Dynamics of gabion weirs and its comparison to reinforced concrete weirs

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Abstract

Weirs are important water divergence structures. Different types of weirs have different hydraulics on upstream as well as downstream flows, resulting in varying construction costs and different safe operation procedures. This study presents the hydraulic comparison of two different types of weirs: reinforced concrete and gabion. These weirs were compared using different hydraulic parameters, including downstream scouring, upstream sedimentation, discharge coefficient, water surface profile, and seepage along the weir and its foundation. Experimental analysis was carried out to estimate scouring, discharge coefficient, and sedimentation. Similarly, seepage analysis was performed using the SEEP/w software, while the water surface profile was drawn using HEC-RAS. Results show that upstream sedimentation and downstream scouring were higher for concrete weirs as compared to gabion weirs due to the fact that some sediment is able to pass through the latter type. In addition, foundation and body seepage of a gabion weir can be reduced by almost 95% when replaced with a reinforced concrete weir. The HEC-RAS results showed that the water surface elevation for a concrete weir is much higher than the gabion. A low discharge coefficient was observed for the concrete weir, as compared to the gabion. To conclude, concrete weirs are more efficient in raising water level and reducing seepage. They are also durable but need better arrangement to control scouring and sedimentation.

Keywords: Discharge coefficient; flow profile; gabion weir; non-porous weir; seepage; scouring; sedimentation.

1. Introduction

As water flows in natural rivers due to gravity, it can be efficiently used by constructing hydraulic structures such as dams and weirs. However, the equilibrium of a river is disturbed by these barriers. The disturbance affects different flow and soil parameters like permeability, water table, porosity, velocity, sedimentation and discharge, etc. (Adamski *et al*., 2005). All types of hydraulic structures succor its unique functions. Weirs function to raise water level and/or to divert water into the off-taking canal (Depeweg *et al.* 2014).

Melting glaciers are a prominent source of river water. During winter season where temperature is quite low, a small quantity of water is flowing in a river. In order to divert water to an off-taking canal, it is important to provide an impermeable weir (Rao 1963). A concrete weir is an impermeable structure, whereas a gabion is permeable. An impermeable weir shows high resistance to water flow as compared to permeable weirs (Nguyen, 2006). Similarly, the head of water is more in the Concrete weir and small in the gabion weir due to porosity difference of the structures. The general equation for a broad crested weir is $Q=2/3\ C_d\ B(2g)^{0.5}\ H^{1.5}$, which is not used for the gabion weir (Boiten 2002). Because physical or chemical materials do not pass through impermeable concrete weirs, their use can cause negative impacts on aquatic environment (Badr & Mowla, 2015). Gabion weirs can be used to divert water in a low-flow period, but during a high flow, it will be flushed out by water pressure (Mohamed, 2010).

One of the most common reasons for constructing a weir in the last fifty years or so was for the purposes of monitoring flow in rivers (Khelifa *et al.*, 2013). Many of these weirs were constructed with the aim of monitoring low flows, amidst rising concern about the reliability of water supplies for domestic and industrial uses (Dabling, 2014). Because of focus on low flows, many such weirs were bypassed in flood conditions, thus giving unreliable data on high flows (Azimi *et al*., 2014).

Due to hydraulic differences among different types of weirs, this study describes the hydraulic principles governing the unsteady reaction of groundwater levels related to weir operations in control drainage systems (Bohne *et al*., 2012). The literature appraisal of the earlier research exertion on weir analysis and predictions shows that a widespread work has been voted by many researchers. Application of computer models could provide a roadmap to efficiently analyze river flow (Lee *et al.*, 2005). The geometry, hydraulics and sediment parameters of the gabion and concrete weirs are different from each other. By replacing one prototype for another under the same conditions, the total regime of the off-taking canal, sediment and eutrophication of water could be changed (Hashemy Shahdany *et al*., 2015).

The objective of this study was to compare two materially different prototypes located at 3 km D/S of the Warsak Dam Peshawar constructed in the west of Khyber Pakhtunkhwa (KP) Province, Pakistan. The discharge coefficient, siltation and scouring in both structures were analyzed in the Hydraulics Laboratory of Civil Engineering Department (CED), University of Engineering and Technology (UET) Peshawar, Pakistan. The results obtained from experimental analysis were plotted using MS Excel and Surfer software (8.0), while the seepage and water surface profile were analyzed using Seep/W Software (2016) and HEC-RAS, respectively, for both types of weirs (Fleenor & Jenson, 2003) . Finally, the results for both types of weirs were compared for efficacy.

2. Materials and methods

The following section explains how the different parameters of sedimentation, scouring, discharge coefficient, and water surface profile were analyzed and compared.

2.1 Experimental setup

The channel at the Hydraulics Laboratory of CED, UET Peshawar Pakistan is 15.85 m long, 0.304 m wide and 0.45 m high. The whole assembly consists of a main channel, centrifugal pump, three water tanks, inflow and outflow valves, and an adjustable gate at the downstream end.

