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Computation of Seepage and Exit Gradient through a Non-Homogeneous Earth Dam without Cut-off Walls by using Geo-Slope (SEEP/W) Software

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Abstract:
In this study, SEEP/W was used to develop a finite element model of a non-homogenous earth dam and for this purpose Hub dam was selected. Two different cases i.e. (i) with cut-off wall and (ii) without cut-off wall were studied to check the behaviour of the dam in terms of seepage flux and exit gradient respectively. The software was also used to simulate the phreatic line behaviour for both cases. The outcome of the simulated results showed that the dam is safe against piping, at its original design as the installation of a cut-off wall found working effectively in reducing internal pore water pressure within the dam and its foundation. For case (i), the phreatic line showed a normal trend as it is falling into the filter drain after passing the core with overall minimum seepage flux of order 2.1130 x 10^{-4} ft^3/sec/ft (21.54 LPH) and exit gradient at downstream toe was recorded 0.099 respectively. However, for case (ii) the dam showed an irregular behaviour as the internal pore water pressure at the subsurface region of the dam foundation was continuously increasing due to unavailability of the cut-off wall and the flow vectors move towards toe drain with high velocity and seepage flux. The overall maximum seepage flux and exit gradient was recorded for the maximum pond level without cut-off wall of order 4.6355 x 10^{-3} ft^3/sec/ft (472.54 LPH) and 0.865 respectively. The comparison results showed that without cut-off walls the seepage flux may increase about (87.314% – 87.493%) and the variation in exit gradient may increase about (48.705% - 63.353%) respectively.

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

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INTRODUCTION

Mostly all dams experience seepage or another, while the dams experiencing seepage may appear in sound condition there may be a damage occurring to the internal structure of the dam. If seepage flow rate appear to be increasing and the flow is not clear and is carrying material internal erosion or piping is likely occurring (Moayed *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 away the fine soil particles and cause piping within the dam (Baghalian *et al.,* 2012). 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 porous medium (Arshad *et al.,* 2014). 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 hydraulic gradient (phreatic line) at a point of seepage discharge respectively (Al-Damluji *et al.,* 2004). 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.

It is necessary to find out the trend of phreatic line as it will allow us to recognize a divide line between dry and submerged soil. The phreatic surface should be kept at or below the downstream toe to avoid piping and control exit gradient (Doherty, 2009). The trend of phreatic line can be well controlled by designing a dam with proper filter drain. The purpose of the filter drain is to restrict the phreatic line almost in upstream side of the dam. The filter prevent 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, finite element method 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.,* 2017). In present research work, by using FEM technique a non-homogeneous section of an earthen dam (Hub dam) was selected to check the behavior of the dam for two different cases i.e. (i) with cut-off wall, and (ii) without cut-off wall; and to compare the results of seepage flux and exit gradient for different scenarios respectively.

MATERIALS AND METHODS

Hub Dam Description

The Hub dam is a rolled earth-fill structure 156 ft high over the deepest foundation, with 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 invert EL 270 ft, established by the relative levels of the irrigable command area and design of 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 supplies (Arshad *et al.,* 2014).

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. 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 earth-fill section in the river portion consisting of a central core of impervious material with pervious fill on either side. On both flanks of 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 dam axis (WAPDA, 2009).

Hub dam is composed of different types of sections, therefore in this research only non-homogenous section i.e. zoned embankment section with 28.5 ft wide cut-off wall at a chainage (CH: 56+00) was selected respectively. The foundation level of the dam was kept at EL 220 ft, while the crest elevation level was kept at EL 352 respectively. The dimension of selected cross section was elaborated in Figure 1.

