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Comparison of SEEP/W Simulations with Field Observations for Seepage Analysis through an Earthen Dam (Case Study: Hub Dam - Pakistan)

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Abstract

The present research work is designed to model seepage analysis of an earthen dam by using finite element approach. For this purpose a research study was conducted on Hub dam, which is a small earthen dam located at about 35 km, north-east of Karachi city, Pakistan. In the study the amount of seepage through and under body of the main dam is computed, profile of phreatic line is simulated for different scenarios and compared with the observed data. For the purpose of this study, SEEP/W the sub-program of Geo-Slope software is used. Data pertaining to design parameters and dam geometry are given as input to the software to compute the unknown parameters. Finally results are validated by comparing them with the observed data. The main dam is composed of three different kinds of reaches; therefore in this research only one reach with core wall i.e. Zoned Embankment Section at CH: 48+75 is studied. Computations are carried out for three different scenarios, that is: maximum pool level, normal pool level, and minimum pool level.

Calibration of the material properties is made on the basis of minimization of error while comparing observed hydraulic heads with the simulated ones. The flownet has been drawn comprising of streamlines, equipotential lines, velocity vectors showing dominant flow (seepage) field and phreatic line depicting seepage behavior of the Hub dam. The seepage flux (discharge), exit gradient and maximum seepage velocity for the entire pond level scenarios and for all the selected section are computed. At lowest *pond level minimum seepage occurs at highest pond level maximum seepage occurs. It is also ascertained that the exit gradient is within the permissible limits that is that less than unity for all the scenarios; thus it also conforms to safety criteria of the dam. Seepage velocities for the entire pond level scenarios and for the selected section are computed; at lowest pond level minimum seepage velocity is observed and at highest pond level maximum velocity occurs.*

Residual head dissipation trend is modeled and predicted for all the sections of interest for different scenarios. At selected section i.e. Zoned Embankment Section at CH: 48+75 for low pond level slightly smoother dissipation rate is followed, however, at higher pond levels a somewhat rapid dissipation of head occurs at sheet pile positions; this of course signifies the effectiveness of sheet pile. Initially dead dissipation follows somewhat smoother trend, however at the position of core wall and sheet pile an abrupt rise in dissipation of head is exhibited, which again signifies the effectiveness of the two seepage control devices.

Validation of any model is made by comparing simulated results against the observed ones; this is done to ensure model applicability. If this comparison shows a good coincidence, then the model developed can be recommended for practice. Table 4 contains the data pertaining to observed piezometeric heads and simulated ones and the relative error. Performance of the model is assessed evaluated on the basis of statistical parameters, i.e. mean error, root mean square error and model efficiency; these results are presented in Table 6.

Keywords: Seepage Analysis, Phreatic Line, Earthen dam, SEEP/W, Finite Element Modeling.

INTRODUCTION

It is well known fact that excessive seepage in any type of a dam is one the root cause to destabilize the dam structure and thereby bring economical havoc. Ensuingly pragmatic efforts are employed to carryout in depth study of the seepage analysis through and beneath the body of a dam. Generally designers by employing different techniques augment safety of a dam and smear errors in computation due to maintenance of water storage, especially by focusing on hydro structure of the dam. The seepage control of any dam may be analyzed by virtue of various available methods. Seepage is the main aspect and its control enjoys main position in designing, construction and maintenance of any dam. Thus a dam engineer must be well versed in understanding seepage problems, their solution and preventive measures monitoring. The flow conditions of any porous environment can be investigated by using numerical techniques framed in the form of a software solution, i.e. computer program Kamanbedast et al. (2011). The main difficulty in diagnosing the seepage problems is fixing the location of phreatic surfaces; which at initial stages cannot be fixed and thus requires iterative processes Kazemzadeh-Parsi et al. (2012). The seepage analysis of a dam is essential for evaluation of its safety and stability especially by using numerical techniques; by doing this one can analyze seepage field and make its comparison under different conditions. By doing this the effect of core and other assorted factors can also be investigated Quanshu et al. (2010).

