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Finite Element Analysis of Seepage and Exit Gradient through a Non-Homogeneous Earth Dam without Filter Drain

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Abstract
In this study, a slave program of Geo-Slope software (SEEP/W) was used to analyze the behavior of phreatic line along with the computation of seepage flux and exit gradient for a non-homogenous earth dam (Hub dam) for two different cases, with filter drain and without filter drain respectively. The meshes were composed of triangular, square, rectangular and trapezoidal type of elements. The mesh for case filter drain comprised of 2,297 nodes, and 2,206 elements, while for non-filter drain, 2,283 nodes, and 2,198 elements were used. The simulation results revealed that the safety of the Hub dam, at its original design, is not endangered from the seepage point of view as the presence of filter drain has a direct effect on reducing positive pore water pressure within the dam. Due to low positive pore water pressure within the dam for filter drain, the phreatic line was falling into the filter drain after passing the core with an overall minimum seepage flux of 2.113 x 10^{-4} ft^3/sec/ft and exit gradient at downstream toe 0.099 respectively. However, when the model was run with same geometry and material properties without filter drain, a very high exit gradient was observed for (normal and maximum pond level) scenarios and the behavior of phreatic line was also found abnormal as it cuts the downstream slope of the dam. Though the seepage flux was found (28 – 29%) less, but due to the absence of free passage within the dam for the removal of extra water, the pore water pressure within the dam especially at downstream face becomes high and leads to a slope failure. This implies that filter drain especially in earth dams plays a pivotal role to control the phreatic line trend and exit gradient by reducing the positive pore water pressure within the dam body and to save the dam from downstream slope failure respectively.
Keywords: Seepage Flux, Exit Gradient, Phreatic Line, Earth Dam, SEEP/W, Geo-Slope Software.

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INTRODUCTION

A dam is a hydraulic structure that stores water for a particular purpose such as a water supply, flood control, irrigation, navigation, sedimentation control and hydropower etc (Doherty, 2009). It is a well known fact that in any dam surplus amount of seepage within the dam body and its foundation, destabilize the structure of the dam and cause dam failure. 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 (Arshad *et al.,* 2014). 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 (Baghalian *et al.,* 2012). 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. However, the hydrostatic pressure on the phreatic line is equal to atmospheric pressure and hence equal to zero (Moayed *et al.,* 2012).

It is necessary to find out the trend of phreatic line as it will enable us to identify 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. 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

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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, 2013). In present research work, Hub dam was selected to study the seepage behavior of earthen dam by using a slave program of Geo-Slope software i.e. (SEEP/W), to simulate phreatic line for non-homogeneous section with and without horizontal filter drain; 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 earthfill 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.

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 upto 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 earthfill 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).

Steps for Modeling of Hub Dam

To develop a numerical model by using SEEP/W, initially a cross section for a non-homogenous section was selected to generate FEM mesh. According to the given conditions the upstream and downstream boundary conditions are assigned as Dirichlet and Neumann boundary nodes respectively. The nodes at the bottom of the foundation of dam are considered with zero-flux (Nuemann) condition (Arshad *et al.,* 2016). The hydraulic conductivities (material properties) for the materials used in dam section are calibrated. Finally, after the development of finite element model, it is verified by the SEEP/W and computation of seepage flux, exit gradient and phreatic line trend for different scenarios of water levels is carried out accordingly.

Selection of Cross Sections for FEM Modeling

Since the main dam is composed of different kinds of reaches, therefore in this research only non-homogenous section was selected respectively. Due to variable ground level elevations, 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.

FEM Mesh Formation and Its Verification by Using SEEP/W Software

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 filter drain, and (ii) non-homogeneous section without filter drain respectively. The hydraulic conductivities of the materials used in mesh development of the cross sections and dimensions remain same except for filter drain. The meshes are composed of triangular, square, rectangular and trapezoidal type of elements (Arshad *et al.,* 2015). The mesh for case (i) comprised of 2,297 nodes and 2,206 elements, while for case (ii) 2,283 nodes and 2,198 elements were used (Arshad, 2015). Figure 2(a) and 2(b) describes the mesh formation of non-homogeneous section with and without filter drain respectively.