2.1.1 Test section preparation

Sediments of median-size D_{50} were used to prepare a test section filled with sediment installation for the weir model and to reflect the actual sediment condition. The test section was 3.04 m long, 0.30 m wide and 0.30 m high. The weir models were prepared carefully and installed individually within the experimental channel.

2.1.2 Weir model preparation

Weir models were constructed as shown in Figures 1 and 2. The dimensions (0.30 m length along the channel width, 0.15 m wide along the channel length and 0.45 m high) of both the models were the same for the sake of comparison. Length of the models was reduced to the width of the channel and analyzed both at upstream and downstream positions.

These models were then placed in the test section one at a time in order to perform the experiments and analyze different parameter effects. A short description of these weir models is given in the subsequent sections.

A concrete weir with a mix design of 1:2:4 mix was prepared and cured for 14 days. To be properly seated, the weir was fixed in the channel with the help of plaster of Paris. Out of the total 0.45 m height, 0.12 m was kept below the soil surface while the remaining 0.35 m was above the soil surface. The weir was designed so as to fulfill the properties of a broad-crested weir. An impermeable cistern was also provided at the downstream of the structure to approximately represent actual field conditions.

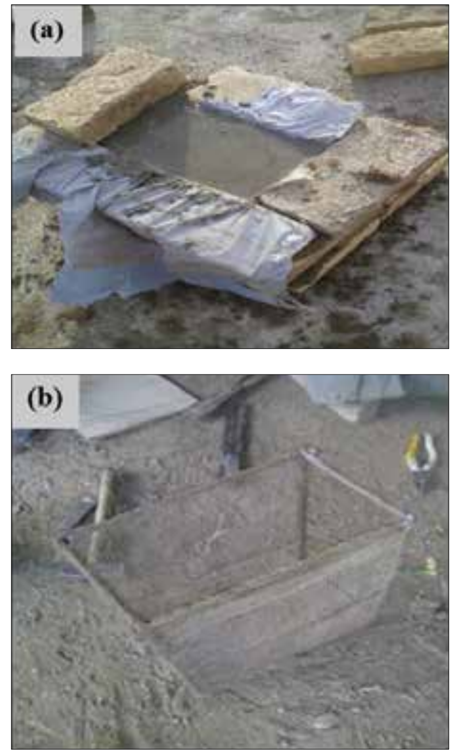

Fig. 1. (a) concrete weir model, (b) gabion weir model

2.1.3 Gabion weir

The dimensions and shape of the gabion weir were the same as the concrete weir. The gabion pebbles were selected with mean grain sizes of 0.078, 0.35 and 1.14 inches (Mohamed, 2010). The apron of the gabion weir consisted of gravels. Like the concrete weir, it was fixed in the channel with the help of plaster of Paris. The bed level of soil was kept 4.7 inches above the channel bed. During the testing, the discharge and other parameters in the channel were kept constant for both weir models.

2.2 Experimental procedure

The experiments were performed once the he tests sections were prepared and placed in the channel. Each model was installed in the middle of the test section one by one. The test section was made smooth and uniform before starting each experiment. The initial bed levels were measured using point gauge and were used as a reference for calculating the scouring and sedimentation. The water was allowed to enter the

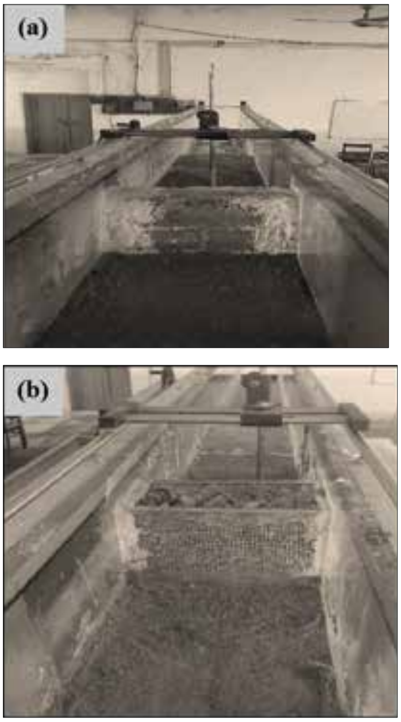

Fig. 2. Laboratory model for (a) concrete weir and (b) gabion weir

channel from three interconnected tanks through a centrifugal pump. The discharge in the channel was calculated to be 0.000164 m^3/s for both structures.

The experiments were continued for different time intervals. After the specified time interval, the flow was stopped, and then the water was allowed to drain out of the channel. The scouring and sedimentation readings were noted after the water was completely removed from the entire channel length and width. The same procedure was repeated for testing the models at time intervals of 15, 30, 60 and 120 minutes for different parameters.