Many computer software's have 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 model SEEP/W can be employed to carry out simulation of seepage and phreatic surface. The SEEP/W program is capable enough to simulate quite effectively seepage rates and phreatic surfaces in homogenous and non-homogenous earthen dams Mohammed et al. (2006). SEEP/W is a finite element computer enabled (CAD) software which is capable enough to solve groundwater flow, seepage and excessive pore water pressure problems within the porous media such as soil and rock. The software is capable enough to resolve the problems ranging from simple saturated steady state issues to saturated/unsaturated time dependent problems. The software is also capable enough to employ in designing of geotechnical, civil, hydrological and mining engineering problems. The principal quality of the software is due to its ability to allow seepage analysis as a function of time and this process is considered as infiltration of precipitation. Due to transient characteristic of the system, it provides a window of opportunity for researchers to analyze such problems; for instance migration of a wetting front and dissipation of excessive pore water pressures Geo-Slope International (2007).

In view of all above facts, the present research work is designed to model seepage analysis of an earthen dam by using finite element approach. For this purpose a research study was conducted on Hub dam, which is a small earthen dam located at about 35 km, north-east of Karachi city, Pakistan. The dam is the only dam built on Hub river, which originates from the Kirthar range mountains from an elevation of about 6000 ft. in the north of Arabian sea and the river after covering a rocky terrain of about 220 km outfalls into the sea. The catchment area comprises of about 3,410 square miles till the dam site. This whole catchment area consists of arid zones of Sindh and Balochistan. The catchment area is confined by Pab range of mountains on its right, while Kirthar range is located on its left side. It is stretched in north-south direction with its far most tip highest elevation close to Khuzdar, approximately at about 7000 ft. above sea level.

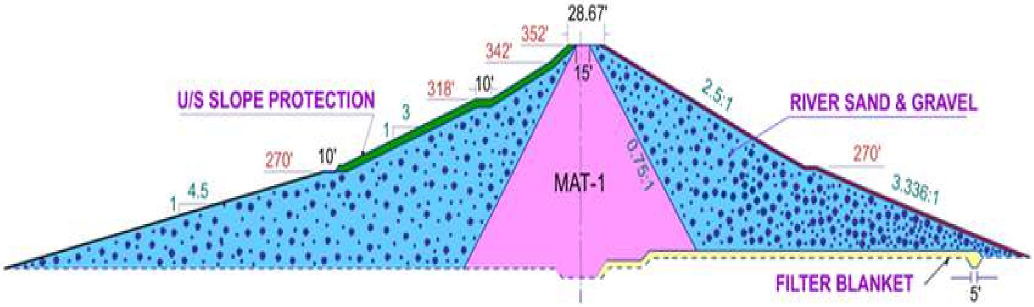

Fig. 01: Zoned Embankment Section at CH: 48+75

The main dam is 15,640 ft long and 152 ft high earthen embankment. Except for a 3,100 ft reach (between Ch. 32 + 00 to 63+00) of zoned section in river valley, the entire length of the embankment is made of homogenous section with a supplemental downstream shell of pervious material. The zoned embankment has silt (intermixed ML and CL material) and clean river sand-gravel in shoulder of the closure section.

The objective(s) of this research work was to study the seepage behavior of earthen dam by using Finite Element analysis, to develop and calibrate a computer model for an earthen dam using FEM based software i.e. the SEEP/W, and to compare observed and simulated data.

Materials and Methods

Steps for Modeling of Hub Dam

In first attempt, in order to achieve the research objectives of the present study cross sections at Zoned Embankment chainage Section i.e. CH: 48+75 was selected for to model by using SEEP/W software. In second attempt the SEEP/W software is used to generate FEM mesh to carry out the seepage analysis. The up- and down-stream boundary conditions are assigned as Dirichlet and Neumann boundary nodes according to given conditions. The nodes at bottom of the foundation of dam are considered with zero-flux (Nuemann) condition. When the model is completely developed then it is verified by the SEEP/W software and after acceptance of the model by the software, it is ready for computation. For the selected cross-section, computation is carried out for different scenarios of water levels. The material properties for the materials used in dam section are calibrated. Finally simulated results obtained from the SEEP/W software for the selected section was compared with the observed data obtained from the WAPDA.

