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Numerical Analysis of Seepage and Slope Stability in an Earthen Dam by Using Geo-Slope Software

Imran Arshad[1]*, Muhammed Muneer Babar[2], Natasha Javed[3]

[1]Star Services LLC, Al Muroor Road – Western Region of Abu Dhabi, (UAE).
[2]IWREM – CASW, MUET, Jamshoro, Pakistan.
[3]CEES, University of Punjab, Lahore, Pakistan.

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***Corresponding author: Imran Arshad; Email: engr_imran1985@yahoo.com**

Abstract
The present research work was conducted to compute seepage and slope stability analysis of Hub dam (earthen dam) by using the slave programs of Geo-Slope software i.e. SEEP/W and SLOPE/W respectively. The simulation results obtained from the SEEP/W program revealed that the average flow rate of seepage at maximum, normal and minimum pond level were 5.728 x 10^{-4} (ft^3/sec/ft), 4.988 x 10^{-4} (ft^3/sec/ft), and 4.513 x 10^{-5} (ft^3/sec/ft) respectively. The exit gradient value in all different pond levels was less than 1.0, and maximum seepage velocity is within permissible limits, which implies that the dam is secure against piping for the entire scenarios. SLOPE/W program was used to analyze static slope stability of embankment slope under various loading conditions. The stability of embankment slopes was checked by four different analysis methods i.e. Bishop, Janbu, Ordinary method of slice and Morgenstern-Price method accordingly. The simulation results revealed that upstream and downstream side of the dam section has a direct effect on the factor of safety. The three different loading cases were analyzed i.e. end of construction (upstream and downstream slope), steady state seepage (downstream slope) at maximum water level at EL 346 ft, and rapid drawdown for (upstream slope) with the minimum factor of safety 1.653, 1.911, 1.634 and 1.766 respectively. From the results achieved, thus it can be concluded that the Hub dam is safe against the danger of piping and slope failure.
Keywords: Seepage, Slope Stability, Phreatic Line, Hub dam, Numerical Modeling, SEEP/W, SLOPE/W.

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INTRODUCTION

One of the most important stages in designing an earthen dam is the precise estimation of seepage quantity, pore-water pressure distribution used in the analysis of slope stability, total head measurements and hydraulic gradients in various sections of the dam to ensure stability and avoid endangering effects such as piping and slope sloughing (Noori *et al.,* 2011; Arsalan, 2001). The durability and stability of the dam depends on its geometry, its components, material properties of each component and the forces to which it is subjected (Tatewar *et al.,* 2012; Wudtke, 2008). Slope stability and seepage analysis of earth dam is very important to ascertain the stability of the structure. While selecting the type of dam, four basic consideration have to be kept in view viz, whether the foundation and the material of construction can safely withstand the stresses set up under the worst conditions, whether economical arrangements can be made to cope with the flood water during and after construction, whether construction materials are locally available or not, and whether means and methods employed for construction make an optimum use of facilities available within reasonable limits (Quanshu *et al.,* 2010).

The stability of the slope and seepage analysis by using computer software's is easy task for geo-technical engineers when the slope information and the material properties are known. The FEM scheme is proficient enough to simulate two-dimensional unsteady and non-uniform flow through a homogeneous, non-homogenous and anisotropic saturated and unsaturated porous body of any earth fill dam (Ersayin, 2006). Many computer software has come in general use, and any hard computations and simulation can be carried out through them by giving them appropriate inputs and data. This results in less error frequency and more detailed analysis when compared with field observations. The numerical modeling computer program i.e. SEEP/W and SLOPE/W of Geo-Slope Company can be employed to carry out simulation of seepage, phreatic surface, slope stability and drawdown conditions for different scenarios (Arshad *et al.,* 2014 and Geo-Slope, 2007). Considering the discussed facts, in the present research work it would be investigated the amount of water seeping through and beneath the dam body by using the SEEP/W program, and the static slope stability analysis by using the SLOPE/W program respectively.

