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Numerical Analysis of Seepage and Exit Gradient through a Non-Homogeneous Earth Dam without Impervious Core by using Geo-Slope Software

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Abstract:
In this study, Geo-Slope software was used to check the behavior of a non-homogenous earth dam (Hub dam) for two different cases i.e. (i) with core and (ii) without core respectively. The simulated results showed that a dam at its original shape and design with core (case - i) is not endangered from an internal erosion and piping, as the central core plays a key role in lowering the phreatic surface within the dam. For each scenario the equipotential lines and stream lines are found normal to each other. The overall minimum seepage flux of order 2.0291 x 10^{-4} ft^3/sec/ft and exit gradient at downstream toe 0.091 was recorded respectively. However, when a dam model was run without core (case - ii), an abnormal behavior of the dam was observed as the phreatic surface cuts the downstream slope of the dam for all the scenarios. A very high exit gradient and seepage flux was recorded at different pond levels. The seepage flux was found (12.768 – 41.378%) more, due to the absence of core the hydraulic conductivity of the shell material is not fine enough to resist the seeping water within the shell due to which the internal pore water pressure increased for all scenarios. Likewise, the absence of core increases the exit gradient for about (85.896 – 91.809%) due to which a high exit gradient was recorded at the toe of the downstream slope. In both cases non-linear behavior was observed due to high pore-water pressure in the shell region without core, the exit gradient at the downstream toe abruptly changed during different scenarios. This implies that a core plays a vital role in earth dams to control the phreatic surface by lowering down the positive pore water pressure within the upstream and downstream of the shell, lowering the seepage flux and exit gradient respectively.

Keywords: Finite Element Analysis, Phreatic Surface, Core, Hub Dam, 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. 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 (Doherty, 2009). 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 (Moayed *et al.,* 2012).

The trend of phreatic line can be well controlled by designing a dam with proper core and a filter drain. The purpose of the core 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, 2013). In present research work, Hub dam was selected to check the behavior of the dam for a non-homogeneous section with and without core at different water heads; 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 15 ft wide cut-off wall at a chainage (CH: 48+75) 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.

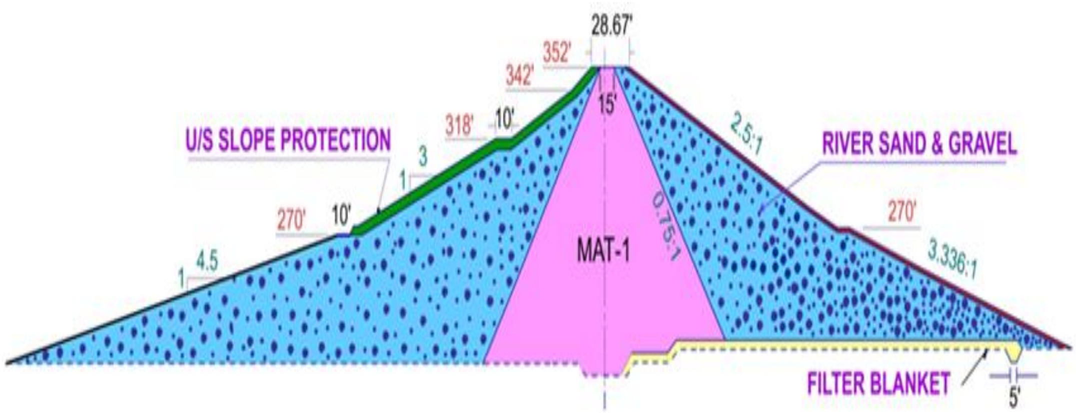

Fig 1. Geometry of Non-Homogeneous Section.

Model Development Methodology

In first attempt initially a cross section for a non-homogenous section was selected to generate FEM mesh and to carry out the critical seepage analysis 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 with different volumetric water content, pore-water pressure and hydraulic conductivity was calibrated and applied to each region respectively. Calibration of the hydraulic conductivities was made on the basis of trial and error, while comparing observed hydraulic heads with the simulated ones (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 core, and (ii) non-homogeneous section without core respectively. The hydraulic conductivities of the materials used in mesh development of the cross sections and dimensions remain same except for core. The meshes are composed of triangular, square, rectangular and trapezoidal type of elements (Arshad *et al.,* 2015). The mesh for case (i) comprised of 2,399 nodes and 2,341 elements, while for case (ii) 2,346 nodes and 2,251 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 core respectively.

