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Finite Element Analysis of Seepage and Exit Gradient underneath Jinnah Barrage Weir Foundation by Using Geo-Slope (Seep/W) Software

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Abstract

In present research work a slave program (SEEP/W) of a Geo-Slope Software, was used to compute the seepage flux and exit gradient under Jinnah barrage weir foundation. 2-D FE model was generated by using four types of elements, i.e. triangular, square, rectangular and trapezoidal. Water seepage is one of the major issues which is to be encountered emphatically as main structure of the weir very much dependent of on seepage due to obvious reasons. Based on the pertinent technical data at its original shape and size at the time of construction the seepage and exit gradient was carried out numerically and further the exit gradient was compared with Khosla's Method. The results showed that at lowest water level at the upstream of the barrage; minimum seepage (5.0995 x 10^{-6} m^3/sec/m) and at highest water level maximum seepage (6.7994 x 10^{-6} (m^3/sec/m) occurs respectively. The exit gradient for all the scenarios was found within the permissible limits of (0.25 to 0.20) for shingle material; which conforms the safety criteria of the weir. The theoretical and simulated exit gradient values was compared to counter check the efficiency of numerical model which showed that amongst all the data sets the RMSE, ME, and AMRE was found (0.007354), (0.006180), and 0.98% respectively. The performance efficiency of the model was founded as 99.995%. The FE model was also verified by comparing the theoretical and simulated values of exit gradient which showed that the slope line was observed to be approximately at 45 degree; which is an evidence that there was no significant difference between theoretical and simulated exit gradient values. Thus, it is concluded that theoretical values of exit gradient are not much different than the simulated ones.

Keywords: Jinnah Barrage, Seepage, Exit Gradient, Khosla's Method, SEEP/W, Geo-Slope.

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INTRODUCTION

As we are well cognizant that weirs are mainly low-level hydraulic structures which are constructed on suitable and potentially viable rivers with the motive, to divert the flow of water river fully or partially (Zhang *et al*., 2012). Furthermore this water is diverted through canals / conduit for various consumptions like irrigation, power generation, flood control, and household and manufacturing usage (Baghalian *et al.,* 2012). These weirs may be having doors or vice versa which are very helpful for flashing out flood to the irrigated domain or to recharge the underground water as well. Weirs are sometimes also enabled to measure the flow. Weirs may be erected on an impervious solid rock foundation as well as pervious foundation (Chaudhry, 2009). In case of pervious foundation, the water seepage arrangements are provided beneath the foundation. The seepage of water directly exerts adverse / conductive effects on any hydraulic systems, which vividly earmarks its importance. The seepage is dependent on the soil media foundation, the flow of water and above all boundary restrictions.

It is imperative to conclude that utmost endeavored critical analysis be exercised to deal with the seepage related problem to ensure smooth and economical viability of a water reservoir in order to avert systems safety / security special attention be paid in case of impervious soil foundation, where the seepage problem occurrence in comparatively very high or vice versa as the difference in water level in upstream and downstream entails in differential pressures which further aggravates the seepage problems (Arshad *et al*., 2017). These structures which are erected on permeable foundation are provided with seepage water exerts pressure on structure perimeters which erodes the under soil which entails in structure failure, apart from it uplift pressure (excessive) and piping effects, are also main contributors, to adversely affect the smooth functioning of structure may resultantly the weir collapse.

The pivotal bottom line of this subject research study is to detect and analyze and specify the cardinal contributing factors that play havoc with the safety / security of Jinnah Barrage Weir whose foundation was designed on permeable soil.

Jinnah Barrage is located 4.82 km downstream of the Kalabagh Town, 202 km downstream of Terbela Dam respectively. The initial construction work of Jinnah Barrage was started in 1939 and it was completed in 7 years of span of time i.e. 1946. It is a gate-controlled weir type barrage with a navigation lock (NDC, 2001). The design includes a road bridge, canal head works, 42 weir bays with clear span of 60 feet (18.3 m) wide respectively. Soil foundation underneath the Jinnah Barrage weir is saturated, isotropic and homogenous; having permeability and unit weight of soil 1.215 x 10^{-5} m/s and 18 KN/m^2 respectively. The width between the abutments and the barrage is (1152.4 m), whereas the crest and floor level of the weir are at EL678, and EL667, respectively. Jinnah barrage was constructed to control the flow of flood for about 9.5 x 10^5 cusec; however, a flood of 1.1 x 10^6 cusec can easily be passed as the barrage guide banks have enough freeboard (Chaudhry, 2008).

Fig. 1. Location Map of Jinnah Barrage

Geo-Slope is a finite element modeling software which is very much competent in modeling the flow of fluid. It also allow to check out the water pressure distribution in content of porous material i.e. soil and rock (Geo-Slope, 2005). It computes very accurately simple and highly tedious seepage related problems with proficiency and authenticity. It also undertakes the unsaturated underground flow problems with great degree of accuracy and comfort (Arshad *et al*., 2014). The problems related to hydraulic conductivity, permeability, water content, changes due to variation in pore water pressure may also be solved with great dependence.

This software transformed the model in to finite element mesh which may be calculated by arranging quadrilateral regions whereby constituting categorizing problem domain. It is arranged to generate number of finite elements automatically inside their regions. The pragmatic ways to use Geo-Slope effectively are identification of problem (input), trouble shooting, and graphical representation of acquired results (output) (Arshad *et al*., 2016). The same strategy was executed to analyze the seepage and exit gradient underneath the foundation of the Jinnah Barrage Weir section.

Whenever, a hydraulic structure is constructed on a pervious foundation; the chances of seeping water beneath the structure become high and which may cause its failure, either by piping or direct uplift. Many engineering problems are complex and cannot be easily solved analytically, therefore; either these problems may solved by using conformal mapping, or by splitting the problem to number of simple shapes. Khosla used split method to overcome the limitation of Bligh's theory (Garg, 2006).

Khosla gave a solution for each shape, and for simplifying the solution, he prepared curves to find the values of pressure at some key points. According to Khosla's opinion, the seeping water moves along a set of streamlines and the other set equipotential lines respectively (Khosla *et al*., 1954). Both these lines are intersecting each other orthogonally and forming a flow net as elaborated in Figure 2a. The streamlines represents the paths along which the water moves through the sub-soil and the equipotential lines represents the paths having the same value of residual head respectively (Aditya *et al*., 2015).