The purpose of this study was to compute the seepage behavior of an earthen dam by using finite element method through SEEP/W computer program, to simulate phreatic line of seepage for homogenous section for various scenarios of the dam; to analyze the slope stability with different analysis methods i.e. Bishop, Janbu, Ordinary method of slice and Morgenstern-Price methods by using SLOPE/W, and to find out the minimum factor of safety and locate the critical slip surface location.

MATERIALS AND METHODS

Location of Hub Dam

The Hub dam is situated 35 km, North-East of Karachi across the Hub River at 67^{o}.5' East and 25^{o}.15' North at Hub, which is adjoining area of Karachi. The Hub River originates from Kirthar Range at an elevation of about 6,000 ft and passes through 220 miles of tertiary rock terrain before joining the Arabian Sea. The reservoir is dependent of Hub River flow, where catchment area comprises of about 3,410 square miles till the dam site.

Selection of Cross Sections for Numerical Modeling

The main dam composed of different kinds of cross sections i.e. Homogenous and Non-homogenous section, but in this research only homogeneous section is studied which is located at CH: 29+00. The ground level elevations are not constant and varying throughout its length. The elevation of crest for the selected cross section throughout the dam length was EL 352 ft, while the elevation level of the ground was EL 250 ft. The dimensions of selected cross sections are given below in Figure 1.

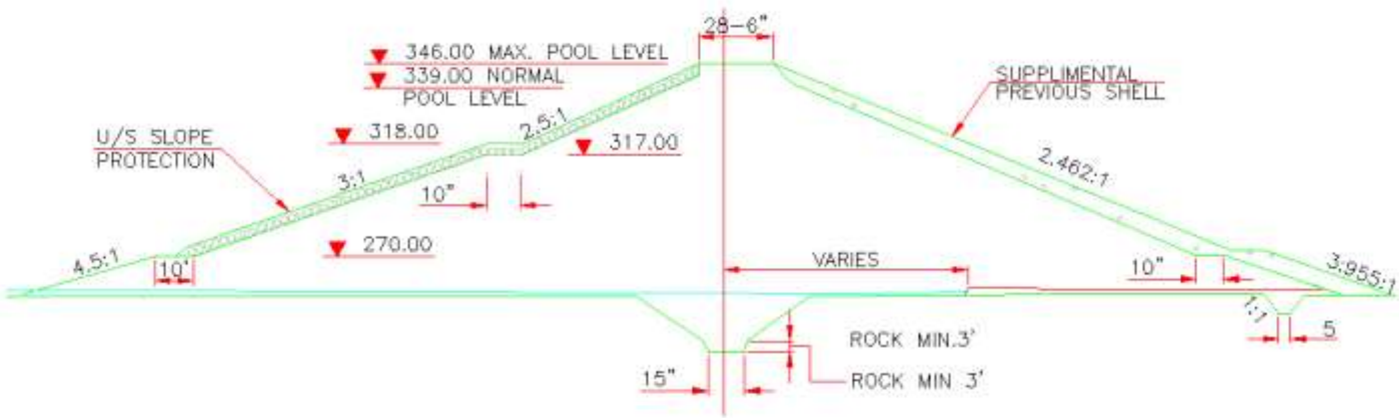

Fig. 1. Geometry of Homogenous Section.

Steps for modeling

To develop a numerical model by using Geo-Slope software for the analysis of seepage and slope stability, in first attempt the cross section at chainage CH: 29+00 was selected. After the selection of cross section by using SEEP/W software FEM mesh for the selected cross section was developed and the seepage analysis was carried out accordingly. According to the given conditions the upstream boundary conditions are assigned as Dirichlet boundary nodes. Similarly, the downstream boundary conditions and the bottom of the foundation are assigned as Neumann boundary nodes (zero-flux) (Bansal *et al.,* 2009). After the development of numerical model, it is verified by the SEEP/W software and computation for different conditions of water levels is carried out accordingly (Arshad *et al.,* 2016 and Al-Damluji *et al.,* 2004). The material properties for the materials used in dam section are calibrated. Computations are carried out for three different scenarios, viz: (i) Maximum pool level (346 ft), (ii) Normal pool level (339 ft), and (iii) Minimum pool level (270 ft) accordingly.

