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Finite Element Analysis of Seepage and Exit Gradient underneath a Hydraulic Structure (Weir) by Using Geo-Slope (SEEP/W) Software

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Abstract:
In this study, a weir section of Runpur bund located in Sindh province of Pakistan was examined. A 2-dimensional model was generated using finite element based software Geo-Slope, SEEP/W. The model was run for two different cases i.e. (i) original design, and (ii) without sheet piles respectively. The study aims to calculate the amount of seepage (q) underneath the weir foundation and to calculate exit gradient (G_E) for five different hydraulic heads i.e. EL 25m, EL 25.7m, EL 26.7m, EL 27.7m, and EL 28.7m respectively. The seepage results showed that at original design a normal behavior of the weir for various hydraulic heads was observed. The overall maximum resultant seepage quantity (q) 7.21×10^{-6} m^3/sec/m and exit gradient (G_E) 0.57 for the hydraulic head EL 28.7m respectively. However, abnormal behavior of the weir without sheet piles was observed with maximum resultant seepage quantity (q) 78.20×10^{-6} m^3/sec/m and exit gradient (G_E) 2.27 for the hydraulic head EL 28.7m respectively. It has been found that without the provision sheet piles the internal pore water pressure underneath the weir foundation was increased and the overall seepage and exit gradient will increase up to 90.78% and 74.88% respectively. Therefore, the weir is not safe without the installation of sheet piles.

INTRODUCTION

Faulty design, improper construction, poor maintenance practices, and poor-quality materials may cause fail for engineering structures. These failures are the hydraulic failure, seepage failure, structural failure, and an earthquake (Aboelela, 2016). The seepage phenomenon is of great importance to be investigated. The effect of seepage on the hydraulic structures is particularly studied for its destructive behavior (Baghalian, 2012). The deteriorative effect of seepage on the hydraulic system might be sudden or by time. The resulting damages can be sorted into partial or overall damages (Arshad *et al.,* 2019). Seepage usually occurs in almost all the hydraulic structures. It may not affect the stability of the structure if the magnitude is within design limits (Issam *et al.,* 2020). But, it will cause the failure of the structure if seepage is uncontrolled or concentrated beyond limits. Small channels are formed that transport material downstream when leakage starts especially for the case of poor soils. As more materials are carried downstream, the channel glow more significant that can cause the barrier to be washed (Irzooki, 2016).

The optimum utilization of water resources for the given purpose cannot be possible without entire consideration of economic and social criteria (Jamel *et al.,* 2016). Paying attention to the expenses allocated to water resources, social benefits of water is important to improve economic development of water industry. On the other hand, the methods used in exploitation of water resources in particular surface water like rivers are different (Karampoor *et al.,* 2015). Each of these methods has specific features and shows different performance in different conditions of river (Mohammad *et al.,* 2012). So, the evaluation of these methods has a major role in improving water utilization. Hydraulic structures which are constructed across the river for storing water resources (Mansuri, 2014).

The saturated and unsaturated zones are observed in all structures which are in contact with the atmosphere. In saturated zone, pore pressure is always positive and increases with increasing depth (Arshad *et al.,* 2019). The pore water pressure is negative in unsaturated zone above water table as compared to atmospheric pressure and with increasing distance from the water table it becomes more negative and near the surface of earth reaches the most negative value (Omofunmi *et al.,* 2017). Considering the effect of seepage and piping on increasing the probability of hydraulic structure failure and decreasing its efficiency, seepage analysis is essential to assess the dam and weir safety level (Najjar *et al.,* 1999). The characteristic of rock, the soil of weir foundation, and the availability of materials for weir construction, design and the shape of the weir and implementation constraints can be effective in selecting the proper procedures for sealing the hydraulic structures (Mansuri *et al.,* 2013).

In the present study, the problem of the seepage under the floor of hydraulic structure (weir) was investigated numerically. For this purpose a weir section of the Ranpur bund was selected and numerical analysis was performed using finite element method. The objective of this study is to investigate the effect of various hydraulic head on the hydraulic structure in terms of seepage and exit gradient at its (i) original design, (ii) without sheet piles, using Geo-Slope SEEP/W software.

MATERIALS AND METHODS

Location

Ranpur bund is located in Sindh province, Pakistan having latitude 24.360474 and longitude is 70.758477 respectively. The profile of the bund axes and weir is elaborated in Figure 1. The weir site consists mainly of quaternary deposit, especially flood plain sediments (sandstone, siltstone, and claystone) (SIDA, 2016).

