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Numerical Analysis of Seepage Losses in an Earthen Canal by SEEP/W Simulations

Imran Arshad[1*], **Muhammed Muneer Baber**[2], **Muhammad Irfan**[3]

[1]SAA Technical & Specialized Services Establishment, Abu Dhabi, United Arab Emirates.
[2]Institute of Water Resources Engineering & Management (USPCASW), MUET, Jamshoro, Pakistan.
[3]Creative Irrigation Consultants, Hyderabad, Pakistan.

Abstract

The free surface seepage is one of the most serious forms of water loss in an irrigation channel network. Nowadays, one of the most powerful and precise techniques utilized for studying the free boundary seepage problem is finite element method. In this paper a slave program of Geo-Slope Software i.e. (SEEP/W) was used for the analysis of seepage from an earthen canal which has been operational for more than hundred years. Seepage from ten different RD was simulated with SEEP/W by using the field parameters accordingly. The simulated results revealed that amongst all the cross sections the overall minimum seepage (6.13 x 10^{-5} ft^3/sec/ft) and maximum seepage (1.17 x 10^{-3} ft^3/sec/ft) occurs at RD – 120+000 and RD – 290+000 respectively. Total seepage (discharge) loss calculated by field observations and SEEP/W simulations was found 243.1 CUSEC (7.45%) and 247.9 CUSEC (8.00%) respectively. The overall statistical analysis of all the research data i.e. RMSE, ME, R.E, and EF to evaluate the performance of the models are found to be 0.78 CUSEC, 0.48 CUSEC, 2.01% and 99.80% respectively. Hence, in contrast with different field analysis methods, SEEP/W software has a proper ability to simulate seepage from earthen canals however; the numerical models must be calibrated for local conditions.

Keywords: Steady State Seepage, Earthen Canal, Finite Element Modeling, Geo-Slope Software, SEEP/W.

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

INTRODUCTION

The irrigation system, mainly earthen channels i.e. (canals, minors and watercourses) in Pakistan was introduced in mid of 19th century. Despite spending huge resources on management and maintenance sectors, the canal head efficiency is estimated at about 74% and the seepage loss from the canal network is 26% (Bashir *et al.,* 1997). In Pakistan seepage losses are usually high and are about 8 to 10 cusec per million square foot of the wetted area of the cross section and amounts to 35 to 40% of diversion into the canal (WAPDA, 2015). Conveyance and application water losses often make canal supplies inadequate for irrigation purposes. Old earthen irrigation channels in permeable soils can lose a lot of water through seepage (Sarki *et al.,* 2008). Large losses through the bed and sides of canal lead to low conveyance efficiency; i.e. (the ratio of water reaching farm turnouts to that released at the source of supply from a river or reservoir). Therefore, earthen canals are inefficient, inadequate from the point of view of reasonable performance (Shehzad *et al.,* 2017, and Leghari *et al.,* 2001).

Seepage from canals has a major impact on surface and groundwater resources management (Yussuff *et al.,* 1994). The free surface seepage may be encountered in many engineering problems involving the flow of water through permeable soils, such as earthen dams, irrigation and drainage, or seepage from earthen channels etc (Carabineanu, 2011). Nowadays, one of the most powerful and precise techniques utilized for studying the free boundary seepage problem is finite element method (Aanjali *et al*, 2017, and Arshad *et al.,* 2014a). In this research the analysis of seepage through an earthen canal at different cross sections (RD) has been discussed. For this purpose Jamrao Canal in Sindh, Pakistan which has been operating for more than hundred years was selected.

The primary focus of this research was to investigate the seepage of an earthen canal i.e. Jamrao Canal by using finite element method. Seepage analyses by using computer software's are easy task for engineers when the cross-sectional configuration and the soil parameters are known (Ersayin, 2006). Many, computer software have come in general use, and any hard computations and simulation can be carried out through them by giving them appropriate inputs and data. These results in less error frequency and more detailed analysis when compared with field observations (Arshad *et al.,* 2014b). The numerical modeling computer program i.e. SEEP/W of Geo-Slope Company can be employed to carry out simulation of seepage of an earthen canals.