Likewise, SLOPE/W software is used under different conditions to evaluate slope stability of the dam. Initially in first attempt a sketch of slope stability problem is drawn for the cross section at chainage CH: 29+00. According to the given conditions the entry and exit location are assigned as up- and down-stream boundary conditions. Then geological parameters, material properties for the materials used in dam section and piezometeric line are drawn and calibrated accordingly (Osuji *et al.,* 2015). After finalizing the numerical model, it is verified by the SLOPE/W software. Then on the basis of specific analysis methods i.e. Bishop, Janbu, Ordinary method of slice and Morgenstern-Price slope stability analysis was carried out accordingly. Finally minimum safety factor was calculated on the basis simulated results obtained from the SLOPE/W software and discussed accordingly (Gokmen *et al.,* 2005). The problems are to be considered for analysis and computation are analysis of the slope stability during or immediately after the construction of dam for upstream and downstream slope, analysis of steady state seepage for upstream and downstream slope, and analysis of dam behavior for sudden drop in reservoir water level for upstream slope.

RESULTS AND DISCUSSION

FEM mesh Fformation and its verification

The FEM mesh for the Homogenous Section (Chainage: CH - 29+00) comprised of 4 different types of elements, i.e. (square, triangular, rectangular and trapezoidal). Each element is of different size and orientation as described in Figure 2.

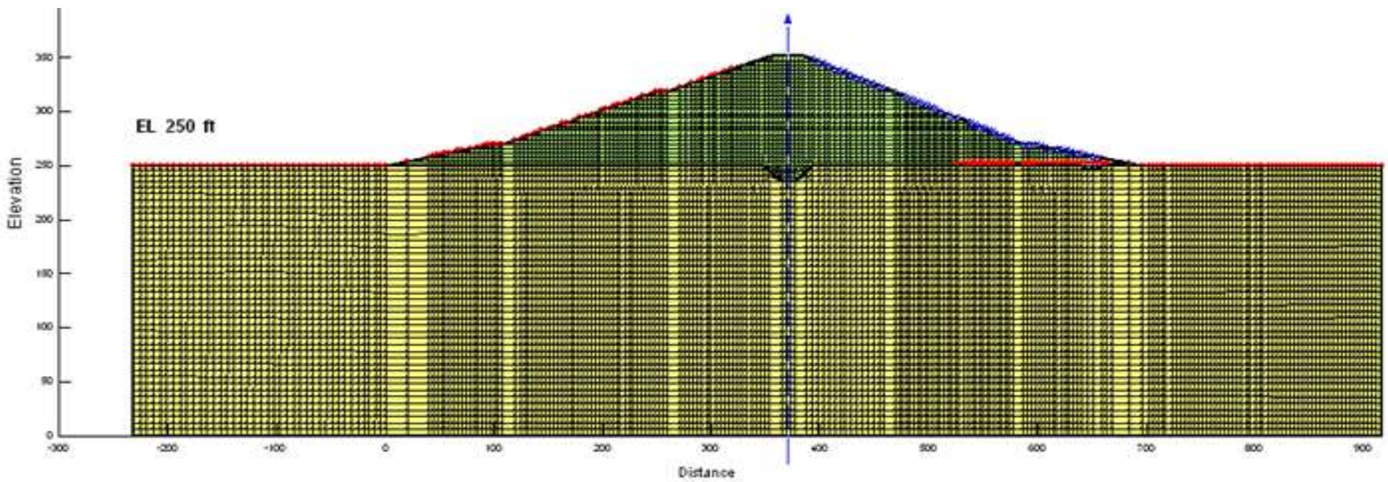

Fig. 2. Mesh Formation for Homogenous Section at (Chainage: 29+00).

