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Combined structures design against bridges scouring (Case Studies: Asalem and Kalachay bridges in the north of Iran)

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ABSTRACT

Various countermeasures are proposed to control scouring around bridge piers. In the present research, a comprehensive study has been carried out to achieve scouring around two bridges in the north of Iran. The research presents a new set of combined structures against bridges scouring. A 1D numerical model is used for predicting depth of total scouring. According to the numerical results, the supercritical regime is observed in downstream of the bridges. For computing local pier scour Froehlich equation has been selected in the numerical model. Economical comparisons among different proposed combined structures have been done to introduce the best scenario for constructing. The results reveal that making Reno Mattress layer around the piers and Sabo works are needed to control scouring for two case studies. The experiences indicate that every armoring layer has to be situated under active bed layer of the river and better to cover vast area.

1-Introduction

Total scour at a roadway crossing is comprised of three components: long-term aggradation or degradation, contraction scour, and local scour. Many standards provide comprehensive scientific and technical documents for implementing structural countermeasures against bridges scouring (Handbook of scour countermeasures designs [2], AASHTO [1], Countermeasures to protect bridge piers from scour by Gary Parker et.al [13], HEC-23 [7], and HEC-18 [6]). For especial cases, more investigations needed to reveal causes toward proposing individual designs. The score computation in the numerical reported herein allow to the user to compute contraction scour and local scour at piers and abutments. The numerical was used for this study does not allow the user to evaluate long-term aggradation and degradation. Long term aggradation and degradation should be evaluated before performing the bridge scour analysis. Procedures for performing this type of analysis are outlined in the HEC No. 18 report, and are beyond the scope of this research. The discussions in this paper are focused on the computation of contraction scour and local pier and abutment scour.

Shirole and Holt [15] stated that 60% of the 1,000 plus bridge failures occurring in the USA could be attributed to bed scour. Melville and Coleman [11] reported that on average at least one serious bridge failure each year could be attributed to scour in New Zealand

Armoring countermeasures, such as riprap stones, are the primary method used to protect bridge piers against scouring; however, these methods have not had definitive success. Recently, making combined structures such as Sabo works have been proposed to reduce the scouring in the near of bridge piers. In Japanese, the direct translation of Sabo (sa-bo) is “sand protection”. Generally the term “Sabo Works” refers to mountain protection systems.

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Some researchers have used the combination of different methods to protect the bridge piers. Chiew [3] used the combination of a slot and riprap to decrease the bridge pier scouring. Zarrati et al. [17] concluded that the scour depth can be controlled completely by a combination of a collar and riprap around a rectangular pier. Zarrati et al. [18] proposed riprap and combination of collar and riprap have been used to control the local scour around cylindrical piers. The collar effect on stable riprap size and covering area around the pier are also examined in that study. Practical design relationships for riprap size around a pier with or without collar were also presented.

In this research, a comprehensive study has been carried out to achieve scouring around two bridges in the north of Iran. The research comprises review of past experiences, sampling and surveying, numerical modelling (1D) study, proposing different structural designs, economic comparison and selecting the best combination of scenarios. The investigations show that combined structures containing Sabo works and making Reno Mattress layer around the piers is needed for two bridges.

2. Materials and Methods

2.1. Estimating scour at bridges

In order to perform a bridge scour analysis, first must develop a hydraulic model of the river each containing the bridge to be analyzed. The HEC-RAS 4.0 model has been used for simulating hydrodynamic behavior in this study. The U.S. Army Corps of Engineer's River Analysis System (HEC-RAS) is software that allows us to perform one-dimensional steady and unsteady flow river hydraulics calculations for a full network of natural and constructed channels. For the steady flow, the basic computational procedure is based on the solution of the one-dimensional energy equation. Energy loses are evaluated by friction (Manning's equation) and contraction/expansion (coefficient multiplied by the change in velocity head). The momentum equation is utilized in situations where the water surface profile is rapidly varied. These situations include mixed flow regime calculations (i.e., hydraulic jump), hydraulic of bridges, and evaluating profiles at river confluences (stream junctions). After performing the water surface profile calculations for the design events, the bridge scour can be evaluated. This section is emphasized on computing contraction scour and local pier and abutment scour.