Numerical Modeling Methodology

The numerical model was created using Geo-Slope (SEEP/W) software and the steady state analysis was selected to simulate the hydraulic conditions beneath the weir foundation. The geometry of the weir in the SEEP/W model is presented in (Figure 2a – 2b). In terms of the weir dimensions, it was 2.1m high above river bed, its cutoff wall was 3.7m below ground level, and its base was 33.8m respectively. The model's sections were divided into segments (elements) using a quad and triangle meshing method. A mesh of 649 nodes, 588 elements, and an approximate global element area size of 2m was created. These meshing approaches select to give accurate analysis for the soil elements underneath dam foundation (GEO-SLOPE, 2012).

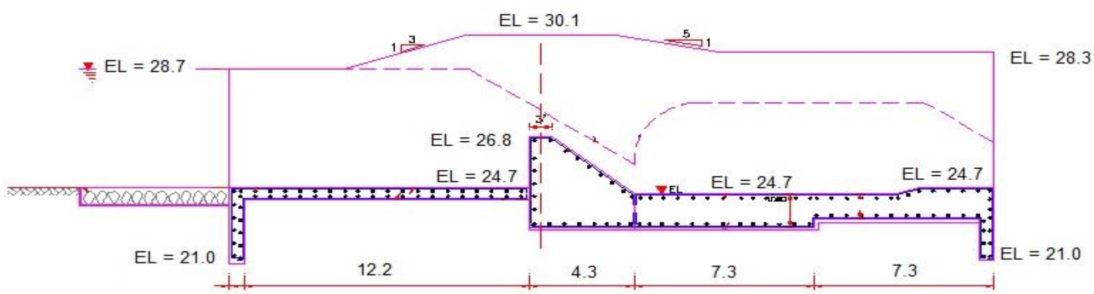

Fig. 1. Ranpur bund and weir profile.

A saturated case was selected for the model in regards to construction and soil materials; it was chosen because it was ideal for a steady state analysis and was a domain that would remain saturated for the duration of the simulation (Shayan *et al.,* 2015). A saturated hydraulic conductivity, anisotropy, saturated volumetric water content, and volume compressibility (Mv) coefficient were entered into the software in order to formulate the model. The interface materials used for conductivity equaled zero (the weir structure and sheet-piles). A head boundary condition was selected, because free water (a reservoir) was present in the model's domain. Therefore, a Dirichlet and Neumann boundary node was assigned on the upstream and downstream slope of the weir (Arshad *et al.,* 2020). Free water means the upstream side are open and the increasing in water quantity are expected. The performance of weir was studied for two different cases i.e. (i) original design, (ii) without sheet-piles at various reservoir levels i.e. EL 25m, 25.7m, 26.7m, 27.7m, and 28.7m respectively. The comparison of numerical simulations is discussed for sheet-piles accordingly.

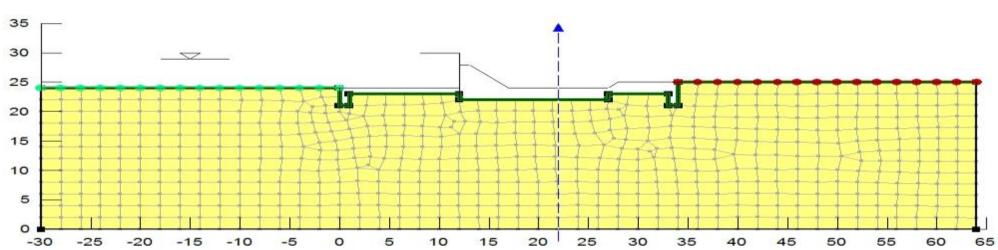

Fig 2a. The SEEP/W Mesh for a weir with sheet plies.

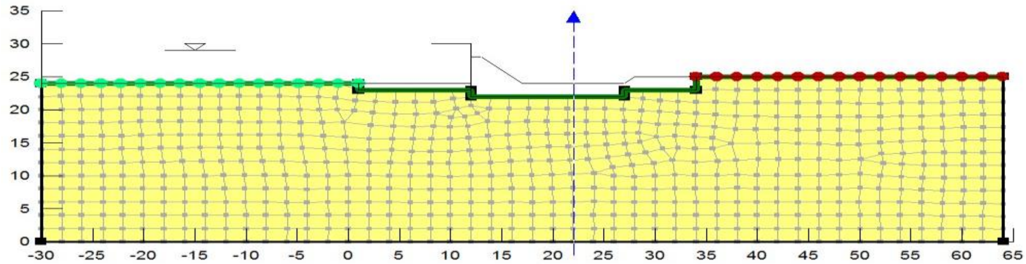

Fig 2b. The SEEP/W Mesh for a weir without sheet plies.