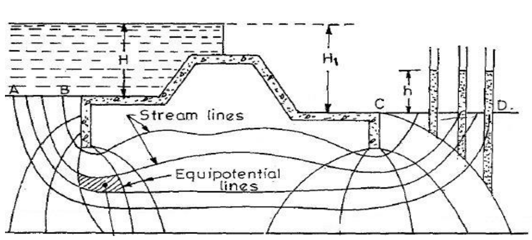

Fig. 2a. Khosla's Flow Net

Khosla analyses various cases mathematically for calculating the uplift pressure which can be helpful for the computation of percentage pressures at different key points i.e. (i) a straight horizontal floor of negligible thickness having sheet pile on the u/s and d/s end (Figure 2b and Figure 2c), (ii) a straight horizontal floor of negligible thickness having sheet pile at some middle position (Figure 2d), and (iii) a straight horizontal floor depressed below the bed with no vertical cut off (Figure 2e) (Anand *et al*., 2011).

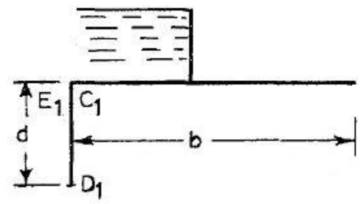

Fig 2.b. A straight horizontal floor having sheet pile on the u/s end

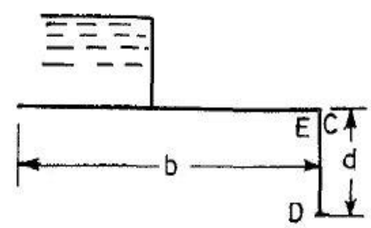

Fig 2.c. A straight horizontal floor having sheet pile on the d/s end

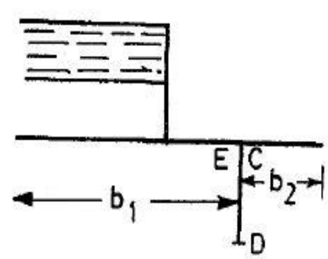

Fig 2.d. A straight horizontal floor having sheet pile at middle position

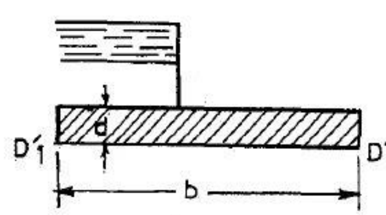

Fig 2.e. A straight horizontal floor depressed below the bed with no vertical cut off

MATERIALS AND METHODS

Finite Element Modeling Procedure

Initially a cross section of a Jinnah barrage weir section, at its original shape and size i.e. without subsidiary weir were adopted and by using SEEP/W finite element mesh was generated (Khassaf *et al.,* 2009). The dimension of the mesh is 128m long and 206m depth respectively. According to the given conditions the upstream and downstream boundary conditions are assigned as Dirichlet boundary nodes while the nodes at the bottom of the foundation of the weir are considered with zero-flux (Nuemann) condition (Arshad *et al.,* 2016). The hydraulic conductivity and a unit weight of soil for the shingle type of soil was adopted as 1.215 x 10^{-5} m/s and 18 KN/m^2, as the soil underneath the weir is saturated, isotropic and homogenous soil respectively. The depth of upstream, middle and downstream sheet pile was assumed as 10m, 6m and 8m respectively. After the development of FE model, it is verified by SEEP/W and computation of seepage flux, seepage velocity, and exit gradient for six different scenarios of water levels at the upstream of the weir is carried out accordingly (Arshad *et al*., 2015). Finally, the simulated results were compared with the observations of Khosla's theory respectively.

Finite Element Mesh Formation and Its Verification

The 2-Dimensional FE model was generated by using four types of elements, i.e. triangular, square, rectangular and trapezoidal. With the help of 2458 nodal points and 2347 elements the mesh was finialized respectively. The material properties for the mesh was calibrated and assigned for the verification by SEEP/W accordingly. The output report confirms that there in no error in vertical and horizontal meshing respectively. Therefore, the FE model is ready for results analysis. (Figure 3a - Figure 3f) describes the mesh formation of weir section respectively.

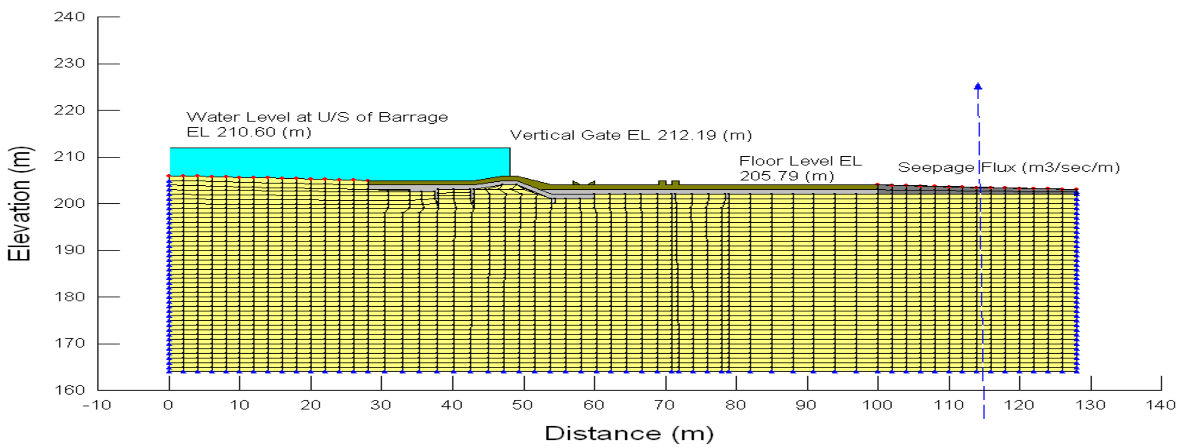

Fig. 3a. Mesh Formation for Jinnah Barrage Weir Section (U/S Water Level = 210.60 m).