Contraction scour occurs when the flow area of a stream is reduced by a natural contraction or a bridge constricting the flow. There are two forms of contraction scour that can occur depending on how much bed material is already being transported upstream of the bridge contraction reach. The two types of contraction scour are called live-bed contraction scour and clear-water contraction scour. Live-bed contraction scour occurs when bed material is already being transported into the contracted bridge section from upstream of the approach section (before the contraction reach). Clear-water contraction scour occurs when the bed material sediment transport in carrying capacity of the flow. To determine if the flow upstream is transporting bed material (i.e., live-bed contraction scour), the numerical model calculates the critical velocity for beginning of motion V_C (for the D_{50} size of bed material) and compares it with the mean velocity V of the flow in the main channel or overbank area upstream of the bridge at the approach section. If the critical velocity of the bed material is greater than mean velocity at the approach section ($V_C > V$), then clear-water contraction scour is assumed. If the critical velocity of the bed material is less than mean velocity at the approach section ($V_C < V$), then live-bed contraction scour is assumed. To calculate the critical velocity, the following equation by Laursen [10] is used:

$$V_c = K_u y_1^{1/6} D_{50}^{1/3} \quad (1)$$

where V_C= critical velocity above which material of size D_{50} and smaller will be transported , m/s; y_1= average depth of flow in the main channel or overbank area at the approach section, m; and K_u= 6.19 (S.I. units).

The HEC No.18 [6] publication recommends using a modified version of Laursen's [9] live-bed scour equation:

$$y_2 = y_1 \left[\frac{Q_2}{Q_1}\right]^{6/7} \left[\frac{W_1}{W_2}\right]^{K_1} \quad (2)$$

$$y_s = y_2 - y_0 \quad (3)$$

where y_s= average depth of contraction scour in (m); y_2 = average depth after scour in the contracted section, (m); y_1= average in depth in the main channel or floodplain at the approach section, (m); y_0 = average depth in the main channel or floodplain at the contracted section before scour, (m); Q_1= flow in the main channel or floodplain at the approach section, which is transporting sediment, (m^3/s); Q_2= flow in the main channel or floodplain at the contraction section, which is transporting sediment, (m^3/s); W_1= bottom width in the main channel or floodplain at the approach section, (m); W_2= bottom width in the main channel or floodplain at the contracted section less pier widths, (m); and K_1= exponent for mode of bed material transport (0.59-0.69 refer to hydraulic reference manual HEC-RAS 4.0).

The recommended clear-water contraction scour equation by the HEC No.18 publication is an equation based on research from Laursen [10]:

$$y_2 = \left[\frac{Q_2^2}{CD_m^{2/3}W_2^2}\right]^{3/7} \quad (4)$$

where D_m = diameter of the smallest non-transportable particle in the bed material ($1.25D_{50}$) in the contracted section, (m); D_{50}= median diameter of the bed material, (m); and $C = 40$ for metric. For calculating y_s (average depth of contraction) use equation 3 same as above.

Pier scour occurs due to the acceleration of flow around the pier and the formation of flow vortices (known as the horseshoe vortex). The horseshoe vortex removes material from the base of the pier, creating a scour hole. As the depth of scour increases, the magnitude of the horseshoe vortex decreases, thereby reducing the rate at which material is removed from the scour hole. Eventually an equilibrium between bed material inflow and outflow is reached, and the scour hole ceases to grow. The factors that affect the depth of local scour at a pier are: velocity of the flow just upstream of the pier; depth of flow; width of the pier; length of the pier if skewed to the flow; size and gradation of bed material; angle of attack of approach flow; shape of the pier; bed configuration; and the formation of ice jams and debris.

In this study, local scour at the piers and abutments is computed by Froehlich [5] equations. A local pier scour equation developed by Dr. David Froehlich [5] and has been used in the software. This equation has been shown to compare well against observed data (FHWA [4]). The equation is:

$$y_s = 0.32\,\phi(a')^{0.62}{y_1}^{0.47}{Fr_1}^{0.22}D_{50}^{-0.09} + a \quad (5)$$

where ϕ = correction factor for pier nose shape: $\phi = 1.3$ for square nose piers; $\phi = 1.0$ for rounded nose piers and $\phi = 0.7$ for sharp nose (triangular) piers; a' = projected pier width with respect to the direction of the flow, (m); y_s= depth of scour, (m); y_1= flow depth directly upstream of the pier, (m); and Fr_1= Froude number directly upstream of the pier.

Local scour occurs at abutments when the abutment obstructs the flow. The obstruction of the flow forms a horizontal vortex starting at the upstream end of the abutment and running along the toe of the abutment, and forms a vertical wake vortex at the downstream end of the abutment.