Computations were carried out for three different scenarios i.e. maximum (346 ft), minimum (270 ft), and normal pool level (339 ft) respectively. At upstream fill level and downstream toe boundary conditions are considered as Dirichlet boundary conditions and at foundation upstream face and bottom level Neuman boundary conditions (zero flux) had been assigned for all the water level scenarios in both cases respectively. After all the necessary inputs, the mesh was then verified by SEEP/W and found that the vertical and horizontal meshing was strong with no error in formation of mesh model. Thus the model was ready for computation and analysis of the results.

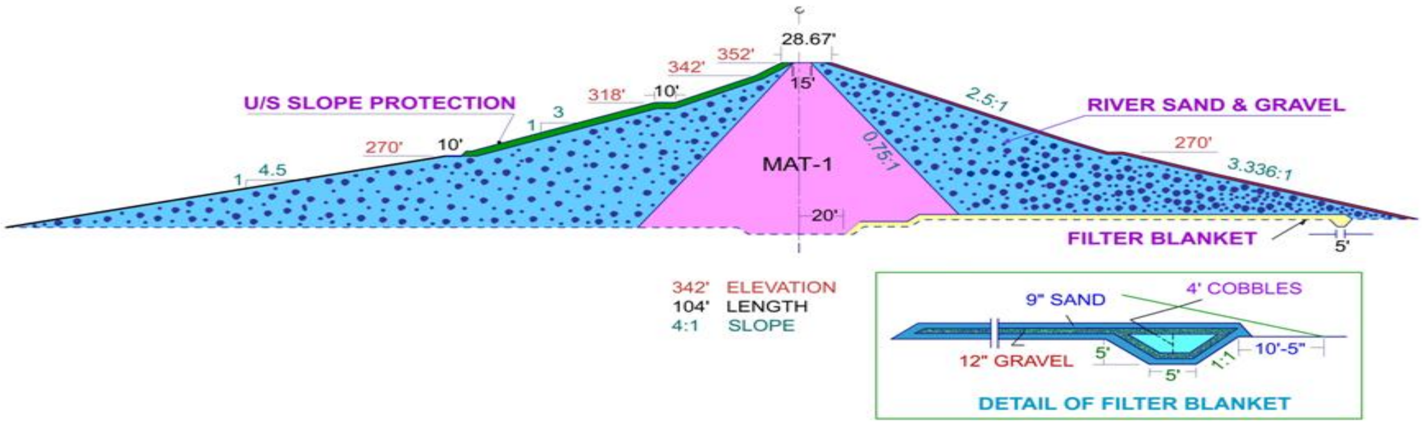

Fig 1. Geometry of Non-Homogeneous Section.