RESULTS AND DISCUSSION

The basic parameters of present research was focused on water seepage analysis and exit gradient respectively. The study of vertical cross section for idealization of permeable soil beneath weir having 588 elements and 649 nodes was accomplished by using four nodal quadrilateral elements (Arshad *et al.,* 2019). The performance of weir was studied for two different cases i.e. (i) original design, (ii) without sheet-piles at various reservoir levels i.e. EL 25m, EL 25.7m, EL 26.7m, EL 27.7m, and EL 28.7m respectively.

The normal behavior of the weir for different hydraulic heads at its original shape and design was observed. The overall maximum resultant seepage quantity (q) and exit gradient (G_E) was found $7.21x10^{-6}$ m^3/sec/m and 0.57 when the total head was 28.7m respectively. Total head was a significant factor in regard to erosion beneath weir foundations. The maximum difference was beneath the weir on the downstream side. This difference pushes water through soil underneath weir body. The low permeability and low cohesion of weir foundation soil increase the possibility of seepage erosion below weir (Al-Saedi, 2020). Figure (3a–3e), describes the SEEP/W simulated results for the case (I) at various reservoir levels. Seepage analysis was conducted for two main reasons: firstly, to calculate seepage flow rate through soil and, secondly, to find the region's exit gradient.

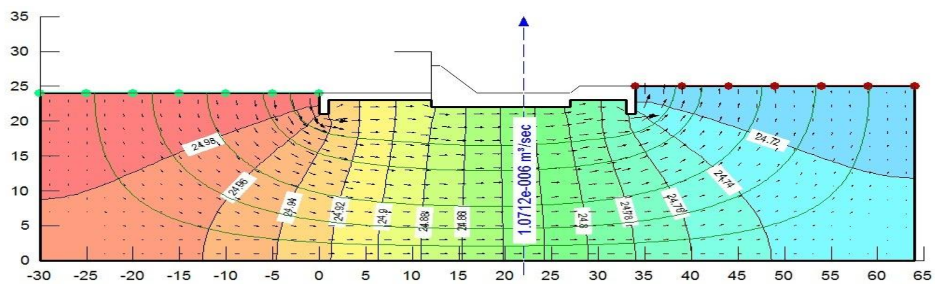

Fig. 3a. SEEP/W model results for a weir with sheet plies (Reservoir level = 25 m).

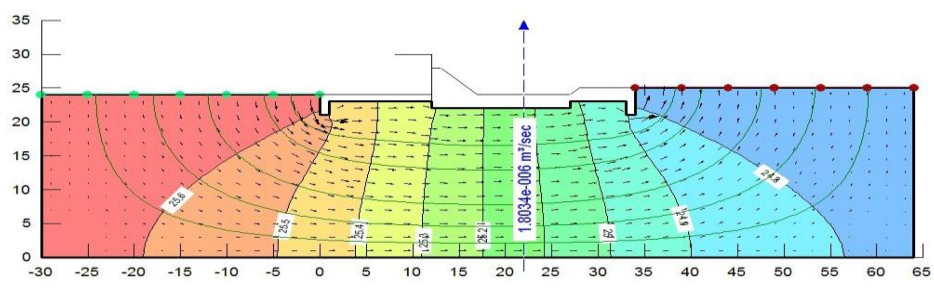

Fig. 3b. SEEP/W model results for a weir with sheet plies (Reservoir level = 25.7 m).

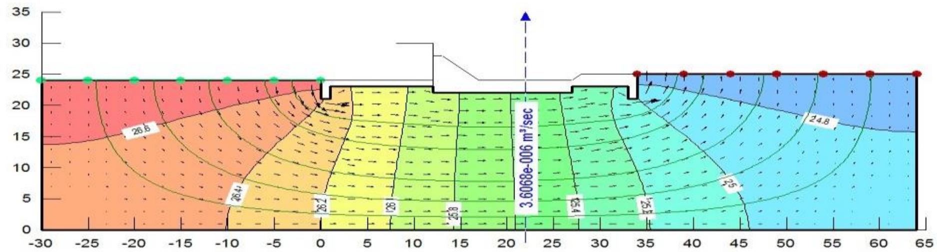

Fig. 3c. SEEP/W model results for a weir with sheet plies (Reservoir level = 26.7 m).

