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Evaluation: Screening, Analysis, and Countermeasures for Bridge Scour for AL-Manshia Bridge

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Abstract*:* This paper aims to study scouring and the recommended countermeasures for Al Manshiya Bridge, which is located in the Blue Nile in Khartoum city. The bridge was constructed in the year 2006, but in 2015; the east embankment approach of the bridge was exposed to scour causing failure of the approach deck slab. The paper follows the general procedure outlined by the Federal Highway Administration (FHWA) for stream stability, evaluating scour at bridges and countermeasures in order to have hydraulically safe bridge. Geomorphic and hydraulic factors affect the stream were studied; a scour analysis was made using Hydrologic Engineering Center - River Analysis System (HEC-RAS) software. To account for long-term, contraction, and local scour potential for the Peak flow event, HEC RAS model was used to construct quasi- unsteady sediment model. In order to protect the bridge, countermeasures for the bridge east abutment and channel adjacent to the bridge are studied, riprap around abutment and spur dikes were considered as the most suitable countermeasures.

Keywords: *Bridge hydraulic, countermeasures, HEC-RAS, river morphology, scour.*

INTRODUCTION

1.1. Study Area:

Al Manshiya Bridge is located in the Blue Nile, Khartoum, Sudan. (15.599109, 32.589807), Fig. No.1. the river reach under study starts from Soba station upstream (15.6001507°, 32.4921971°) to Khartoum station downstream (15.5217047°, 32.618138°)

1.2. Problem statement:

Blue Nile at AL Manshiya bridge location is a wide perennial stream with bed material range of silt and sand. The location of the bridge is in the bend of the river whereas banks materials are silt and sand. The banks are submerged in high flow causing wide flood plain.

1.3. Objective:

In order to study bridge current state and recommend the necessary countermeasure for future actions this paper aims to:

1- Study the geomorphological and hydraulic characteristic of the Blue Nile zone under study.
2- Carry out analysis of scour developed in the bridge applying judiciously HEC-RAS modeling facilities.
3- Study and entertain different alternatives as countermeasures.

2. Methodology:

General procedure followed in this research is based on Federal Highway Administration (FHWA) for stream stability and evaluation

2.1. Data Collection:

Data used for this study is based on bathymetric surveys held in 2008 and 2017 in cooperation between university of Khartoum faculty of engineering and ministry of infrastructure. The data Collection included detailed topography, Bathymetry, aerial photography, and stream flow and stage data. Data used also includes preceded site visits to validate assumptions, collected channel and floodplain data, and include observations pertinent to the scour analysis.

Using this data, a hydraulic model was created using the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center's River Analysis System (HEC-RAS) (USACE, 2010a). This hydraulic model provided the information necessary to calculate the different scour depths for the different parts of AL Manshiya Bridge.

2.2. Stream stability Geomorphic and hydraulic Conditions:

Geomorphological conditions are evaluated in order to analyze stream stability; geomorphic condition for the bridge location is as follow:

1) At AL Manshiya Bridge location, the channel and boundaries are alluvial. Its width varies. Lateral migration of the channel has occurred along some parts by artificial encroachments including roads and residential development.
2) The channel has several visible failures along its banks and appears to be active in some locations. This channel is exposed to high floods, which can cause severe scour and erosion in unprotected areas.
3) Geomorphologic factors that affect stream stability, as shown in Fig 2, are useful in characterizing the stream, as well as hydraulic location and design factors that affect stream stability for Al Manshiya Bridge (HEC-20).

Based on stream stability classification, the stream is considered in a good stability (HEC-20). Due to the observed scour at bridge site, bridge scour evaluations are conducted to determine whether this scour is critical. A scour critical bridge is one with abutment or pier foundations that are rated as unstable.

Fig .1. study area of the Blue Nile River reach and Bridge location

Fig .2. Stability characteristics of the study area

2.3. Evaluating scour at bridge:

HEC-RAS is used to make predictions of quantitative changes in streambed elevation due to changes in the stream and watershed characteristics.

A model of the bridge current situation was developed to estimate scour depth. Then five scenarios of scour countermeasures were proposed to lower the effect of scour and stream stability problem without influencing negatively surrounding elements.

2.4. Model Procedure:

The detailed hydraulic evaluations are performed using techniques outlined by hydraulic Engineering Center.

