,* 2018). The computed amount of seepage is useful in estimating the loss of water from the reservoir, while the pore water pressure distribution gives a rough idea to observe a trend of the hydraulic gradient (phreatic line) at a point of seepage discharge respectively (Al-Damluji *et al.,* 2004). The phreatic line within the dam body is the line having negative hydrostatic pressure above the line and positive hydrostatic pressure below the line respectively (Moayed *et al.,* 2012).

It is necessary to find out the trend of the phreatic line as it will allow us to recognize a divider line between dry and submerged soil (Doherty, 2009). The trend of the phreatic line can be well controlled by designing a dam with proper barriers (cut-off walls) and filter drain. The purpose of the filter drain is to restrict the phreatic line almost to the upstream side of the dam while the roll of the cut-off wall is to control the trend of seeping water in its foundation. The filter prevents passing of fine particles into the drain, while the drain allows the removal of a surplus amount of internal water to control pore water pressure within the dam body respectively (Garg, 2006). Nowadays, before the implementation of a mega structural work, FEM is used to analyze the behavior of complex structures, as it will give an idea to an engineer about its stability and durability (Arshad *et al.,* 2017a). In this research work, a homogeneous earth dam without a cut-off wall was analyzed by using FEM technique and the results for seepage flux and exit gradient for different scenarios have been compared respectively.

MATERIALS AND METHODS

Study Model (Hub Dam)

The model used in this research study is Hub dam which is a rolled earth-fill structure 156 ft high over the deepest foundation, with a crest length of 15,640 ft. It is located at about 35 km, northwest of Karachi city. The top of the dam at elevation 352 ft is 28.66 ft wide width 26.5 ft clears width of road exclusive of the parapet wall. The reservoir occupies a broad undulating valley between the western slopes of Kirthar and eastern slopes of Pub ranges of mountains which narrows down in the upstream direction. The water spread area of the reservoir surface is 24,939 acres or 38.96 square miles at maximum water level which has been fixed at elevation 346. Gross storage at full reservoir level EL 346 will be 857,000 acre-feet of water. The minimum operational level, at the sluice, inverts EL 270 ft, established by the relative levels of the irrigable command area and design of the main canal, corresponds to 760,000 acre-feet of the live storage and 97,000 acre-feet of dead storage. The allocated annual supplies from the reservoir have been fixed as 193,000 acre-feet of water, thereby the reservoir will provide for a large carry-over capacity amounting to more than 3 years of supplies.

The upstream face of the dam has 2 berms each 10 ft wide at EL 270 and 318 ft respectively. The slope varies from 4.5 to 1 up to elevation EL 270 ft, 3 to 1 between elevations EL 270 and 318 ft, 2.5 to 1 between elevation 318 to 342 ft, and 2 to 1 between elevations 342 to 352 ft at the top of the dam (Arshad *et al.,* 2019b). The downstream face of the dam from its crest elevation EL 352 ft down to elevation EL 318 ft is sloped 2 to 1, from the flattening to 2.5 to 1 down to berm at elevation EL 270, thereafter the slope has been kept as 3 to 1 respectively. Slope protection consists of random fill of river run sand and gravel. The dam has a zoned earthfill section in the river portion consisting of a central core of impervious material with pervious fill on either side. On both flanks of the river, the dam has a homogenous semi-impervious section. Embankment drains at the downstream termination of the horizontal filter blanket (filter drain) are located at the toe running parallel to the dam axis (WAPDA, 2009).

Steps for Modeling of Hub Dam

In this research study a homogenous section of a Hub dam with foundation level (EL 250 ft), and the crest level (EL 352 ft) was selected respectively. Initially, by using SEEP/W the FEM mesh for a homogenous section was generated and the upstream and downstream boundary conditions are assigned as Dirichlet and Neumann boundary nodes respectively (Arshad *et al.,* 2019a). The domain is discretized into a mesh by 12,346 elements through placement of nodal points 12,495 (Arshad *et al.,* 2014a). After assigning the boundary conditions the flux section in the middle of the dam and material properties were assigned respectively. The material properties were calibrated by using trial and error method by applying the identical guess values of hydraulic conductivities for all the materials used in the section then assigned (Table 1). Finally, the numerical model is verified by the software and computation of seepage flux, exit gradient and phreatic line trend for three different scenarios of water levels i.e. maximum (346 ft), minimum (270 ft), and normal pool level (339 ft) is carried out accordingly. The dimensions of the selected homogenous cross-section and typical mesh formation were elaborated in Figure 1 and Figure 2 respectively.