GOVERNING EQUATIONS

In this research work, finite element approach is employed to solve the governing differential equations pertaining to seepage through body of dam its foundation. The SEEP/W software (program) is a sub-program of the Geo-Slope (software) computer, which is used to cater for seepage problems through porous soil media. SEEP/W is a FEM based CAD type software used to analyze seepage and groundwater flow problems. Following partial differential equation (PDE) is the governing equation used for modeling of SEEP/W program:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_x \frac{\partial H}{\partial y}\right) + Q = \frac{\partial \theta}{\partial t}$$

…..1

where

H- is hydraulic head, Kx- and Ky- are hydraulic conductivity in x- and y-directions, respectively, Q- is the applied source or sink terms, t- is the time domain and $\theta -$ volumetric water content.

Eq. (1) is a two-dimensional non-linear second order PDE and caters for transient flow conditions; its derivation involves the basic constitutive law of Darcy for groundwater flow, given as below:

$$v = -K\,\nabla H$$

…..2

where

$$\nabla H = \begin{bmatrix} \dfrac{\partial H}{\partial x} \\ \dfrac{\partial H}{\partial y} \end{bmatrix}$$

…..3

in which v- is average velocity through soil media known as the Darcian velocity; K- is hydraulic conductivity of the soil material; and ∇H - is the gradient of hydraulic head in x- and y- directions.

The Eq. (1) is time variant and states that 'the difference between the flow entering an elemental volume and leaving an elemental volume at a point is equal to the change in the volumetric water content in a particular time'. If the volume of influx equals to the volume of out flux then the equation caters for steady state conditions, thus the right hand of the equation changes to zero.

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_x \frac{\partial H}{\partial y}\right) + Q = 0$$

…..4

Changes in volumetric water content depend upon properties of the soil and changes in the stress state. Following set of two variables essentially describe the state of stress under saturated and unsaturated conditions, that is (ua) and (ua - uw), where ua - represents pore air pressure and uw - stands for pore water pressure.

The SEEP/W programme is based on constant total stress conditions i.e. no loading and unloading of soil mass is involved. Other aspect is that the pore air pressure remains constant during transient process i.e. ua - remains constant, which implies that volumetric water content remains unchanged. Volumetric water content changes are dependent on changes in (ua - uw). A change in volumetric water content in terms of change in pore water pressure is represented by the following equation:

$$\partial\theta = m_w \, \partial u_w$$

…..5

where mw- is slope of the storage curve.

The total hydraulic head is as under:

$$H = \frac{u_w}{\gamma_w} + y$$

…..6

where

uw- is pore water pressure, γ_w- is specific weight of water, H – Total hydraulic head, and y- is elevation head.

Now equation (6) can be arranged as:

$$u_w = (H - y)$$

…..7

Substituting equation (7) into equation (5) we get the following equation:

$$\partial\theta = m_w \gamma_w \, \partial(H - y)$$

…..8

Now by substituting the above equation in equation (3) we get the following expression:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = m_w \gamma_w \frac{\partial (H-y)}{\partial t}$$

…..9

As the subject elevation is static, due to which the derivatives of (y) w.r.t time vanishes and consequently the differential equation appended below will be the resultant differential equation:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = m_w \gamma_w \frac{\partial H}{\partial t}$$

…..10

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

FEM meshes for the selected section are developed by using the SEEP/W software. The material properties for each section with proper dimensions are made as input to the software respectively and verification for each cross section has been made accordingly. The FEM mesh at the selected Section is composed of four types of elements, i.e. triangular, square, rectangular and trapezoidal type of elements of different sizes Fig. 02. The number of nodes is 2,299 and the total number of elements is 2,206.