2.2.1 Scouring and sedimentation

The experiments were conducted to find out the amount of sedimentation on upstream of weir and scouring on its downstream. The readings along the length, width and depth were taken for the plane sediment bed before the start of each experiment. Similarly, at the end of the experiment, the x, y and z readings were noted along the same points as taken before the testing, and then the differences were calculated. Sedimentation shows above the datum line, while below the datum line is the scouring of the soil bed. The readings were taken along the channel length up to 277 cm. The same procedure was repeated four times for different time intervals for the concrete and gabion weirs. The readings were then plotted using the Surfer Software and MS Excel.

2.2.2 Discharge coefficient

The discharge coefficient was calculated for different discharges for both types of weirs. After installation in the channel, the heads of water over the gabion weir and concrete weir were calculated using a point gauge. Three different heads were calculated by increasing the velocity. The discharge coefficient for the concrete weir was found

$$C = \frac{Q}{L}(H)^{\frac{3}{2}} \quad , \tag{1}$$

using the conventional broad crested weir formula as:

where Q is the actual discharge, L is the width of the weir and H is the head of the water above crest of the weir. In this formula, the head of water above the crest of weir was calculated corresponding to the discharge, and then the value of C was estimated. The discharge coefficient for the gabion weir was calculated

$$C = -1.77 + 0.55\, log(Re) - 0.78\, \frac{H}{L} + 0.35\, \frac{d_m}{p} + 0.085\, S_r \tag{2}$$

$$\text{for } S_r = \frac{y_1 - y_2}{H} \quad R_e = \frac{Q\rho}{B\mu},$$

using the formula suggested by Mohamed (2010).

where *Sr* is the submergence ratio, *Re* is Reynold's number, Q is the discharge, and y_1 and y_2 are water depths upstream and downstream for the gabion weir, respectively. B is the channel width, H is the water head above the weir, p is the weir height, L is the length of the weir, and *dm* is the mean stone size used in the gabion weir construction. Finally, ρ is the fluid (water) density, g is the gravity of acceleration and μ is equal to the dynamic viscosity of the fluid (water).

3. Seepage analysis

Seepage through the weir body and foundation is another parameter for comparison. For this purpose, Seep/W software was used. Both weirs were modeled in the software according to the field conditions. The downstream apron was also provided for both types of weirs according to the dimensions in the field. Different materials and properties were defined in the software according to the field conditions, which were obtained from data provided by the Irrigation Department Peshawar, Pakistan. After inputting the data, the analysis was carried out under steady state conditions. From the seepage analysis, the phreatic line and the quantity of water seeping through the weir were calculated (Figure 8).

4. HEC-RAS analysis

Another parameter considered for the comparison of weirs was the water head availability of the off-taking canal. For this purpose, the water surface profile of the river for concrete and gabion weir was required. HEC-RAS software developed by the US Army Corps of Engineers was used for the calculation of the water surface profile for the two types of weirs. The data required for HEC-RAS include the flow discharge in the river, the weir model type, and the cross sections of the river upstream and downstream for both types of weirs covering 2.5 kilometers on both sides of the weir structure. A total of 20 cross sections were taken 100 meters apart from each other. Out of the 20, 15 cross sections were upstream, while the remaining five were downstream of the weir. The analysis for both models was performed under steady state conditions for average flow, a flow of a 500-year return period, and a flow for a 2010 flood. The gabion weir and concrete gated weir were analyzed separately. The flow characteristics, geometry of the structure, geometry of the river and canals, and other flow and sediment parameters for both weirs were kept constant except for the discharge coefficient, Manning's n value, and 4 vertical gates (in the case of the concrete weir).

5. Results and discussion

The results obtained from experimental analysis, seepage analysis and HEC-RAS are discussed in the following subsections.

5.1 Experimental results

Experiments were conducted to get the information about scouring, sedimentation and Discharge Coefficient. After conducting the required set of experiments, the results obtained for each parameter are shown and discussed in the following sections.

5.1.1 Scouring and sedimentation

To calculate the scouring of the downstream weirs and sedimentation upstream, several experiments were conducted. To get the data for different parameters, the x-coordinates (along channel length, mm), y-coordinates (along channel width, mm) and z-coordinates (depth or height, mm) were taken before the experiment, when the bed was flat and after conducting the experiment at the same points. Readings at corresponding points showed either sedimentation or scouring. The data collected were plotted using Surfer Software to draw the contour maps of the affected area. The same data along the center line of the channel were also drawn using MS Excel in order to visually show the effect of weir structure on sedimentation/scouring along the length of the channel. Figs. 3(a), 3(b), 4(a), 4(b), 5(a), 5(b), 6(a) and 6(b) are contour maps based