***2.4.1. Geometric data*:** The geometric model used in the study was constructed based on extensive bathymetric survey (x,y,z) data for river reach of about 30 km, having 931 cross section with different spacing along it defining the main channel and overbank geometry and characteristics. Cross sections were placed approximately at an average of 50m, Furthermore; cross-sections were interpolated to account for hydraulic change and expansion and contraction characteristics. The bridges and relief culvert location were defined and their substructure and deck. Fig (3) and Fig (4) shows the river schematic on HEC-RAS.

***2.4.2. Hydraulic computation through the bridge*:** The flow through Al Manshiya Bridge is considered low flow condition where water surface does not reach lower chord of the reach. To compute highest losses through the bridge Energy based method, momentum based method and WSPRO methods were used.

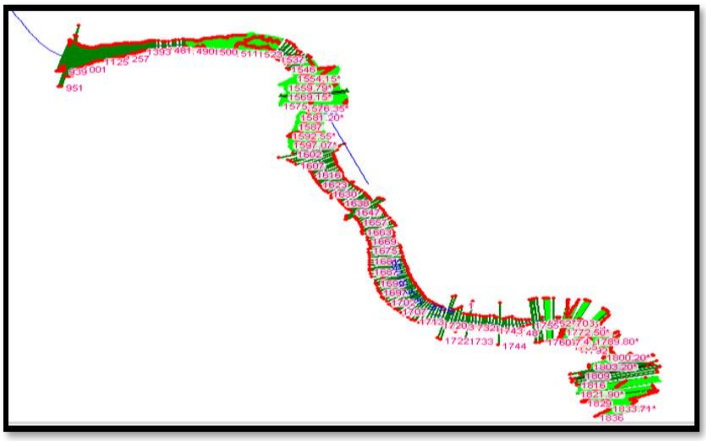

Fig .3. Geometric Data for the reach

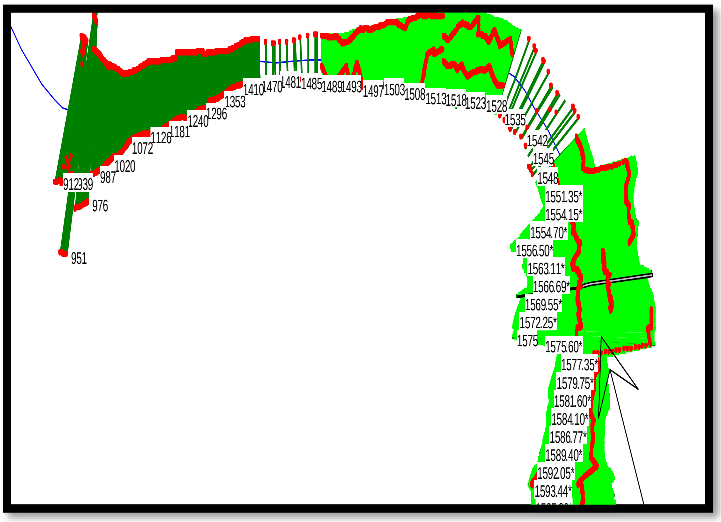

Fig .4. River System Schematic

***2.4.3. Steady flow*:** To generate water surface profile , steady state model peak flow is used; boundary condition defined as the water surface level for upstream condition at Soba station and rating curve as downstream boundary condition obtained from Khartoum station .

2.4.4. Quasi-unsteady flow data: In order to generate sediment model quasi-unsteady flow is used, Flow series for years are used as upstream boundary condition and stage series as downstream boundary condition for the same period.

***2.4.5. Sediment Data*:** Maximum water depth is defined as maximum alluvial depth of the river at AL Manshiya bridge location soil classification is obtained from soil report of the river to define bed gradation used in the model particle size varies from (0.06 to 4 mm)

2.**4.6. Calibration and validation:** The calibration of the hydraulic model built in HEC-RAS is performed based on the comparison of computed and observed values of water levels, and the manual adjustment of Manning's n parameter values. For the estimation of Manning's n values, In order to reduce model errors, flow resistance coefficient "n" values estimates are then refined by comparing outputs from the model runs with measured data of recorded water levels.

The hydraulic model built in HEC-RAS software has been calibrated for time series of water level measurements at Khartoum station.