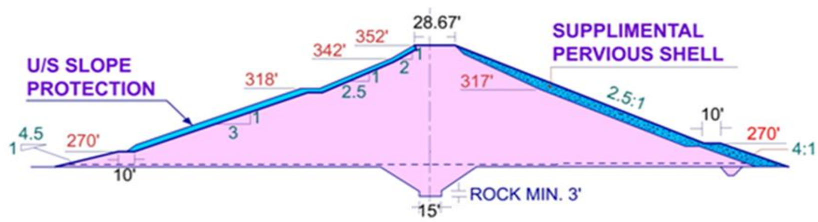

Fig. 1. The geometry of the Homogeneous Section.

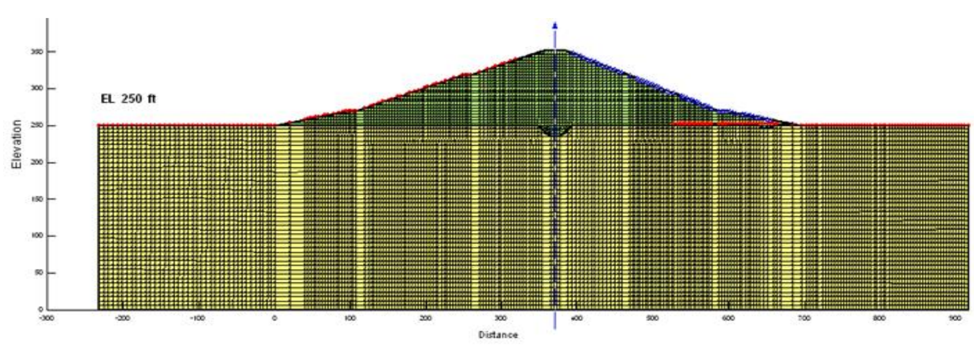

Fig. 2. Typical Mesh formation for homogeneous section.

International Journal of
Alternative Fuels and Energy
2020; 4(2): 20-28

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

S. No.	Material type	Hydraulic conductivity (ft/sec)	
		* Guess Values	Calibrated Values
1	Foundation	10^{-4} to 10^{-6}	3.225×10^{-6}
2	Shell	10^{-5} to 10^{-6}	2.000×10^{-5}
3	Filter Drain	10^{-2}	3.280×10^{-2}

* Source: WAPDA

RESULTS AND DISCUSSION

The sub-program of Geo-Slope software i.e. (SEEP/W) was used to compute the behavior of seepage flux and exit gradient for two different cases i.e. (i) with cut-off wall and filter drain (ii) without cut-off wall and filter drain; through a homogenous section of the dam and its foundation respectively. The seepage and exit gradient were computed at three different pond level scenarios i.e. maximum, minimum, and normal pond level respectively (Arshad *et al.,* 2014b). The SEEP/W software gives output in terms of flow-net which comprises streamlines, equipotential lines, velocity vectors showing dominant flow (seepage) field, and phreatic line depicting seepage behavior of the earth dam. The results revealed that the presence of cut-off wall and filter drain has a positive effect on the seepage and exit gradient. The main function of the cut-off wall and filter drain installation is to control the seepage velocity moving towards the toe drain and to prevent the passage of fine particles into the drainage conduit respectively. Therefore, the chances of higher exit gradient and phreatic line to cut the downstream slope face of the dam become minimum and controllable. The behavior of the cut-off wall and filter drain presence for both cases at different pond levels elaborated respectively in (Figure 3a – Figure 5b).

It is evident from Figure 3a that at minimum pond level the presence of the cut-off wall and filter drain has a direct effect on controlling seepage flux with an order of 2.513×10^{-4} ft^3/sec/ft and exit gradient at the downstream toe 0.351 respectively. Figure 3b showed some different behavior of where there was no cut-off wall and filter drain installed. The velocity vector comes out from the foundation at toe region of the dam with seepage flux of order 25.580×10^{-4} ft^3/sec/ft respectively. Furthermore, due to unavailability of the cut-off wall and filter drain, the high exit gradient of 1.662 was noted which may adversely affect the behavior of the dam. These results are according to the findings of (Aasma, 2015), who also computed the seepage flux and exit gradient through an earthen dam without a cut-off wall and filter drain using Geo-Slope software.