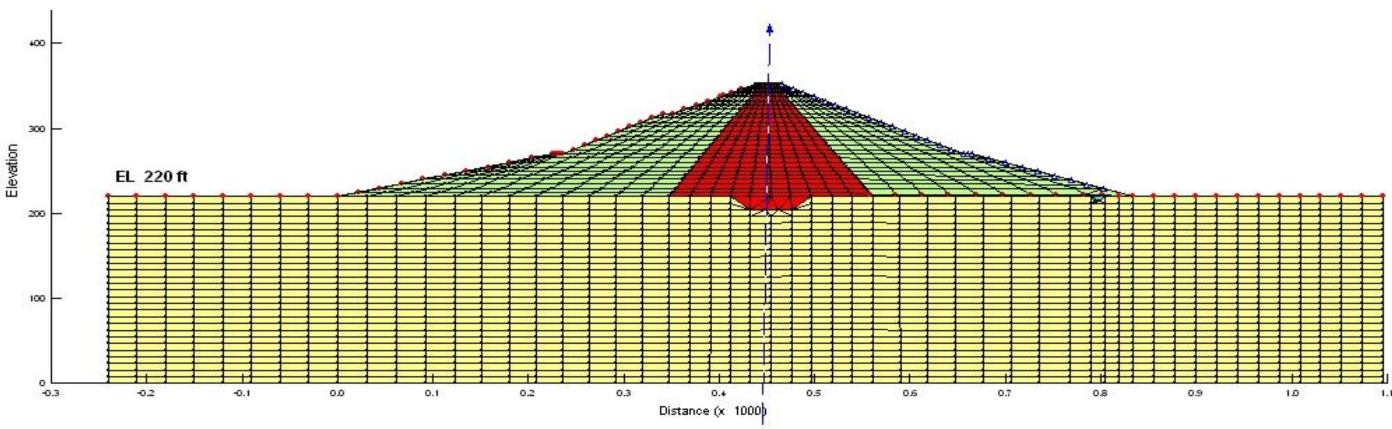

Fig. 2(a). Mesh formation for non-homogeneous section with filter drain

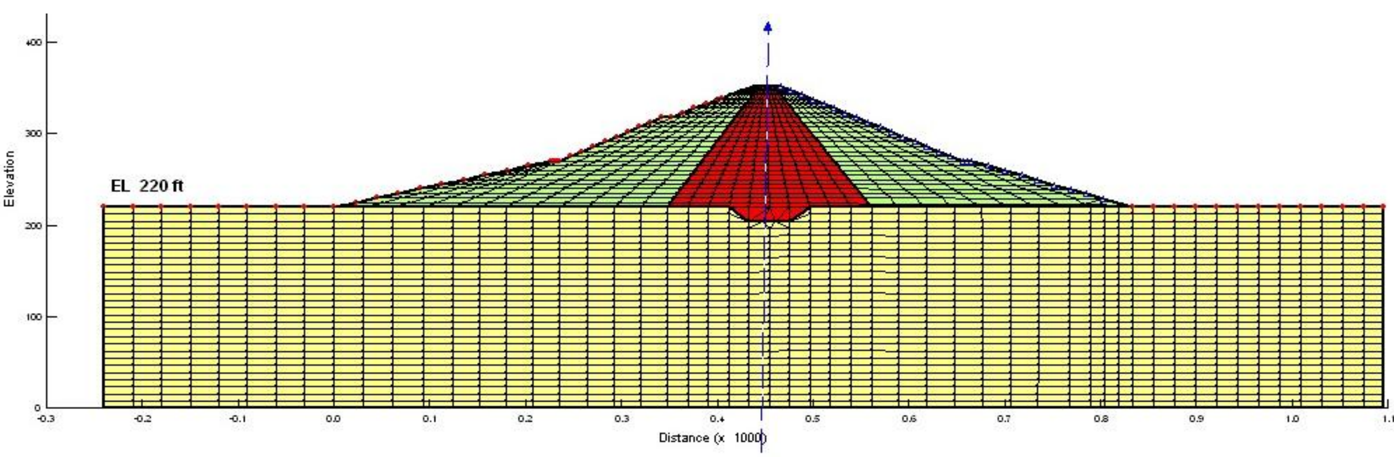

Fig. 2(b). Mesh Formation for Non-Homogeneous Section without filter drain

RESULTS AND DISCUSSION

Calibration of Material Properties (Hydraulic Conductivity) of an Earth Dam

In order to calibrate the material properties of the earth dam, initially identical guess values of hydraulic conductivities for all the materials used in the section were first specified and then assigned. Calibration of the hydraulic conductivities was made on the basis of trial and error, while comparing observed hydraulic heads with the simulated ones. These guess and calibrated hydraulic conductivities (material properties) values for different types of materials used in the earth dam are presented below in Table 1 respectively.

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

Seepage Flux and Exit Gradient

The SEEP/W software was used to compute the seepage flux and exit gradient for two different cases i.e. (i) with filter drain and (ii) without filter drain through the 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 flownet which comprises of streamlines, equipotential lines, velocity vectors showing dominant flow (seepage) field and phreatic line depicting seepage behavior of the earth dam. The results showed that the presence of the filter drain has a direct effect on seepage and exit gradient. The purpose of the filter drain was to restrict the phreatic line almost in the upstream side of the dam. The drain allows the removal of excess internal water to control pore water pressure within the dam body and filter prevent the passage of fine particles into the drainage conduit respectively. Therefore, the chances of phreatic line to cut the downstream slope face of the dam become minimum and controllable. The behavior of phreatic line within the dam for both cases at different pond levels elaborated respectively in Figure 3(a) and Figure 3(b).