Froehlich analyzed 170 live-bed scour measurements in laboratory flumes by regression analysis to obtain the following equation:

$$y_s = 2.27K_1K_2(L')^{0.43}{y_a}^{0.57}Fr^{0.61} + y_a \quad (6)$$

where y_s= scour depth, (m); K_1= correction factor for abutment shape (vertical-wall abutment=1.00, vertical abutment with wing walls=0.82 and spill-through abutment =0.55); K_2= correction factor for angle of attack (θ) of low with abutment. θ =90 when abutments are perpendicular to the flow, θ <90 if embankment points downstream, and θ >90 if embankment points upstream. $K_2 = (\theta/90)^{0.13}$; L'= Length of abutment (embankment) projected normal to flow, (m); y_a= average depth of flow on the floodplain at the approach section, (m); and Fr =Froude number of the floodplain flow at the approach section.

The total depth of scour is computed based on a combination of contraction scour and local scour at each individual pier and abutment in this study.

3. Result and discussion

3.1. Case study 1. Asalem Bridge

Asalem Bridge is located along the main road between Talesh and Fooman cities on Navroud River in Gilan province in the north of Iran. It is a four-span bridge with about 75m length. Figure 1 shows Asalem Bridge. Navaroud river in the near of the bridge is so steep because of long time unsustainable sand mining (harvesting) and for this reason, it was always subjected to erosion and damage. During a long term, it has been tried to save the bridge by many forms of armoring devices near its piers and abutments. But those structural countermeasures could not make a safe condition especially when the flood occurred. A comprehensive study has been carried out to propose combined structures against scouring. The combination of Sabo dams (impermeable) in downstream of the bridge and making Reno mattress (gabion mattress) around the piers would be designed for this case study.

Fig.1.Asalem Bridge (side view)

Details are first given below of the numerical modelling study of the hydraulic and scouring behavoir in the Asalem Bridge. The model simulation was based on field surveyed data, hydrological data and measurement data obtained from the field study for two basic scenarios. One of the scenarios describes exist situation and second one investigate the hydraulic situation after constructing Sabo dams in downstream of the bridge. For study scouring at the bridges the 100-year flood has been computed in Navroud River and this amount is 180 m^3/s . Boundary condition for upstream and downstream is selected energy slope in the numerical model with the amount of 0.0084 and 0.01445 respectively. The model is run for steady state condition. Figure 2 present the surface water that is predicted by the numerical model for exist situation (first scenario). Table 1 also indicates flow parameters such as flow velocity, Froude number and etc for this scenario. For the second scenario three Sabo dams are situated in downstream of the bridge and the model is run again. Figure 3 shows the layout of three Sabo dams (impermeable). Figure 4 and table 2 present the numerical results related to this issue.

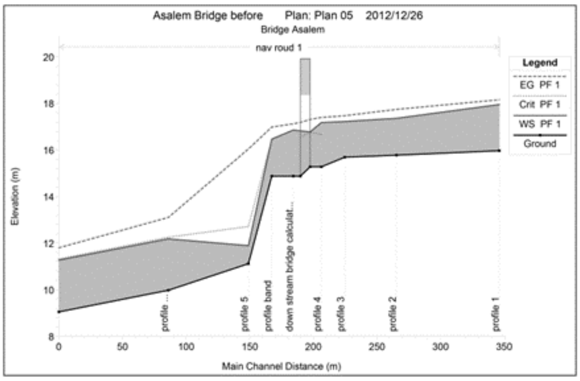

Fig.2. Water surface profile for exist situation (first scenario) in Asalem Bridge

Table 1. Hydraulic results related to first scenario in Aslem Bridge

Profile	Min El. (m)	Vel. (m/s)	Flow Area (m^2)	Top Width (m)	Fr
1	15.97	2.00	89.91	65.77	0.55
2	15.78	2.74	65.75	59.84	0.83
3	15.69	2.21	81.61	61.58	0.61
4	15.28	2.06	87.39	59.64	0.54
Down bridge	14.88	2.29	78.48	57.64	0.63
band	14.88	3.19	56.51	55.06	1.00
5	11.12	9.02	19.95	33.34	3.72
6	9.98	4.25	42.38	26.00	1.06
7	9.05	3.22	55.93	64.49	1.10