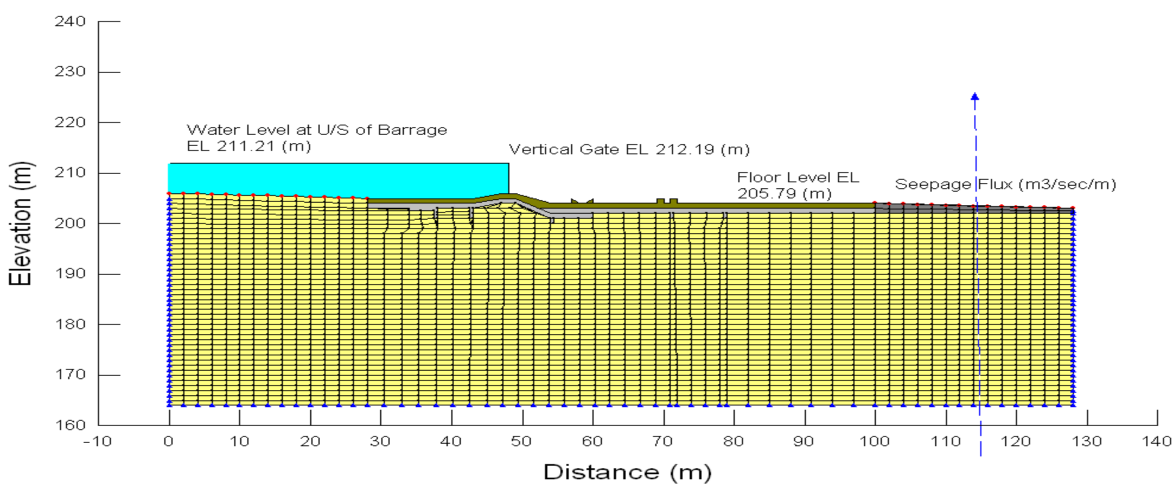

Fig. 3b. Mesh Formation for Jinnah Barrage Weir Section (U/S Water Level = 211.21 m).

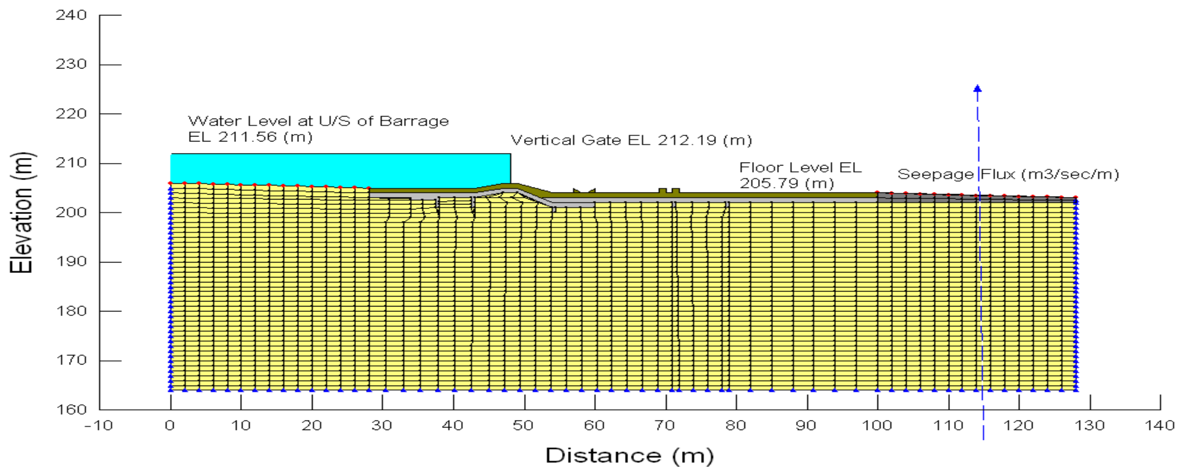

Fig. 3c. Mesh Formation for Jinnah Barrage Weir Section (U/S Water Level = 211.56 m).

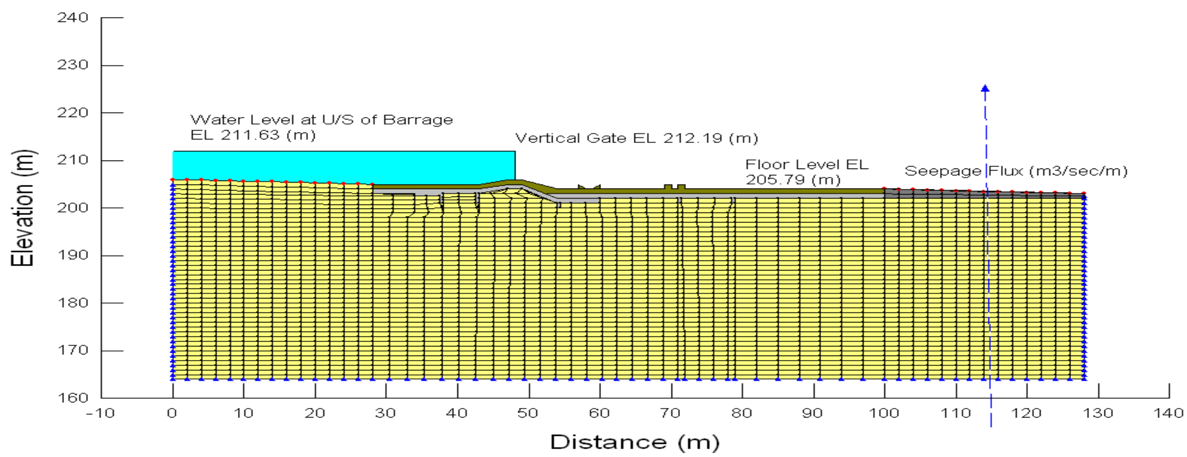

Fig. 3d. Mesh Formation for Jinnah Barrage Weir Section (U/S Water Level = 211.63 m).

