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Managing Local Scour Downstream of Cross-River Structures Case Study: Balaroud Inverted Siphon

[1]B. Lashkar-Ara, [2]S.MH. Ghotbi and [2]A. Armaghani

[1]Jundi-Shapur University of Technology, Dezful, Dezful, Iran
[2]Civil Engineering, Jundi-Shapur University of Technology, Dezful, Iran

Abstract: Scouring or removal of alluvial material by flowing water is a natural phenomenon which occurs as a part of the morphological changes of rivers. Scour occurs often resulting from increased turbulence and forces that develop in the flowing water due to the presence of structures. These structures exposed to the interaction between flowing water and alluvial material. Although the cost of repair of damaged infrastructure is often significant, the indirect costs of such events can be even greater. In this paper the scour phenomenon on the Balaroud river bed has been investigated. An inverted siphon crosses the Balaroud river acts like a grade control structures. Passing of the river flow over the roof of the siphon has created a deep scour hole downstream. In this study first a field survey was conducted, then the river flow conditions was computed for different flood period. Comparison of measured and computed scour depth showed that Schoklitch formula can predict the scour depth in a reasonable manner. Measures for river bed protection including downstream of inverted siphon structure have been presented.

Key words: Inverted Siphon · Scour · Schoklitch · Balaroud river · Alluvial material · Gabion

INTRODUCTION

Scour is the removal of soil particles by flowing water. While the entrainment of upland soils from overland runoff is included in this definition, scour on river systems generally refers to the removal of material from the bed and banks of the river from streamflow.

Hydraulic structures that obstruct the flow pattern in the vicinity of the structure may cause local scour. The increased turbulence caused by the interaction between the structure and the flow of water introduces elevated forces that impact the earth material on the riverbed and around the structure. If the resistance offered by the earth material against scour in inadequate, the elevated forces will dislodge the material and remove it, thus forming a scour hole. A new equilibrium may eventually be reached as hydraulic conditions are adjusted, turbulence is reduced concomitantly with the forces it causes and these forces are eventually resisted by the inherent strength of the earth material. Local scour is occurred downstream hydraulic structures because local velocity is more than critical velocity. The reasons are as following [1]:

- Inadequate energy dissipation
- Instability hydraulic jump
- The constitution eddy current flow

Scour at submerge structures such as inverted siphon arises when the water jet exiting the structure is able to lift the sediment particles and transports those particles downstream of the impacted area. The jet impact area is transformed into an energy dissipater and a scour hole is formed. In some cases jet-type flow can produce sever local scouring in the streambed immediately downstream of the structure and can lead to failure by undermining of the structure.

Problem Definition: The study area is a part of Balaroud river, located in the south west of Iran. The west channel of Dez irrigation and drainage network with capacity of 157 cubic meters per second, irrigate 50000 hectares from Andimeshk and Shoush area, cross the Balaroud riverbed by means of an inverted siphon structure (Fig. 1).

The siphon has been constructed 30 years ago. During the past three decades, the bed level has reached to the roof of the siphon and therefore the siphon acts

Corresponding Author: B. Lashkar-Ara, Jundi-Shapur University of Technology, Dezful, P.O. Box 64615-334, Dezful, Iran. Tel: +98-641-6268000.