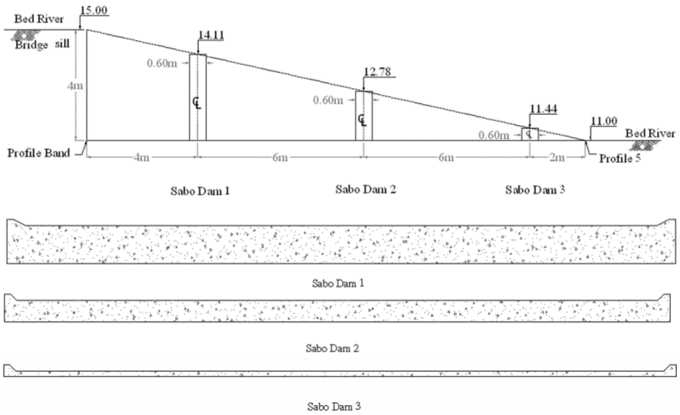

Fig.3. The layout of three Sabo dams situated in downstream of Asalem Bridge (length for three dams is 55m and heights of three dams are 3.61m, 2.28m and 0.94m respectively)

Scour at Asalem Bridge piers is computed by the numerical model. Figure 5 presents the pattern of scour and table 3 indicates the results for every pier separately. As can been seen from figure 3 and table 2, the performance of Sabo dams reduces flow velocity and effect on the hydraulic regime in downstream of the bridge. The flow velocity near the bridge and around the piers (>2m/see table 1.) confirms that making armoring layer need to tackle scouring processes (Fig.6)

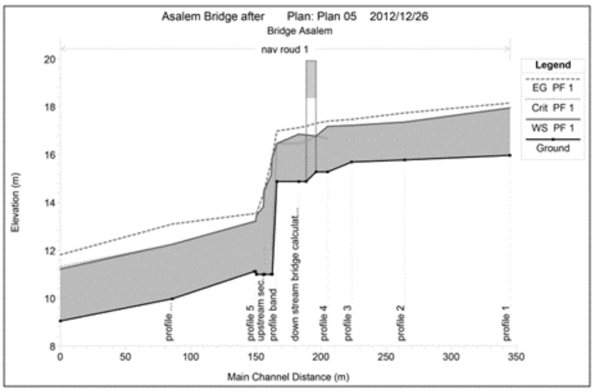

Fig.4. Water Surface profile for second scenario in Asalem Bridge

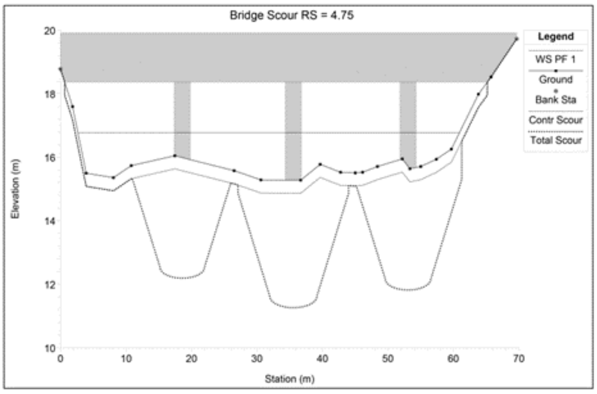

Fig.5. The scour pattern of Asalem Bridge piers

Table 2. Hydraulic results related to second scenario in Aslem Bridge

Profile	Min El. (m)	Vel. (m/s)	Flow Area (m^2)	Top Width (m)	Fr
1	15.97	2.00	89.91	65.77	0.55
2	15.78	2.74	65.75	59.84	0.83
3	15.69	2.21	81.60	61.58	0.61
4	15.28	2.06	87.39	59.64	0.54
Down bridge	14.88	2.29	78.52	57.65	0.63
band	14.88	3.19	56.51	55.06	1.00
Upstream Sabo 1.	11.00	0.68	266.24	54.66	0.10
Upstream Sabo 2.	11.00	0.93	192.92	54.89	0.16
Upstream Sabo 3.	11.00	1.35	132.89	53.58	0.27
5	11.12	2.55	70.65	40.93	0.62
6	9.98	4.07	44.22	26.26	1.00
7	9.05	3.41	52.75	63.73	1.20

Table 3. Scouring results at the Asalem Bridge piers

Discharge m^3/s	D_{50} mm	D_{95} mm	Contraction scour* m	Local scour m	Total scour m
180	0.18	25	-	-	-
Pier 1.			0.41	3.38	3.79
Pier 2.			0.41	3.61	4.02
Pier 3.			0.41	3.48	3.89

* computed by the live-bed equation

The combination of Sabo works and making armoring layer are suggested to control scouring for this case study.