Altogether 12,346 elements and 12,495 nodes were used to develop the mesh. The materials were first created and then assigned to the mesh with proper dimensions and its verification has been made accordingly (Arshad *et al.,* 2015). Identical guess values using trial and error method were specified for the section. These guess and calibrated values for the subject cross section are presented below (Table 1). Finally, SEEP/W verified the mesh generation and reported that there is no error in development of numerical model and it is ready for computation.

Table 1. Material Properties of Hub Dam

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

*Source: WAPDA (Water and Power Development Authority)

Likewise, SLOPE/W program is used for numerical modeling for the cross section at chainage CH: 29+00. According to the given conditions the entry and exit location are assigned as up- and down-stream boundary conditions. Then geological parameters, material properties and piezometeric line are drawn and its calibration was took place accordingly. The shear and geological parameters at the time of construction were adopted (Table 2). SLOPE/W then verified the model development and found no error in generation of numerical model.

Analysis of Seepage by SEEP/W

In order to estimate the amount of water seeps through the dam and its foundation SEEP/W program of Geo-Slope software was used and flownet has been drawn as an output (Figure 3 – Figure 5). The flownet consists of streamlines, equipotential lines, velocity vectors and phreatic line respectively. Flownet is an evident that the stream lines and equipotential lines are normal to each other, which conforms to seepage theory (Arshad*.,* 2015). The efficacy of filter blanket at high water levels is more significantly demonstrated at homogeneous section CH: 29+00.

Similarly the output report also illustrates the seepage flux, exit gradient and maximum seepage velocity for the selected cross section at different water levels Table 3. The results revealed that minimum seepage (4.513 x 10^{-5} ft^3/sec/ft) was found, when the water level in the dam was at lower elevation i.e. EL 270 ft. Likewise, the maximum seepage (5.728 x 10^{-4} ft^3/sec/ft) was recorded, when the water level in the dam was at higher elevation i.e. EL 346 ft. However, at normal water level i.e. EL 339 ft, the seepage was recorded (4.988 x 10^{-4} ft^3/sec/ft). From results it can be considered that the overall average water seeping through the dam and its foundation at normal water level was around 50.84 liters per hour. These results are according to the findings of (Osuji *et al.,* 2015, and Arshad *et al.,* 2014), who also compute the seepage flux for an earthen dam during their research study.

Table 2. Geological Parameters of Hub Dam

S. No.	Material type	Unit Weight *p* (kN/m^3)	Cohesion c (kPa)	Friction Angle ϕ (degree)	Hydraulic conductivity (ft/sec)
1	Foundation	20	275	45^o	3.225 x 10^{-6}
2	U/S Shell	19	0	35^o	2.000 x 10^{-5}
3	D/S Shell	19	0	35^o	2.000 x 10^{-5}
4	Filter Blanket	18.5	0	30^o	3.280 x 10^{-2}

Table 3. Computed seepage flux, exit gradient and maximum seepage velocity at Homogeneous Section for different pond levels

Parameters	Upstream Pond Levels		
	Minimum (270 ft.)	Normal (339 ft.)	Maximum (346 ft.)
Seepage flux (ft^3/sec/ft)	4.513 x 10^{-5}	4.988 x 10^{-4}	5.728 x 10^{-4}
Exit gradient	0.174	0.313	0.479
Max. seepage velocity (ft/sec)	3.761 x 10^{-6}	4.143 x 10^{-6}	4.382 x 10^{-6}

