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

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Abstract:
In this study, a homogeneous section of an earthen dam (Hub dam) with and without cut-off wall 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 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, the dam showed abnormal behavior as an overall extremely high exit gradient (1.879) along with the maximum overall seepage flux of order 17.182 x 10^{-4} ft^3/sec/ft respectively. The comparison showed that seepage flux (29.382% – 76.946%) and exit gradient (68.604% – 75.845%) through the dam and its foundation was found more when there are no cut-off walls. 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, Seepage Flux, Exit Gradient, Phreatic Line, SEEP/W, Geo-Slope Software.

INTRODUCTION

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 at 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 in the upstream side of the dam while the roll of 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 drain allows the removal of 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 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.

MATERIAL AND METHODS

Hub Dam (Pakistan)

The model used in this research study is Hub dam which is a rolled earthfill 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 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 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 the 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 the 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.

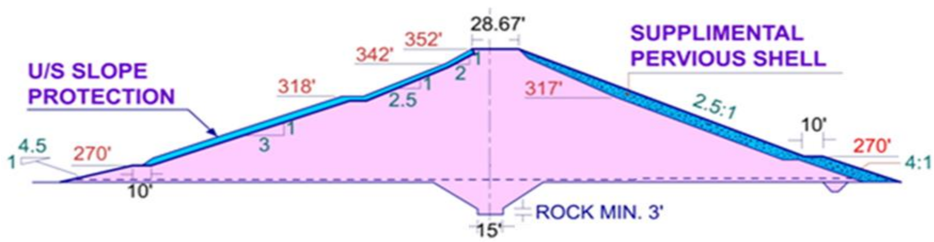

Fig. 1. The geometry of the Homogeneous Section.

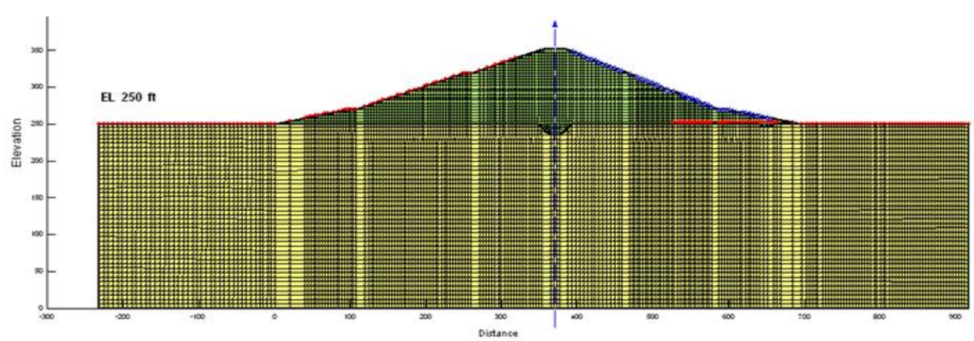

Fig. 2. Typical Mesh formation for homogeneous section.

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

S. No	Material type	Hydraulic conductivity (ft/sec)	
		* Guess Values	Calibrated Values
01	Foundation	10^{-4} to 10^{-6}	3.225×10^{-6}
02	Shell	10^{-5} to 10^{-6}	2.000×10^{-5}
03	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 (ii) without cut-off wall; 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 has a positive effect on the seepage and exit gradient. The main function of the cut-off wall 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 cut-off wall 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 cut-off wall 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 installed. The velocity vector comes out from the foundation at toe region of the dam with seepage flux of order 3.559×10^{-4} ft^3/sec/ft respectively. Furthermore, due to the unavailability of cut-off wall, the high exit gradient of 1.118 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 using Geo-Slope software.

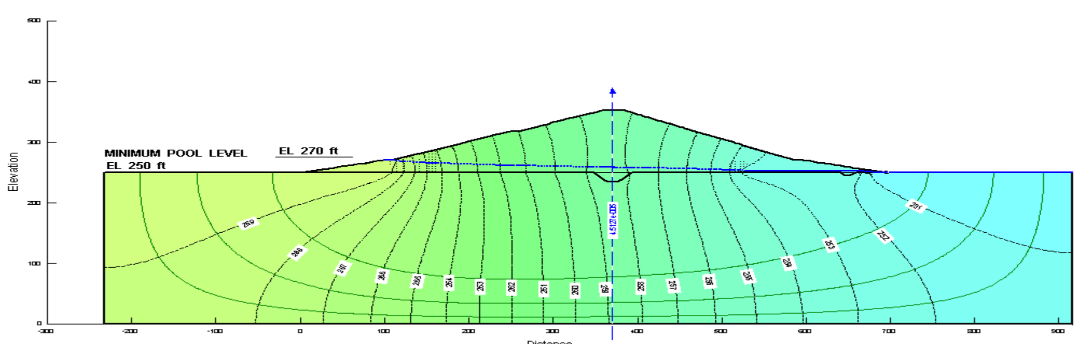

Fig. 3a. Flow-net for Homogeneous Section with Cut-Off Wall (Pond level = 270 ft)