MATERIALS AND METHODS

General Description of Jamrao Canal

The Jamrao Canal was proposed in 1867 for the first time and the survey work was finally sanctioned in 1872, which was completed in two years. As originally designed and sanctioned, the Jamrao Canal bed width was 125 ft and the full supply depth was 8 ft to carry a flow of 3,100 cusecs with a mean velocity of 3.1 feet per second. The upper part of the canal was excavated in pure sand where a bed slope of 1 in 5000 was provided. From the management point of view, the Jamrao Canal and its distribution system has been divided into five sub-divisions i.e. Khadro Sub-division (from RD 0 to 163), Jhol Sub-division (from RD 163 to 291), Mirpurkhas Sub-division (from RD 291 to 448 of Jamrao and RD 0 to 143 of West Branch), Kot Ghulam Muhammad Sub-division (from RD 448 to 602 of Jamrao Canal), and Digri Sub-division (RD 143 to 303 of West Branch). At present, the total culturable command area (CCA) of Jamrao Canal is about 8, 92,000 acres. The length of the main canal is about 124 miles, while the network of distributaries and minors is 426 miles in length (Khan, 1996).

Steps for Modeling Jamrao Canal

To develop a numerical model of Jamrao Canal by using SEEP/W software, in first attempt one cross sections from each of ten reaches (RD) with average bed width and flow depth were selected. After the selection of cross sections the SEEP/W software is used to generate FEM mesh and the seepage analysis was carried out accordingly. After the mesh formation the material properties obtained from WAPDA are then assigned and calibrated accordingly. Once the model fully developed the boundary conditions are then assigned as Dirichlet and Neumann boundary nodes. After the development of complete model, it is then verified by the SEEP/W software and computation for seepage is carried out accordingly. Finally simulated results obtained from the SEEP/W software for each section are compared with the field observations obtained by WAPDA Pakistan.

Governing Equation

In this research work, finite element approach is employed to solve the governing differential equations pertaining to seepage through an earthen canal. 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 (Geo-Slope, 2012). Following partial differential equation (PDE) is the governing equation used for modeling of SEEP/W program:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_x \frac{\partial H}{\partial y}\right) + Q = \frac{\partial \theta}{\partial t} \quad \ldots..1$$

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 θ – volumetric water content.

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

In order to develop a 2-D, finite element model slave program of Geo-Slope Software (GeoStudio 2012, version 8.0.7.6129) i.e. (SEEP/W) was used for the analysis of seepage loss. Initially by using SEEP/W steady state seepage method a finite element mesh was generated (Arshad *et al.,* 2017). The mesh is around 900 ft long, 80 ft in height and having an area of 70,178 ft^2 respectively. The average ground level elevation of 80 ft was adopted in each case. Likewise, the average bed width of 147 ft, average depth of channel from ground surface of 9.6 ft, and unit weight of water 62.4 lb / ft^3 was assumed in each case (Durga *et al.,* 2017). The mesh is composed of two types of elements, i.e. square and rectangle with the approximate global element size of 15 ft respectively. The domain is discretised into mesh by 300 elements through placement of 366 nodal points with maximum number of iterations 500 and with tolerance of 0.001% respectively.

After the development of numerical model the material properties for the material used in newly developed mesh were calibrated. For calibration of material properties for the ten selected cross sections of the Jamrao canal, the hydraulic conductivity values obtained from WAPDA was assigned to the mesh and calibrated by using Van Genuchten Function estimation method accordingly. The general mesh formation of Jamrao Canal is displayed in Fig. 1.

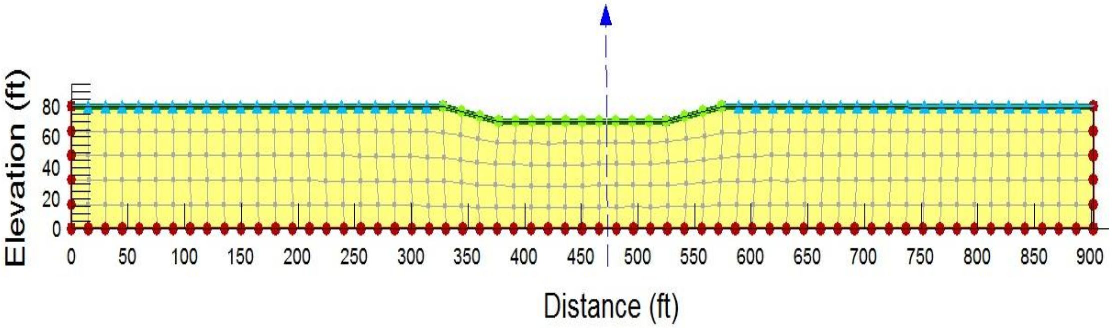

Fig. 1. Mesh Formation for Jamrao Canal.