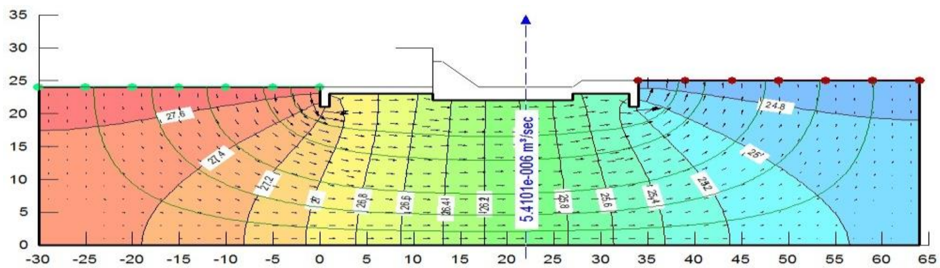

Fig. 3d. SEEP/W model results for a weir with sheet plies (Reservoir level = 27.7 m).

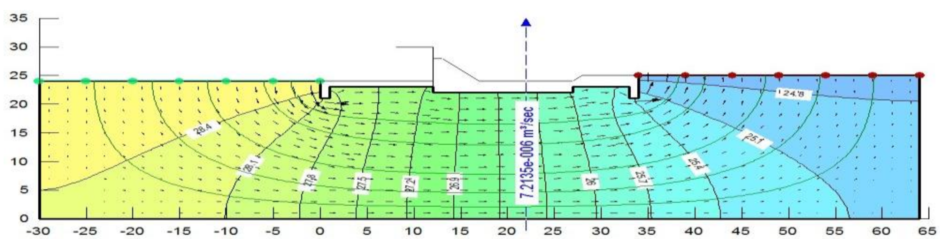

Fig. 3e. SEEP/W model results for a weir with sheet plies (Reservoir level = 28.7 m).

Likewise, seepage analysis was performed for a weir without sheet piles under steady-state condition for a different water reservoir levels. The overall maximum resultant seepage quantity (q) and exit gradient (G_E) was found 78.20x10^{-6} m^3/sec/m and 2.27 when the total head was 28.7m respectively. For the five various hydraulic heads scenarios the velocity vector showed an abnormal behavior and comes out from the river bed at the downstream of the weir section.

The comparison of both cases showed that without the installation of sheet piles the internal pore water pressure beneath the weir foundation will increase and the overall seepage and exit gradient will increase up to 90.78% and 74.88% respectively. Therefore, the weir is not safe without the provision of sheet piles. Figure (4a–4e), describes the SEEP/W simulated results for the case (ii) at different reservoir levels. The numerical results of seepage flux (q) and exit gradient (G_E) for both cases have the same trend. Also, the presence of sheet piles leads to decrease of seepage flux (q) and exit gradient (G_E). These results are according to the findings of (Nassralla *et al.,* 2015; Saleh *et al.,* 2009) who reported that the results obtained for exit gradient (G_E) clear that, when the hydraulic structure supported using the sheet pile foundation at any position under foundation floor the result uplift pressure increase with increasing the effective hydraulic head. The exit gradient (G_E) increase when there was no sheet pile provided to the hydraulic structure. The seepage flux (q) decreased by decreasing the hydraulic head and decrease with the sheet pile installation.

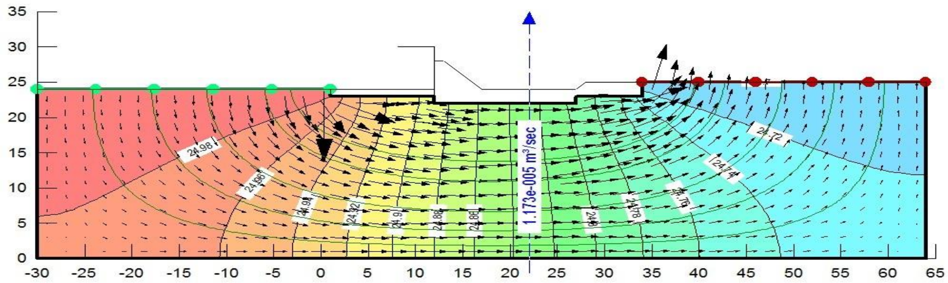

Fig. 4a. SEEP/W model results for a weir without sheet plies (Reservoir level = 25 m).