2.5. Models for Scour Prediction:

1. **Short-Term General Scour**_The short-term general scour depth is related to the peak flood.
2. **Long-term aggradation degradation:** Three HEC-RAS defined equations are used to estimate long-term sediment aggradation and degradation at AL Manshiya Bridge area. The effect is measured for period of 10 years, the equations used for transport function are Ackers-white, Toffaleti and Yang equations. these equations were selected due to their similarity to the study area characteristics i.e. bed material size limitation (total bed equations).For fall velocity several method are used such as Ruby, Toffaleti, Van Rijn, Report12 and Dietrich.
3. **Contraction scour:**_Is performed in HEC RAS by calculating critical velocity for beginning of the motion of the particles to know if the flow from upstream is transporting bed material, to indicate the type of the contraction scour either live-bed or clear water contraction scour.

Critical velocity was evaluated by Larsen 1936:

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

Where:

V_c = critical velocity above which material of size D_{50} and smaller will be transported.

y_1 = Average depth of flow in the main channel or overbank area at approach section.

D_{50} = Bed material particle size in a mixture of which 50% are smaller.

K_u = 6.19 (S.I units)

Live bed contraction: scour is obtained by a modified version of Larsen's 1960 equation:

$$\frac{y_2}{y_1} = \left(\frac{Q_2}{Q_1}\right)^{6/7}\left(\frac{W_1}{w_2}\right)^{k1} \quad (2)$$

$y_s = y_2 - y_o$ = (average contraction scour depth)

Where:

Y_1= Average depth in the upstream main channel, (m)

Y_2 = Average depth in the contracted section, (m)

Y_0 = Existing depth in the contracted section before scour, (m)

Q_1= Flow in the upstream channel transporting sediment, (m3/s

Q_2= Flow in the contracted channel, (m3/s)

W_1= Bottom width of the upstream main channel that is transporting bed material, (m)

W_2 = Bottom width of main channel in contracted section less pier width(s), (m)

K_1= are obtained according to table (1)

Table 1. Mode of bed material transport

Mode of Bed Material Transport	k_1	V*/T
Mostly contact bed material discharge	0.59	<0.50
Some suspended bed material discharge	0.64	0.50 to 2.0
Mostly suspended bed material discharge	0.69	>2.0

Where:

$$V^* = (\vartheta_o/\Delta)^{1/2} = (g y_1 S_1)^{1/2}, \quad (3)$$

T = fall velocity of bed material based on the D_{50}, m/s

g= Acceleration of gravity (9.81 m/s^2)

S_1= Slope of energy grade line of main channel, (m/m)

ϑ_o = Shear stress on the bed, (Pa (N/m^2))

Δ = Density of water (1000 kg/m^3)

Clear-water contraction scour: developed by Larsen (1963):

$$y_2 = \left(\frac{K_u Q^2}{D_m{}^{2/3} W^2}\right)^{3/7} \quad (4)$$

$y_s = y_2 - y_o$ = (average contraction scour depth)

Where:

y_2 = Average equilibrium depth in the contracted section after contraction scour, (m)

Q = Discharge through the bridge or on the set-back overbank area at the bridge associated with the width, (m^3/s)

D_m = Diameter of the smallest non-transportable particle in the bed material (1.25 D_{50}) in the contracted section, (m)

W = Bottom width of the contracted section less pier widths, (m)

Y_0 = Average existing depth in the contracted section, (m)

K_u= 0.025 SI units

Two scour prediction formulas are used in Hec RAS model (i.e., Froehlich equation and CSU equation)

CSU (Colorado State University) equation:

$$y_s = 2.0 K_1 K_2 K_3 K_4 a^{0.65} y_1^{0.35} F^{0.43} \quad (5)$$

Where:

y_s = Depth of scour in meters

K_1 = Correction factor for pier nose shape

K_2 = Correction factor for angle of attack of flow

K_3 = Correction factor for bed condition

K_4 = Correction factor for armoring of bed material

a = Pier width in meters

y_1 = Flow depth directly upstream of pier in meters

F = Froude No. directly upstream of the pier

Froehlich equation:

$$y_s = 0.32\varphi(a`)^{0.62} y_1^{0.47} Fr_1^{0.22} D_{50}^{-0.09} + a \quad (6)$$

Where:

y_s = the depth of pier scour

φ= Correction factor for pier nose shape: φ = 1.3 for square nose

a`= the projected pier width with respect to the direction of the flow, (m).

a = the pier width (m)

3. BRIDGE SCOUR AND STREAM INSTABILITY COUNTERMEASURES:

Countermeasures for local scour at abutments is made either by altering flow away from abutment or by making the flow area around the abutment more resistant to erosion.