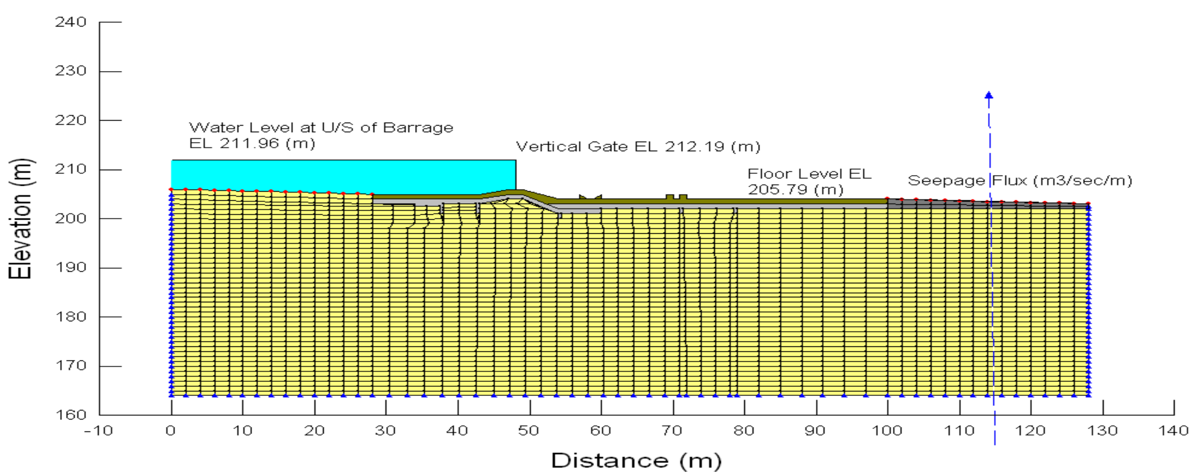

Fig. 3e. Mesh Formation for Jinnah Barrage Weir Section (U/S Water Level = 211.96 m).

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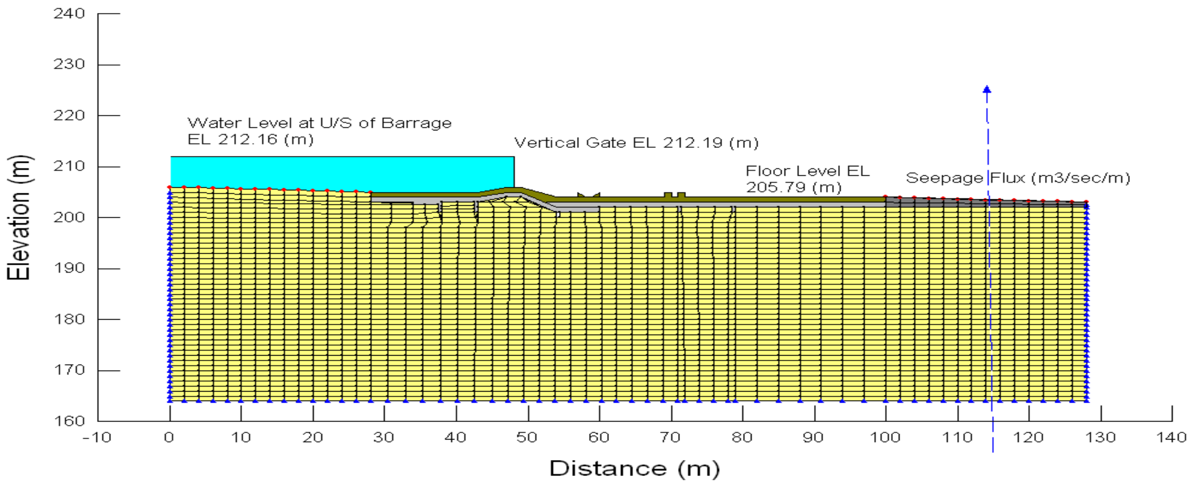

Fig. 3f. Mesh Formation for Jinnah Barrage Weir Section (U/S Water Level = 212.16 m).

RESULTS AND DISCUSSION

Analysis of Subsurface Flow below Jinnah Barrage Weir Structure

The scaled model of the weir section and its foundation along with different seepage control measures, developed in the SEEP/W, was analysed for seepage quantity. The SEEP/W software gives output in terms of flownet which consist of a streamlines, equipotential lines, and velocity vectors; showing seepage flow below the weir structure respectively. The results (Table 1) confirmed that the streamlines and equipotential lines are normal to each other, and vectors displaying the velocity of the flow direction. The results showed that at lowest water level at the upstream of the weir; minimum seepage occurs i.e. 5.0995 x 10^{-6} (m^3/sec/m); and at highest water level maximum seepage occurs i.e. 6.7994 x 10^{-6} (m^3/sec/m) respectively.

Likewise, seepage velocities were also computed for various water level scenarios. The result showed that at low water level at the upstream of the weir minimum seepage velocity was obtained i.e. 1.6571 x 10^{-6} (m/sec); and at high water level maximum seepage velocity was observed i.e. 2.2095 x 10^{-6} (m/sec). The flownet at different water levels scenarios are elaborated in (Figure 4a – Figure 4f) respectively. Similar results were reported by (Khan et al., 2013), who conducted their research work on the seepage behavior of a proposed Golen Gol weir (Pakistan), by using SEEP/W and concluded that seepage control measure are very important during a weir construction as it helps to overcome the considerable amount of seeping water flow.

Table 1. Simulated seepage flux, exit gradient and maximum seepage velocity at various head of water.

S No.	Head of Water U/S of the Weir	Discharge over Weir Section	Simulated Results Obtained Through SEEP/W		
			Seepage Flux	Maximum Seepage Velocity	Exit Gradient
	m	CUMEC	m^3/sec/m	m/sec	*ie*
1	210.60	2831.69	5.0995 x 10^{-6}	1.6571 x 10^{-6}	0.202
2	211.21	8495.06	5.9301 x 10^{-6}	1.9270 x 10^{-6}	0.214
3	211.56	14158.43	6.2199 x 10^{-6}	2.0212 x 10^{-6}	0.219
4	211.63	19821.80	6.2875 x 10^{-6}	2.0431 x 10^{-6}	0.222
5	211.96	23842.79	6.6062 x 10^{-6}	2.1467 x 10^{-6}	0.227
6	212.16	26901.01	6.7994 x 10^{-6}	2.2095 x 10^{-6}	0.231