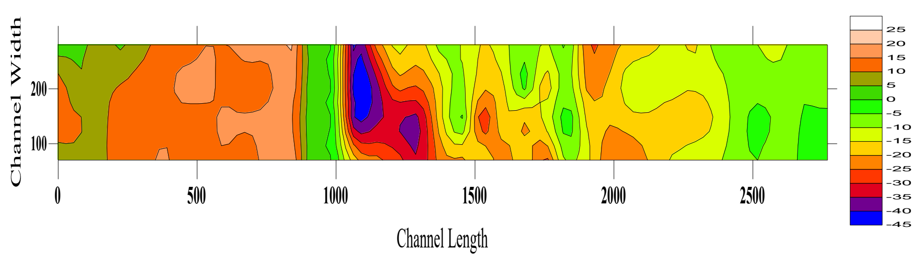

Fig. 3(a). Contour map showing the affected area around gabion weir for 15-minute duration

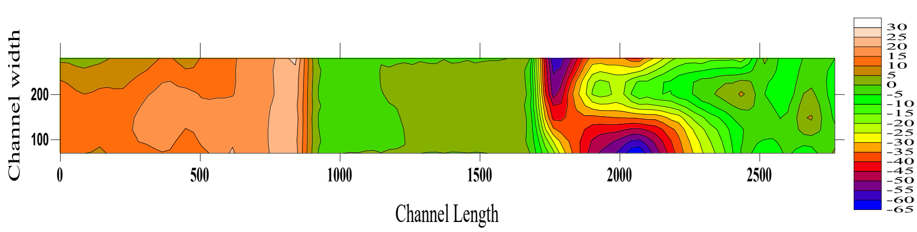

Fig. 3(b). Contour map showing the affected area around concrete weir for 15-minute duration

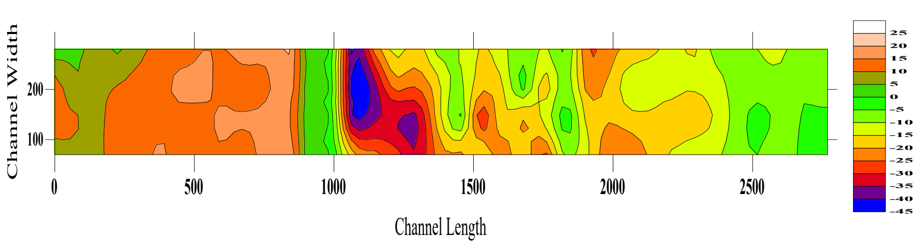

Fig. 4(a). Contour map showing the affected area around gabion weir for 30-minute duration

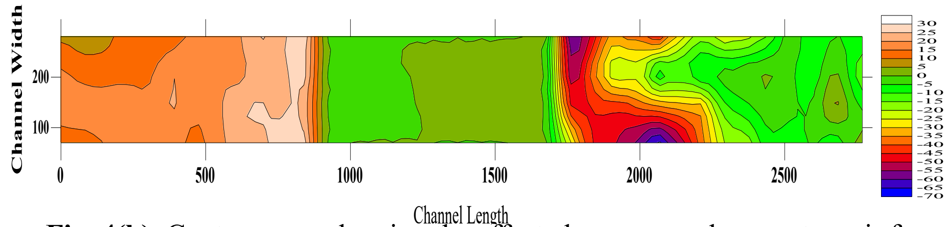

Fig. 4(b). Contour map showing the affected area around concrete weir for 30-minute duration

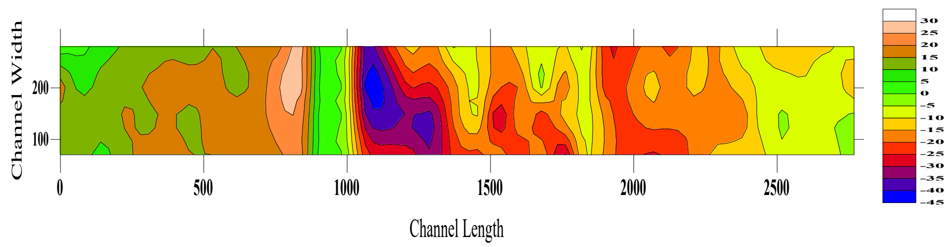

Fig. 5(a). Contour map showing the affected area around gabion weir for 60-minute duration

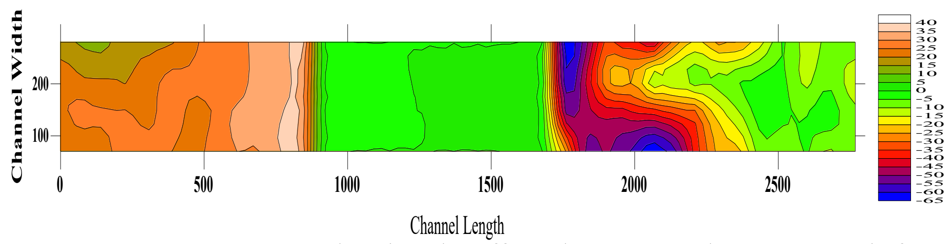

Fig. 5(b). Contour map showing the affected area around Concrete weir for 60-minute duration