It can be observed from Figure 3a that at minimum pond level the presence of filter blanket has a direct effect on phreatic line as it is falling into the filter drain after passing the core having seepage flux of order 2.113×10^{-4} ft^3/sec/ft and exit gradient at the downstream toe 0.099 respectively. Figure 3b showed some different behavior of phreatic line at minimum pond level with no filter drain. As the velocity vectors after passing the core comes out from the foundation with seepage flux of order 1.488×10^{-4} ft^3/sec/ft and joins the downstream shell and increases the pore water pressure respectively. High exit gradient of 0.898 was recorded in this case which may adversely affect the behavior of the dam. 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 with and without filter drainage system within the dam.

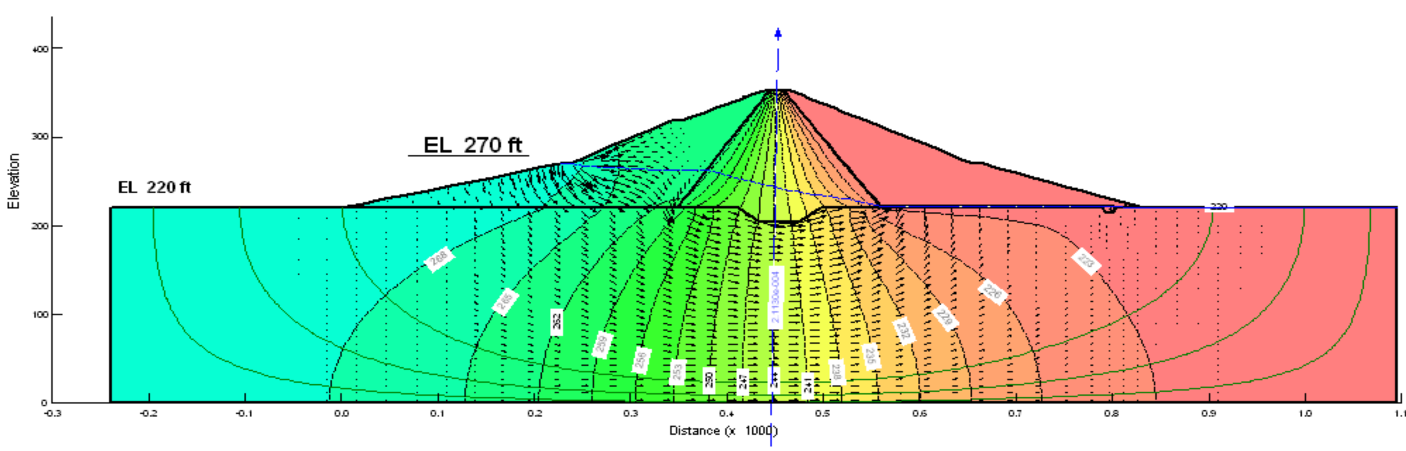

Fig. 3(a). Flownet for Non-Homogeneous Section with Filter Drain (Pond level = 270 ft)