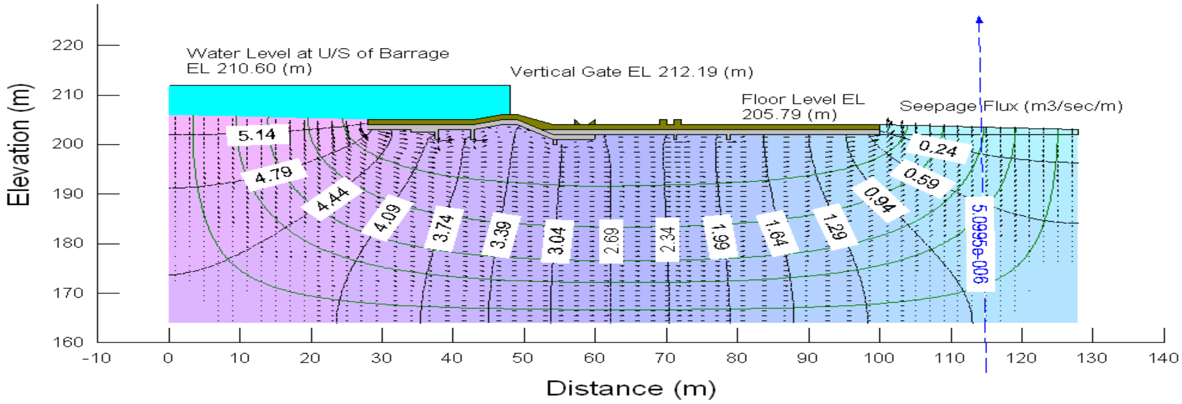

Figure 4.a. Flownet for Jinnah Barrage Weir Section (Upstream Water Level = 210.60 m).

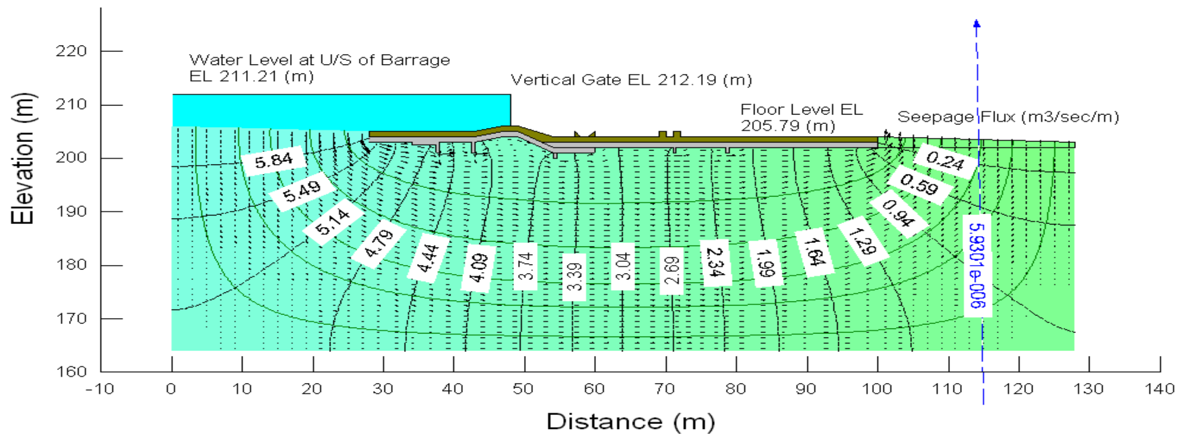

Figure 4.b. Flownet for Jinnah Barrage Weir Section (Upstream Water Level = 211.21 m).

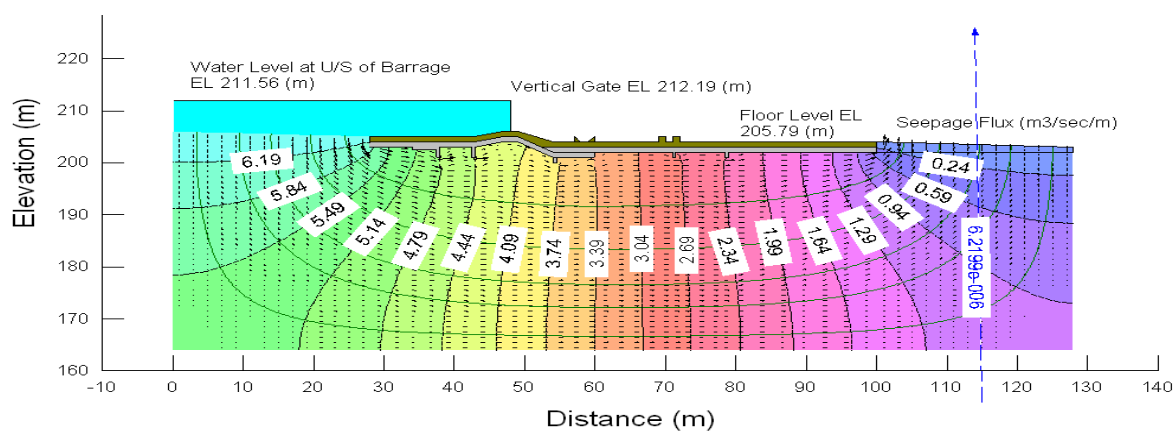

Figure 4.c. Flownet for Jinnah Barrage Weir Section (Upstream Water Level = 211.56 m).

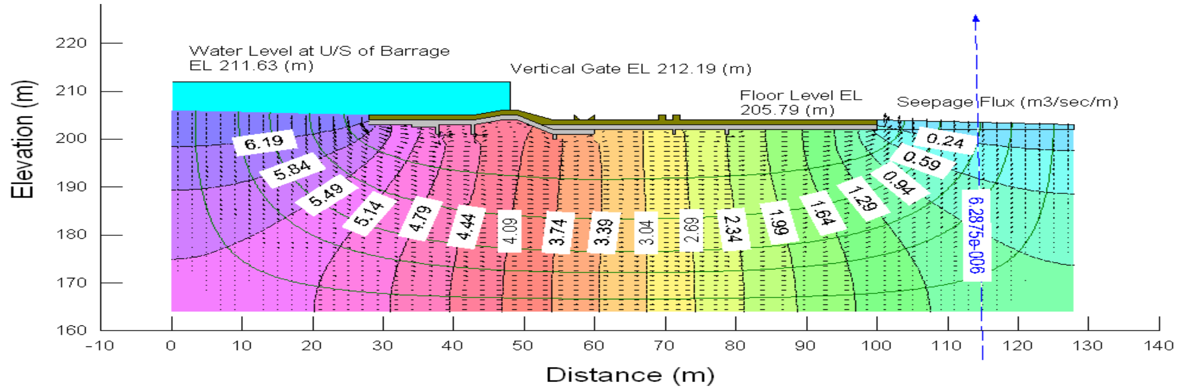

Figure 4.d. Flownet for Jinnah Barrage Weir Section (Upstream Water Level = 211.63 m).