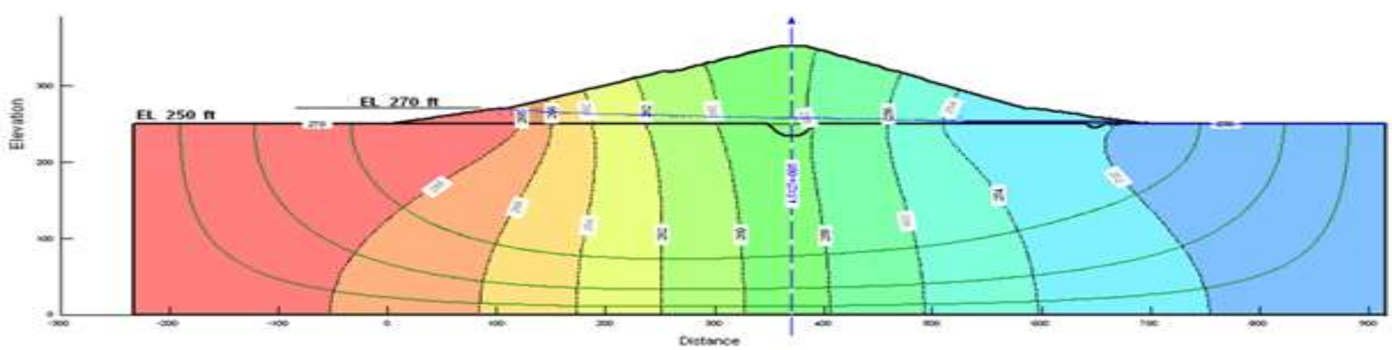

Fig. 3. Flownet for homogeneous section at (Pond level = 270 ft).

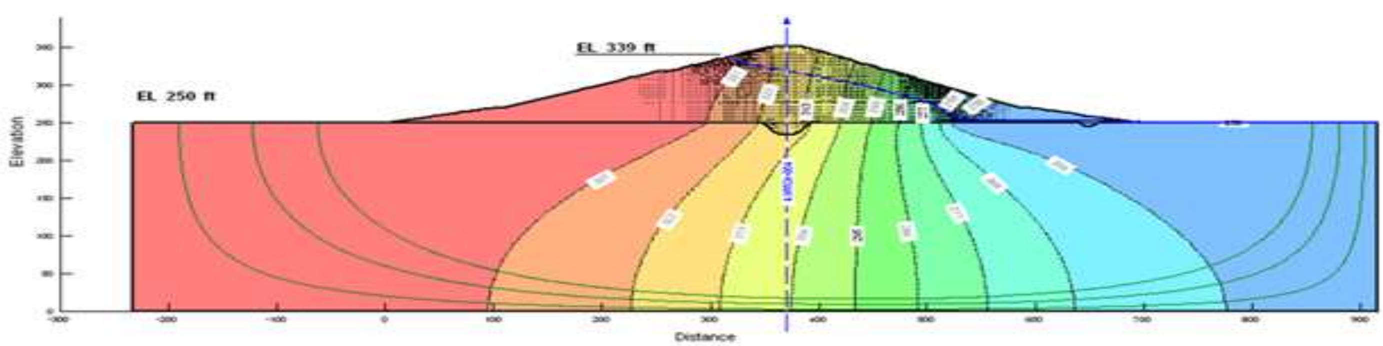

Fig. 4. Flownet for homogeneous Ssection at (Pond level = 339 ft.)