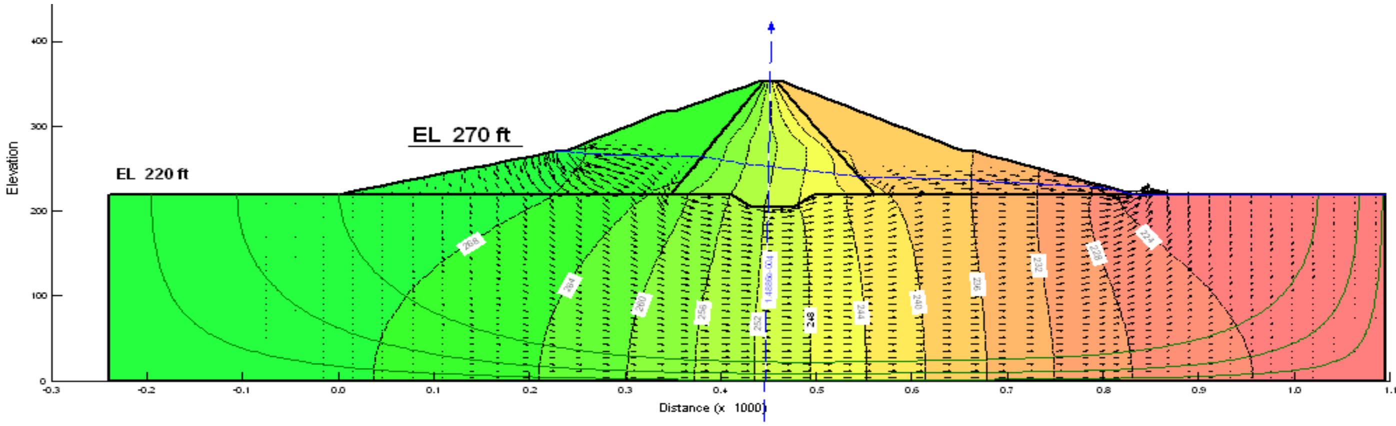

Fig. 3(b). Flownet for Non-Homogeneous Section without Filter Drain (Pond level = 270 ft)

Likewise, Figure 4(a) showed that at normal pond level the movement of pore water from upstream to the downstream face of the dam is normal as phreatic line is falling into the filter drain after passing the core having seepage flux of order 5.470 x 10^{-4} ft^3/sec/ft 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 filter drain which conforms; the seepage theory. Figure 4(b) showed an abnormal behaviour of phreatic line at normal pond level without filter drain.

The simulated result indicated that the phreatic line cuts the downstream slope of the dam at a distance of 777 ft and an elevation 237 ft due to which dam may suffer from a slope failure. Furthermore, due to excessive pore water movement and pressure within the dam an exit gradient at the downstream toe of order 1.181 was observed; which is beyond the permissible limit with seepage flux 3.915 x 10^{-4} ft^3/sec/ft respectively. Therefore, we can consider that the dam without filter drain is not safe against piping as there is a possibility of internal erosion due to seepage. These results are according to the findings of (Aasma, 2015) and (Arshad *et al.,* 2017), who also computed the seepage flux through a homogeneous earth dam with and without filter drain using Geo-Slope software.

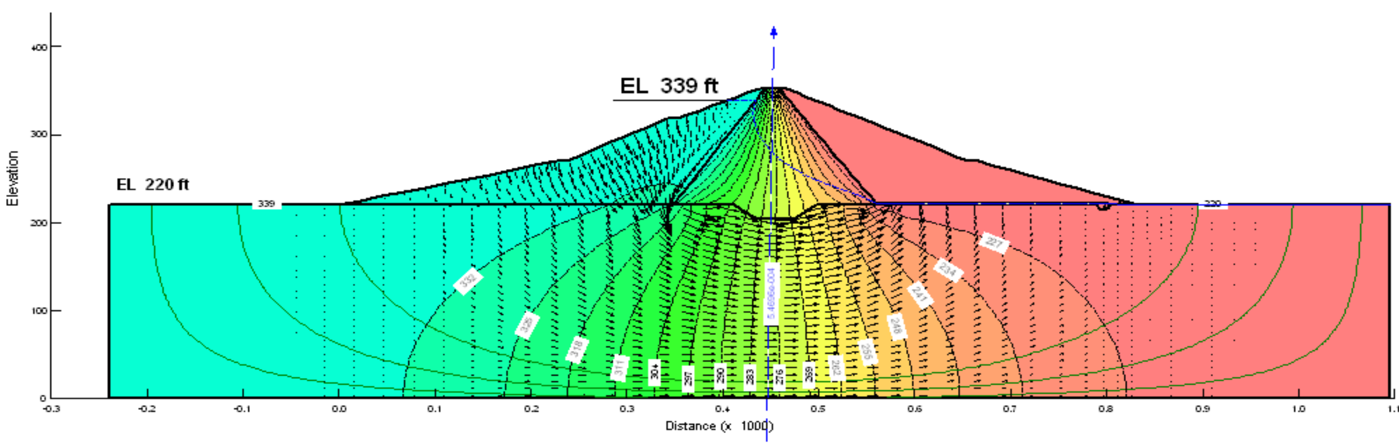

Fig. 4(a). Flownet for Non-Homogeneous Section with Filter Drain (Pond level = 339 ft)