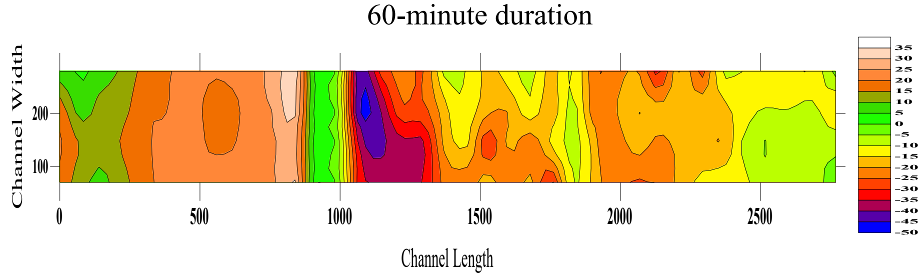

Fig. 6(a). Contour map showing the affected area around gabion weir for 120-minute duration

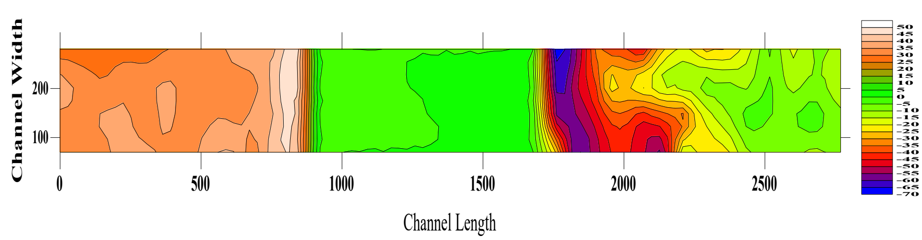

Fig. 6(b). Contour map showing the affected area around Concrete weir for 120-minute duration

on the data. MS Excel based plots are shown in Figure 7. The above contour plots show the variation of scouring and sedimentation with respect to zero datum taken before the start of each experiment. It is clear from the figures that sedimentation occurs upstream and scouring happens downstream of the weir. Both sedimentation and scouring were higher for the concrete weir because it did not allow the sediments to pass through, and thus depositing it. Similarly, the water flowing over the weir was clean, causing more scouring downstream of the weir. However, it was observed that scouring occurred at the end of the impermeable apron provided at the downstream end of the concrete weir. For the gabion weir, some of the sediments passed through the pores in the weir. Thus, sediment deposition was less than with the concrete weir. The figures clearly show that the sedimentation and scouring for both types of weirs increases with experiment duration.

To further explain the position of sedimentation and scouring along the centerline of the channel (dimension in mm), excel plots were

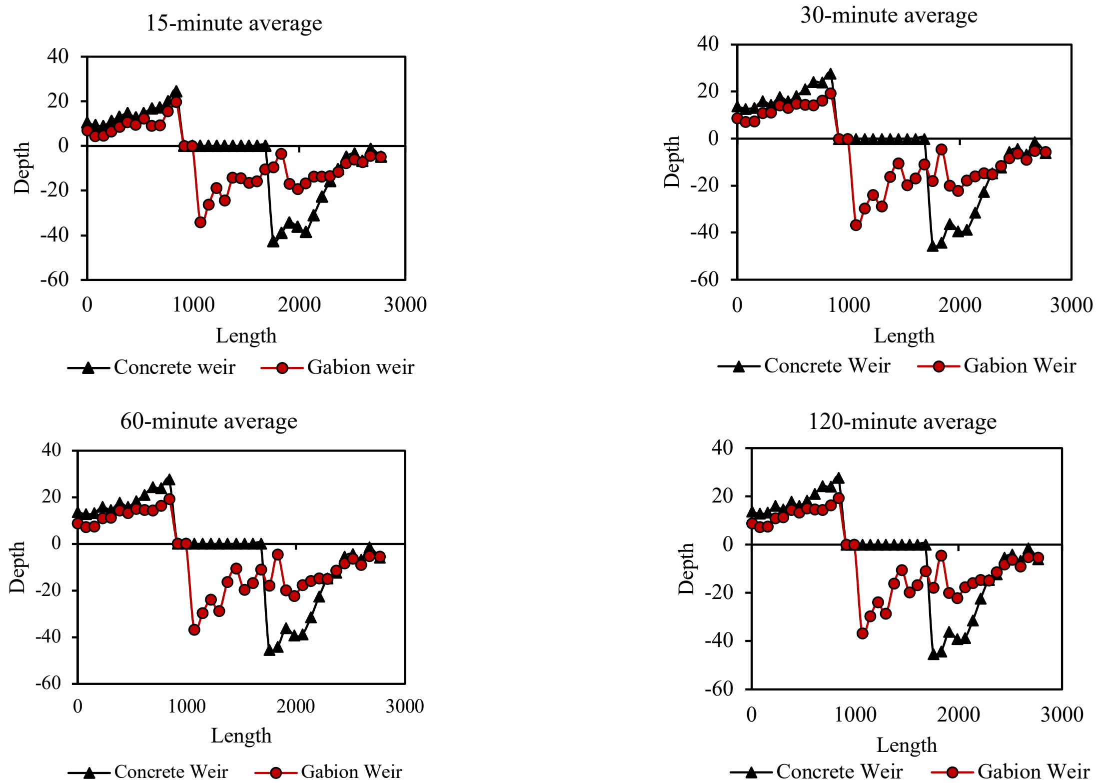

Fig. 7. Longitudinal profiles of sedimentation and scouring for both types of weir models at different durations

drawn for both types of weirs (Figure 7).