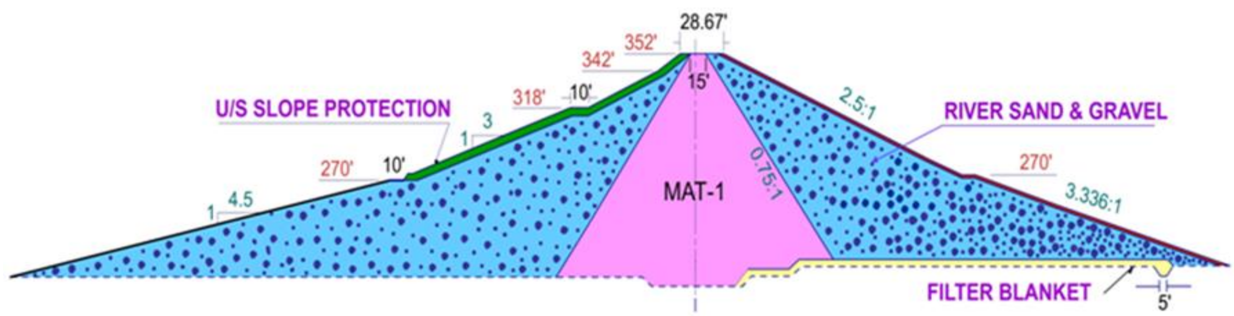

Fig. 1. Geometry of Non-Homogeneous Section.

Model Development Methodology

In first attempt initially a cross section for a non-homogenous section was selected to develop a FEM mesh by using SEEP/W. The units and scale for the drawing page has been set in imperial units and the axes scale was drawn to sketch the model accordingly. Then based on the coordinates obtained from AutoCAD the model was sketched. After sketching the model the domain is then created with the help of region command and dam foundation, shell, core and filter (toe drain) was created with different color respectively (Nasim, 2007). Then by using the key-In command the material properties was calibrated and applied to each region respectively. Calibration of the hydraulic conductivities was made on the basis of trial and error method, by using observed hydraulic heads as a reference (Table 1). Boundary conditions was created and assigned in a similar way as the materials (Aasma, 2016). A hydraulic boundary condition (Dirichlet boundary nodes) was applied on the upstream face of the dam, potential seepage boundary condition (Neumann boundary nodes) was applied on the downstream face of the dam, and zero pressure boundary condition (Neumann boundary nodes) was applied onto the toe drain of the dam where the pressure will be zero kilo-Pascal's (Arshad *et al.,* 2016). In the final step, a newly developed finite element mesh was verified, analyzed and solved by using solve manager option and computation of seepage flux, exit gradient and phreatic line trend for different scenarios of water levels is carried out accordingly.

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
1	Foundation	10^{-4} to 10^{-6}	3.000×10^{-6}
2	Shell	10^{-5} to 10^{-6}	2.385×10^{-5}
3	Core	10^{-8} to 10^{-7}	2.000×10^{-8}
4	Filter Drain	10^{-2}	3.280×10^{-2}

* Source: WAPDA

Model Verification

In order to fulfill the objectives of the present research work by using Geo-Slope software (SEEP/W), cross sections were developed for 2 cases i.e. (i) non-homogeneous section with cut-off wall, and (ii) non-homogeneous section without cut-off wall respectively. The hydraulic conductivities of the materials used in mesh development of the cross sections and dimensions remain same except for cut-off wall. The mesh composed of triangular, square, rectangular and trapezoidal type of elements (Arshad *et al.,* 2015). The mesh for case (i) comprised of 2,421 nodes and 2,403 elements, while for case (ii) 2,512 nodes and 2,489 elements were used (Arshad, 2015). Computations were carried out for three different cases i.e. maximum (346 ft), minimum (270 ft), and normal pond level (339 ft) respectively. Figure 2a and 2b describes the mesh formation of non-homogeneous section with and without cut-off wall respectively.

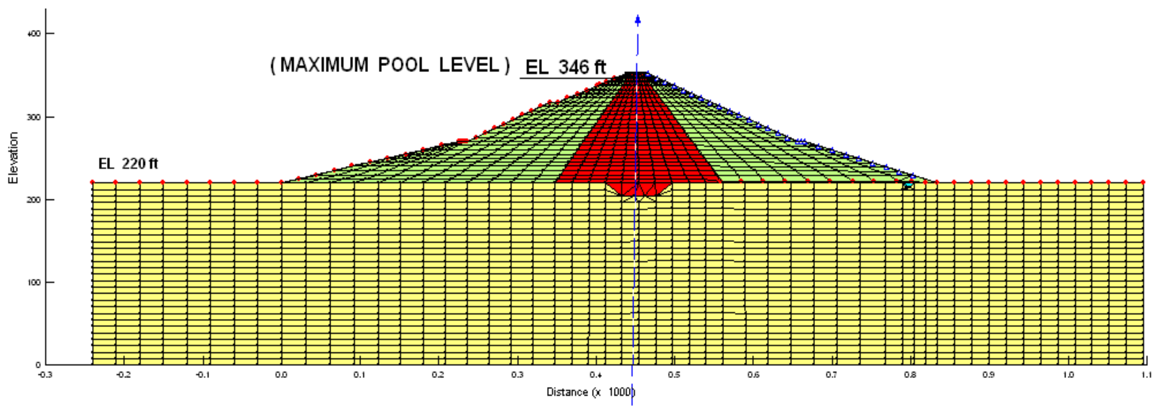

Fig. 2a. Mesh formation for non-homogeneous section with cut-off wall.