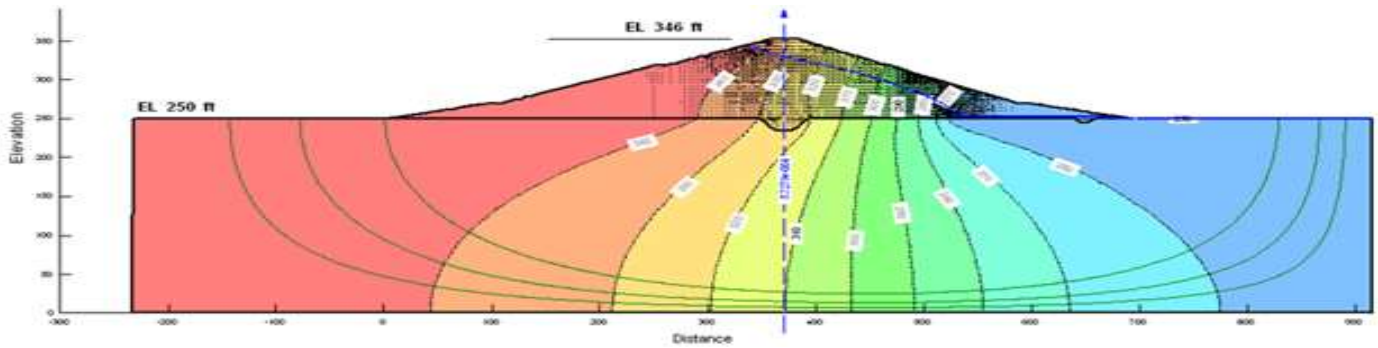

Fig. 5. Flownet for homogeneous section at (Pond level = 346 ft.)

Likewise the output report also ascertained that the exit gradient of the selected section was found less than unity for all the water levels which conforms the safety criteria of the dam. (Figure 6 - Figure 8) describes the graphical representation of seepage flux, exit gradient, and maximum seepage velocity as a function of different water level respectively. Almost for all the water levels a linear trend was observed, however the exit gradient and maximum seepage velocity rises exponentially with the rise of water level in the upstream. Similar results were reported by (Gokmen *et al.,* 2005), who also highlighted same parameters during the study of Jeziorsko earthfill dam in Poland.

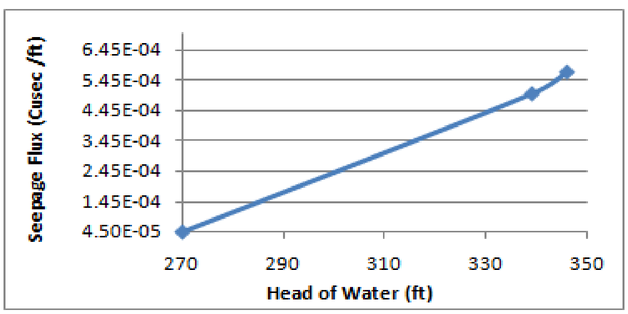

Fig. 6. Seepage flux vs. pond levels at homogeneous section at CH: 29+00.

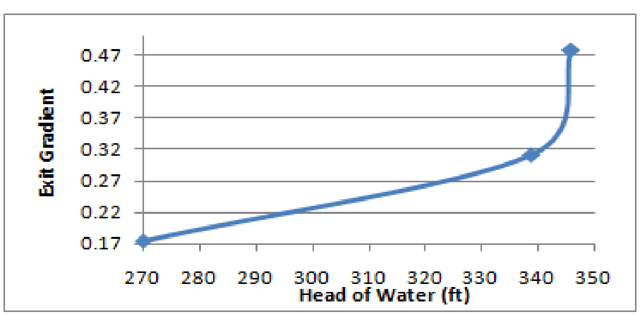

Fig. 7. Exit gradient vs. pond levels for Homogeneous Section at CH: 29+00.

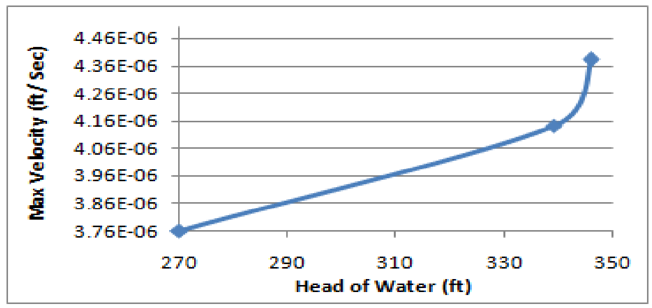

Fig. 8. Max. Seepage velocity vs. pond levels for Homogeneous Section at CH: 29+00.