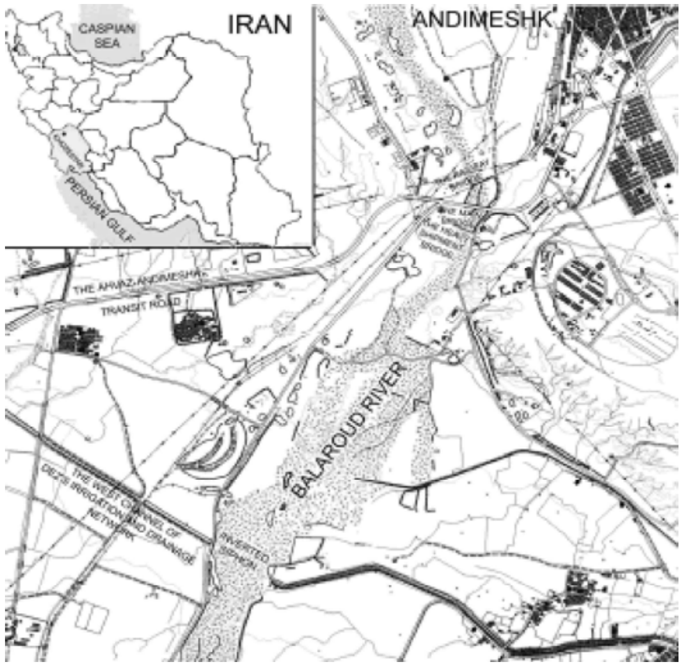

Fig. 1: Location of the steady area

Fig. 2: Flow over the top of inverted siphon

Fig. 3: Scour at right side of Balaroud inverted siphon

as a grade control structure in the river bed (Fig.2). Because of this, a deep scour hole was observed three years ago on the right hand side of the river bed downstream of the structure after a flood (Fig.3). Because of the importance function of the siphon and the possibility of its failure, a study was conducted to investigate the cause and to determine any reliable measures for controlling the scour hole. This paper will briefly present the results of this investigation.

MATERIAL AND METHODS

In present study, a limited part about 11.785-kilometer length from Balaroud River is selected. This part is located between South Balaroud Bridge and Sabzab Bridge. Based on Iranian watershed zonal the river basin is one of the subdivisions of Dez watershed. The Balaroud River is originated from Gadahour Mountain in 58 km north of Andimeshk. The hydrological regime in this river is raining regime and at the end of the spring, river flow is decreases quickly and is secured from groundwater. This river after drain the north lowland of Andimeshk reaches in Dez River in Batvand hydrometry station. The length of Balaroud River from its source to reach place in Dez River is 100 km and its watershed area is about 1,200 km^2.

To calculate the water yield and flood intensity, the mean daily discharge and the instantaneous peak discharge has been selected from the Dokouhe hygrometry station. This station has been installed in October 1984 and still recording.

Table 1: Discharge in Balaroud River for different return periods of flood

Return Period year	5	10	25	50	100	500
Discharge m^3/sec	1008	1284	1668	1991	2407	3253

Table 2: Cross-sections and bed material grading

Section Number	Distance Km	D_{50} mm	D_{90} mm
2	0.467	28	65
4	1.477	26.5	59
7	3.259	31	>80
10	4.943	21.3	61.7
11 siphon	5.488	24.9	60.7
12	6.089	30	>80
13	6.651	15	50
16	8.394	16	50
20	10.212	17	55

Table 3: Depth of flow for different return periods of flood

Section Number	Depth of flow (m)					
	5	10	25	50	100	500
2	1.97	2.22	2.51	2.7	2.9	3.13
4	1.62	1.77	1.95	2.1	2.28	2.6
7	1.4	1.53	1.75	1.91	2.12	2.47
10	1.49	1.6	1.73	1.82	1.92	2.1
11 siphon	0.65	0.73	0.82	0.89	0.98	1.13
12	1.68	1.4	1.56	1.68	1.83	2.1
13	1.36	1.49	1.65	1.77	1.92	2.19
16	1.63	1.8	2	2.15	2.31	2.59
20	1.63	2.03	2.23	2.38	2.54	2.84

Table 4: Velocity of flow for different return periods of flood

Section Number	Velocity of flow (m/sec)					
	5	10	25	50	100	500
2	3.97	4.36	4.73	4.82	4.83	4.96
4	3.18	3.44	3.69	3.87	4.08	4.45
7	2.20	2.34	2.50	2.62	2.76	3.06
10	2.20	2.35	2.53	2.65	2.79	3.01
11 siphon	4.75	4.99	5.68	5.73	5.60	5.05
12	2.29	2.50	2.74	2.90	3.08	3.37
13	2.37	2.52	2.75	2.91	3.11	3.43
16	2.29	2.53	2.82	3.04	3.26	3.45
20	1.65	1.71	1.84	1.93	2.06	2.5

Table 5: Values of a and m in Eq.1

Researcher name	a	m
Straub (1953)	1.49	1/6
Neill (1968)	1.58	0.1
Bogardi (1968)	1.7	0.095
Maynord (1987)	3.33	0.1

Table 6: Velocity at point of incipient motion for different return periods of flood

Section Number	Velocity of incipient motion (m/sec)					
	5	10	25	50	100	500
2	1.57	1.59	1.61	1.62	1.63	1.64
4	1.51	1.52	1.53	1.54	1.56	1.58
7	1.59	1.60	1.62	1.63	1.65	1.67
10	1.37	1.38	1.39	1.39	1.40	1.41
11 siphon	1.29	1.30	1.31	1.32	1.34	1.35
12	1.55	1.56	1.58	1.59	1.60	1.62
13	1.18	1.19	1.20	1.21	1.22	1.23
16	1.23	1.24	1.25	1.26	1.27	1.29
20	1.27	1.29	1.30	1.31	1.31	1.33