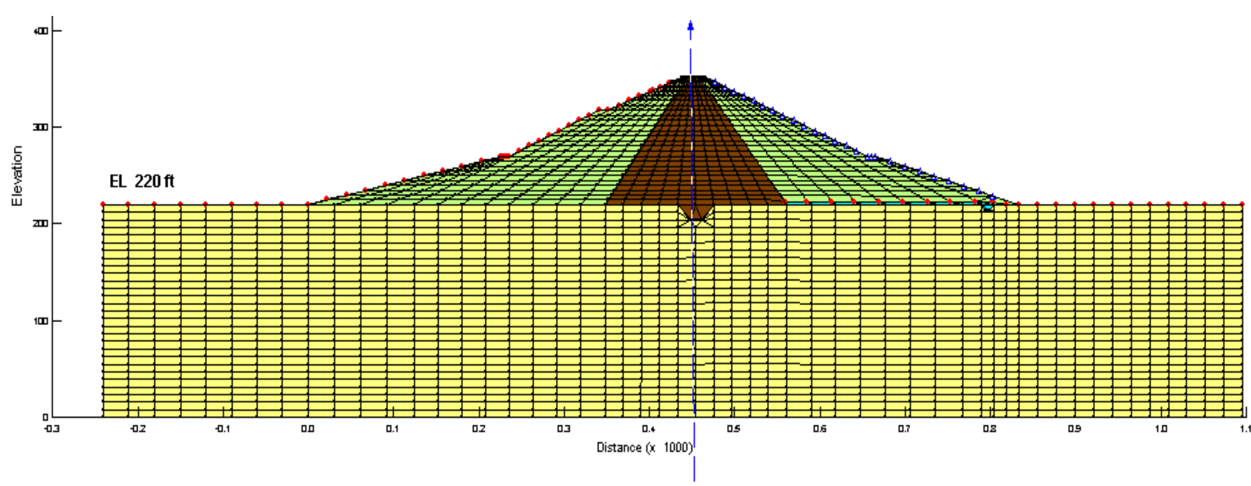

Fig. 2a. Mesh formation for non-homogeneous section with core.

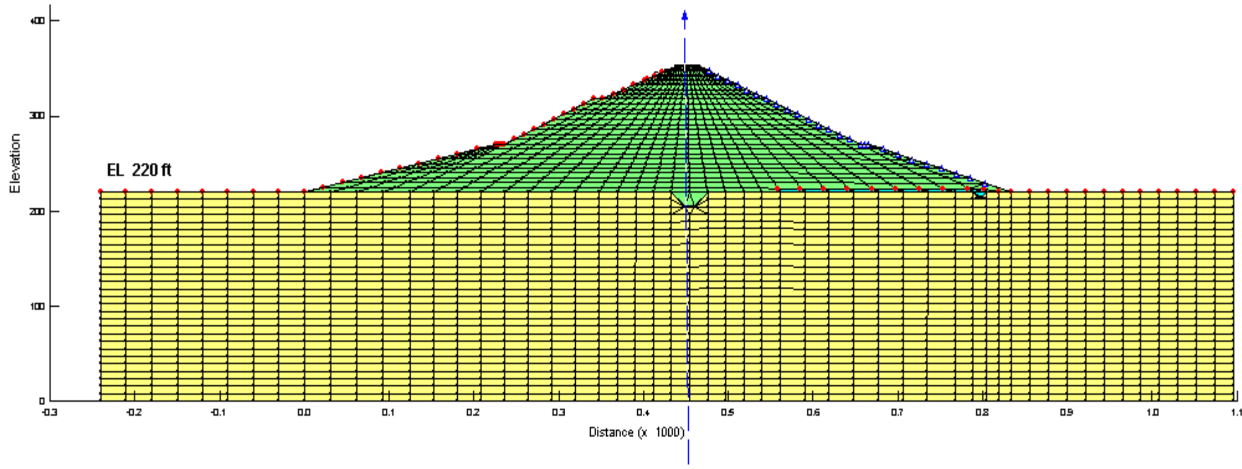

Fig. 2b. Mesh Formation for Non-Homogeneous Section without core.