Likewise, Figure 4a at a normal pond level showed a regular movement of pore water as the phreatic line is dropping into the filter drain, and the velocity vectors also following the trend of the phreatic line. The velocity of the seeping water on the foundation of the dam was found controllable having seepage flux of order 3.571×10^{-4} ft^3/sec/ft and exit gradient at the downstream toe 0.414 respectively. The trend of streamlines and equipotential lines were found normal which conforms; the seepage theory.

Figure 4b showed an abnormal behaviour of phreatic line at normal pond level without cut-off wall and filter drain as the simulated result indicated that the phreatic line cuts the downstream slope of the dam at a distance of 532.32 ft and an elevation 299.19 ft due to which dam may suffer from a slope failure. Furthermore, due to excessive pore water movement and pressure within the dam and its foundation, an exit gradient at the downstream toe of order 2.225 was observed; which is beyond the permissible limit with seepage flux 142.82×10^{-4} ft^3/sec/ft respectively. Therefore, we can consider that a homogenous dam without cut-off wall and filter drain is not safe against piping as there is a possibility of internal erosion due to seepage. Similar results were reported by (Osuji *et al.,* 2015), who also computed the seepage flux and exit gradient for the case of Jebba dam with and without cut-off and filter drainage system within the dam.

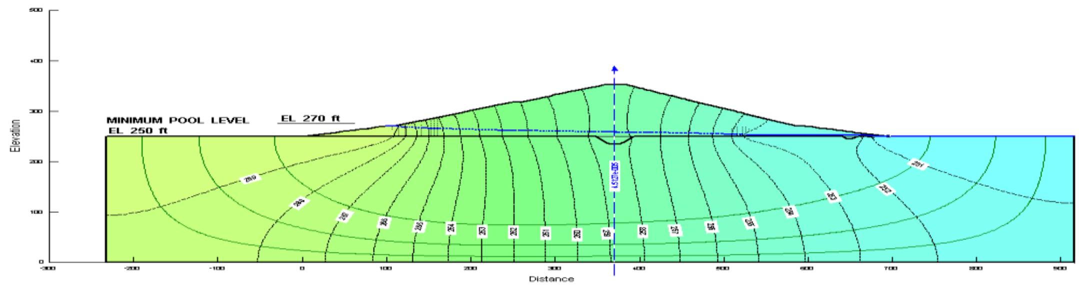

Fig. 3a. Flow-net for Homogeneous Section with Cut-Off Wall and Filter Drain (Pond level = 270 ft).

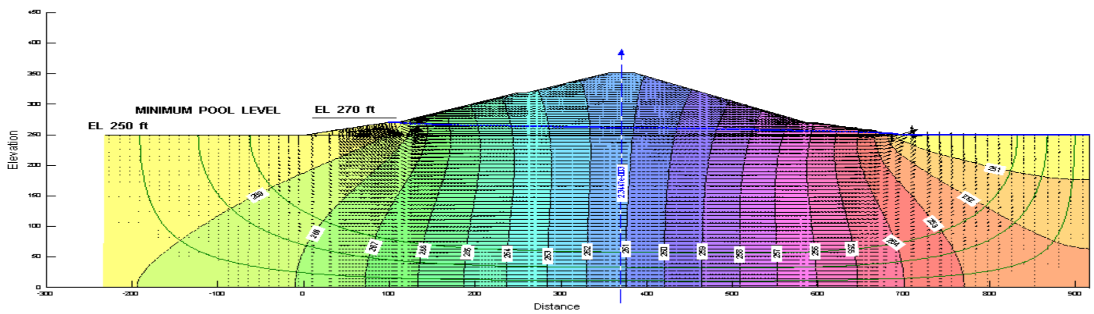

Fig. 3b. Flow-net for Homogeneous Section without Cut-Off Wall and Filter Drain (Pond level = 270 ft).