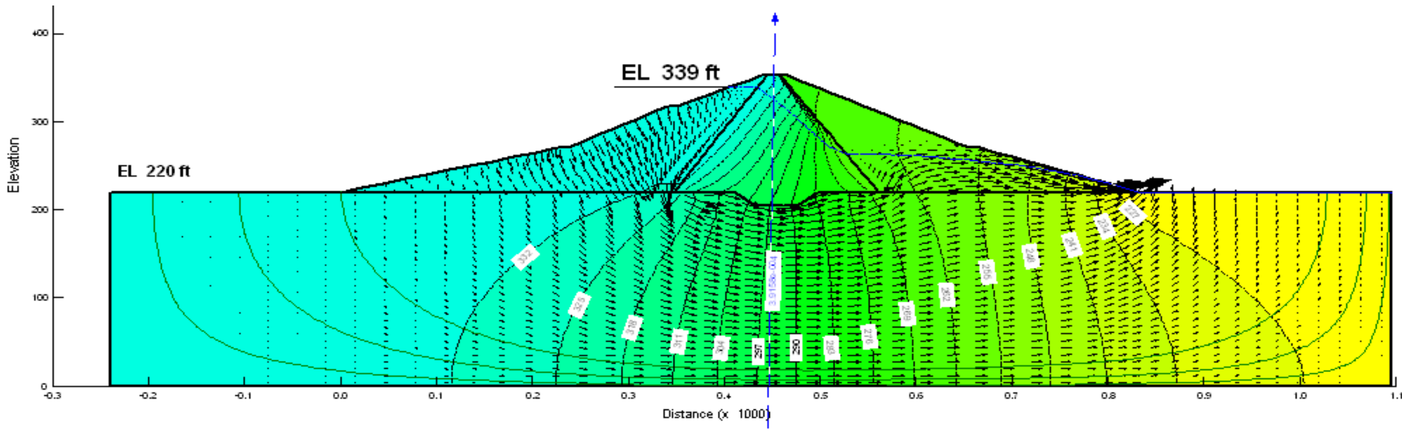

Fig. 4(b). Flownet for Non-Homogeneous Section without Filter Drain (Pond level = 339 ft)

Similarly seepage flux and exit gradient for the maximum pond level was computed for both cases. Figure 5(a) showed that at maximum pond level the dam with filter drain is having seepage flux of order 5.798 x 10^{-4} ft^3/sec/ft and exit gradient 0.317 respectively. The trend of phreatic line 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. 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.

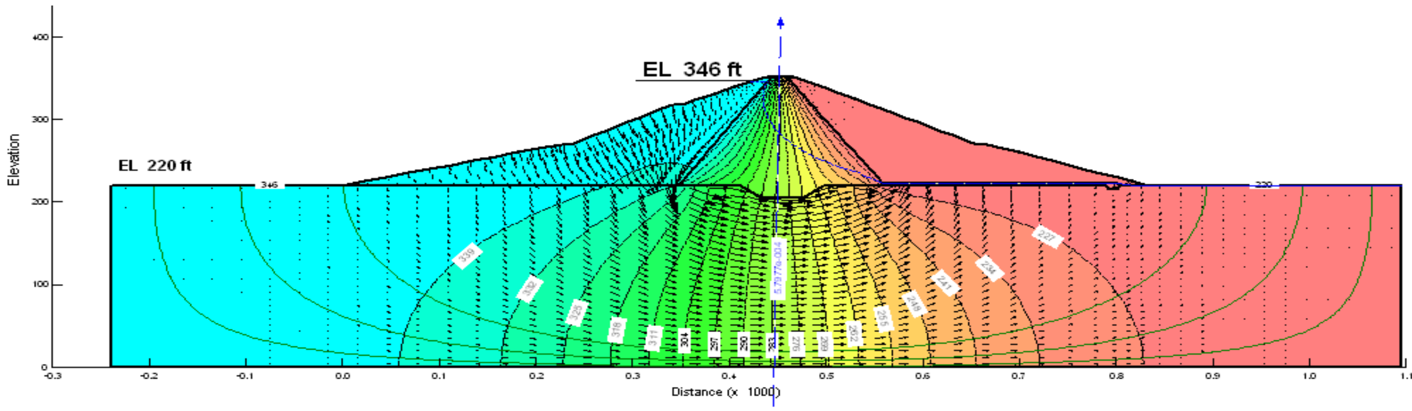

Fig. 5(a). Flownet for Non-Homogeneous Section with Filter Drain (Pond level = 346 ft)