3.2.Designing protection works for Asalem Bridge

Design guidelines for gabions are based on laboratory experiments conducted by Parker et al. [13] under the NCHRP 24-07 project, Agrawal et al. [2] and HEC-23 [7]. Other recommended sources of information on design of gabions are U. S. Armey Corps of Engineers [16], Maynord [12] and Racin [14]. According to the flow velocity around the piers and other hydraulic parameters a Reno mattress (gabion mattress) is designed for constructing around piers of Asalem Bridge. Figure 6 shows the layout of Reno mattress for Asalem Bridge piers.

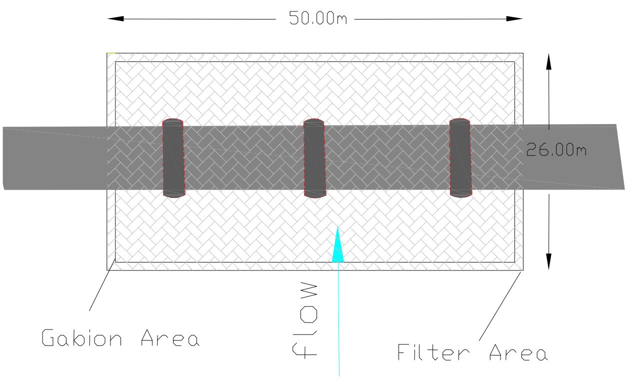

Fig.6.The layout of Reno mattress at Asalem Bridge piers

A filter blanket is proposed below the Reno mattress. Reno mattress has to be situated below the active bed river in order to prevent local turbulence. For this case the gabion thickness and stone size are selected 40cm and 10 cm. The level installation for the Reno mattress should be proposed 30 cm below the active bed layer of the river. Two set of structural countermeasures are suggested to control scouring processes for this case study. The combined structures containing Sabo works and Reno mattress work together to control scouring around the bridge piers and downs stream of the bridge. Also an economical investigation would be carried out among other structural countermeasures to evaluate proposed combined structure that explained in this section.

3.3. Case study 2. Kalachay Bridge

Kalachay Bridge is located at the 9th km of Roodsar-Ramsar road in Gilan province in the north of Iran. This bridge is along a diversion road toward Kalachay city on a river of the same name (Fig. 7). As shown in the figure it is a two-span bridge and has about 80m length.
Since this bridge is over a watery and steep river, it was always exposed to erosion and damage. During a long term it has been trying to save it by some form of armoring devices near its piers and abutment. But neither worked efficient and effective. The most important structure that partially prevents against scour now, is a not completed stepped spillway that located in 50m downstream of the bridge. Some parts of this structure have been destroyed during the flood time (Fig. 8).


Fig.7. Kalachay Bridge (side view)
Fig. 8. Stepped spillway in downstream of Kalachay Bridge

To cope with the influx of flood to the left bank and residential areas, there is a long non-reinforced concrete wall that has fractures in many places due to local scour under its foundation (Fig. 9).

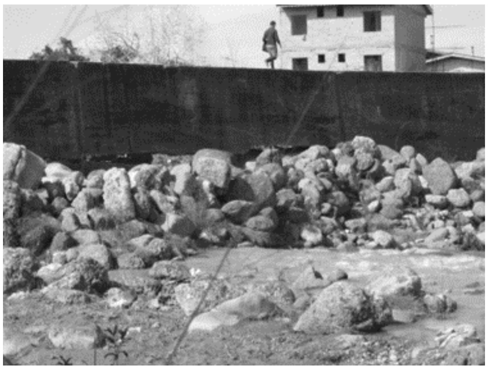

Fig.9. Concrete wall in downstream of Kalachay Bridge at the left bank side

3.4. Numerical model results for Kalachay Bridge

For study scouring at the bridges the 100-year flood has been computed in Kalachay River (or Polroud River) and this amount is 720 m^3/s . Boundary condition for upstream and downstream is selected normal depth in the numerical model with the amount of 0.0013 and 0.002 respectively. The model is run for steady state condition. Figure 10 present the surface water that is predicted by the numerical model for exist situation. Table 4 also indicates flow parameters such as flow velocity, Froude number and etc for this scenario. The results of the model executing indicate that in upstream of the bridge (profile 2) the flow regime is sub critical with a maximum velocity of 2.48 m/s. In the previous section of the bridge due to the narrowing and reduced cross section of the river, the regime gradually is changed to critical and supercritical so that in immediate downstream section(profile 6) velocities reached to 5.85 m/s. The Froude number reduces to less than 1 when the flow passes after the bridge abutment and the stepped spillway that is located about 30 meters far from the Pier Bridge and reaches to a wide stilling basin.
Scour at Kalachay Bridge pier is computed by the numerical model. Figure 11 presents the pattern of scour and table 5 indicates the amount of scouring around the pier. The results of hydraulic model led to develop the existing structures or design some new ones. There are 2 main subjects for protection: total scour around the bridge pier and progressive contraction scour along the bed river.