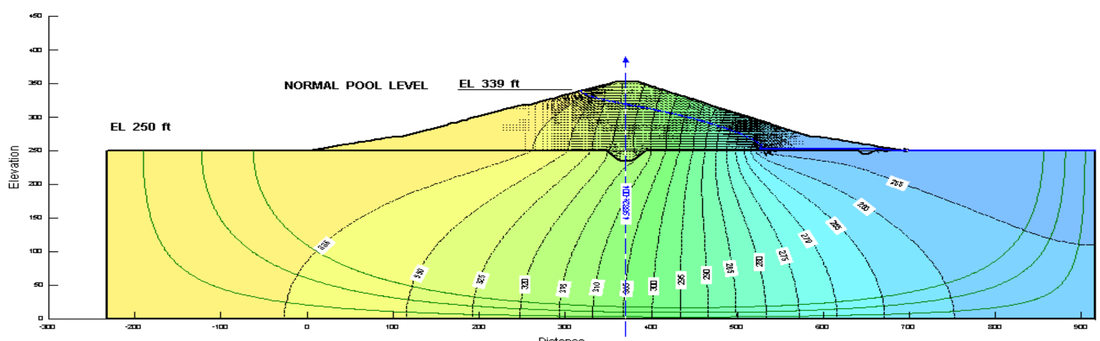

Fig. 4a. Flow-net for Homogeneous Section with Cut-Off Wall and Filter Drain (Pond level = 339 ft).

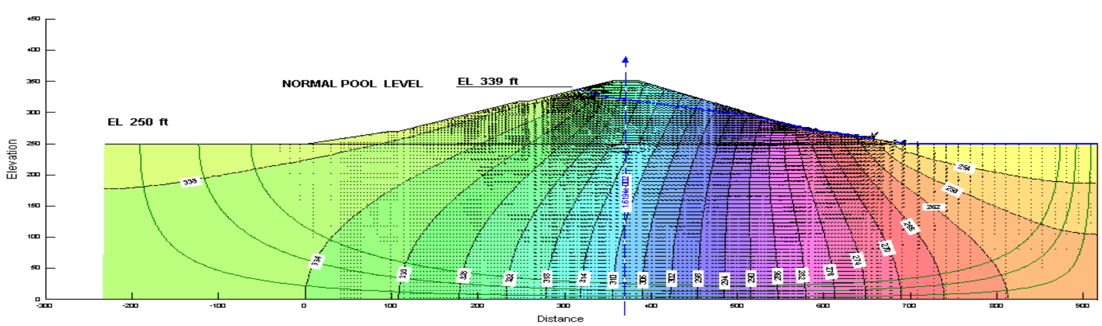

Fig. 4b. Flow-net for Homogeneous Section without Cut-Off Wall and Filter Drain (Pond level = 339 ft)

International Journal of
Alternative Fuels and Energy
2020; 4(2): 20-28

Similarly, for the maximum pond level, the seepage flux and exit gradient were analyzed for both cases. Figure 5a showed that at maximum pond level the homogenous dam with cut-off wall and filter drain is having seepage flux of order 3.961 x 10^{-4} ft^3/sec/ft and exit gradient 0.517 respectively. The trend of velocity vectors and the phreatic line was relatively similar as observed for the case of normal and minimum pond levels. These results are according to the findings of (Gokmen *et al.,* 2005), who also observed the variation of phreatic line and velocity vectors within the dam body and foundation for the case of Jeziorsko earth-fill dam in Poland.

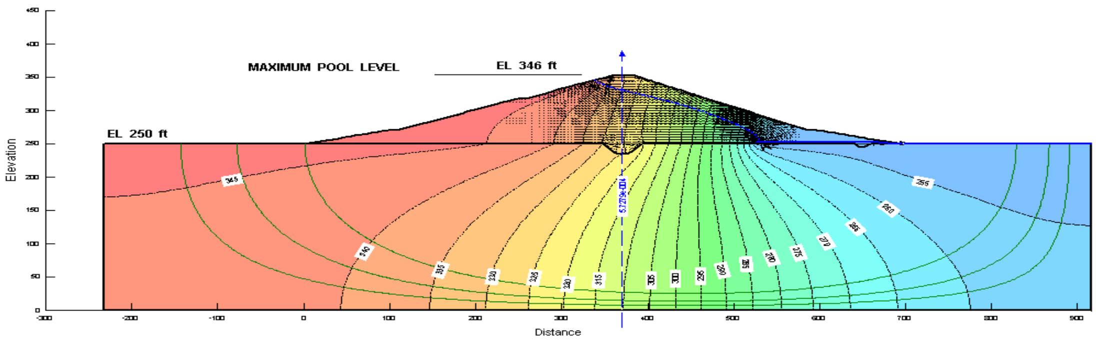

Fig. 5a. Flow-net for Homogeneous Section with Cut-Off Wall and Filter Drain (Pond level = 346 ft).