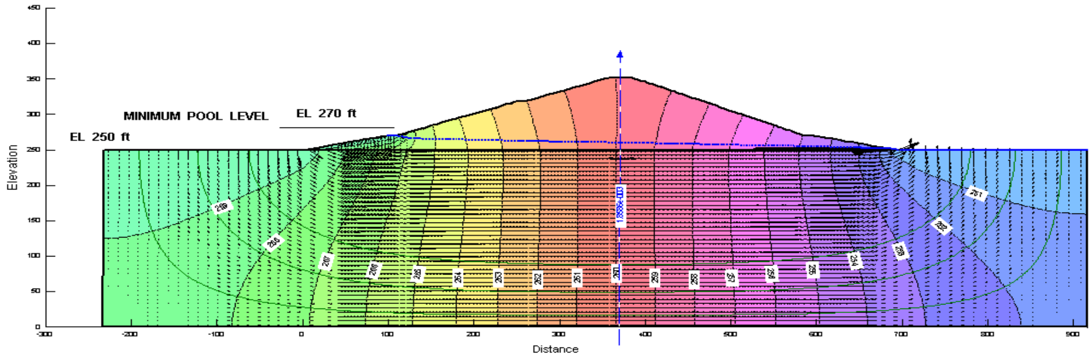

Fig. 3b. Flow-net for Homogeneous Section without Cut-Off Wall (Pond level = 270 ft)

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 x 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 behavior of phreatic line at normal pond level without cut-off walls as the simulated result indicated that the phreatic line cuts the downstream slope of the dam at a distance of 576.57 ft and an elevation 273.74 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 1.714 was observed; which is beyond the permissible limit with seepage flux 10.053 x 10^{-4} ft^3/sec/ft respectively. Therefore, we can consider that a homogenous dam without cut-off wall 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.

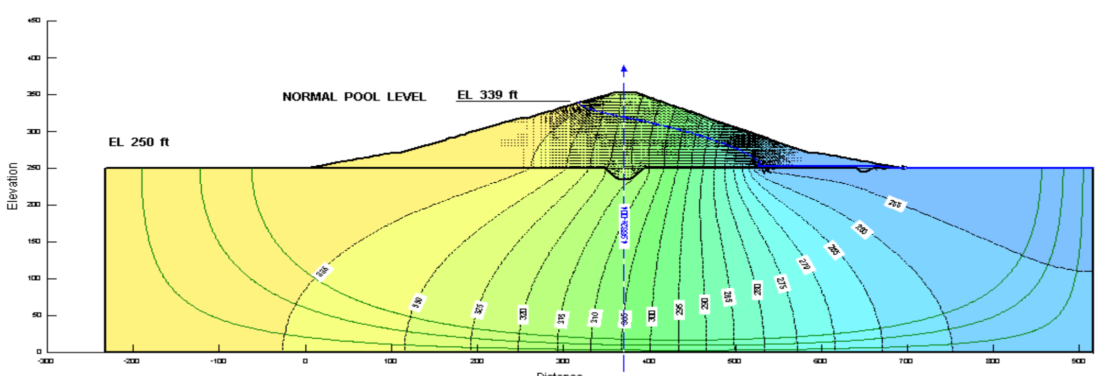

Fig. 4a. Flow-net for Homogeneous Section with Cut-Off Wall (Pond level = 339 ft)

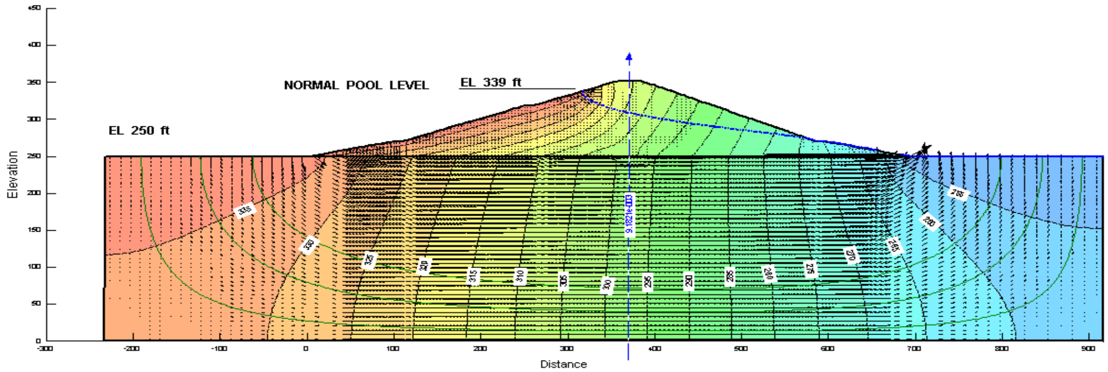

Fig. 4b. Flow-net for Homogeneous Section without Cut-Off Wall (Pond level = 339 ft)

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 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 earthfill dam in Poland.