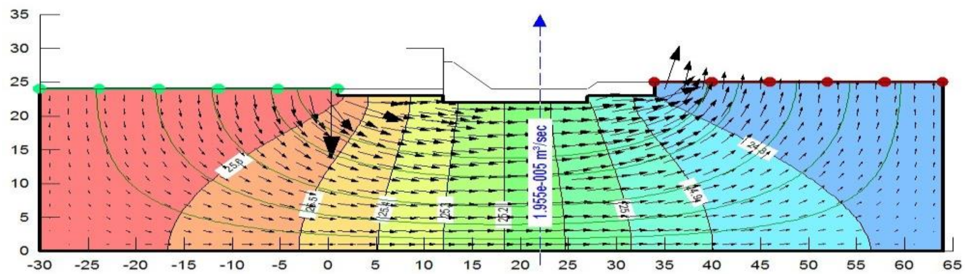

Fig. 4b. SEEP/W model results for a weir without sheet plies (Reservoir level = 25.7 m).

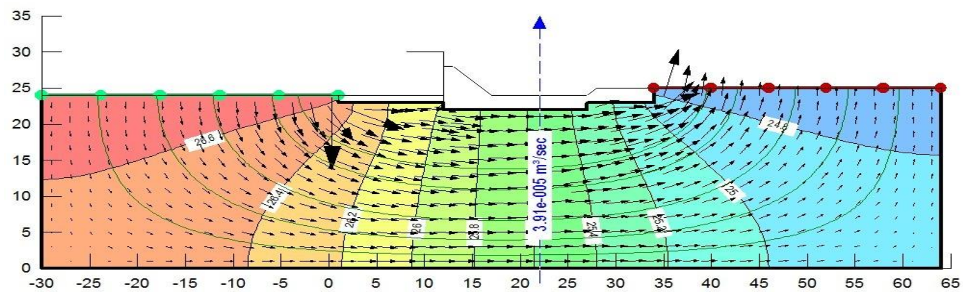

Fig. 4c. SEEP/W model results for a weir without sheet plies (Reservoir level = 26.7 m).

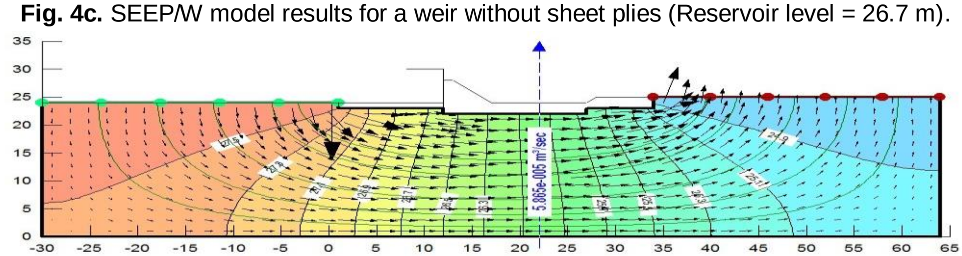

Fig. 4d. SEEP/W model results for a weir without sheet plies (Reservoir level = 27.7 m).

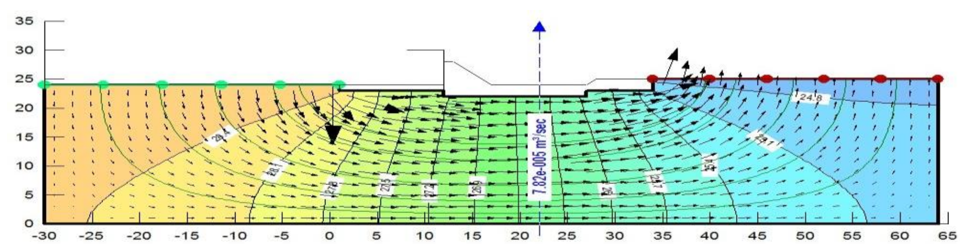

Fig. 4e. SEEP/W model results for a weir without sheet plies (Reservoir level = 28.7 m).

Table 2. The SEEP/W model results of Ranpur Bund Weir for different water levels in reservoir.