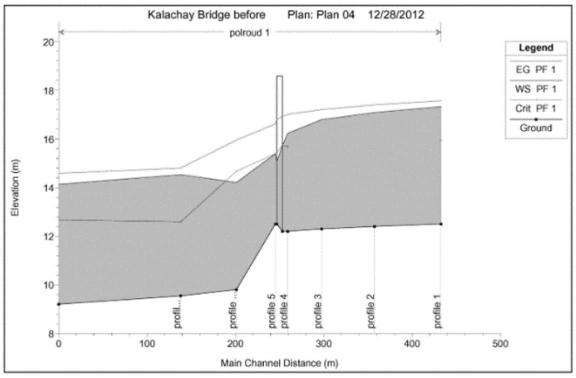

Fig. 10. Water surface profile for exist situation) in Kalachay Bridge

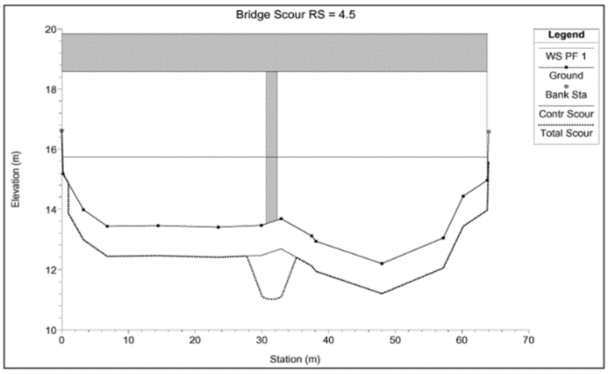

Fig. 11. The scour pattern of Kalachay Bridge piers

Table 4. Hydraulic results for exist situation in Kalachay Bridge

Profile	Min El. (m)	Vel. (m/s)	Flow Area (m^2)	Top Width (m)	Fr
1	12.50	2.16	334.08	128.10	0.43
2	12.40	2.48	290.84	138.91	0.55
3	12.30	2.83	254.29	114.62	0.61
4	12.20	3.91	184.11	63.90	0.74
5	12.50	4.91	146.63	60.61	1.01
6	9.80	5.85	123.14	74.74	1.45
7	9.54	2.30	313.35	79.53	0.37
8	9.20	2.96	243.36	63.61	0.48

Table 5. Scouring results at the Kalachay Bridge piers

Discharge m^3/s	D_{50} mm	D_{95} mm	Contraction scour* m	Local scour m	Total scour m
720	3.2	25	-	-	-
Pier.			1.00	1.57	2.57

* computed by the live-bed equation

3.5. Designing protection works for Kalachay Bridge

In order to reduce erosion and scour around the bridge pier, creating a protective layer around the pier is necessary. Riprap is defined as a layer of natural rock. Because of its sheer dead weight, it acts like a shield and protects the soil underneath. It prevents direct contact of soil with the erosive forces that are generated at high flood velocities. Gabion as armoring countermeasure has the same performance and with a reliable flexibility can be used more easily. Although using of both is common, riprap for the cases that the velocity in bridge section is more than 11ft/s (like this case study), doesn’t be recommended [2]. Flexibility, porosity, formability, enabling the use of the smaller grains stone river, and compatibility with the environment, are the benefits that designers are encouraged to use a thinner version of gabions is known as Reno mattress.

Thickness and stone size of mattress based on the Handbook of Scour Countermeasures Designs [2]. should be selected for lower bound on the critical (design) velocity for a conservative design. In this case, for a critical velocity of 5.85m/Sec, gabion thickness of 60cm and stone size of 10cm should be selected. The minimum volume of gabion basket was calculated by the equation recommended in Agrawal et al. [2] as 1.2 m^3. The recommended extent and layout of gabions shall be 2D from all faces of the piers, where D is the width of the pier (Fig. 12) and for this case is calculated 2m.