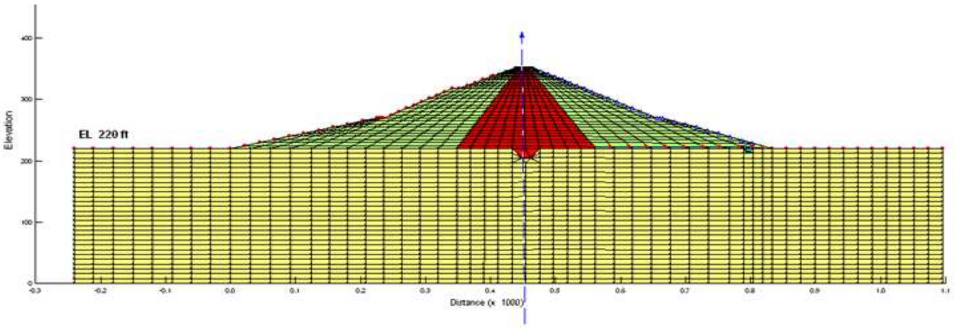

Fig. 02: Mesh Formation for Zoned Embankment Section at Ch: 48+75.

After all the necessary inputs, the computer program SEEP/W verified the mesh development and delivered report that the vertical and horizontal meshing is strong enough and there is no error in formation of mesh model. Thus the model is ready for computation and analysis of the results.

Setting of Boundary Conditions

Computations are carried out for following three different scenarios, viz: (i) Maximum pool level (346 ft), (ii)Normal pool level (339 ft), and (iii) Minimum pool level (270 ft).

Boundary conditions are set as: (i) At fill level up- and down-stream boundary conditions are considered as Dirichlet boundary conditions for all the above given scenarios, and (ii) In foundation up-, down- and bottom level are considered as with zero-flux condition i.e. Neuman boundary conditions for all the above given conditions.

Problem Considered for Analysis and Computation

The following problems are to be considered for analysis and computation:

- Development of flow net by tracing streamlines and equipotential lines for different conditions.
- Observation of velocity vectors and thereby seepage behaviour for different conditions.
- Profile of the phreatic line for different conditions.
- Estimation of seepage quantity through the dam profile and its foundation for different conditions.
- Computation of Exit gradient, maximum velocity and Residual head along the dam foundation under different conditions.

Results and Discussion

Calibration of Material Properties of Hub Dam Model

For calibration of material properties for the selected section of the Hub dam, initially identical guess values were specified for all the sections. These guess values for different types of materials used in the dam are presented below in Table 1. Calibration of the material properties is made on the basis of minimization of error while comparing observed hydraulic heads with the simulated ones.

Table 1: Material Properties (Guess Values)

S. No	Material type	* Hydraulic conductivity (ft/sec)
01	Foundation	10^{-4} to 10^{-6}
02	Shell	10^{-5} to 10^{-6}
03	Core	10^{-8} to 10^{-7}
04	Filter Blanket	10^{-2}

* Source: WAPDA

Using SEEP/W software, the material properties (hydraulic conductivities) calibrated for the selected section are presented in Table 2.

Table 2: Calibrated Values of Material Properties
for Selected Section at CH: 48+75.

S. No	Material type	Hydraulic conductivity (ft/sec)
01	Foundation	3.015×10^{-6}
02	Shell	2.385×10^{-5}
03	Core	2.000×10^{-8}
04	Filter Blanket	3.280×10^{-2}

Flownet with Stream- and Equipotential Lines, Phreatic Line Behaviour and Velocity vectors

The SEEP/W software is also used to get seepage analysis through the dam and its foundation for different pond level scenarios. For this purpose, using the software flownet has been drawn for all the selected sections as shown in Fig. 3 – 5. The flownet comprises of streamlines, equipotential lines, velocity vectors showing dominant flow (seepage) field and phreatic line depicting seepage behavior of the Hub dam. From the Figures it is revealed that the stream and equipotential lines are normal to each other, which conforms to seepage theory. The effectiveness of filter blanket and core wall at higher pond levels is more significantly demonstrated at the selected section.