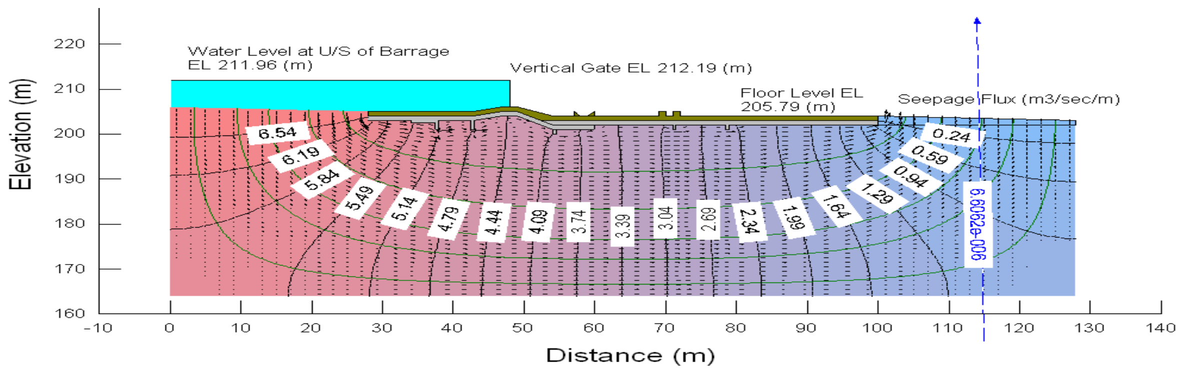

Figure 4.e. Flownet for Jinnah Barrage Weir Section (Upstream Water Level = 211.96 m).

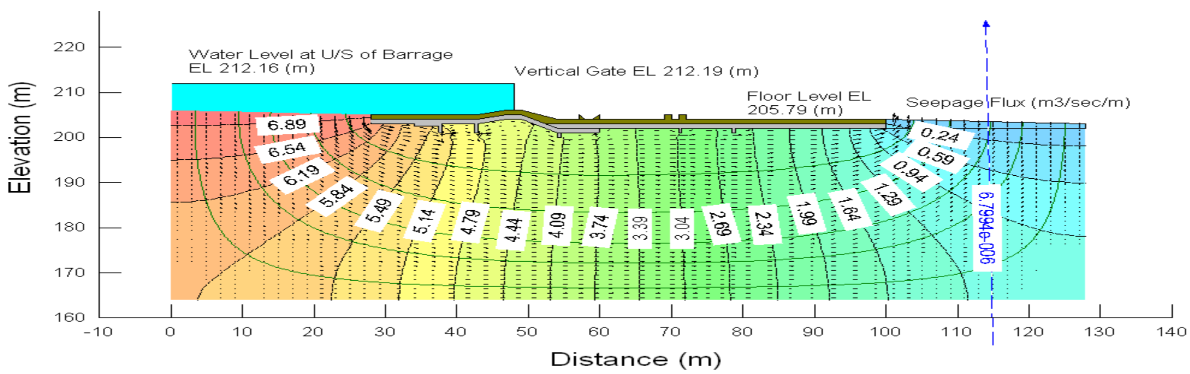

Figure 4.f. Flownet for Jinnah Barrage Weir Section (Upstream Water Level = 212.16 m).

Similarly, the simulated results showed that the exit gradient at various water level at the upstream of the weir was found within reasonable limits i.e. in between (0.25 to 0.20) for shingle material; thus it also conforms the safety criteria of the weir. (Figure 5a – Figure 5c) shows a graphical relationship for seepage flux, maximum seepage velocity and exit gradient as function of water level. All graphs followed a linear behavior; which describes that as the water level rises on the upstream the seepage flux, seepage velocity and exit gradient will also rises linearly. These results are according to the findings of (Khassaf *et al*., 2009), who conducted their research work on Diyala weir (Egypt), by using SEEP/W and found that the simulated exit gradient is very close to the theoretical readings.

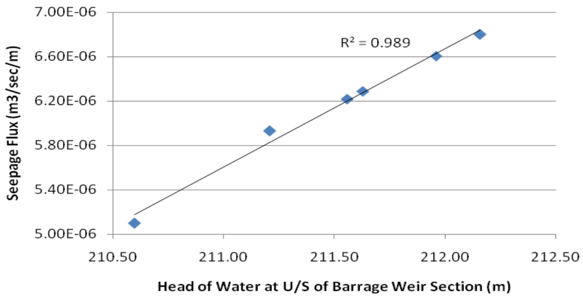

Figure 5.a. Simulated Seepage Flux vs. Head of Water at U/S of Barrage Weir Section.

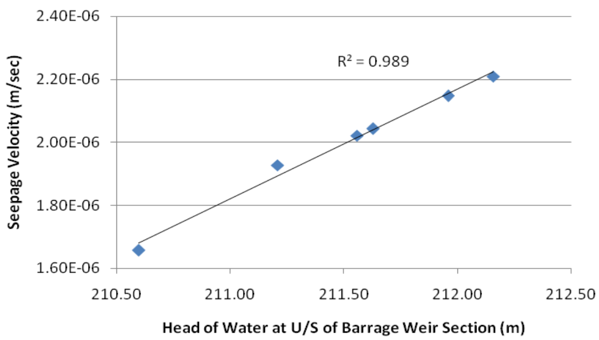

Figure 5.b. Simulated Max. Seepage Velocity vs. Head of Water at U/S of Barrage Weir Section.

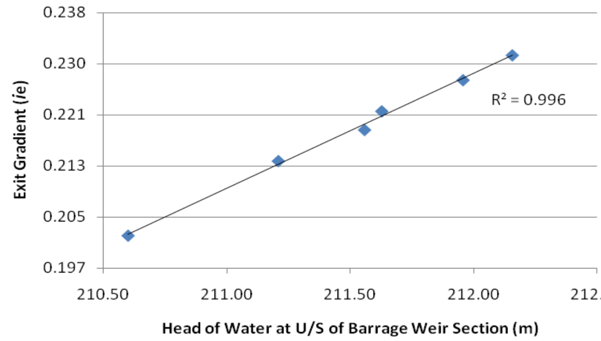

Figure 5.c. Simulated Exit Gradient vs. Head of Water at U/S of Barrage Weir Section.