RESULTS AND DISCUSSION

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) a dam with core and (ii) without core 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 flow-net which comprises of the total head contours, velocity vectors and phreatic surface respectively. The results showed that the presence of the core has a direct effect on seepage and exit gradient. The purpose of the core was to restrict the phreatic line and internal pore water pressure almost at the upstream face of the dam 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 in respectively in (Figure 3a – Figure 5b).

It can be observed from Figure 3a that at maximum pond level the presence of core has a direct effect on phreatic line as after passing the core it is directly falling into the filter drain with seepage flux of order 5.5648 x 10^{-4} ft^3/sec/ft and exit gradient at the downstream toe 0.401 respectively. However, figure 3b showed some different behavior of phreatic surface, as due to the unavailability of the core a high pore water pressure developed in an upstream and downstream shell and the velocity vectors comes out from the downstream shell with a seepage flux of order 9.4926 x 10^{-4} ft^3/sec/ft. Extremely high exit gradient of order 1.411 was recorded in this case which indicates that dam is not safe against piping. The simulated result indicated that the phreatic line cuts the downstream slope of the dam at a distance of 631 ft and an elevation 280 ft due to which dam may suffer from a slope failure. 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 earth-fill dam in Poland.

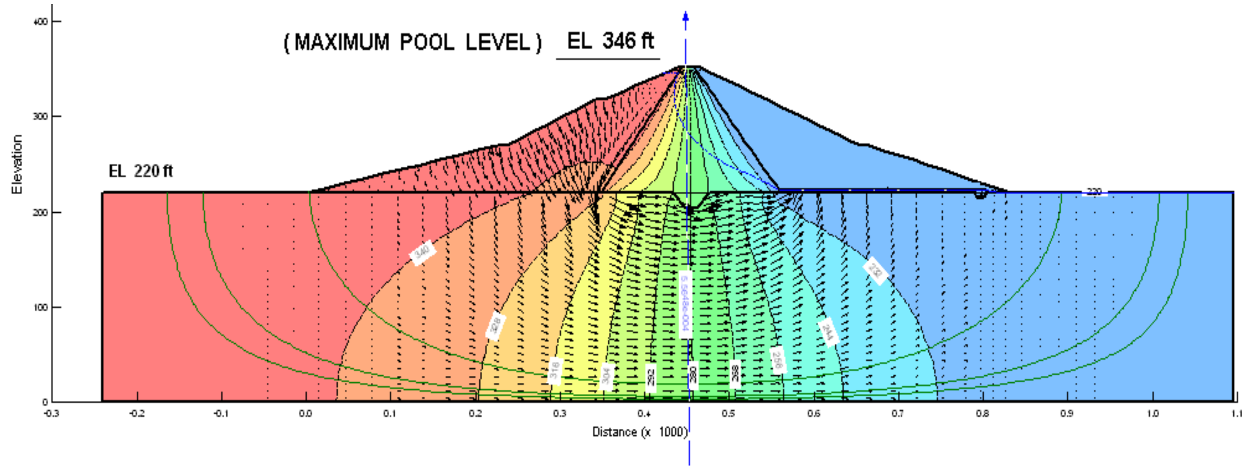

Fig. 3a. Flow-net for Non-Homogeneous Section with Core (Pond level = 346 ft)