The study of streamflow record in this station shows that the mean annual discharge is 6.8 m^3/sec. The standard deviation of mean discharge is 3.68 m^3/sec and the coefficient of variation is 54 percent, which shows high variable change in this river. Calculation of flood for different return periods are presented in Table 1. Field survey was conducted to take 24 river cross sections upstream and downstream of the siphon. The bed material size distribution was also determined. Table 2 shows the results at some sections. Then the flow conditions were calculated by a one dimensional unsteady mathematical model.

The 500 years return period flood was selected based on the previous flood damages and rate of allowable risk of broken structure. Applying the above discharge, the flow depth and the flow velocity was computed at each cross section. The results are shown in Table 3 and Table 4.

As it can be seen from the final results, the flow velocity is increased when flow passed over the siphon. The Froude number upstream and downstream of the siphon is sub critical while at the cross section No.11 which siphon is located reaches as high as 1.81. To determine whether the river bed sediments are transported by this flow velocity, the velocity at the point of motion was determined by applying the following formula [1].

$$\frac{V}{[g\,(G_S-1)\,D_S]^{0.5}} = a\left(\frac{d}{D_S}\right)^m \qquad (1)$$

where V = velocity of incipient motion; g = gravity acceleration; G = density of grain; Ds = equivalent diameter of D_{50}; d = flow depth; a, m = constant coefficients that has been determined by different researcher as it has been shown in Table. 5.

With setting data from Tables 1 and 2 in equation 1, the velocity of incipient motion was determined by Straub (1953), Neill (1968), Bogardi (1968) and Maynord (1987) methods [1]. Average of these forth methods are presented in Table 6.

Comparison of data of table 6 and table 4, show that the flow velocity at all cross sections is generally more than the flow velocity at threshold conditions which means general river bed degradation occurs.

Local Scour: In the present study, the scour depth is calculated applying Schoklitsch (1932) equation. He was a pioneer who conducted experimental tests and developed equation to predict the maximum scour hole depth downstream of drops structure. This relation is as follow [1]:

$$d_S = 4.75 \frac{H^{0.2} q^{0.5}}{D_{90}{}^{0.3}} - d_T \qquad (2)$$

where d_S = maximum scour depth measured from downstream riverbed; H = different between energy line in upstream and tailwater surface; q = discharge per unit width; D_{90} = sediment size; d_T = tailwater depth.

Data Applied in Eq. 2 Are as Follow:

The river bottom width where siphon located is 795 meter. The elevation of the roof of siphon from sea level is +111.3. The river slope in the upstream and downstream of siphon is 0.003 and 0.0053, respectively. The Manning's coefficient estimated to be 0.03 and the D_{90} size is 60.7 mm. The maximum discharge recorded in the Dokouhe hygrometry station, upstream of the study area, in 1996 was 1500 cubic meter per second which is equal to 25-year flood.

Entering the above data into Eq. 2, the minimum bed elevation in the downstream of structure was calculated to be 107.9. The minimum scour bed elevation which has been measured, showing in Fig. 4, is equal to 107.8 meter. This means that the Schoklitsch's equation can predict the scour depth very well.

Based on the above discussion, the maximum scour hole was predicted for the 500 years flood and it was found that the scour bed elevation can reach as low as 106.5 which is the bottom elevation of the structure and can cause the failure of the structure.

River Bed Erosion Potential: Although the local scour is a major threat for the failure of the inverted siphon, other potential for bed degradation exist which can cause failure of any measures for scour protection. Among these are 17 gravel mining around the study area. They usually excavated the river bed alluvial material, then carrying to the factory and after separating fine aggregate they return the coarse gravel and cobble and stockpile them in the riversides. Discharge of waste materials to riversides narrow the cross-section which can cause the increase of flow velocity in these sections. Therefore sediment-carrying capacity increases. In other words, riverbed in these sections is more eroded.