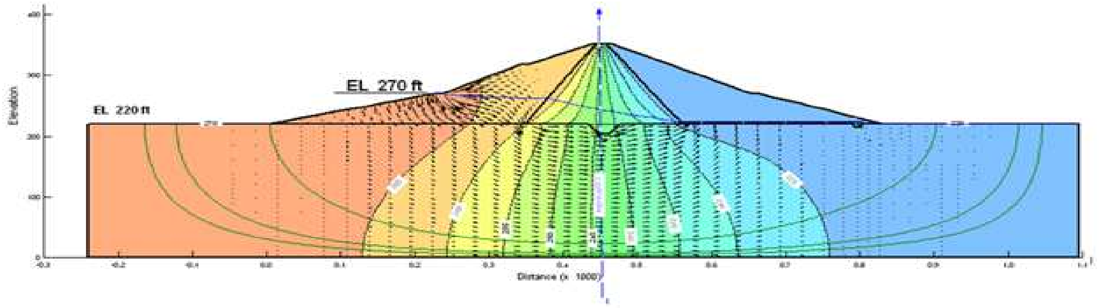

Fig. 3: Flownet for Selected Section at CH: 48+75 (Pond level = 270 ft.)

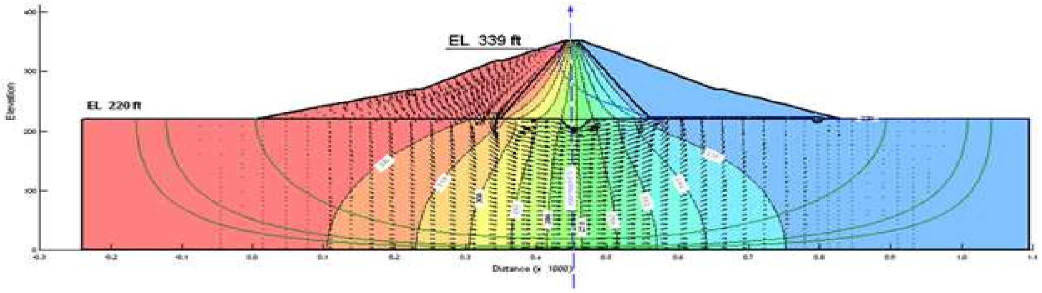

Fig. 4: Flownet for Selected Section at CH: 48+75 (Pond level = 339 ft.)

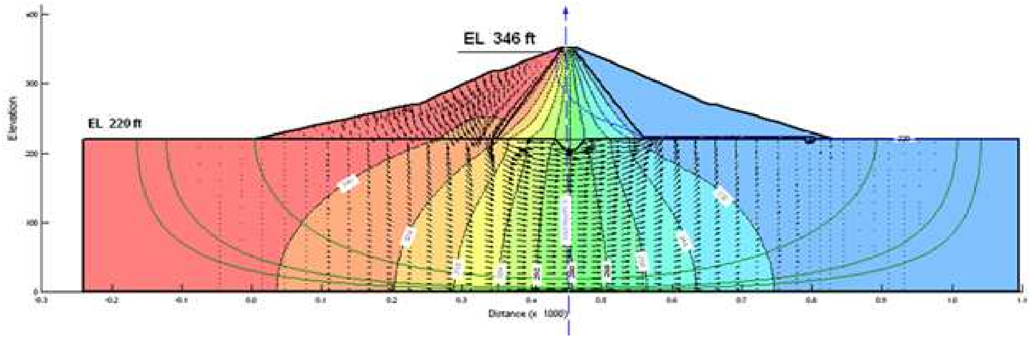

Fig. 5: Flownet for Selected Section at CH: 48+75 (Pond level = 346 ft.)

Seepage Flux, Exit Gradient and Maximum Seepage Velocity

Using the SEEP/W software, the seepage flux (discharge), exit gradient and maximum seepage velocity for the entire pond level scenarios and for the selected section are computed; these are listed in Table 3. At lowest pond level minimum seepage occurs that is of the order of 2.029 x 10^{-4} (ft^3/sec/ft); at highest pond level maximum seepage occurs which is of the order of 5.565 x 10^{-4} (ft^3/sec/ft). A graphical correlation of seepage flux versus pond level is also shown in Fig. 6.