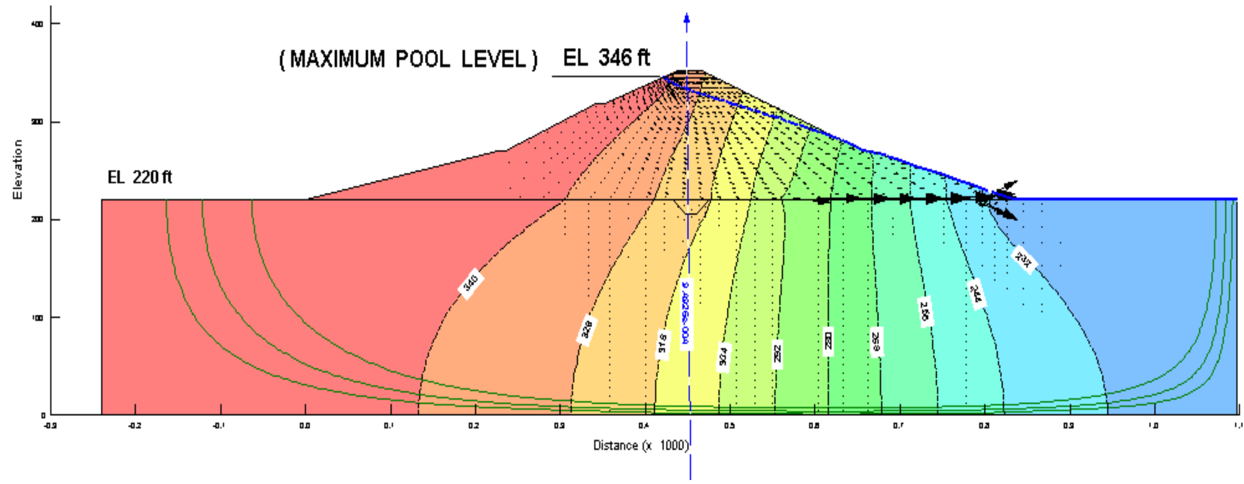

Fig. 3b. Flow-net for Non-Homogeneous Section without Core (Pond level = 346 ft).

Likewise, Figure 4a 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 5.2499 x 10^{-4} ft^3/sec/ft and exit gradient at the downstream toe 0.171 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. However, the figure 4b showed an abnormal behavior of phreatic line at normal pond level without core.

The simulated result indicated that the phreatic line cuts the downstream slope of the dam at a distance of 645 ft and an elevation 274 ft due to which dam may suffer from a slope failure. Furthermore, due to excessive pore water movement and pressure within the dam body an exit gradient at the downstream toe of order 1.322 was observed; which is beyond the permissible limit with seepage flux 8.4418 x 10^{-4} ft^3/sec/ft respectively. Therefore, for the present cross-section of the dam we can consider that the dam without core is not safe against piping as there is a possibility of internal erosion due to seepage. These results are according to the findings of (Arshad *et al.,* 2017), who also computed the seepage flux through a non-homogeneous earth dam with and without filter drain using Geo-Slope software.

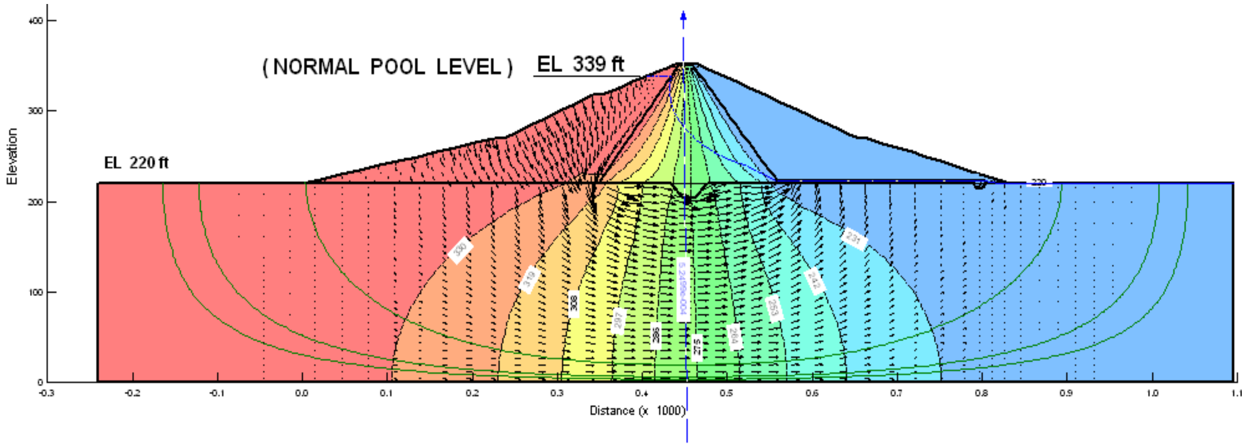

Fig. 4a. Flow-net for Non-Homogeneous Section with Core (Pond level = 339 ft).