Figure 7 profiles show that sedimentation occurred on the upstream side of both weir structures, but values were higher for the concrete weir. Scouring occurred at the downstream side of both weir types but was less pronounced for the gabion weir

Discharge coefficient (C)

The discharge coefficients for both hydraulic structures were found by varying the discharge using Equation 1

5.2 Seepage analysis results

The seepage analysis for both types of weirs was carried out using Seep/W Software. The results obtained are shown in Figure 8 for the gabion and concrete weirs. It was exhibited that seepage of the concrete weir is far less than for the gabion weir. The amount of seepage calculated for the concrete weir was 5.2453×10^{-17} m^3/sec, while it was 6.6402×10^{-16} m/sec for the gabion weir. The main cause for this is the porosity of the structure and provision of the cut-off wall of the concrete weir.

5.3 HEC-RAS results

Both weirs were modeled in HEC-RAS to determine the

Table 1. Calculated discharge coefficients for both weir models

S. No.	Discharge (Cumecs)	C (Gabion)	Head/Length (Gabion)	C (Concrete)	Head/Length (Concrete)
1	$2.207\ e^{-3}$	4.50	0.029	2.76	0.062
2	$2.307\ e^{-3}$	3.78	0.039	2.67	0.065
3	$2.500\ e^{-3}$	3.11	0.042	2.50	0.072

Table 1 shows that the discharge coefficient depends upon the type of weir structure. The discharge coefficient of the gabion weir is greater than that of the concrete weir. It was also noted that by increasing the head to length ratio, the discharge coefficient for both weirs decreases.

water surface profile of the river. The analysis was carried out while the water was in a steady-state flow. The HEC-RAS model was run for both types of weirs. The results are shown in Table 2 for the concrete weir and in Table 3 for the gabion weir. The water surface profile along the river length is shown in Figure 9 for the concrete and

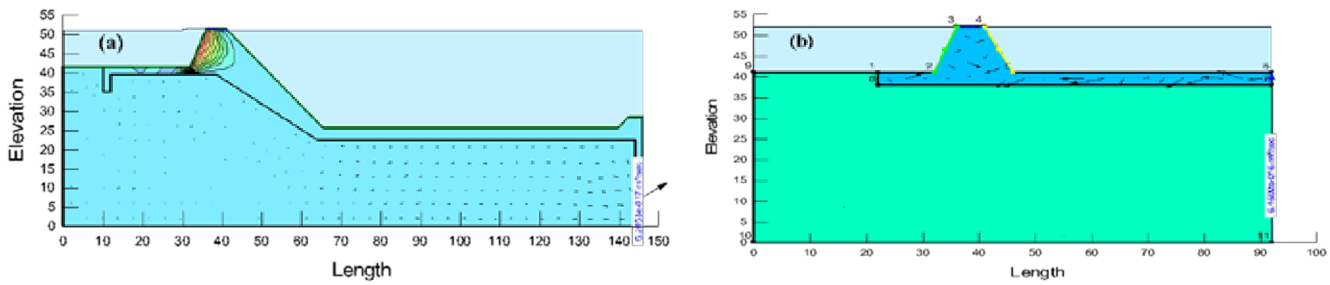

Fig. 8. Seepage analysis reults for the (a) concrete and (b) gabion weir using Seep/W software