Parameters	Total Head (meter)									
	Weir With Sheet piles					Weir Without Sheet piles				
	25 (m)	25.7 (m)	26.7 (m)	27.7 (m)	28.7 (m)	25 (m)	25.7 (m)	26.7 (m)	27.7 (m)	28.7 (m)
Seepage Flux x 10^{-6}	1.07	1.80	3.61	5.41	7.21	11.73	19.55	39.10	58.65	78.20
Exit gradient	0.15	0.21	0.33	0.45	0.57	1.07	1.25	1.59	1.88	2.27

For the case of weir section of the Ranpur bund when sheet piles are not provided water can escape from any part of the downstream area, because of high potential seepage face, which may lead to seepage failure (Liu *et al.,* 2019). Figure (05 - 06) explain a graphical relation for seepage flux (q) and exit gradient (G_E) as a function of elevations, respectively.

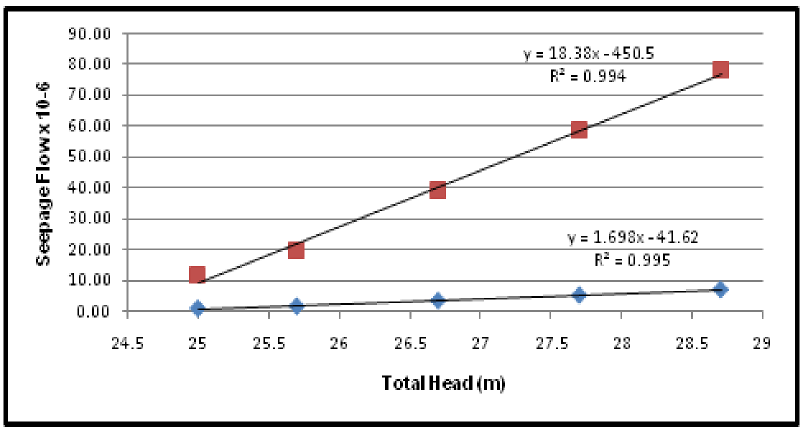

Fig. 5. Relationship between different hydraulic head vs. seepage flux.

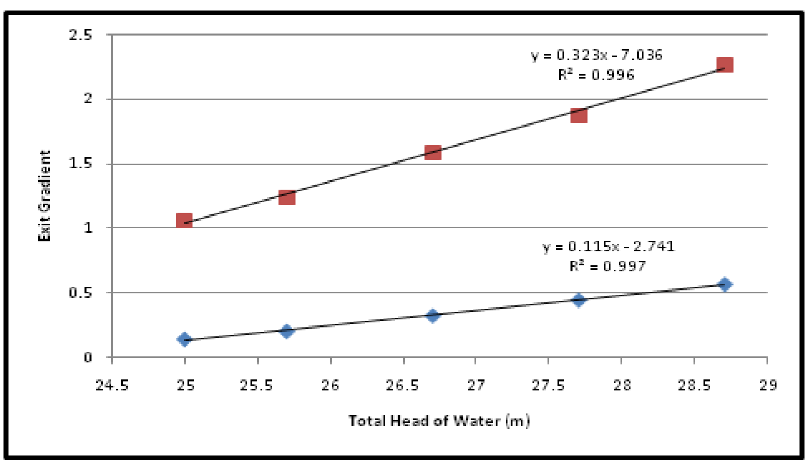

Fig. 6. Relationship between different hydraulic head vs. exit gradient.

CONCLUSION

From the result relations after study the case of study numerically, can be concluded that to decrease the seepage flux (q) and exit gradient (G_E) values under the hydraulic structure foundation sheet piles must be used as it was prescribed in original design. Without the presence of sheet piles there will be an increase in exit gradient (G_E) and the resultant seepage discharge (q) through the soil layers under the hydraulic structure floor either upstream or downstream sheet pile. The results showed that at original design a normal behavior of the weir for different hydraulic heads was observed with overall maximum resultant seepage quantity (q) 7.21×10^{-6} m^3/sec/m and exit gradient (G_E) 0.57 for the hydraulic head EL 28.7m respectively. However, at same hydraulic head EL 28.7 an abnormal behavior of the weir without sheet piles was observed with maximum resultant seepage quantity (q) 78.20×10^{-6} m^3/sec/m and exit gradient (G_E) 2.27 respectively. Presence of the sheet piles positively effect to control seepage flux (q) and exit gradient (G_E). Without the presence of sheet piles the internal pore water pressure underneath the weir foundation was increased and the overall seepage and exit gradient will increase up to 90.78% and 74.88% respectively. Therefore, the weir is not safe without the presence of sheet piles. Hence, it can be concluded that the numerical methods give deep understanding for hydraulic and geotechnical problems.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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