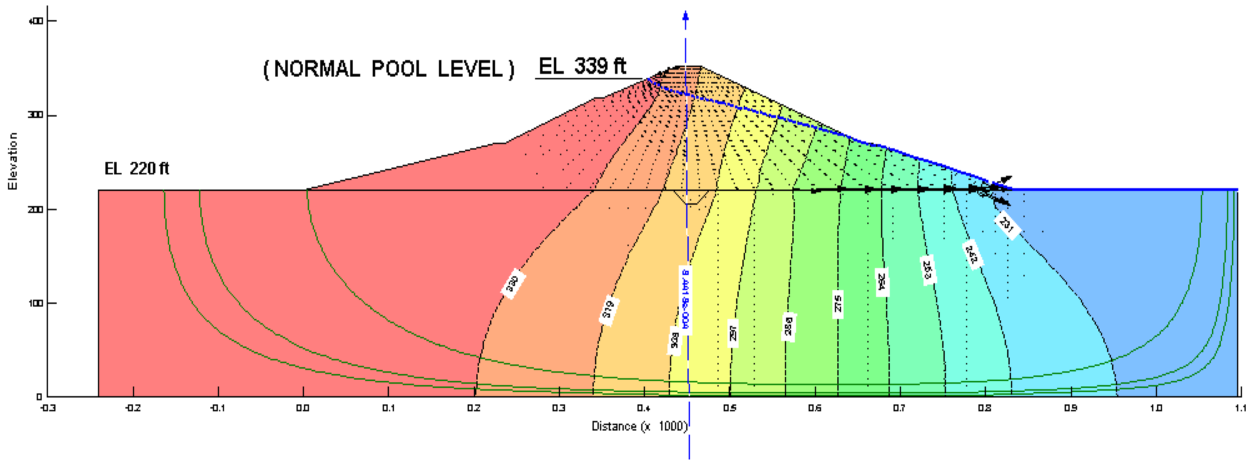

Fig. 4b. Flow-net for Non-Homogeneous Section without Core (Pond level = 339 ft).

Similarly seepage flux and exit gradient for the minimum pond level was computed for both cases. Figure 5a showed that at minimum pond level the dam with core is having seepage flux of order 2.0291 x 10^{-4} ft^3/sec/ft and exit gradient 0.091 respectively. The trend of phreatic line was relatively similar as observed in normal and maximum 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.

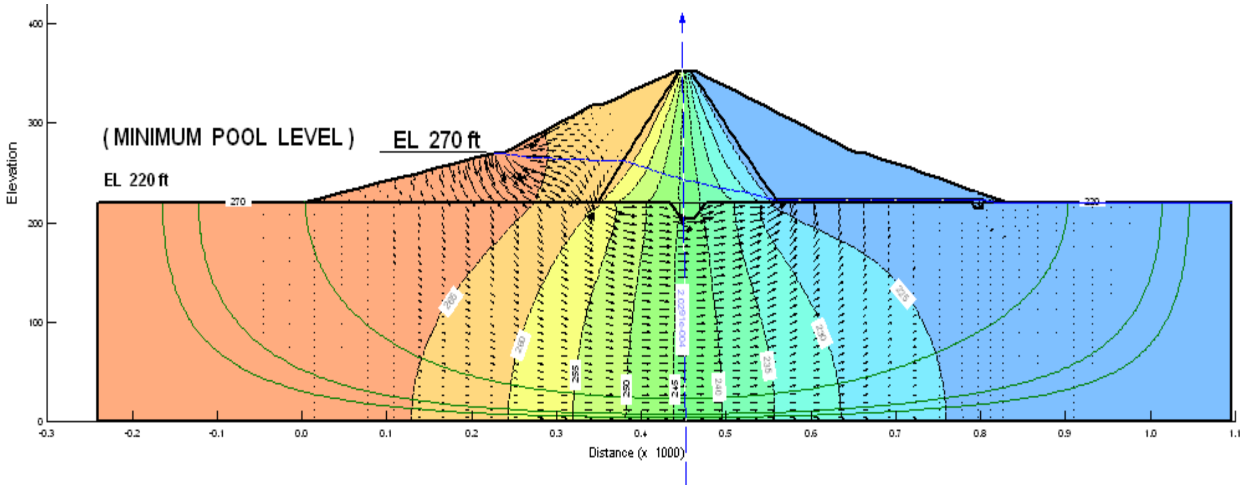

Fig. 5a. Flow-net for Non-Homogeneous Section with Core (Pond level = 270 ft).