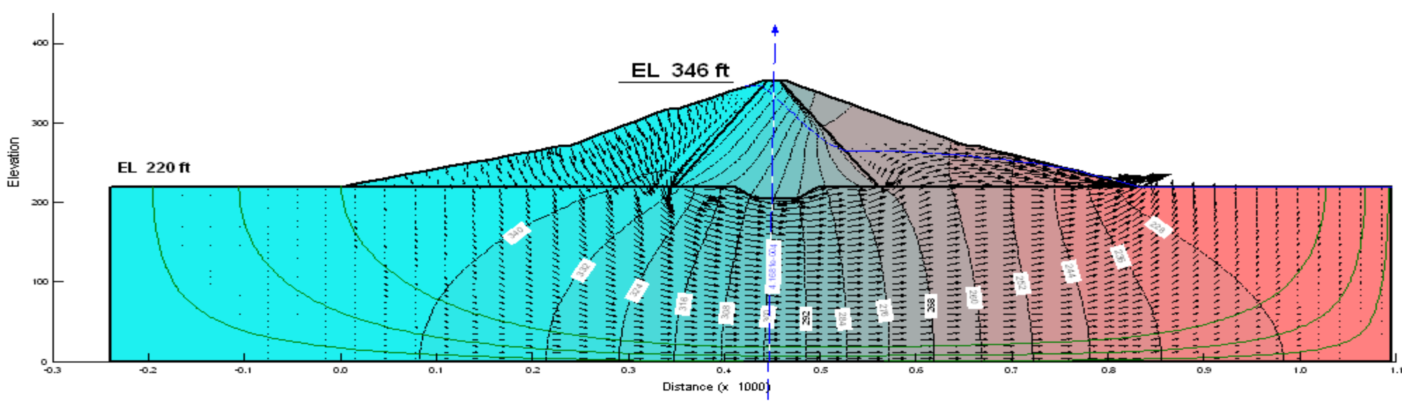

Fig. 5(b). Flownet for Non-Homogeneous Section without Filter Drain (Pond level = 346 ft)

Once again the dam showed an anomalous behaviour of phreatic line at maximum pond level without filter drain as mention in Figure 5(b). The simulated result indicated that the phreatic line cuts the downstream face of the dam at a distance of 752 ft and an elevation 245 ft due to which possibility of internal erosion may occur which tends to a slope failure. Furthermore, the velocity vectors after passing the core comes out from the foundation with seepage flux of order 4.168 x 10^{-4} ft^3/sec/ft and joins the downstream shell and increases the pore water pressure respectively. Extremely high exit gradient of order 1.313 was recorded in this case which indicates that dam is not safe against piping. Complete analysis results were elaborated in Table 2 respectively. These results are according to the findings of (Gokmen *et al.,* 2005), who also observed the variation of phreatic line within the dam body along with high exit gradient for the case of Jeziorsko earthfill dam in Poland.

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

Parameters	Upstream Pond Levels					
	With Filter Drain			**Without Filter Drain**		
	Minimum 270 (ft.)	**Normal 339 (ft.)**	**Maximum 346 (ft.)**	**Minimum 270 (ft.)**	**Normal 339 (ft.)**	**Maximum 346 (ft.)**
Seepage flux (ft^3/sec/ft)	2.113 x 10^{-4}	5.470 x 10^{-4}	5.798 x 10^{-4}	1.488 x 10^{-4}	3.915 x 10^{-4}	4.168 x 10^{-4}
Exit gradient	0.099	0.188	0.317	0.898	1.181	1.313

Figure 6 and 7 showed a graphical relationship between seepage flux and exit gradient at different pond levels when the dam is with or without filter drain respectively. The graphs showed that seepage flux through the dam and its foundation was found (28 - 29%) less when there is no filter drains on the downstream face of the dam. This is due to the continuous movement of the water within the dam especially in the downstream shell is more, as there is no free passage to pass internal pore water to the drain collectors, the water from upstream shell and foundation finds its way moving towards the downstream shell. The movement of water was found slow due to no internal free drain but the impact was found high as phreatic line trend is abruptly changing during different scenarios.