In order to solve the model numerically, boundary conditions are first created and then assigned to the mesh. In all the cases Neumann type boundary conditions with zero flux condition is executed on the bottom, left and right side of the mesh. Furthermore, Dirichlet boundary conditions (FSL Level) are assigned to the channel cross section(s) respectively. In order to get precise results in all cases as seepage flow with capillarity action and air flow intrusion was selected therefore; potential seepage face boundary was executed on the overall ground level of the mesh respectively. After assigning the materials and boundary conditions; the flux section, to compute the seepage flux was executed to the mesh. The flux section was assigned at the middle of cross section(s) in all cases accordingly.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 models. Thus the model is ready for computation and analysis of the results (Arshad *et al.,* 2016).

RESULTS AND DISCUSSION

Contours of the Channel, Equipotential Line, Phreatic Lines (Streamlines), Flow Lines, Seepage Flux and Velocity Vectors

The computer software Geo-Slope is used to get seepage analysis from an earthen canal for the ten different reaches with same average flow depths and bed widths. For this purpose, the quantity of seepage was computed by using the slave program of Geo-Slope software i.e. SEEP/W and flownet has been drawn for all the selected cross section(s) of Jamrao Canal. From the obtained results it is revealed that the equipotential lines and velocity vectors are normal to each other, which conforms to seepage theory. The SEEP/W velocity vectors and equipotential lines are identical shape wise and location reference. Amongst all the cross sections the overall minimum seepage velocity observed for RD – 120+000; that is of the order of (1.24×10^{-6} ft/sec); and maximum seepage velocity was found for RD – 290+000 ; which is of the order of (4.122×10^{-6} ft/sec) respectively.

Likewise, during steady state seepage the phreatic line (streamlines) and flow lines are also estimated using flownet developed by SEEP/W. The phreatic lines are described with a legend colour blue and flow lines are described with a legend colour green respectively. However, the contours of the channel are described with different legendry colors in each case. The trend of the phreatic lines and flow lines are almost same in all cross sections as shown in Figures 2 (a) – 2 (j).

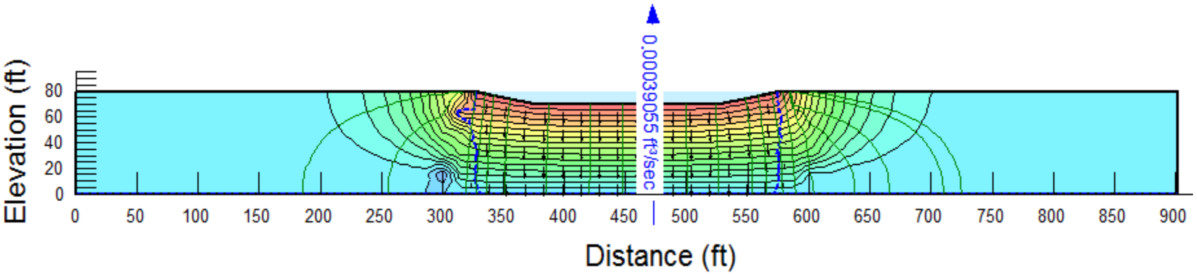

Fig. 2 (a). Flow-net of Jamrao Canal for RD 030+000 (Seepage = 3.90 x 10^{-4} ft^3/sec/ft)