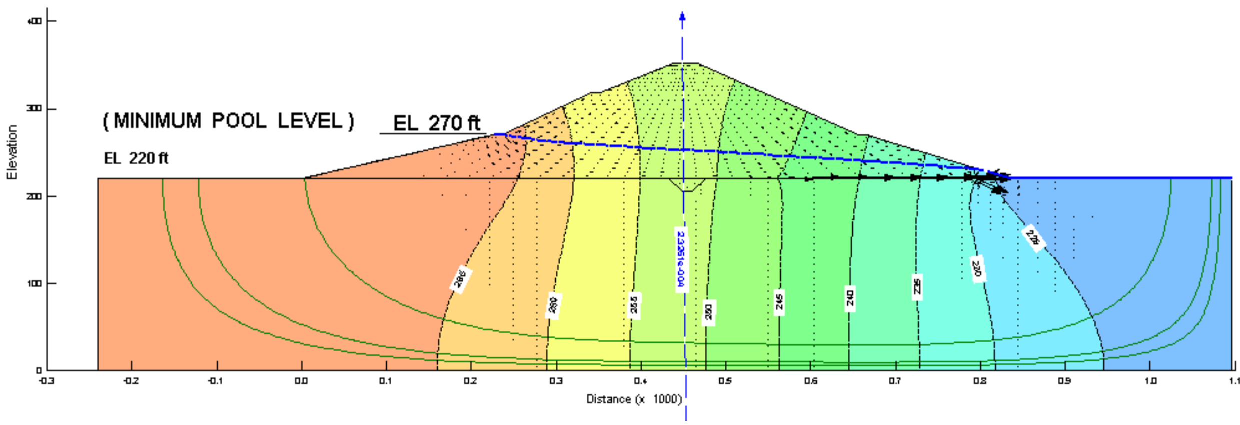

Fig. 5b. Flow-net for Non-Homogeneous Section without Core (Pond level = 270 ft).

Once again the dam showed an anomalous behaviour of phreatic line at minimum pond level without core as mention in Figure 5b. The simulated result indicated that the phreatic line cuts the downstream face of the dam at a distance of 802 ft and an elevation 230 ft, due to which possibility of internal erosion may occur which tends to a slope failure. Furthermore, the velocity vectors due to no installation of core; comes out from the downstream shell with seepage flux of order 2.3261 x 10^{-4} ft^3/sec/ft. A high exit gradient of 1.111 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. Complete analysis results were elaborated in Table 2 respectively.

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

Parameters	Upstream Pond Levels					
	With Core			Without Core		
	Minimum 270 (ft.)	Normal 339 (ft.)	Maximum 346 (ft.)	Minimum 270 (ft.)	Normal 339 (ft.)	Maximum 346 (ft.)
Seepage flux (ft^3/sec/ft)	2.0291×10^{-4}	5.2499×10^{-4}	5.5648×10^{-4}	2.3261×10^{-4}	8.4418×10^{-4}	9.4926×10^{-4}
Exit gradient	0.091	0.151	0.199	1.111	1.322	1.411

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 core respectively. The graphs showed that seepage flux was found (12.768 – 41.378%) more; when there is no core installed in between the centre of upstream and downstream shell of the dam. Due to the absence of core the hydraulic conductivity of the shell material is not fine enough to resist the seeping water within the shell due to which the internal pore water pressure increased in all scenarios. The movement of the water was observed high due to internal piping in the shell region which results in quick movement of water within the shell and which move towards the free drain and downstream slope and cuts the slope respectively. The impact of phreatic line trend is abruptly changing during different scenarios.

On the other hand, the absence of core increases the exit gradient for about (85.896 – 91.809%) due to which a high exit gradient was recorded at the downstream slope. Though in both cases for exit gradient non-linear behavior was observed but due to high pore-water pressure in the shell region without core, the exit gradient at the downstream toe abruptly changed during different scenarios.