Residual Head Dissipation Trend

Residual head dissipation trend (Table 2) is also modeled for various water level at the upstream of the weir. The simulated results showed that at low water level smoother dissipation rate is followed, however, as the water level goes on rising somewhat the dissipation rate is also changing gradually, this of course signifies the effectiveness of sheet pile; this is displayed in Figure 6.

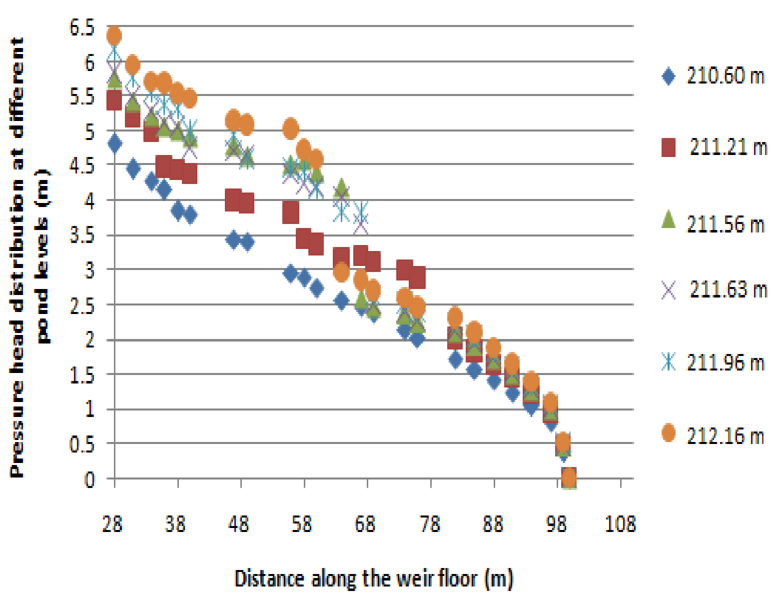

Figure 6. Total Pressure Head Distribution at different Water Level underneath Jinnah Barrage Weir Floor Section.

Table 2. Total Pressure Head Distribution at different Water Level underneath Jinnah Barrage Weir Floor Section.

S. No.	Distance along the Weir Floor	Total Pressure Head Distribution at Different Water Level on the U/S side with no D/S Flow.					
		Water Level	Water Level	Water Level	Water Level	Water Level	Water Level
		210.6	211.21	211.56	211.63	211.96	212.16
	(m)	(m)	(m)	(m)	(m)	(m)	(m)
1	28	4.81	5.42	5.77	5.84	6.17	6.37
2	31	4.45	5.18	5.43	5.49	5.77	5.94
3	34	4.28	4.97	5.22	5.27	5.54	5.70
4	36	4.15	4.48	5.06	5.11	5.37	5.69
5	38	3.85	4.43	5.00	5.05	5.31	5.53
6	40	3.81	4.38	4.91	4.75	4.99	5.46
7	47	3.44	4.00	4.79	4.70	4.93	5.14
8	49	3.40	3.96	4.65	4.64	4.59	5.08
9	56	2.95	3.82	4.52	4.37	4.46	5.02
10	58	2.89	3.43	4.59	4.24	4.41	4.72
11	60	2.75	3.36	4.41	4.19	4.16	4.59
12	64	2.57	3.17	4.20	4.05	3.84	2.95
13	67	2.48	3.20	2.60	3.65	3.82	2.85
14	69	2.38	3.10	2.47	2.50	2.62	2.70
15	74	2.14	2.99	2.37	2.40	2.52	2.59
16	76	2.02	2.88	2.25	2.27	2.39	2.46
17	82	1.73	2.01	2.11	2.13	2.24	2.31
18	85	1.57	1.83	1.92	1.94	2.04	2.10
19	88	1.41	1.64	1.72	1.74	1.83	1.88
20	91	1.24	1.44	1.51	1.52	1.60	1.65
21	94	1.04	1.21	1.27	1.28	1.34	1.38
22	97	0.82	0.95	1.00	1.01	1.06	1.09
23	99	0.38	0.45	0.47	0.47	0.50	0.51
24	100	0.00	0.00	0.00	0.00	0.00	0.00

Comparison of SEEP/W with the Observations of Khosla's Theory

By using Khosla's theory, initially the uplift pressures at upstream and downstream end of the weir for all the sheet piles was calculated and after that exit gradient was calculated respectively. The comparative results showed that for all the scenarios the d/s floor of the weir was suitably safeguarded against the uplift pressure and exit gradient was also found within the safe limits. These results are elaborated in (Table 3) respectively.

Table 3. Comparison of SEEP/W and Khosla's Method for Exit Gradient (ie) at different Head of Water at U/S of Weir Section.

S No.	Head of Water U/S of the Barrage Weir Section	Discharge over Weir Section	Exit Gradient		
			SEEP/W	Khosla's Method	Difference
	m	CUMEC	ie	ie	(%)
1	210.60	2831.69	0.202	0.204	-0.20000
2	211.21	8495.06	0.214	0.209	0.50000
3	211.56	14158.43	0.219	0.212	0.70000
4	211.63	19821.80	0.222	0.214	0.80000
5	211.96	23842.79	0.227	0.218	0.90800
6	212.16	26901.01	0.231	0.221	1.00000

The comparative results showed that at lowest head of water at the upstream; minimum exit gradient was recorded with overall minimum exit gradient of (0.202) and at highest head of water maximum exit gradient occurs overall maximum exit gradient of (0.231) respectively. Figure 7 shows a linear graphical relationship for SEEP/W and Khosla's Method for exit gradient (ie) at different head of water at U/S of weir section, describing that the comparative results are close to each other.

MODEL VALIDATION

Model validation is a key tool to compare the simulated and observed results which assure the model performance and its efficiency. On the basis of good coincidence among the comparative results, the model can be used for practice respectively. Table 4 describes statistical analysis of the data pertaining to theoretical and simulated exit gradient. On the basis of statistical parameters the performance of the model can be determined. Statistical parameters i.e. Mean Error (ME), Root Mean Square Error (RMSE) and Model Efficiency (EF) are determined respectively.