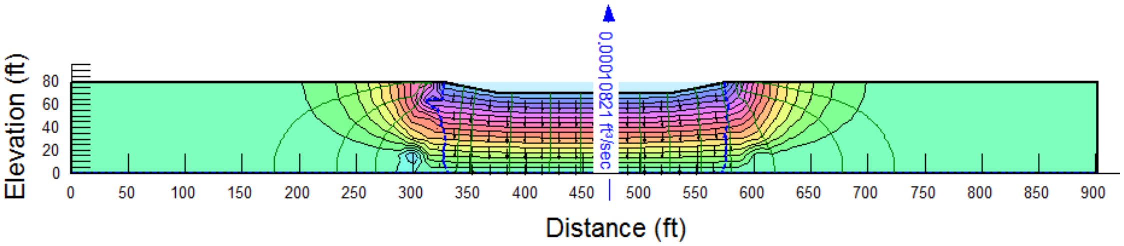

Fig. 2 (b). Flow-net of Jamrao Canal for RD 090+000 (Seepage = 1.08 x 10^{-4} ft^3/sec/ft)

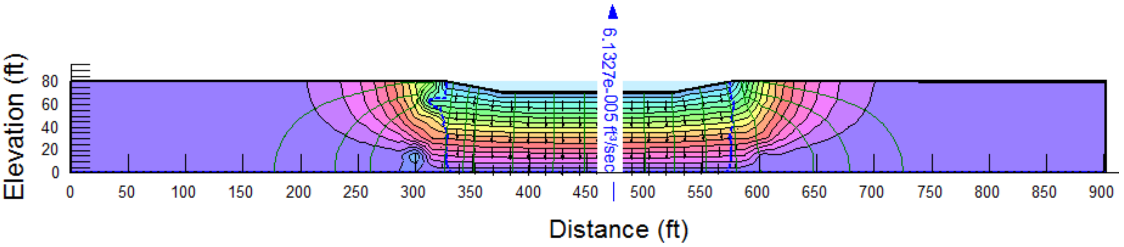

Fig. 2 (c). Flow-net of Jamrao Canal for RD 120+000 (Seepage = 6.13 x 10^{-5} ft^3/sec/ft)

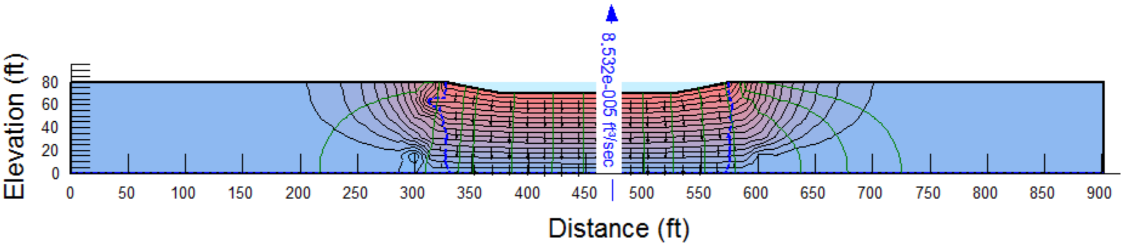

Fig. 2 (d). Flow-net of Jamrao Canal for RD 220+000 (Seepage = 8.53 x 10^{-5} ft^3/sec/ft)

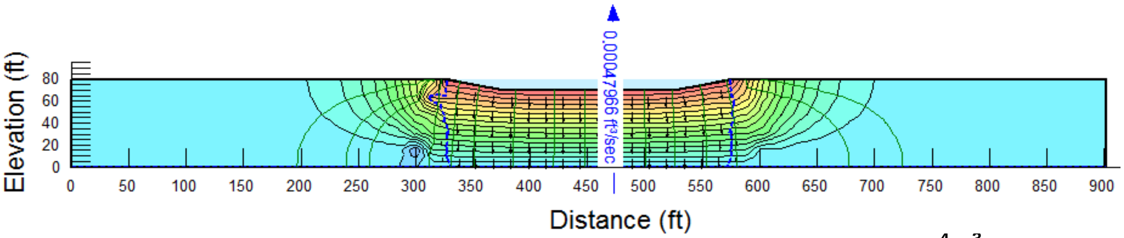

Fig. 2 (e). Flow-net of Jamrao Canal for RD 245+000 (Seepage = 4.79 x 10^{-4} ft^3/sec/ft)