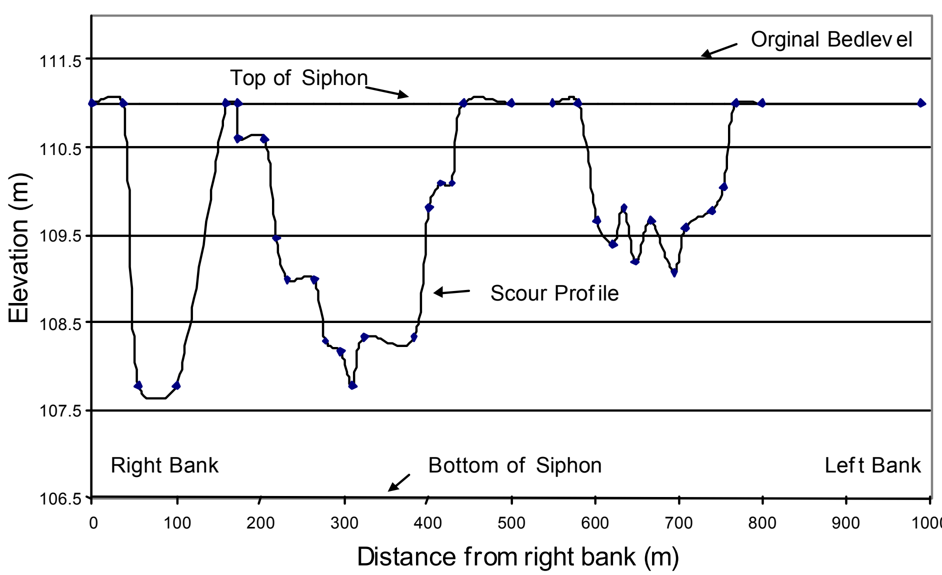

Fig. 4: Longitudinal profile of scour hole

Most of the transported bed material will deposit in the excavated area. The flow velocity after crossing the excavated area and reaches to the normal channel section decreases. However, river has no sediment load to transport; naturally hungry-water erodes the bed river.

From the field survey it was found that about 54 percent of total annually incoming sediments material is excavated and removed from the river bed. This is almost twice the value which should be. According to the study of Georgiev (1990), maximum allowable excavation gravel from the river bed should be in the order of 25-30 percent [2].

Head cutting is a second process of bed degradation which usually starts from the excavated area. Head-cutting often moves long distances upstream and into tributaries, in some watersheds moving as far as the headwaters or until halted by geologic controls or man-made structure [3, 4]. When head-cutting halted by hydraulic structures, riverbed level gradually degrades and makes a significant difference between upstream and downstream structure, which creates a falling jet in this place. This develops a local scour downstream of structure [5].

When a river and or slope profile has sudden drop in the longitudinal or flow direction, the excessive kinetic energy at falling jet strongly impacts the riverbed and result in a scour hole. Such scour holes can often is observed in incised rivers and gullies [6]. In field visit, a strong scour and expose buried foundation of siphon structure has been observed. Because the morphology of riverbed in this section is arterial, parts of scour hole continue and connected to thalweg in downstream. Figure 3 has been shown result from jet scour and head-cut halted by Balaroud inverted siphon structure.

Fig. 5: Installation of gabion stepped spillway

Measures to Control River Bed Erosion: When the first scour hole was observed, the scour hole was filled with riprap by the local authority to control the local scour. However, the next flood removed almost all the filled material. In this study it was decided to design a stepped gabion spillway downstream of inverted siphon structure. It is more economical compare to the conventional concrete spillway. In this structure, the energy is dissipated. as water flows downstream. Flow through the rock mixes with the flow over the crest, resulting in energy dissipation by Jet impingement as well as due to friction loss through the rock fill. In addition, the energy is dissipated as flow cascade from one step to another. Figure 5 shows installation of gabion stepped spillway.

After placing the gabion stepped spillway, further scour downstream of gabion spillway was found during the flood season (Fig. 5). Therefore it was found that other measures must be considered to reduce the general river flow velocity. Three alternatives were examined in this regards as follow:

- Widening the river cross section by removal of the deposited waste materials.
- Gentle the river bed slope by constructing grade control structures.
- Combination of the above measures.