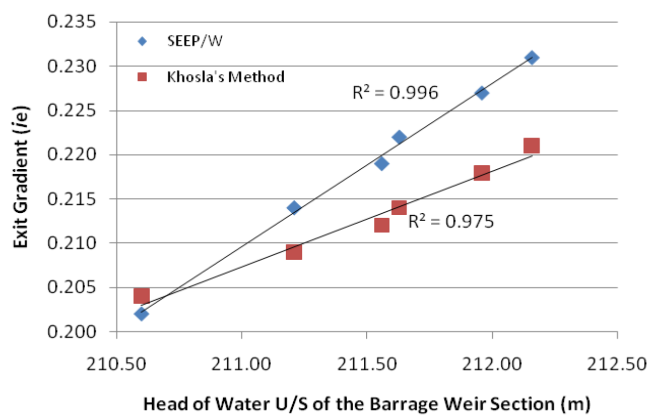

Fig. 7. Comparsion of SEEP/W and Khosla's Method for Exit Gradient (ie) at different Head of Water at U/S of Barrage Weir Section.

Table 4. Theoretical and Simulated Exit Gradient at different Head of Water at U/S of Weir Section.

S. No	Head of Water U/S of the Barrage	Exit Gradient		Relative error (%) $= \frac{(ie_t - ie_s)}{ie_t}$	$(ie_{si} - ie_{ti})$	$(ie_{si} - ie_{ti})^2$	$(ie_{ti} - ie_{ta})^2$
		Theoretical Results	Simulated Results				
	(m)	ie(t)	ie(s)				
1	210.60	0.204	0.202	0.980	-0.00200	0.00000400	1.15330
2	211.21	0.209	0.214	-2.392	0.00500	0.00002500	1.14259
3	211.56	0.212	0.219	-3.302	0.00700	0.00004900	1.13619
4	211.63	0.214	0.222	-3.738	0.00800	0.00006400	1.13193
5	211.96	0.218	0.227	-4.167	0.00908	0.00008245	1.12360
6	212.16	0.221	0.231	-4.525	0.01000	0.00010000	1.11708

$$ME = \frac{1}{n}\sum_{i=1}^{n}\left(ie_{si} - ie_{ti}\right) \quad (1)$$

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

$$EF = 1 - \frac{\sum_{i=1}^{n}\left(ie_{si} - ie_{ti}\right)^2}{\sum_{i=1}^{n}\left(ie_{ti} - ie_{ta}\right)^2} \quad (3)$$

Where;

ie_{si} = i^{th} value of simulated exit gradient,

ie_{oi} = i^{th} value of theoratical exit gradient, and

ie_{oa} = average of theortical exit gradient.

The results showed that amongst all the data sets the RMSE, ME, and AMRE was found (0.007354), (0.006180), and 0.98% respectively. The performance efficiency of the model was founded as 99.995%. Similar results were reported by (Arshad, *et al.*, 2018), who conducted their research work on the seepage behavior of an earthen canal i.e. (Jamrao Canal) by using SEEP/W and found RMSE (0.78 CUSEC), ME (0.48 CUSEC), R.E (2.01%), and EF (99.80%) respectively.

The FE model was also verified by comparing the theoretical and simulated values of exit gradient which showed that the slope line was observed to be approximately at 45 degree; which is an evidence that there was no significant difference between theoretical and simulated exit gradient values (Figure 8). Thus, it is concluded that theoretical values of exit gradient are not much different than the simulated ones.

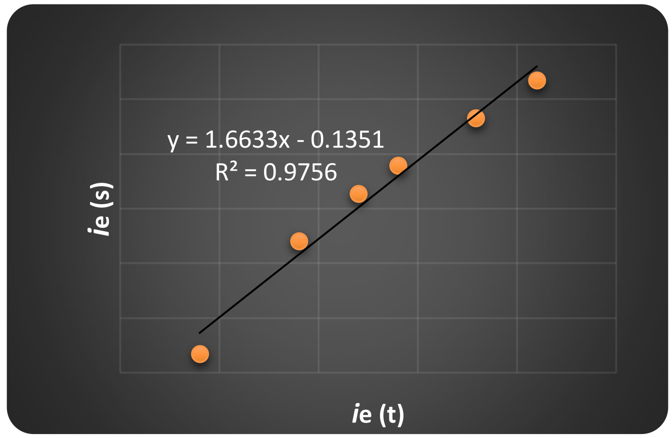

Fig. 8. Relationship between theoretical and simulated exit gradient at different Head of Water at U/S of Weir Section.

CONCLUSION

In present research work, the slave program (SEEP/W) of a finite element based software i.e. Geo-Slope was used to compute the seepage flux and exit gradient under Jinnah barrage weir foundation respectively. A cross section of Jinnah Barrage Weir at its original shape and size at the time of construction i.e. without subsidiary weir was adopted and by using SEEP/W finite element mesh was generated and the simulated results was compared with khosla's method respectively. The dimension of the mesh is 128m long and 206m in depth respectively. The hydraulic conductivity for the shingle type of soil was adopted as 1.215 x 10^{-5} m/s. The simulated results revealed that at lowest water level at the upstream of the barrage; minimum seepage (5.0995 x 10^{-6} m^3/sec/m) and at highest water level maximum seepage (6.7994 x 10^{-6} (m^3/sec/m) occurs respectively. The exit gradient for all the scenarios was found within the permissible limits of (0.25 to 0.20) for shingle material; which conforms the safety criteria of the weir. The theoretical and simulated exit gradient values was compared to counter check the efficiency of numerical model which showed that amongst all the data sets the RMSE, ME, and AMRE was found (0.007354), (0.006180), and 0.98% respectively. The performance efficiency of the model was founded as 99.995%. The FE model was also verified by comparing the theoretical and simulated values of exit gradient which showed that the slope line was observed to be approximately at 45 degree; which is an evidence that there was no significant difference between theoretical and simulated exit gradient values. Thus, it is concluded that theoretical values of exit gradient are not much different than the simulated ones.

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CONFLICT OF INTEREST

The authors declare that no competing interests exist.

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