Likewise it is also ascertained that the exit gradient is within the permissible limits that is that less than unity for all the scenarios and at the selected sections for study; thus it also conforms to safety criteria of the dam. Fig. 7 shows a graphical relationship for exit gradient as function of pond level. In this case initially a linear behavior is followed; however the exit gradient rises exponentially as the pond level increases.

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

Parameters	Upstream Pond Levels		
	Minimum 270 (ft.)	Normal 339 (ft.)	Maximum 346 (ft.)
Seepage flux (ft^3/sec/ft)	2.029 x 10^{-4}	5.250 x 10^{-4}	5.565 x 10^{-4}
Exit gradient	0.137	0.274	0.402
Max. seepage velocity (ft/sec)	1.775 x 10^{-6}	2.678 x 10^{-6}	3.181 x 10^{-6}

Similarly seepage velocities for the entire pond level scenarios and for the selected section are computed; at lowest pond level minimum seepage velocity is observed which is of the order of 1.775 x 10^{-6} (ft/sec); and at highest pond level maximum velocity occurs is of the order of 3.181 x 10^{-6} (ft/sec). Fig. 8 shows a graphical relationship for maximum seepage velocity as a function of pond level; under this case at first a linear behavior is followed, however the velocity rises exponentially as the pond level goes up on increasing.

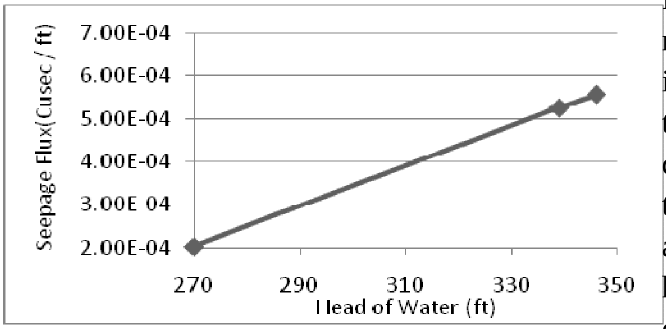

Fig. 6: Seepage flux vs. pond levels at Selected Section at CH: 48+75

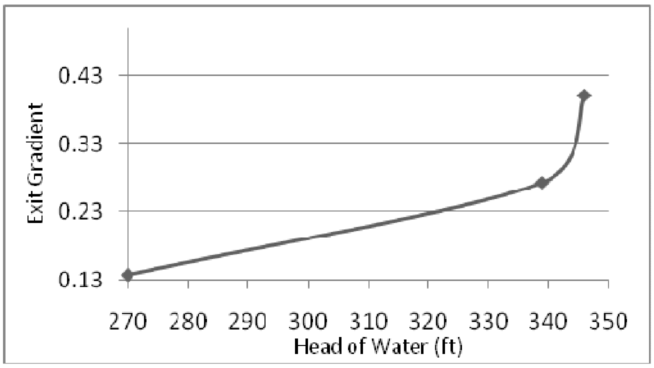

Fig. 7: Exit gradient vs. pond levels at Selected Section at CH: 48+75

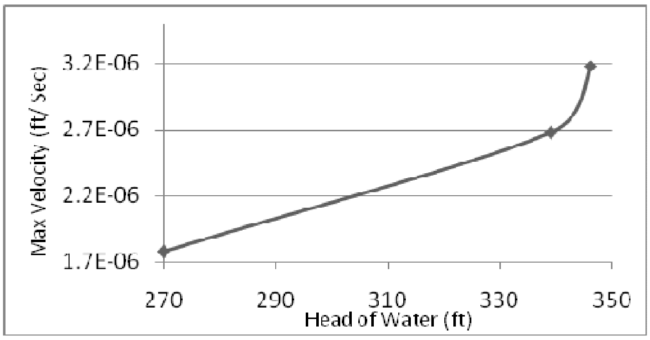

Fig. 8: Max. Seepage velocity vs. pond levels Selected Section at CH: 48+75

Residual Head Dissipation Trend

Residual head dissipation trend is also modeled and predicted for all the sections of interest for different scenarios. From Fig. 9 through Fig. 11, it can be seen that initially dead dissipation follows somewhat smoother trend, however at the position of core wall and sheet pile an abrupt rise in dissipation of head is exhibited, which again signifies the effectiveness of the two seepage control devices.