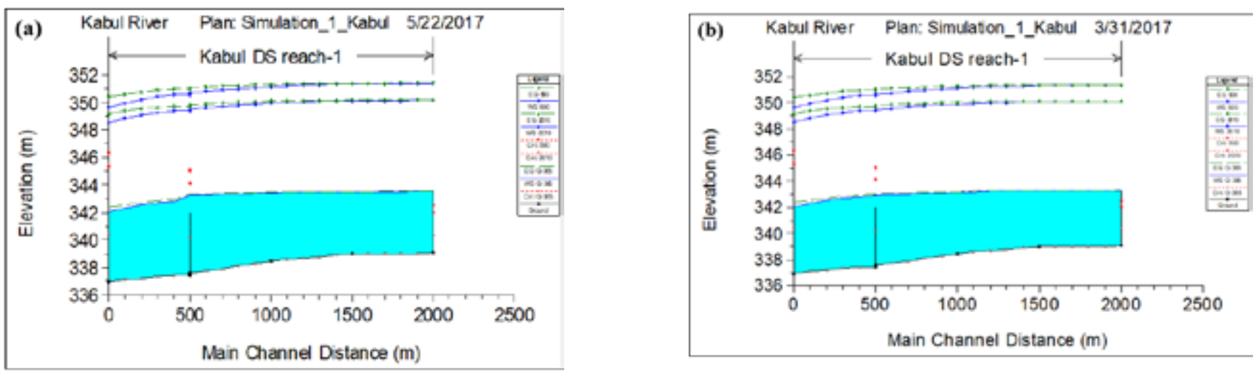

Fig. 9. Water surface profile results for (a) concrete and (b) gabion weir using HEC-RAS

gabion weirs.

From Figures 9(a) and (b), it is evident that the water surface profile for the concrete weir is much higher than the surface profile for the gabion weir under the same conditions. The reason is that the concrete weir is impermeable and will not allow any water to pass through its body. It helps in diverting more water to the off-taking canal. The results obtained from the HEC-RAS model as shown in Table 2 and 3 for the concrete and gabion weir respectively. There were a total of 15 cross sections upstream and 5 downstream, but since our major interest was in the water surface elevation and other parameters around the weir, only two cross sections for each upstream and downstream are shown in the tables below. Here, Q-365 represents the average annual flow, 2010 is the mean flow recorded for a 2010 flood, and 500 mean flow corresponds to a 500-year return period. The flow profiles and the tabulated values of both weirs clearly showed that for constant discharge, the rise in water level was at a maximum with the concrete weir and at a minimum with the gabion weir. This shows that the concrete weir provides a sufficient amount of water

Table 2. HEC-RAS model results for concrete weir

Reach	X-section	Profile	Q Total (Cumecs)	Min Ch El (m)	W.S. Elev (m)	Crit W.S. (m)	E.G. Elev (m)	E.G. Slope	Vel Chnl (m/s)	Flow Area (m2)	Top Width (m)	Froude No.
Kabul River	8	**Q-365**	625.3	337.7	343.3		343.4	0.00034	1.12	558.15	146.4	0.18
	8	**2010**	4200	337.7	349.6		349.9	0.00061	2.3	1835.8	274.9	0.27
	8	**500**	5390	337.7	350.8		351.1	0.00061	2.51	2192.8	324.5	0.28
	7	**Q-365**	625.3	337.5	343.2	340.2	343.3	0.00038	1.22	514.38	129.7	0.19
	7	**2010**	4200	337.5	349.5	344.1	349.8	0.00073	2.52	1690.9	268.1	0.3
	7	**500**	5390	337.5	350.7	345.1	351.1	0.00073	2.75	2030.7	309.7	0.3
	Inline Structure (RCC Weir)											
	5	**Q-365**	625.3	337.4	342.8		342.9	0.00068	1.47	424.3	124.6	0.25
	5	**2010**	4200	337.4	349.4		349.8	0.00091	2.68	1566.7	232.7	0.33
	5	**500**	5390	337.4	350.6		351	0.00089	2.92	1862.1	266.7	0.33
	4	**Q-365**	625.3	337.3	342.7		342.8	0.00096	1.66	377.63	120.4	0.3
	4	**2010**	4200	337.3	349.2		349.7	0.00105	2.87	1464.6	217.4	0.35
	4	**500**	5390	337.3	350.4		350.9	0.00111	3.11	1730.7	236.9	0.37

Table 3. HEC-RAS model results for gabion weir

Reach	X-section	Profile	Q Total (Cumecs)	Min Ch El (m)	W.S. Elev (m)	Crit W.S. (m)	E.G. Elev (m)	E.G. Slope	Vel Chnl (m/s)	Flow Area (m2)	Top Width (m)	Froude No.
Kabul River	8	**Q-365**	625.3	337.7	343		343.1	0.0004	1.22	513.27	142.9	0.21
	8	**2010**	4200	337.7	349.6		349.9	0.0006	2.31	1824.9	272.4	0.27
	8	**500**	5390	337.7	350.8		351.1	0.0006	2.52	2185.7	323.8	0.28
	7	**Q-365**	625.3	337.5	342.9	340.2	343	0.0005	1.32	473.05	126.6	0.22
	7	**2010**	4200	337.5	349.5	344.1	349.8	0.0007	2.53	1679.6	266.9	0.3
	7	**500**	5390	337.5	350.6	345.1	351	0.0007	2.76	2023.5	309.4	0.31
	Inline Structure (Gabion Weir)											
	5	**Q-365**	625.3	337.4	342.8		342.9	0.0007	1.47	424.3	124.6	0.25
	5	**2010**	4200	337.4	349.4		349.8	0.0009	2.68	1566.7	232.7	0.33
	5	**500**	5390	337.4	350.6		351	0.0009	2.92	1862.1	266.7	0.33
	4	**Q-365**	625.3	337.3	342.7		342.8	0.001	1.66	377.63	120.4	0.3
	4	**2010**	4200	337.3	349.2		349.7	0.0011	2.87	1464.6	217.4	0.35
	4	**500**	5390	337.3	350.4		350.9	0.0011	3.11	1730.7	236.9	0.37