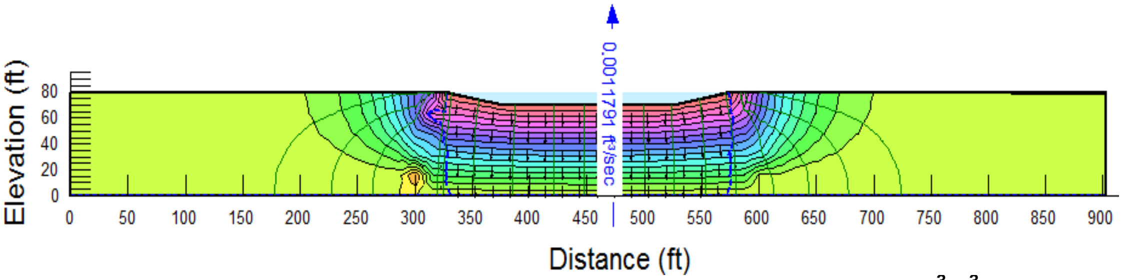

Fig. 2 (f). Flow-net of Jamrao Canal for RD 290+000 (Seepage = 1.17 x 10^{-3} ft^3/sec/ft)

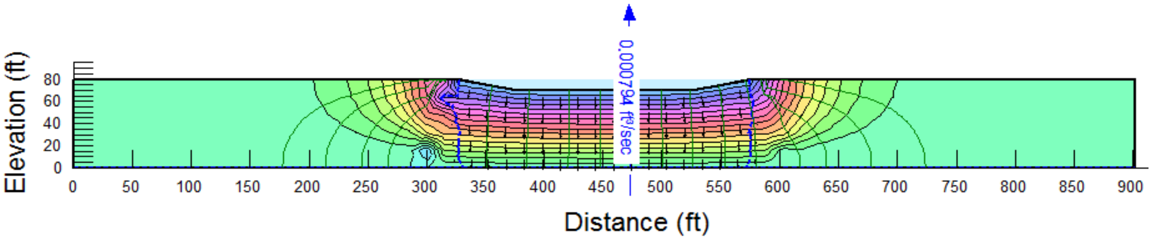

Fig. 2 (g). Flow-net of Jamrao Canal for RD 330+000 (Seepage = 7.94 x 10^{-4} ft^3/sec/ft)

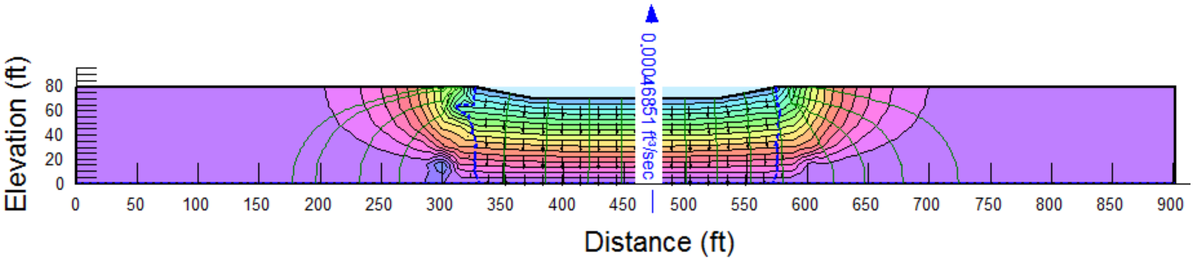

Fig. 2 (h). Flow-net of Jamrao Canal for RD 430+00 (Seepage = 4.68 x 10^{-4} ft^3/sec/ft)

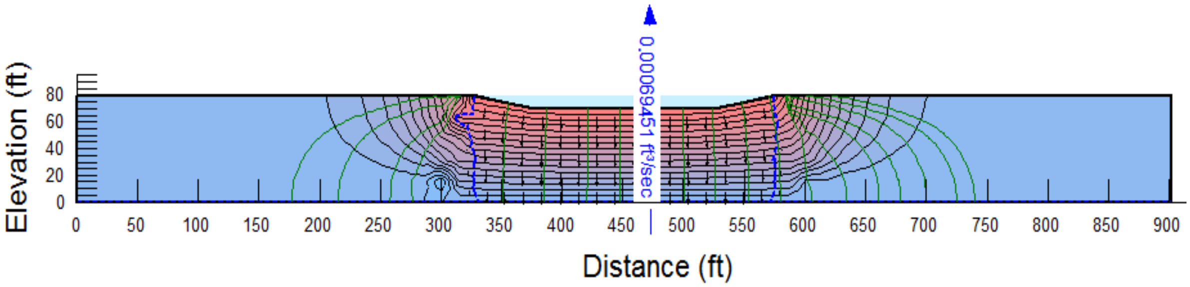

Fig. 2 (i). Flow-net of Jamrao Canal for RD 475+000 (Seepage = 6.94 x 10^{-4} ft^3/sec/ft)