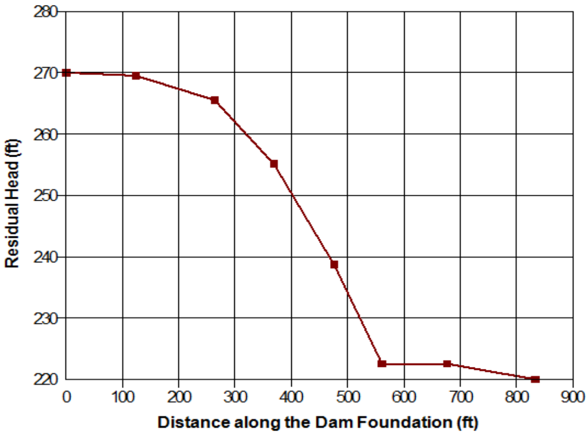

Fig. 9: Head dissipation trend along the dam foundation
Selected Section at CH: 48+75 (270 ft. pond level)

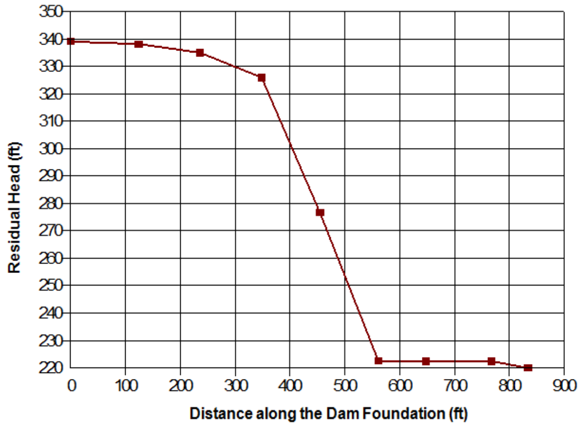

Fig. 10: Head dissipation trend along the dam foundation
Selected Section at CH: 48+75 (339 ft. pond level)

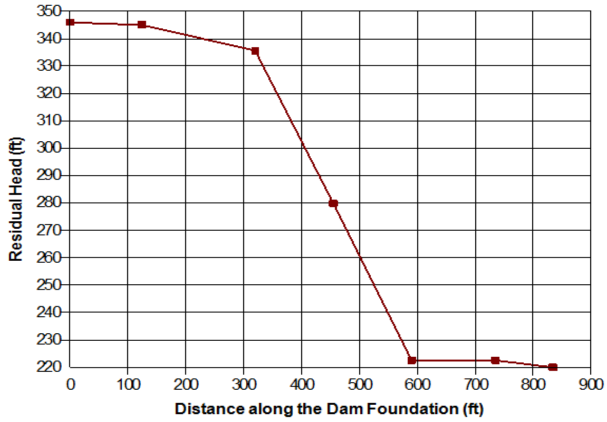

Fig. 11: Head dissipation trend along the dam foundation
Selected Section at CH: 48+75 (346 ft. pond level)

Model Validation

Validation of any model is made by comparing simulated results against the observed ones; this is done to ensure model applicability. If this comparison shows a good coincidence, then the model developed can be recommended for practice. Table 4 contains the data pertaining to observed piezometeric heads and simulated ones and the relative error.