During steady state seepage, the stability is critical only for the downstream slope of embankment. It is assumed that the steady seepage condition is developed when reservoir is full at maximum retention level i.e. at EL 346 ft. The phreatic surface is estimated using flownet development by SEEP/W program. It is therefore assumed that the downstream drain will drain out the seepage and no seepage pore pressure will develop in downstream filling material. Table 4 describes the comparison between field piezometers and simulated reading for homogeneous section at maximum pond level i.e. EL 346 ft. The comparison shows that the simulated values of piezometeric heads are very close to the observed values. Similar results were obtained by (Nasim., 2007) for the case study of Al-Adhaim dam.

Table 4. Comparison between field piezometers and simulated reading for homogeneous section at maximum pond level (pond level 346 ft.).

Sections	X - distance (ft.)	*Observed head H_o (ft.)	Simulated head H_s (ft.)	Relative error (%)
Homog-eneous Section	357	342	343.26	-0.367
	437	289	291.17	-0.745
	487	273	275.69	-0.975
	587	261	264.53	-1.334

Analysis of Stability of the Slope by SLOPE/W

The SLOPE/W software is used to get slope stability analysis for the upstream and downstream slope for different scenarios and checked by different analysis methods accordingly. The analysis is carried out in terms of effective stresses. Pore pressures for various loading conditions are estimated as subsequently described. For each case analysis the critical slip surface yielding the minimum safety factor is found by rigorous search. The section at which the dam height become maximum is selected for stability analysis, because this is the critical section for stability as compared to other and will give the minimum factor of safety. From SLOPE/W simulations it may be noted that the minimum safety factors on all loading cases were having critical surface near outer faces only, and location of the critical slope surface along with the safety factors obtained by different methods.

Both upstream and downstream slopes are analyzed for end of construction. The pore pressures which remain in the filling material of upstream and downstream shell at the end of construction depend on the placement moisture content, the pore pressure response to loading at the relevant stress and moisture content, the rate of dissipation and the rate of construction. Considering the free draining nature of filters blanket, it is assumed that no construction pore pressures will develop in these zones. It is also assumed that the foundations will not be saturated during construction and will therefore not develop pore pressure. Typical result for downstream slope after the construction of dam with minimum safety factor 1.634 for Steady State Seepage Condition is elaborated in Figure 5 accordingly.

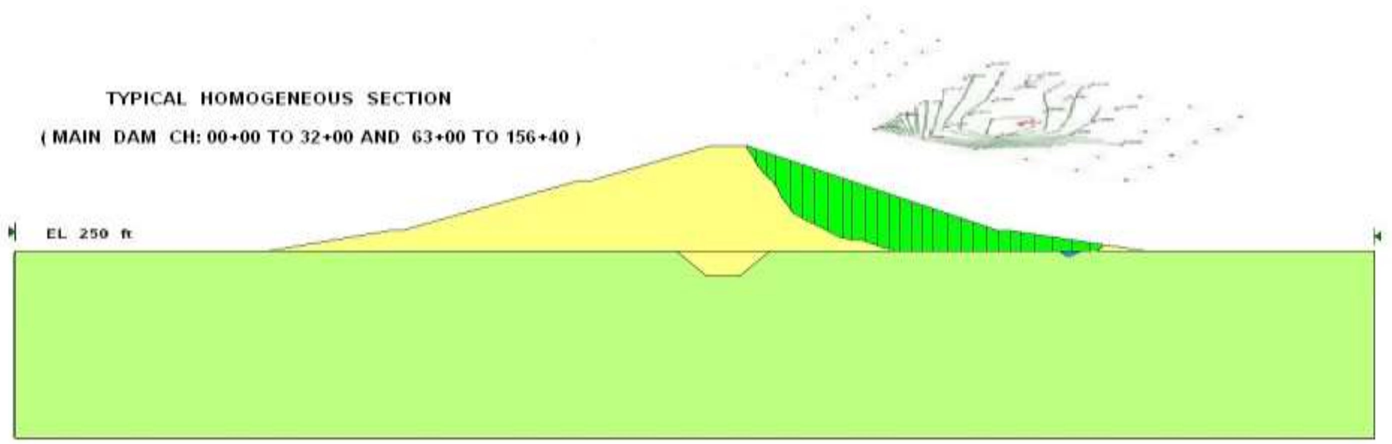

Fig. 5. Fs.min equal to 1.634 for steady state seepage condition at downstream slope for homogeneous section at CH: 29+00.