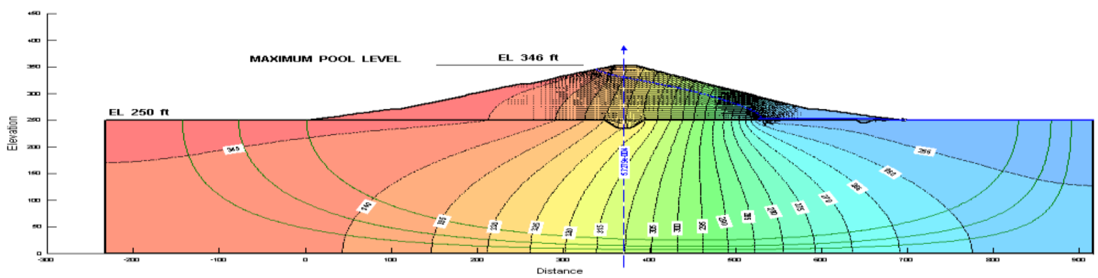

Fig. 5a. Flow-net for Homogeneous Section with Cut-Off Wall (Pond level = 346 ft).

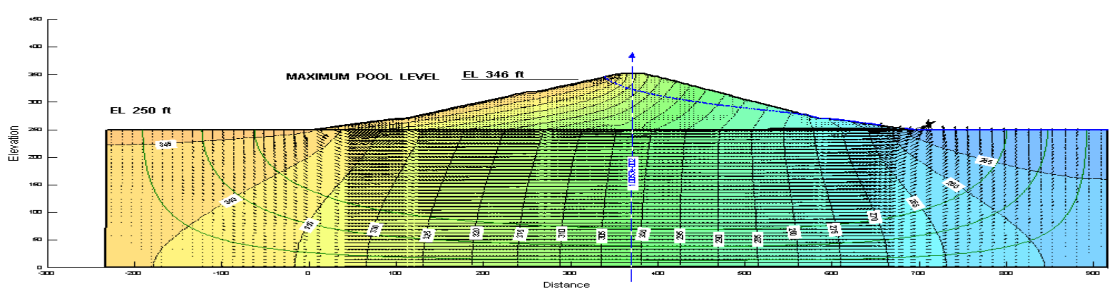

Fig. 5b. Flow-net for Homogeneous Section without Cut-Off Wall (Pond level = 346 ft).

Once again, the dam showed an irregular behavior of phreatic line at maximum pond level without cut-off wall as mention in Figure 5b. The simulated result indicated that due to the unavailability of the cut-off wall the phreatic line cuts the downstream face of the dam at a distance of 571.53 ft and an elevation

276.46 ft due to which possibility of internal erosion may occur which tends to slope failure. Furthermore, the velocity vector comes out from the foundation at the toe region with seepage flux of order 17.182 x 10^{-4} ft^3/sec/ft and extremely high exit gradient of order 1.879 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 behavior 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 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	3.559	10.053	17.182
Exit gradient	0.351	0.414	0.517	1.118	1.714	1.879

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 respectively. The comparison showed that seepage flux through the dam and its foundation was found (29.382% – 76.946%) more when there are no cut-off walls. 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 increases the exit gradient for about (68.604% – 75.845%). For the case of Hub dam, if the homogeneous section of the dam is without cut-off wall 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 slope failure. The results are according to the findings of (Nasim, 2007) and (Arshad *et al.,* 2017b), who also observed the same trend for seepage flux and exit gradient for Al-Adhaim and Hub dam respectively.

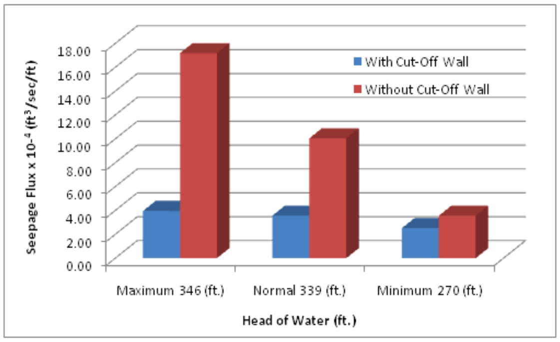

Fig. 6. The relationship between seepage flux at different pond levels when the dam is with and without filter drain.

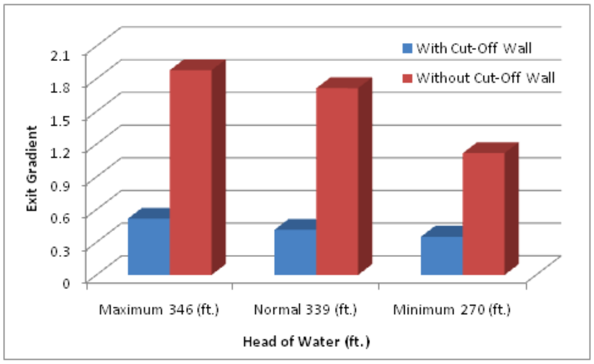

Fig. 7. The relationship between exit gradient at different pond levels when the dam is with and without filter drain.

CONCLUSION

In 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, 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, the dam showed abnormal behavior as 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 17.182 x 10^{-4} ft^3/sec/ft and exit gradient 1.879 at the downstream toe was computed when there was no cut-off wall installed. The comparison showed that seepage flux (29.382% – 76.946%) and exit gradient (68.604% – 75.845%) through the dam and its foundation was found more when there are no cut-off walls. 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

There is no conflict of interest.

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