Table 4: Observed and simulated hydraulic heads (normal pool level 339 ft)

Sections	X - distance (ft.)	Observed head H_o (ft.)	Simulated head H_s (ft.)	Relative error (%) $= \frac{(H_o - H_s)}{H_o} \times 100$
CH: 48+75	435	305	306.47	-0.482
	477	259	260.73	-0.668
	527	236	238.19	-0.928
	653	225	222.60	1.067

Performance of the model is assessed evaluated on the basis of statistical parameters. Following parameters that is mean error (ME), root mean square error (RMSE) and model efficiency (EF) are assessed [Willmut, 1982]; their formulation is given below and computational steps are performed in Table 5.9.

$$ME = \frac{1}{n}\sum_{i=1}^{n}(H_{si} - H_{oi})$$

…..11

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(H_{si} - H_{oi})^2\right]^{0.5}$$

…..12

$$EF = 1 - \frac{\sum_{i=1}^{n}(H_{si} - H_{oi})^2}{\sum_{i=1}^{n}(H_{oi} - H_{oa})^2}$$

…..13

where

Hsi is the ith value of simulated head,

Hoi is the ith value of observed head, and

Hoa is the average or mean of observed head.

Table 5: Observed and simulated hydraulic heads with statistical computational steps (pond level 339 ft.)

Sections	X-distance	Observed head H_o (ft.)	Simulated head H_s (ft.)	$(H_{si} - H_{oi})$	$(H_{si} - H_{oi})^2$	$(H_{oi} - H_{oa})^2$
CH: 48+75	435	305	306.47	1.47	2.161	1072.5625
	477	259	260.73	1.73	2.993	175.5625
	527	236	238.19	2.19	4.796	1314.0625
	653	225	222.6	-2.4	5.760	2232.5625

The EF is another parameter to evaluate the performance of the model. For the developed simulation model, RMSE and ME values are found 2.019 and 0.745 ft, respectively and the maximum relative error amongst all the data sets is 1.067 %. Thus it is found that the performance of the model is good enough with model efficiency of 99.60 %.

Table 6: Summary of statistical parameters showing model performance

Statistical Parameters	Values
Mean Error (ME)	0.735
Root Mean Square Error (RMSE)	2.019
Model Efficiency (EF)	99.60 %
Maximum relative error	1.067 %.

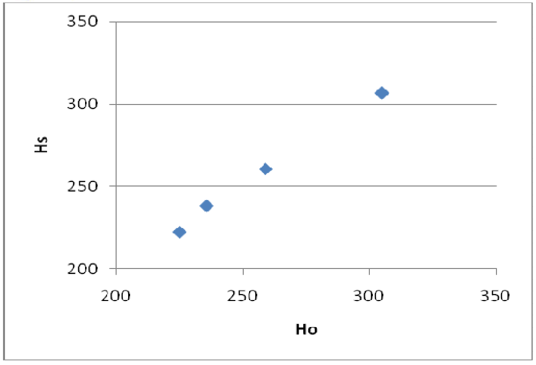

Fig. 12: Relationship between observed and simulated hydraulic heads.

Additionally verifiability of the model is also made by comparing observed and simulated values of piezometeric heads; such graph is illustrated in Fig. 12. The slope of the line is observed to be approximately at 45 degree; thus the Fig. indicates no considerable difference between observed and simulated head values. Consequently, it is concluded that simulated values of piezometeric heads are not much different than the observed ones.

Summary and Conclusions

From FEM analysis of seepage through earthen dam using SEEP/W software, we evaluated that the phreatic line has been simulated at the selected section for the three scenarios i.e. Minimum, Normal and Maximum pool levels and compared with the actual data and the model demonstrates high efficiency and good fitness. Through the study it is observed that dam safety is not endangered from the seepage point of view since the phreatic line pattern follows standard design criterion. For the three scenarios of Minimum, Normal and Maximum pool levels the exit gradient value is within permissible limits (i.e. less than 1.0) for the selected section, which implies that the dam is safe against piping for all the scenarios and there is no any possibility of internal erosion due to seepage. Estimated seepage flux is minimum and maximum seepage velocity is within safe limits. Cut off wall exhibit substantive effect on dissipating the residual head, and therefore its effectiveness and of the core wall is demonstrated significantly.

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