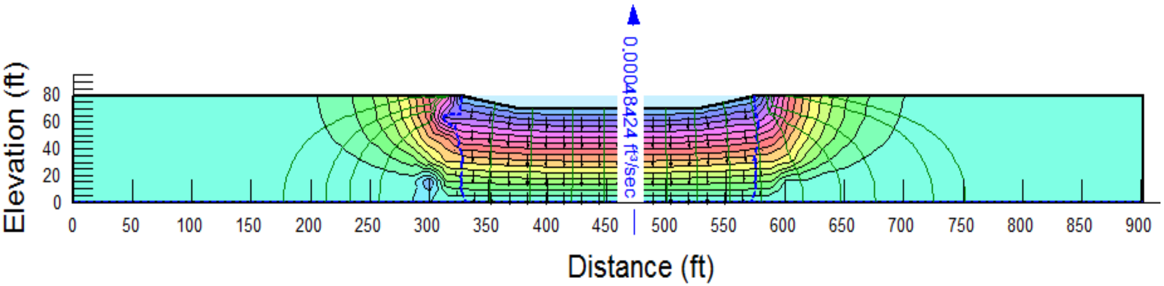

Fig. 2 (j). Flow-net of Jamrao Canal for RD 540+000 (Seepage = 4.84×10^{-4} ft^3/sec/ft)

Similarly, amongst all the cross sections the overall minimum seepage (6.13×10^{-5} ft^3/sec/ft) and maximum seepage (1.17×10^{-3} ft^3/sec/ft) occurs at RD – 120+000 and RD – 290+000 respectively. Total seepage (discharge) loss calculated by field observations and SEEP/W simulations was found 243.1 CUSEC (7.45%) and 247.9 CUSEC (8.00%) respectively. All the field and simulated analysis results for selected cross section(s) are depicted in Table 1 and Table 2 respectively.

The results showed that the SEEP/W computer program has evaluated the numerical model of all selected RD and concluded that the modeling of the cross section is acceptable. From the above results it is also clear that the SEEP/W computer program has a good ability for the computation of the seepage for large earthen canals like Jamrao Canal in which discharge sometimes exceeds from 3100 ft^3/sec.

Model Verification

In order to verify the finite element model predicted results are compared with the field observations for the acceptability of the model. If the comparison shows a good coincidence, then the model developed can be recommended for practice. (Table 3) contains the data pertaining to observed seepage and simulated ones and the relative error. Results obtained from WAPDA are compared with the simulations results.

Table 1. Field Results for all Selected Cross Section(s) of Jamrao Canal

S. No	RD		RD at which seepage calculated	Hydraulic conductivity [k]	Seepage Calculated	Section Length "L"	Total Seepage Through Given Length	Total Seepage Through Canal	Total Discharge Losses
	From	To	(ft)	(ft/sec)	(ft^3/sec/ft)	(ft)	(ft^3/Sec)	(ft^3/sec)	%
1	000+000	060+000	030+000	4.60×10^{-5}	3.81×10^{-4}	60000	22.85	243.1	7.84%
2	060+000	105+000	090+000	6.53×10^{-6}	1.04×10^{-4}	45000	4.68		
3	105+000	170+000	120+000	$4.03\ 10^{-6}$	5.92×10^{-5}	65000	3.85		
4	170+000	232+500	220+000	7.20×10^{-6}	8.70×10^{-5}	62500	5.44		
5	232+500	267+500	245+000	3.38×10^{-5}	4.74×10^{-4}	35000	16.57		
6	267+500	310+000	290+000	8.26×10^{-5}	1.16×10^{-3}	42500	49.22		
7	310+000	380+000	330+000	3.93×10^{-5}	7.83×10^{-4}	70000	54.84		
8	380+000	452+500	430+000	4.00×10^{-5}	4.41×10^{-4}	72500	31.94		
9	452+500	507+500	475+000	5.74×10^{-5}	6.84×10^{-4}	55000	37.65		
10	507+500	540+000	540+000	5.08×10^{-5}	4.94×10^{-4}	32500	16.06		