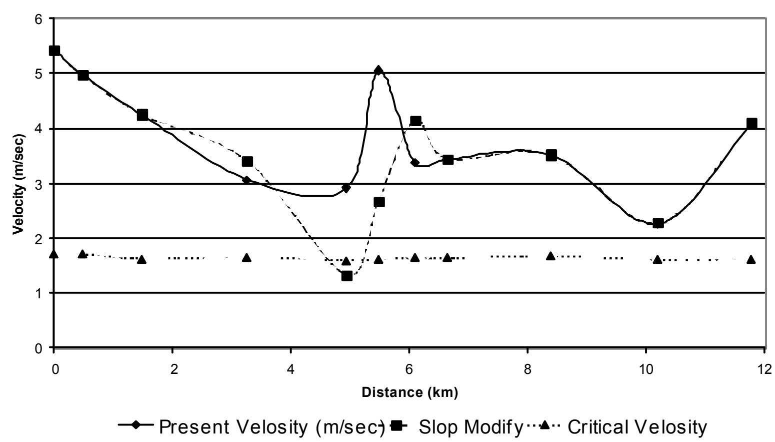

Fig. 6: Flow velocity in alternative A compared with the situation prior

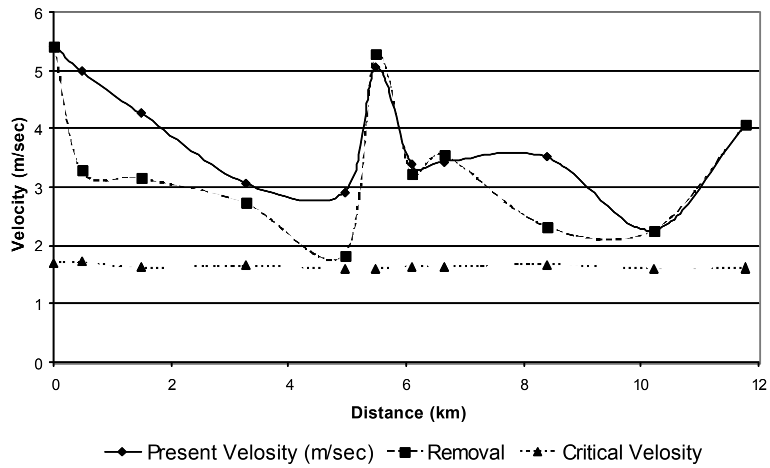

Fig. 7: Flow velocity in alternative B compared with the situation prior

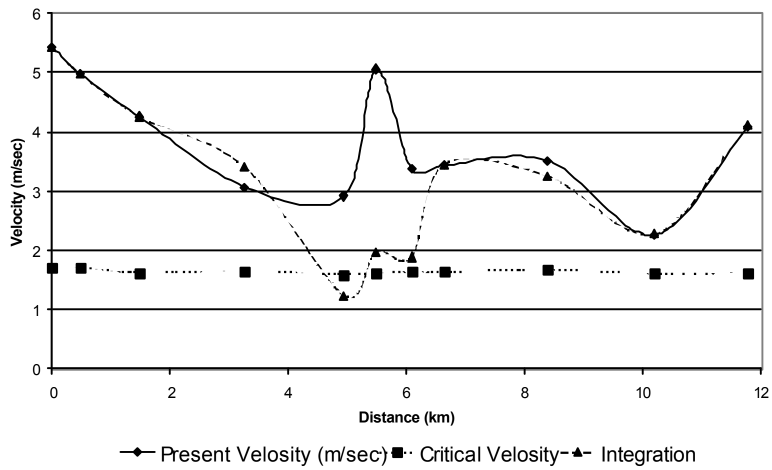

Fig. 8: Flow velocity in alternative C compared with the situation prior

Fig. 9: The bed downstream was covered with natural stone

The results are shown in Figures 6, 7 and 8 for the above alternatives respectively. As it can be seen from Fig. 6, widening of the cross section can reduce the flow velocity as much as 0.7 meter per second. However, the flow velocity is still high enough in the downstream of the siphon. From Fig.7, one may see that modification of river bed slope highly is reduced the flow velocity at upstream and downstream of the siphon. This condition is even improved in alternative C.

From the hydraulic and economical point of view, the alternative C was selected for managing the process of scouring in the Balaroud river. The scenario C was carried out and to protected the structures, the bed downstream was covered with natural stone like an stilling basin. (Fig. 9).

CONCLUSIONS

During the past three years, a sever scour depth occurred at Balaroud river bed which if not fixed the inverted siphon, which crossing the river, may collapse.

To manage the scour problem in this river, a comprehensive field survey and computational approach was conducted. The major conclusions from this study are as follow:

- Schoklitch's formula can predict the local scour downstream of graded control structure very well.
- Gabion stepped spillway was found an economical hydraulic structures for controlling the river bed degradation.
- To manage river bed degradation, a combination of river widening and decreasing the river bed slope was found to be the best alternative.
- Extracting the volume of sediments from the river bed must be reduced by half of its value.

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