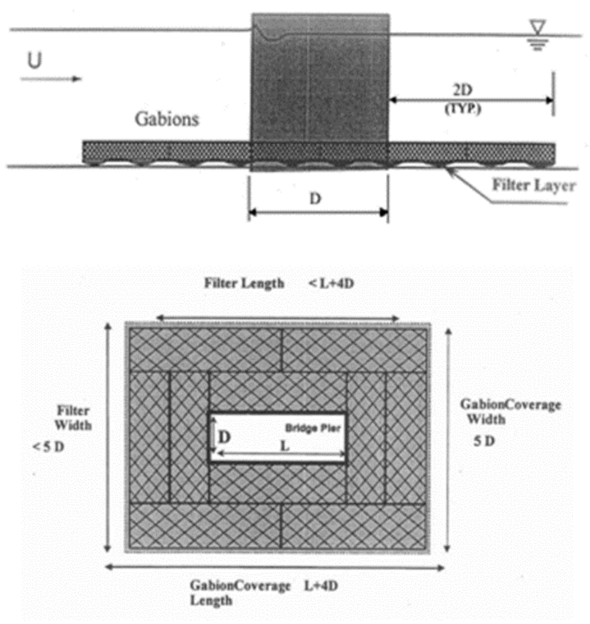

Figure 12. Extent of Reno mattress and geo-textile filter around the bridge pier [2]

According to antiquity of Kalachay Bridge, so far various methods to prevent scour and flooded the land adjacent to the river has been used that in most cases have temporary managed to hold service in this old bridge. A concrete wall on the left bank and an incomplete stepped spillway on downstream of the bridge play the basic role to control scouring processes now. A new stone and cement wall has designed to replace with the old one with an easier performance and a good harmony with other structures. Also repairing and changing the existing stepped spillway to a Sabo work form is being considered. In order to support fish migration and providing environmental sustainability, a fish ladder is designed in the middle of the spillway. Figure 13 shows the layout of Sabo work and stone and cement wall that proposed for this case study.

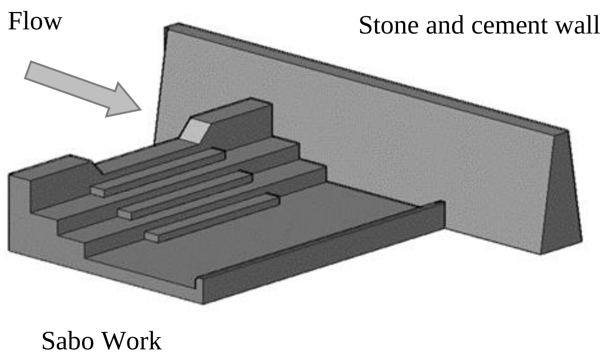

Fig.13. The layout of Sabo work and wall for the Kalachay Bridge

3.6. Economical Investigations

In this research for each bridge some protective techniques are considered to overcome scour around the bridge and downstream of the bridge. A few structural countermeasures could be proposed ac-cording to engineering aspects for two cases studies. Table 6 presents the economical investigations among different variants. For making reasonable comparisons, the cost of construction for any measures with different type of materials such as stone, concrete and etc has been evaluated by the same manner. It has been tried to select the most economical variant among acceptable engineering measures. However in one option for wall protection in Kalachay Bridge (Table 6.), the stone and cement wall is selected despite of its further cost to gabion wall because to keep the harmony with the other structure like Sabo-work made by stone and cement in its adjustment.

Table 6. Economical investigations

Type of Protection	Kalachay Bridge		Asalem Bridge	
Protection around the bridge pier (s)	Type of structure	Evaluated cost (USD)	Type of structure	Evaluated cost (USD)
	Rip Rap	Not Recommended	Rip Rap	14000
	Reno Mattress	2400	Reno Mattress	13500
Protection Downstream of the bridge	Type of structure	Evaluated cost (USD)	Type of structure	Evaluated cost (USD)
	Sabo Work	96500	Sabo Dam	23000
			Gabion Spillway	56000
Wall protection	Type of structure	Evaluated cost (USD)	Type of structure	Evaluated cost (USD)
	Reinforced Concrete	21500	Not Recommended	
	Stone and Cement	15500		
	Gabion Stair	14000		