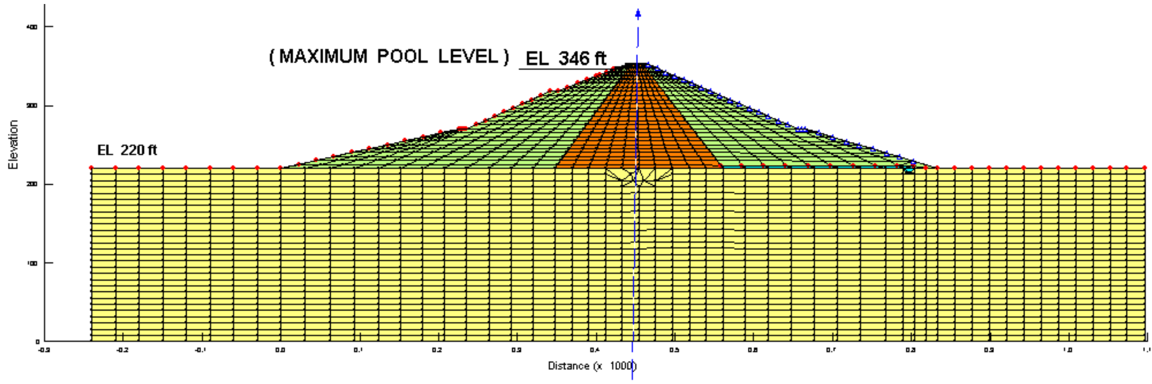

Fig. 2b. Mesh Formation for Non-Homogeneous Section without cut-off wall.

RESULTS AND DISCUSSION

Seepage Flux and Exit Gradient

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 non-homogenous dam and its foundation respectively. The seepage and exit gradient was computed at three different pond level scenarios. The SEEP/W software gives output in terms of flow-net which comprises of total head contours, streamlines, and velocity vectors showing dominant flow (seepage) field and phreatic line depicting seepage behavior of the earth dam. The results revealed that the existence of a cut-off wall has a positive effect in controlling seepage and exit gradient. The main role of the cut-off wall is to control the seepage flow and to reduce the internal pore water pressure mainly at the sub-surface region of the dam foundation respectively. Therefore, the chances of the movement of the high velocity flow vectors towards the toe drain become minimum and controllable. The behavior of phreatic line within the dam for both cases at different pond levels elaborated in respectively in (Figure 3a – Figure 5b).

It is an evident from Figure 3a that at minimum pond level the presence of cut-off wall has a direct effect in reducing a seepage flux as it acts as a barrier and due to which the movement of flow vectors towards toe drain is controllable. The seepage flux of order 2.1130 x 10^{-4} ft^3/sec/ft (21.54 LPH) with an exit gradient at the downstream toe 0.099 was observed respectively. Figure 3b showed some different behavior of flow vectors at minimum pond level with no cut-off wall. The seepage flux of order 1.6656 x 10^{-3} ft^3/sec/ft (169.79 LPH) was recorded for the same numerical model without cut-off wall. Furthermore, due to unavailability of the cut-off wall the flow vectors moves with high velocity which exceeds the exit gradient at the toe of the dam up to 0.193 respectively. These results are according to the findings of (Aasma, 2016), who also computed the seepage flux by using Geo-Slope software through an earthen dam and concluded that vertical barriers plays an active role in lowering the velocity of seepage flux and internal pore water pressure in the sub-surface region of the dam.