For the case of rapid drawdown it is assumed that reservoir will be at maximum conservation level i.e. at EL 346 ft for a sufficiently long time so that the steady seepage condition will develop in the dam embankment and reservoir is rapidly emptied. In rapid drawdown case, stability will be critical for the upstream slope only. The pore pressures under rapid drawdown are estimated assuming no dissipation of pore pressures in the shell. All other embankment zones are assumed to be free draining. Similar results were observed by (Khattab., 2010), who also compute slope stability for a Mosul dam during his research study. Summary results of slope stability analysis along with minimum acceptable safety factors as adopted in the design criteria are shown below (Table 5).

Table 5. Summary results of safety factor for stability slope analysis of Hub dam.

S. No.	Analysis Method	End of Construction		Steady State Seepage	Rapid Drawdown
		Upstream Slope	Downstream Slope	Downstream Slope	Upstream Slope
1	Janbu	1.687	1.911	1.649	1.766
2	Bishop	1.921	2.299	1.879	2.027
3	Ordinary Slice	1.653	1.967	1.634	1.811
4	Morgenstern- Price	2.048	2.261	1.835	2.103

CONCLUSION

In the present study using the Geo-Slope software, seepage and slope stability analysis in Hub dam (earthen dam) was studied. SEEP/W software was used to compute seepage, while SLOPE/W was used for the analysis of slope stability. Results of the study showed that the average flow rate of seepage at maximum, normal and minimum pond level are 5.728 x 10^{-4} (ft^3/sec/ft), 4.988 x 10^{-4} (ft^3/sec/ft), and 4.513 x 10^{-5} (ft^3/sec/ft) respectively. As the level in the pond increases the quantity of seepage also increases, therefore the loss of water in the dam ultimately increases. On the basis of results obtained the average seepage rate at normal pond level in the case of Hub dam is around 50.84 liters per hour. The exit gradient value (i.e. less than 1.0) and maximum seepage velocity is within permissible limits, which ensures that there is now any danger of piping and possibility of internal erosion due to seepage for all the scenarios. However, as the water level in the upstream rises the velocity also rises exponentially. This is because initially there was a linear laminar flow but as the pond level is rising the flow is laminar but non-linear. The phreatic line has been simulated and compared with field observations. The compared results showed that field piezometer readings of the Hub dam are very close to the simulated readings; however some variation has been observed which may be due to personal errors. Thus, the results from this program showed acceptable accuracy compared with the experiments results.

SLOPE/W program is used to analyze static slope stability of embankment slope under various loading conditions. The stability of embankment slopes was checked by four different analysis methods i.e. Bishop, Janbu, Ordinary method of slice and Morgenstern-Price method accordingly. The simulation results revealed that upstream and downstream side of the dam section has a direct effect on the factor of safety. The analysis has been carried out in terms of effective stresses conditions. The three different loading cases were analyzed i.e. end of construction (upstream and downstream slope), steady state seepage (downstream slope) at maximum water level at EL 346 ft, and rapid drawdown for (upstream slope) with minimum factor of safety 1.653, 1.911, 1.634 and 1.766 respectively. The detailed summary results of safety factor for stability slope analysis of Hub dam are elaborated in Table 5. From the results achieved from numerical modeling, it is found that the parameters studied have a significant influence on the safety factor of the slope stability of hub dam and thus it can be concluded that the Hub dam is safe against the danger of piping and slope failure.

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CONFLICT OF INTEREST

There is no conflict of interest.

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