4. Conclusion

In this research, a comprehensive study has been carried out to achieve scouring around two bridges in the north of Iran. The research comprises review of past experiences, sampling and surveying, numerical modelling (1D) study, proposing different structural designs, economic comparison and selecting the best combination of scenarios. In a course of time, many structural armoring layers were proposed and made by different materials around piers and abutments of Asalem and Kalachay bridges. But those methods have not showed well performance. The mathematical 1D model (HEC-RAS 4.0) has been used in this study. For computing local pier scour Froehlich equation has been selected in the numerical model. The total depth of scour is calculated based on a combination of long-term bed elevation changes, contraction scour and local scour at each individual pier and abutment. The amount of total depth of scour for the single pier of Kalachay bridge is calculated 2.57m and the values for right, middle and left piers in Asalem bridge are predicted 3.79m, 4.02m and 3.89m respectively. Sensitivity analysis and calibrating has been done by field data. Significant difference bed level was observed between upstream and downstream in both bridges. Different combination of Sabo works, retaining walls and armoring layers have been suggested to control scouring. The results show that Reno Mattress layer around the piers is needed for two bridges. Besides, Sabo dams (impermeable) for Asalem Bridge and single Sabo dam (stair and impermeable) for Kalachay Bridge have been selected among different scenarios for constructing. The experiences reveal that every armoring layer has to be situated under active bed layer of the river and better to cover vast area. The writers wish to thank the Water Research Institute in Iran for supporting river and coastal engineering group to carry out this research study. Also, the writers appreciate Mrs. Rashtbary for preparing layouts and plans of the paper.

5. References

1. AASHTO. (1998), "*AASHTO LRFD Bridge Design Specifications*", American Association of State Highway and Transportation Officials, second Edition.

2. Agrawal, A. K., Ali khan, M. and Yi, Z. (2005), " *Handbook of scour countermeasures designs*", Final Report.

3. Chiew Y. M. (1992), "Scour protection at bridge piers", Journal of Hydraulic Engineering. Vol. 118, No. 9, pp. 1260–1269.

4. Federal Highway Administration, (1996), "*Channel Scour at Bridges in the United States*", Publication No. FHWA-RD-95-184, Washington D.C.

5. Froehlich, D.C. (1991), "Analysis of onsite measurements of scour at piers", Proceeding of the ASCE National Hydraulic Engineering Conference, Colorado Spring Co.

6. HEC-18. (1991), "*Evaluating scour at bridges. Hydraulic Engineering Circular No. 18*", Federal Highway Administration (FHWA), USDOT, Washington, D.C.

7. HEC-23. (2001), "Bridge Scour and Stream Instability". Countermeasures. Hydraulic Engineering Circular No. 23, Federal Highway Administration, FHWA Publication Number: NHI-01-003

8. Hydrological Engineering Center, 2008. HEC-RAS, River Analysis System, Hydraulic Reference Manual", U.S. Army Corps of Engineers, Davis, CA.

9. Laursen, E. M. (1960), "Scour at Bridge Crossing", ASCE, Journal of Hydraulic Engineering, Vol. 89, No. HY 3.

10. Laursen, E. M. (1963), "An Analysis of Relief Bridges", ASCE, Journal of Hydraulic Engineering, Vol.92, No. HY 3.

11. Melville B. W. and Coleman S. E. (2000), "*Bridge*", Water Resources Publications LLC, Littleton, Colorado.

12. Maynord, S. T. (1995), "Gabion-Mattress Channel-Protection Design", Journal of Hydraulic Engineering, ASCE, Vol. 121 No. 7, pp 519-522

13. Parker, G., Toro-Escobar, C. and Voigt, R. L. (1998), "*Countermeasures to Protect Bridge Piers from Scour*", User's Guide and Final Report. NCHRP 24-7, National cooperative Highway Research Program, Transportation Research Board, National Research Council.

14. Racin. J.A. (1993), "Gabion Facilities along the Pacific Coast Highway", Report No.FHWA-CA-TL-93-17. California Department of Transportation, Sacramento California, 60 pp.

15. Shirole, A. M. and Holt R. C. (1991), "*Planning for a comprehensive bridge safety assurance program. Transportation Research Record*", No. 1290, Transportation Research Board, Washington D.C., pp. 39–50.

16. U.S. Army Corps of Engineers. (1991b), "*Wire Mesh Gabions*", U.S. Army Corps of Engineers, Report CW-02541.

17. Zarrati, A. R., Gholami H., and Azizi M. (1999), "Simultaneous application of collar and riprap to control scouring around bridge piers", 2nd Iranian Hydraulics Conference, University of Science and Industry, Vol. 1, pp. 233–240 (in Farsi).

18. Zarrati, A. R., Chamani, M. R., Shafaie, A. and Latifi, M. (2010), "Scour countermeasures for cylindrical piers using riprap and combination of collar and riprap", International Journal of Sediment Research, Vol. 25, No. 3, pp. 313–321.