* Measured Discharge: 3100 CUSEC

Table 2. Simulated Results for all Selected Cross Section(s) of Jamrao Canal by SEEP/W

S. No	RD		RD at which seepage calculated	Hydraulic conductivity [k]	Seepage Calculated	Section Length "L"	Total Seepage Through Given Length	Total Seepage Through Canal	Total Discharge Losses
	From	To	(ft)	(ft/sec)	(ft^3/sec/ft)	(ft)	(ft^3/Sec)	(ft^3/sec)	%
1	000+000	060+000	030+000	4.60×10^{-5}	3.90×10^{-4}	60000	23.433	247.90	8.00%
2	060+000	105+000	090+000	6.53×10^{-6}	1.08×10^{-4}	45000	4.86		
3	105+000	170+000	120+000	$4.03\ 10^{-6}$	6.13×10^{-5}	65000	3.9845		
4	170+000	232+500	220+000	7.20×10^{-6}	8.53×10^{-5}	62500	5.3325		
5	232+500	267+500	245+000	3.38×10^{-5}	4.79×10^{-4}	35000	16.765		
6	267+500	310+000	290+000	8.26×10^{-5}	1.17×10^{-3}	42500	50.11175		
7	310+000	380+000	330+000	3.93×10^{-5}	7.94×10^{-4}	70000	55.58		
8	380+000	452+500	430+000	4.00×10^{-5}	4.68×10^{-4}	72500	33.93		
9	452+500	507+500	475+000	5.74×10^{-5}	6.94×10^{-4}	55000	38.17		
10	507+500	540+000	540+000	5.08×10^{-5}	4.84×10^{-4}	32500	15.7378		

* Measured Discharge: 3100 CUSEC

Table 3. Observed and simulated seepage with statistical computational steps

S. No	RD (ft)		Section Length "L"	Observed Seepage Q_o	Simulated Seepage Q_s	Relative error = $\frac{(Q_o - Q_s)}{Q_o} \times 100$	$(Q_{si} - Q_{oi})$	$(Q_{si} - Q_o)^2$	$(Q_{oi} - Q_{oa})^2$
	From	To	ft.	CUSEC	CUSEC	(%)			
1	000+000	060+000	060+000	22.85	23.433115	-2.55	0.58	0.34	0.14
2	060+000	105+000	045+000	4.68	04.865212	-3.85	0.18	0.03	343.90
3	105+000	170+000	065+000	3.85	03.986255	-3.54	0.14	0.02	375.37
4	170+000	232+500	062+500	5.44	05.332512	1.98	-0.11	0.01	316.29
5	232+500	267+500	035+000	16.57	16.765556	-1.18	0.20	0.04	44.28
6	267+500	310+000	042+500	49.22	50.111751	-1.81	0.89	0.80	675.76
7	310+000	380+000	070+000	54.84	55.585231	-1.35	0.74	0.55	999.54
8	380+000	452+500	072+500	31.94	33.931256	-6.23	1.99	3.96	75.96
9	452+500	507+500	055+000	37.65	38.172263	-1.38	0.52	0.27	208.09
10	507+500	540+000	032+500	16.06	15.737812	2.01	-0.32	0.10	51.33

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

$$ME = \frac{1}{n} \sum_{i=1}^{n} (Q_{si} - Q_{oi}) \quad \text{….. (2)}$$

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n} (Q_{si} - Q_{oi})^2 \right]^{0.5} \quad \text{….. (3)}$$

$$EF = 1 - \frac{\sum_{i=1}^{n} (Q_{si} - Q_{oi})^2}{\sum_{i=1}^{n} (Q_{oi} - Q_{oa})^2} \quad \text{….. (4)}$$

where

Q_{si} is the ith value of simulated Seepage,
Q_{oi} is the ith value of observed Seepage, and
Q_{oa} is the average or mean of observed Seepage.