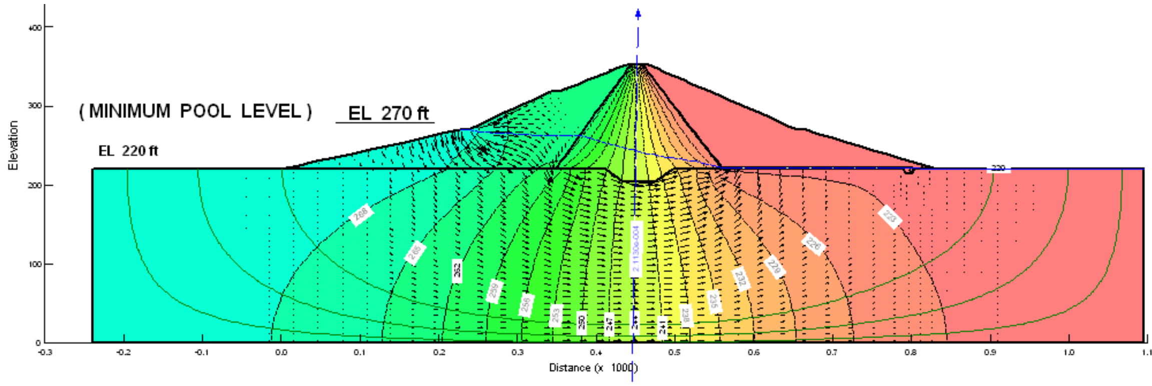

Fig. 3a. Flow-net for Non-Homogeneous Section with Cut-off Wall (Pond level = 270 ft)

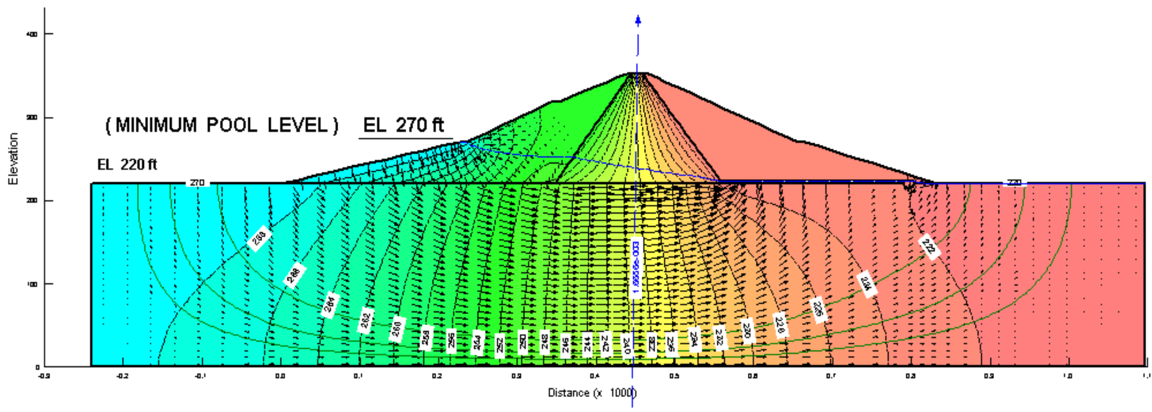

Fig. 3b. Flow-net for Non-Homogeneous Section without Cut-off Wall (Pond level = 270 ft)

Likewise, Figure 4a at normal pond level showed a regular movement of pore water from upstream to the downstream face of the dam as the flow vectors are lower down due to the presence of a cut-off wall and all the vectors joins the filter drain having seepage flux of order 5.4696 x 10^{-4} ft^3/sec/ft (55.75 LPH) and exit gradient at the downstream toe 0.188 respectively. The streamlines and equipotential lines were normal to each other and the movement of velocity vectors was towards the filter drain which conforms; the seepage theory.

Figure 4b showed an abnormal behaviour of flow vectors at normal pond level without cut-off wall. The simulated result indicated that as there is no vertical barrier installed at the middle of the dam foundation the flow vectors at the subsurface of the dam foundation moves with high velocity and the orientation of equipotential lines are also changed. Though the dam is still safe as the flow vectors joins the filter drain but, the seepage flux 4.3732 x 10^{-3} ft^3/sec/ft (445.80 LPH) and exit gradient (0.491) at the toe of the drain was recorded more. Similar results were reported by (Osuji *et al.,* 2015), who also computed the quantity of seepage and exit gradient for the case of Jebba dam.