On the other hand, the absence of filter drain increases the exit gradient for about (75 – 88%) due to which at the downstream high exit gradient was recorded. Though in both cases for exit gradient non-linear behavior was observed but due to high pore-water pressure within the dam without filter drain, the exit gradient at the downstream toe abruptly changed during different scenarios. For the case of Hub dam, if the dam is without filter drain then it will be endangered from the seepage point of view since the phreatic line pattern does not follow the standard design criterion and due to excessive exit gradient internal erosion may occur, which may tends to a slope failure. The results are according to the findings of (Nasim, 2007) and (Arshad *et al.,* 2014), who also observed same trend for seepage flux and exit gradient for Al-Adhaim and Hub dam respectively.

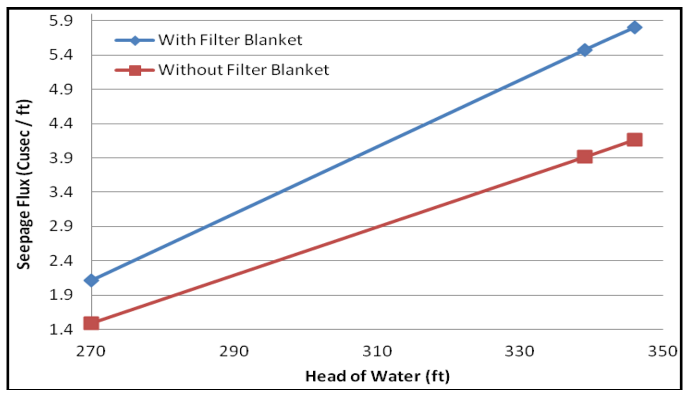

Fig. 6. The relationship between seepage flux at different pond levels when the dam is with and without filter drain

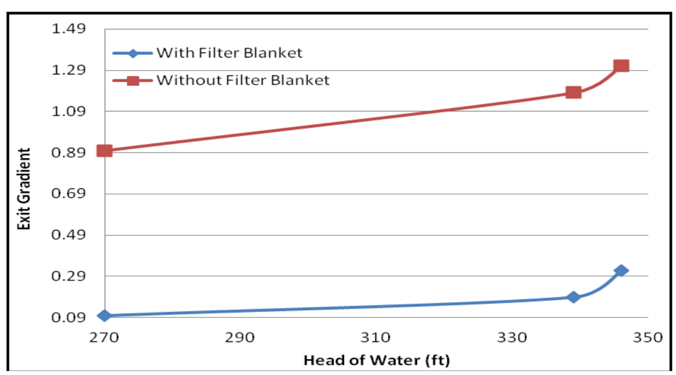

Fig. 7. The relationship between exit gradient at different pond levels when the dam is with and without filter drain

CONCLUSION

In present research work, the slave program (SEEP/W) of a finite element based software i.e. Geo-Slope was used to compute the seepage flux and exit gradient through a non-homogenous earth dam for two different cases i.e. (i) with filter drain and (ii) without filter drain respectively. The software was also used to simulate the phreatic line behavior for both cases. The simulation results revealed that the safety of the earth dam (Hub dam), at its original design is not endangered from seepage point of view as the presence of filter drain has a direct effect on reducing positive pore water pressure within the dam. Due to low positive pore water pressure within the dam for case (i), the phreatic line is falling into the filter drain after passing the core with overall minimum seepage flux of 2.113×10^{-4} ft^3/sec/ft and exit gradient at downstream toe 0.099 respectively. In addition to this for each scenario the equipotential lines and stream lines are also found normal to each other.

However, when the model is run with same geometry and material properties without filter drain (case - ii), a very high exit gradient was observed for (normal and maximum pond level) scenarios and the behavior of phreatic line was also found abnormal as it cuts the downstream slope of the dam. Hence, it can be concluded that filter drain especially in earth dams plays a pivotal role to control the phreatic line trend and exit gradient by reducing the positive pore water pressure within the dam body and to save the dam from downstream slope failure respectively.

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CONFLICT OF INTEREST

There is no conflict of interest.

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