The EF is another parameter to evaluate the performance of the model. The overall statistical analysis of all the research data i.e. RMSE, ME, R.E, and EF to evaluate the performance of the models are found to be 0.78 CUSEC, 0.48 CUSEC, 2.01% and 99.80% respectively. Similar results were reported by (Arshad *et al*, 2015), who conducted their research work on the seepage behavior of an earthen watercourse i.e. (1-R Qaiser Minor – Tando Jam) by using finite element method through SEEP/W computer program and found the overall statistical analysis of all the research data i.e. RMSE (0.0265 LPS), ME (0.0170 LPS), R.E (1.525%), and EF (99.958%) respectively.

Table 4. Summary of statistical parameters showing model performance

Statistical Parameters	Values
Mean Error (ME)	0.48 CUSEC
Root Mean Square Error (RMSE)	0.78 CUSEC
Model Efficiency (EF)	99.80%
Absolute Maximum relative error	2.01%

Additionally verifiability of the model is also made by comparing observed and simulated values of seepage; such graph is illustrated in Fig. 3. The slope of the line is observed to be approximately at 45 degree; thus the figure indicates no considerable difference between observed and simulated seepage values. Consequently, it is concluded that simulated values of seepage for the selected RD are not much different than the observed ones

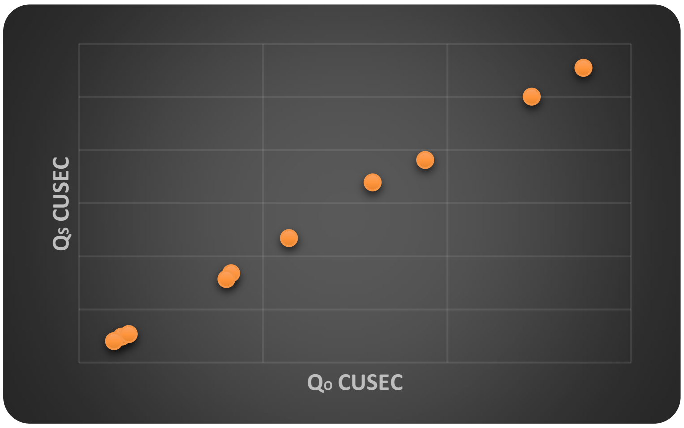

Fig. 3. Relationship between observed (Qo) and simulated (Qs) seepage flux.

CONCLUSION

In the present research study a numerical models of ten different selected cross sections of Jamrao Canal based of FEM using sub-program of Geo-Slope Software i.e. SEEP/W was developed and calibrated. The models have been used to study the seepage behavior of the earthen canals. Seepage from ten different RD was simulated with SEEP/W by using the field parameters accordingly. The outcome of the research study revealed that the SEEP/W velocity vectors and equipotential lines found identical shape wise and location reference. Amongst all the cross sections the overall minimum seepage velocity observed for RD – 120+000; that is of the order of (1.24 x 10^{-6} ft/sec); and maximum seepage velocity was found for RD – 290+000 ; which is of the order of (4.122 x 10^{-6} ft/sec) respectively. Likewise, during steady state seepage the phreatic line (streamlines) and flow lines are also estimated using flownet developed by SEEP/W. The phreatic lines are described with a legend colour blue and flow lines are described with a legend colour green respectively. Similarly, amongst all the cross sections the overall minimum seepage (6.13 x 10^{-5} ft^3/sec/ft) and maximum seepage (1.17 x 10^{-3} ft^3/sec/ft) occurs at RD – 120+000 and RD – 290+000 respectively. Total seepage (discharge) loss calculated by field observations and SEEP/W simulations was found 243.1 CUSEC (7.45%) and 247.9 CUSEC (8.00%) respectively.

The comparison of field and simulated data shows that the results achieved from field study is about 2% lower than SEEP/W simulations respectively. The overall statistical analysis of all the research data i.e. RMSE, ME, R.E, and EF to evaluate the performance of the models are found to be 0.78 CUSEC, 0.48 CUSEC, 2.01% and 99.80%respectively (Table 4). Additionally verifiability of the model is also made by comparing observed and simulated values of seepage; such graph is illustrated in Fig. 3. The slope of the line is observed to be approximately at 45 degree; thus the Fig. indicates no considerable difference between observed and simulated seepage values. Consequently, it is concluded that simulated values of seepage for the selected RD are not much different than the observed ones. Hence, in contrast with different field analysis methods, SEEP/W software has a proper ability to simulate seepage from earthen canals however; the numerical models must be calibrated for local conditions.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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