to the off-taking canals in low peak seasons as compared to the gabion weir. The data also reveal that the critical water surface, energy grade line, flow velocity, flow area, and the Froude numbers are different. The results inferred from the that there is a notable difference for the water level upstream of the weir for the average annual flow, but for the rest of the flows the, difference is minimal. The reason is that the weir only affects low flows. For high flows, the water surface remains the same regardless of the weir type. However, since weirs are normally constructed to divert a sufficient quantity of water in low-flow seasons, the concrete weir showed a better efficacy when compared to data from the gabion weir. While this may be a benefit, concrete weirs are more expensive. Hence, the results suggest that replacing the gabion weir with the concrete weir will significantly affect flow conditions in the Kabul River and the water supply flowing into the off-taking canal.

6. Conclusion

This analysis shows that concrete and gabion weirs behave different in regards to seepage, discharge coefficient, scouring, sedimentation and water surface profile. The findings can be summarized as follows:

1. Although scouring occurs downstream on both weirs, concrete weirs showed more. Therefore, if concrete weirs are adopted, additional measurements will be needed for its protection (i.e. apron), which will increase costs.
2. The discharge coefficient is higher for the gabion weir, resulting in more discharge through the river, and less quantity is diverted to the off-taking canal. Thus, the latter type is less efficient in its primary function. In addition, the discharge coefficient of weirs decreases by increasing the head to length ratio and vice versa.
3. Siltation occurs on the upstream sides of the weirs but is greater for the concrete weir. This is the deficiency because it will cause a reduction in the capacity of the river and may cause water overflow along the river banks.
4. Seep/W Software results showed that the foundation seepage is at a maximum for the gabion weir and at a minimum for the concrete weir. This is because sheet piles are provided in the latter case. Yet, concrete weirs are still more stable structures and last longer in comparison.
5. HEC-RAS results showed that for the same discharge, there was a notable difference in the water surface elevation, thus resulting in a different efficiency in supplying water to the off-taking canal.
6. This discussion applies only to the average annual flow because, when there are high flows, the weir effect is negligible. This results in almost the same height of water in the Kabul River.
7. Finally, it can be concluded that RC concrete weirs are more stable and efficient structures as compared to the temporary gabion weir ones. While they may be advantageous, they are more expensive.

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ديناميكيات السد الترابي ومقارنتها مع السد المصنوع من الخرسانة المسلحة

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الملخص

السد هو أحد الهياكل الهامة لعزل المياه. توجد لدى أنواع مختلفة من السدود هيدروليكية مختلفة عند المنبع وكذلك عند المصب، مما أدى إلى وجود تكاليف مختلفة للبناء واتخاذ تدابير لازمة للتشغيل الآمن. تعرض هذه الدراسة المقارنة الهيدروليكية لنوعين مختلفين من السدود وهما السد المصنوع من الخرسانة المسلحة والسد الترابي. وتمت مقارنة هذه السدود باستخدام معلمات هيدروليكية مختلفة مثل التصفية بجرف المياه في اتجاه مجرى النهر، والترسيب في المنبع، ومُعامل التفريغ، وملامح سطح الماء والتسريب على طول السد وأساسه. تم إجراء تحليل تجريبي لتقدير التصفية، ومعامل التفريغ والترسيب. وبالمثل، تم إجراء تحليل التسريب باستخدام برنامج SEEP / w بينما تم رسم ملامح سطح الماء باستخدام HEC-RAS. بعد إجراء التحليل، وجدنا أن درجة الترسيب في المنبع والتصفية في اتجاه المجرى كانت أعلى بالنسبة للسد الخرساني مقارنةً بالسد الترابي بسبب أن النوع الأخير يسمح لبعض الرواسب بالمرور عبره. استنتجت الدراسة أيضاً أنه تم خفض التسريب من أساس وجسم السد الترابي بنسبة 95٪ تقريباً عند استبداله بالسد المصنوع من الخرسانة المسلحة. وأظهرت نتائج HEC-RAS أن ارتفاع سطح الماء بالنسبة للخرسانة المسلحة أعلى بكثير من السد الترابي. وبالمثل، لوحظ انخفاض في معامل التفريغ بالنسبة للسد الخرساني مقارنةً بالسد الترابي. وفي النهاية، يتضح أن السد الخرساني هو أكثر كفاءة في رفع مستوى الماء والحد من التسريب كما أنه دائم التحمل، ولكنه يحتاج إلى ترتيبات أفضل للتحكم في التصفية والترسيب.