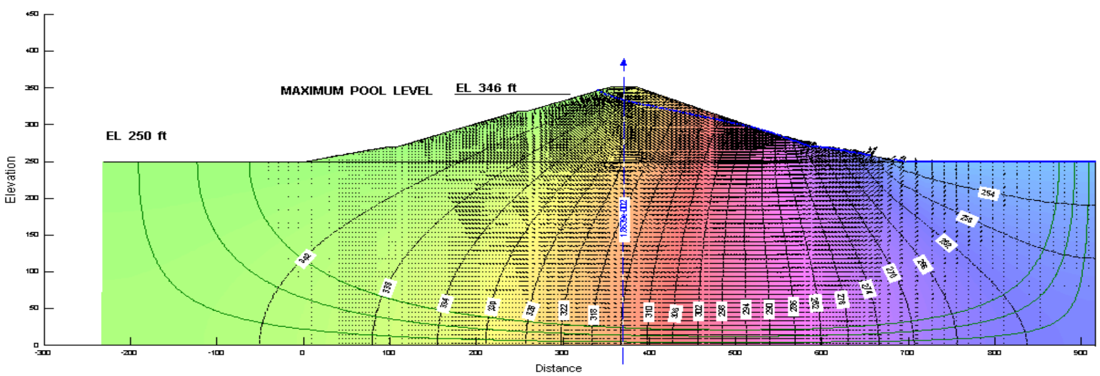

Fig. 5b. Flow-net for Homogeneous Section without Cut-Off Wall and Filter Drain (Pond level = 346 ft).

Once again the dam showed an irregular behaviour of phreatic line at maximum pond level without cut-off wall and filter drain as mention in Figure 5b. The simulated result indicated that due to unavailability of the cut-off wall and filter drain the phreatic line cuts the downstream face of the dam at a distance of 511.35 ft and an elevation of 307.52 ft due to which possibility of internal erosion may occur which tends to a slope failure. Furthermore, the velocity vector comes out from the foundation at the toe region with seepage flux of order 165.81 x 10^{-4} ft^3/sec/ft and extremely high exit gradient of order 3.112 respectively. Similar results were observed by (Khattab, 2010), during the case study of Mosul dam, who also computed seepage flux and exit gradient along with phreatic line behaviour for different scenarios. Complete analysis results were elaborated in Table 2 respectively.

Table 2. Computed seepage flux and exit gradient at the homogeneous section with and without cut-off wall and filter drain for different pond levels.

Parameters	Upstream Pond Levels					
	With Cut-Off Wall			Without Cut-Off Wall		
	Minimum 270 (ft.)	Normal 339 (ft.)	Maximum 346 (ft.)	Minimum 270 (ft.)	Normal 339 (ft.)	Maximum 346 (ft.)
Seepage flux ($x10^{-4}$) (ft^3/sec/ft)	2.513	3.571	3.961	25.58	142.82	165.81
Exit gradient	0.351	0.414	0.517	1.662	2.225	3.112

Figures 6 and 7 showed a comparison between seepage flux and exit gradient at different pond levels when the dam is with or without cut-off wall and filter drain respectively. The comparison showed that seepage flux through the dam and its foundation was found (90.176% – 97.611%) more when there are no cut-off walls and filter drain respectively. This is due to the continuous movement of the water within the dam especially in the foundation, as there is no any barrier installed to control internal pore water pressure, due to which the water seeping from the upstream and foundation finds its way moving towards the downstream and cuts the toe to make its way out respectively. On the other hand, the absence of cut-off wall and filter drain increases the exit gradient for about (78.880% – 83.386%). For the case of Hub dam, if the homogeneous section of the dam is without cut-off wall and filter drain then it can face the piping problem as a high-velocity vector was recorded in the foundation and the phreatic line pattern also does not follow the standard design criterion and due to excessive exit gradient at the toe of the dam, the internal erosion may occur, which may tend to a slope failure. The results are according to the findings of (Nasim, 2007) and (Arshad *et al.,* 2017b), who also observed same trend for seepage flux and exit gradient for Al-Adhaim and Hub dam respectively.