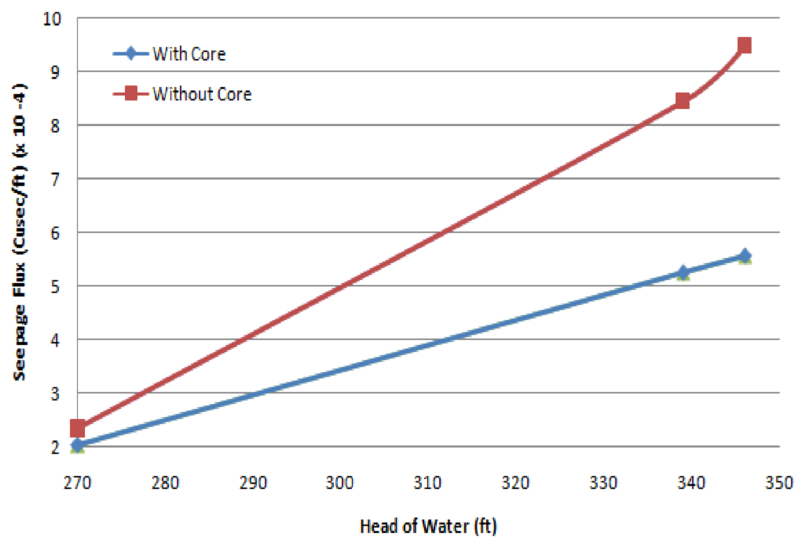

Fig. 6. The relationship between seepage flux at different pond levels when the dam is with and without core.

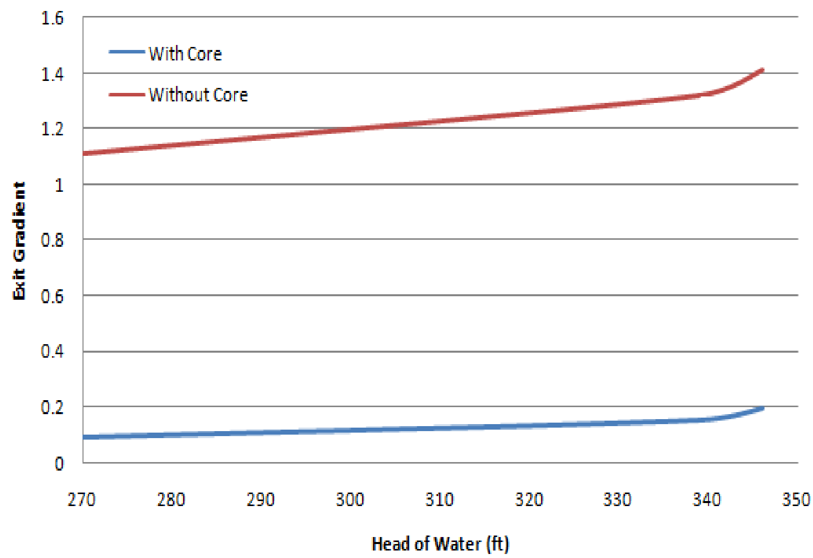

Fig. 7. The relationship between exit gradient at different pond levels when the dam is with and without core.

For the selected case of Hub dam, if the dam is without core (CH: 48+75) 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.,* 2017), who also observed same trend for seepage flux and exit gradient for Al-Adhaim and Hub dam respectively.

CONCLUSION

In present research work, the slave program (SEEP/W) of a finite element based software i.e. Geo-Slope was used to check the behavior of a non-homogenous earth dam for two different cases i.e. (i) with core and (ii) without core respectively. The software was used to simulate total head contours, velocity vectors and the phreatic surface respectively. The simulated results for a non-homogenous section of a (Hub dam) at a chainage (CH: 48+75), showed that at original shape and design with core (case - i) the dam is not endangered from an internal erosion and piping, as the central core plays a key role in lowering the phreatic surface within the dam. For each scenario the equipotential lines and stream lines are found normal to each other. The movement of velocity vectors after passing the core was towards filter drain which conforms; the seepage theory with overall minimum seepage flux of 2.0291 x 10^{-4} ft^3/sec/ft and exit gradient at downstream toe 0.091 respectively.

However, in (case - ii), when the model is run with same shape and design without core, an abnormal behavior of the dam was observed as the phreatic surface cuts the downstream slope of the dam for all the scenarios. A very exit gradient and seepage flux was recorded at different pond levels. Hence, it can be concluded that a central core in an earth dams plays a critical role to control the phreatic surface by lowering down the positive pore water pressure within the upstream and downstream of the shell, lowering the seepage flux and exit gradient respectively.

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CONFLICT OF INTEREST

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

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