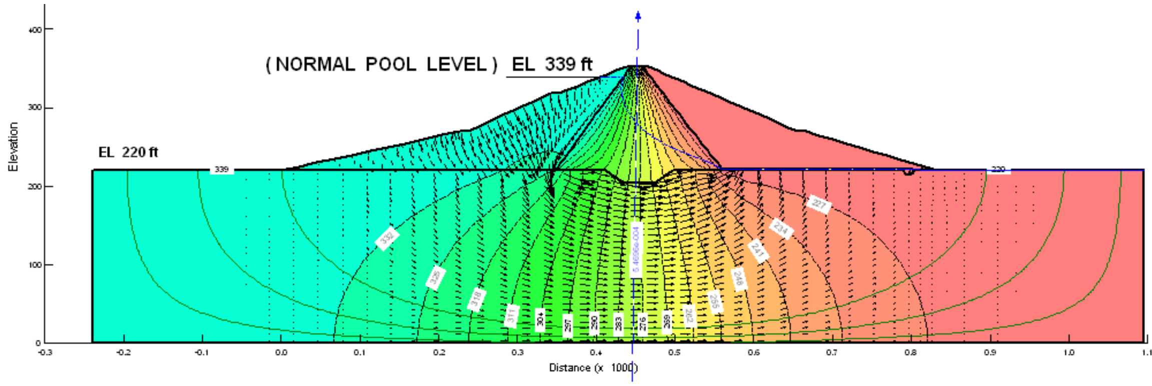

Fig. 4a. Flow-net for Non-Homogeneous Section with Cut-off Wall (Pond level = 339 ft).

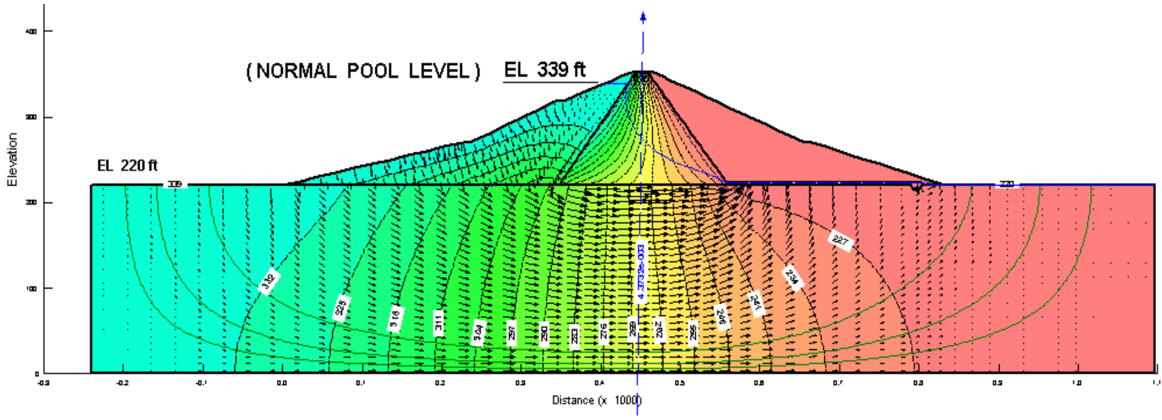

Fig. 4b. Flow-net for Non-Homogeneous Section without Cut-off Wall (Pond level = 339 ft).

Similarly seepage flux and exit gradient for the maximum pond level was computed for both cases. Figure 5a showed that at maximum pond level the non-homogenous dam with cut-off wall is having seepage flux of order 5.7977 x 10^{-4} ft^3/sec/ft (59.10 LPH) and exit gradient 0.317 respectively. The trend of phreatic line and flow vectors was relatively similar as observed in normal and minimum pond levels and the streamlines and equipotential lines were also normal to each other which conforms; the seepage theory. These results are according to the findings of (Gokmen *et al.,* 2005), who also observed the variation of phreatic line and flow vectors within the dam body and its foundation along with high exit gradient for the case of Jeziorsko earth-fill dam in Poland.