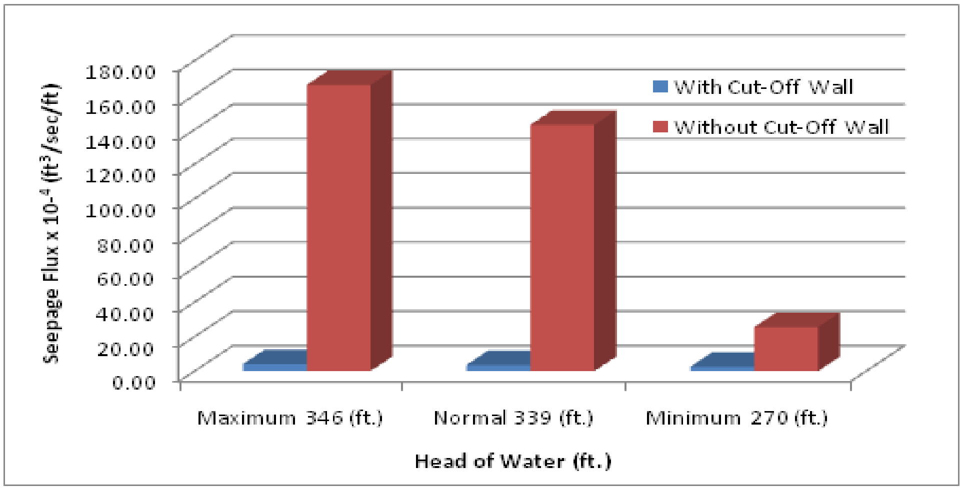

Fig. 6. The relationship between seepage flux at different pond levels when the dam is with and without cut-off wall and filter drain.

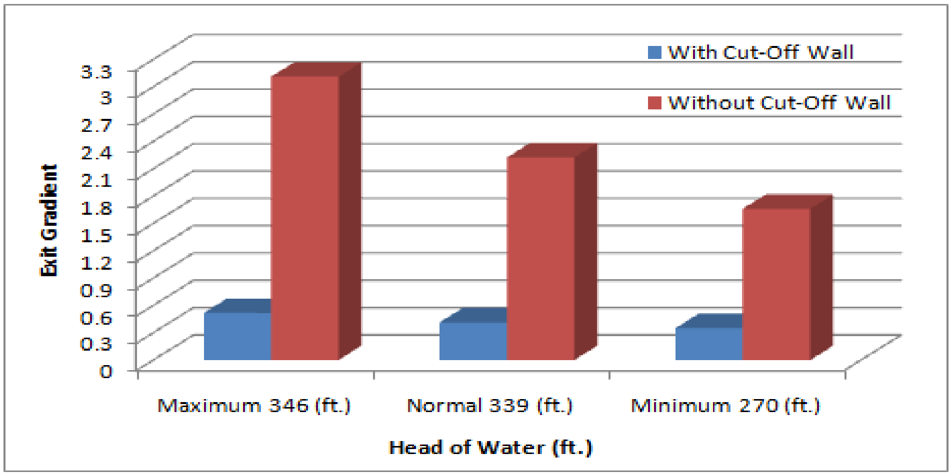

Fig. 7. The relationship between exit gradient at different pond levels when the dam is with and without cut-off wall and filter drain.

CONCLUSION

In the present research work, a homogeneous section of Hub dam with and without cut-off wall was analyzed by using FEM based software SEEP/W, and the results for seepage flux and exit gradient for three different scenarios i.e. maximum (346 ft), minimum (270 ft), and normal pool level (339 ft) is studied accordingly. The simulated results for case (i) with cut-off wall and filter drain, showed that the dam is safe against piping, at its original design for all the scenarios as the phreatic line and velocity vectors in the foundation show a normal trend with overall minimum seepage flux of 2.513 x 10^{-4} ft^3/sec/ft and exit gradient at downstream toe 0.351 respectively. However, for case (ii) without cut-off wall and filter drain, the dam showed abnormal behavior as an extremely high exit gradient was observed for all the scenarios. The velocity vectors for the seeping water within the dam and its foundation and phreatic line trend were recorded abnormal as it cuts the downstream slope of the dam when the FEM model was run for maximum and minimum pond level respectively. The maximum overall seepage flux of order 165.81 x 10^{-4} ft^3/sec/ft and exit gradient 3.112 at the downstream toe was computed when there was no cut-off wall and filter drain installed. The comparison showed that seepage flux (90.176% – 97.611%) and exit gradient (78.880% – 83.386%) through the dam and its foundation was found more when there are no cut-off wall and filter drain. Which is the result of continuous movement of the water within the dam especially in the foundation, as there is no any barrier installed to control internal pore water pressure, due to which the water seeping from the upstream and foundation finds its way moving towards the downstream and cuts the toe to make its way out respectively.

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CONFLICT OF INTEREST

All the authors have declared that no conflict of interest exists.

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