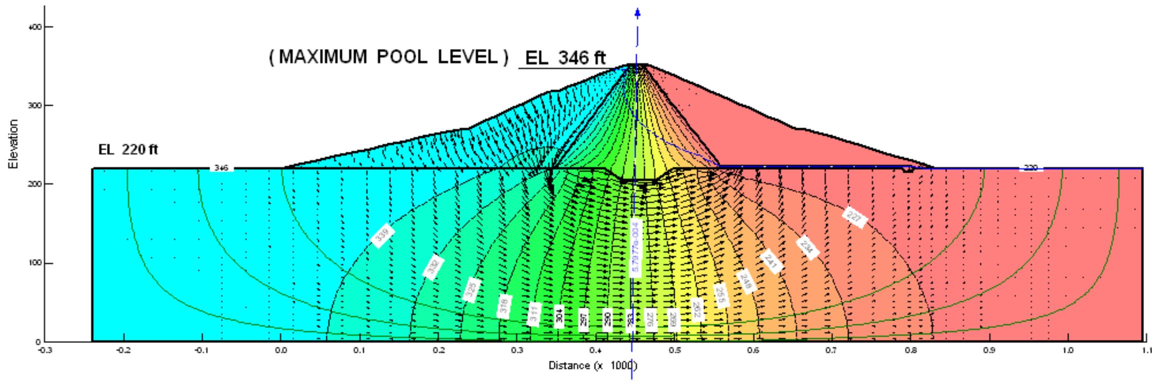

Fig. 5a. Flow-net for Non-Homogeneous Section with Cut-off Wall (Pond level = 346 ft).

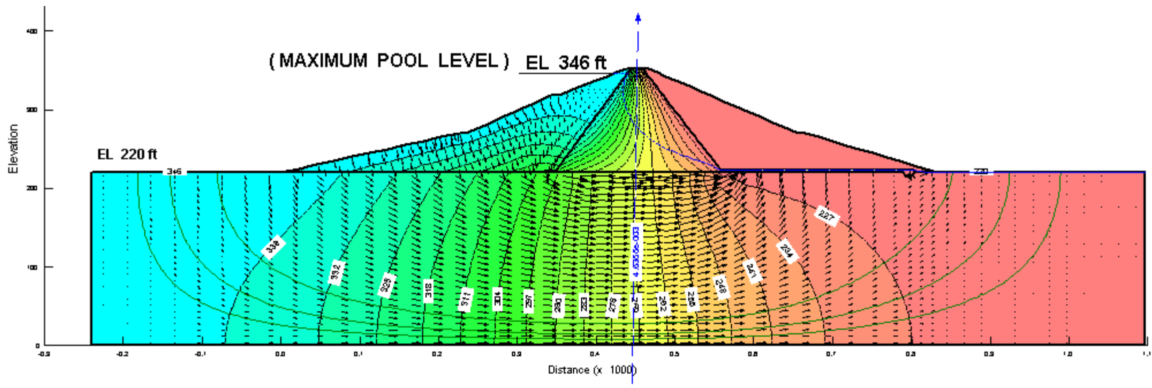

Fig. 5b. Flow-net for Non-Homogeneous Section without Cut-off Wall (Pond level = 346 ft).

Once again the dam showed an irregular behaviour of equipotential lines and flow vectors at maximum pond level without cut-off walls as mention in Figure 5b. The simulated results showed that as the total head goes on increasing the orientation of the equipotential lines may also vary which may create a possibility of internal erosion as the exit gradient (0.865) for this case was recorded very high with seepage flux of order 4.6355 x 10^{-3} ft^3/sec/ft (472.54 LPH) respectively. Therefore, we can consider that a non-homogenous dam without cut-off walls is not safe against piping as there is a possibility of internal erosion due to seepage from the sub-surface region of the dam. 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 non-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 (LPH)	21.54	55.75	59.10	169.79	445.80	472.54
Exit gradient	0.099	0.188	0.317	0.193	0.491	0.865

Figure 6 and 7 showed a graphical relationship between seepage flux and exit gradient at different pond levels when the dam is with and without cut-off walls respectively. The graphs showed that seepage flux through the dam and its foundation was found (87.314% – 87.493%) more when there are no cut-off walls. On the other hand, the absence of cut-off walls increases the exit gradient for about (48.705% – 63.353%) due to which at the downstream toe a high exit gradient was recorded. Though in both cases for exit gradient non-linear behavior was observed but due to excessive water pressure within the dam foundation without cut-off walls, the exit gradient at the downstream toe abruptly changed during different scenarios. For the case of Hub dam, if the non-homogeneous section of the dam is without cut-off walls then seepage flux will increased which ultimately leads to a huge water loss from the dam. The results are according to the findings of (Nasim, 2007) and (Arshad *et al.,* 2017), who also observed same trend for seepage flux and exit gradient for Al-Adhaim and Hub dam respectively.

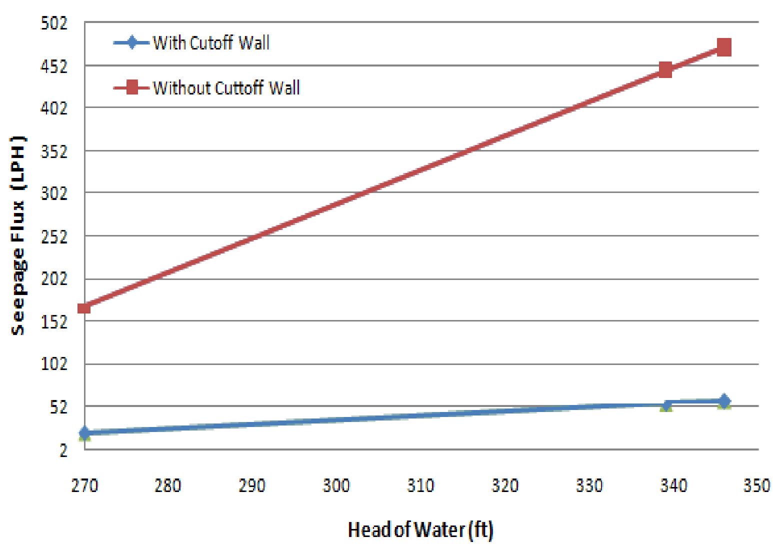

Fig. 6. The relationship between seepage flux at different pond levels when the dam is with and without cut-off wall

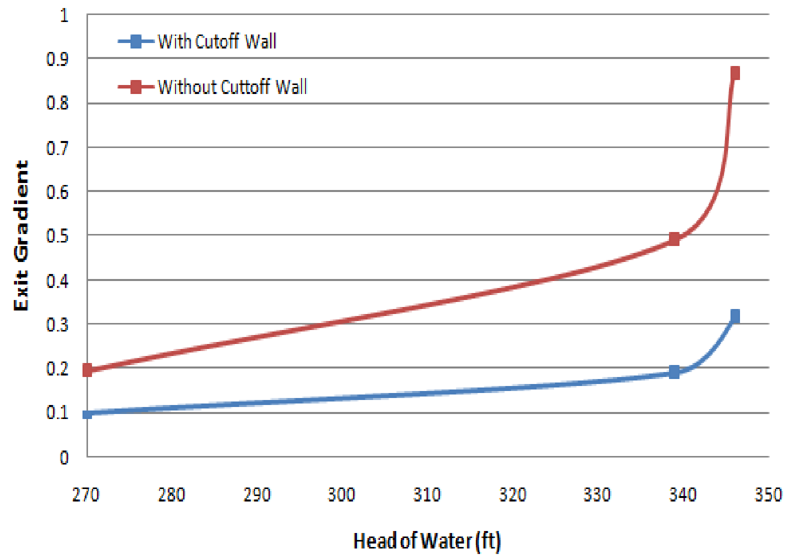

Fig. 7. The relationship between exit gradient at different pond levels when the dam is with and without cut-off wall

CONCLUSION

In present research work, the sub-program of Geo-Slope Software (SEEP/W), was used to develop a non-homogenous earth dam and for this purpose Hub dam was selected. Two different cases i.e. (i) with cut-off wall and (ii) without cut-off wall was studied to check the behavior of the dam in terms of seepage flux and exit gradient respectively. The software was also used to simulate the total head contours, flow vectors, and phreatic line behavior for both cases. The outcome of the simulated results showed that the dam is safe against piping. In both cases the phreatic line behavior is normal for all scenarios but, due to the unavailability of the cut-off wall the seepage flow from the sub-surface of the dam increased and there may be chances of dam failure in-case of super flood. Hence, it can be concluded that cut-off walls or vertical barriers especially in earth dams plays an important role to reduce the seepage flux and exit gradient by lowering the internal pore water pressure at the sub-surface of the dam foundation respectively.

CONFLICT OF INTEREST

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

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