Hydraulic Engineering Circular No. 23 proceeds a countermeasure matrix for various sets of countermeasures based on their functional application, suitable river environment and maintenance resources.

Based on this matrix, experience in Sudan , environmental safety ,Well-established , reliable design criteria based on lab/field studies; transverse spur dikes upstream of the bridge is chosen as a flow altering method, and riprap around the abutment as a resistance to scour countermeasure.

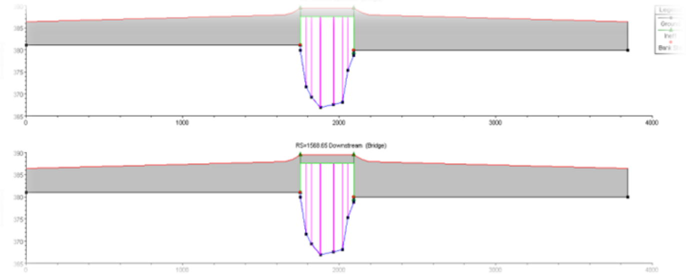

Fig .5. Bridge cross section obtained from 2010 bathymetric data

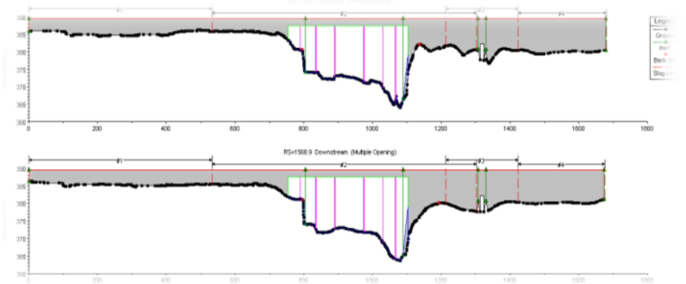

Fig .6. Bridge cross section obtained from 2017 bathymetric data

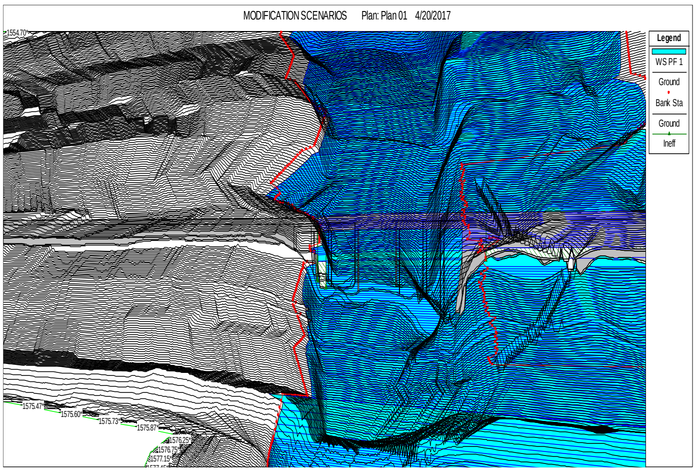

Fig .7. xyz plot for cross section in high flow season

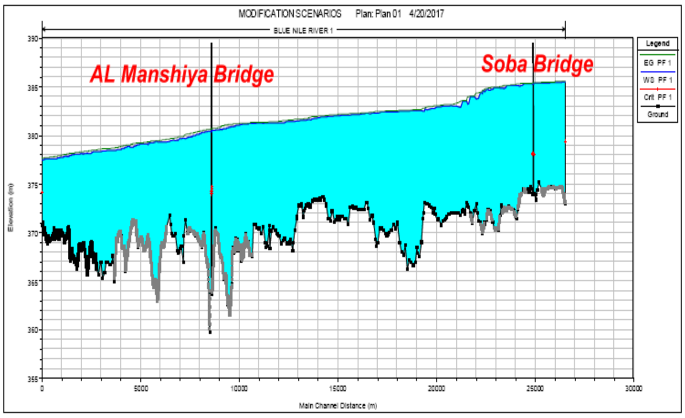

Fig .8. side view for the reach including the two bridges

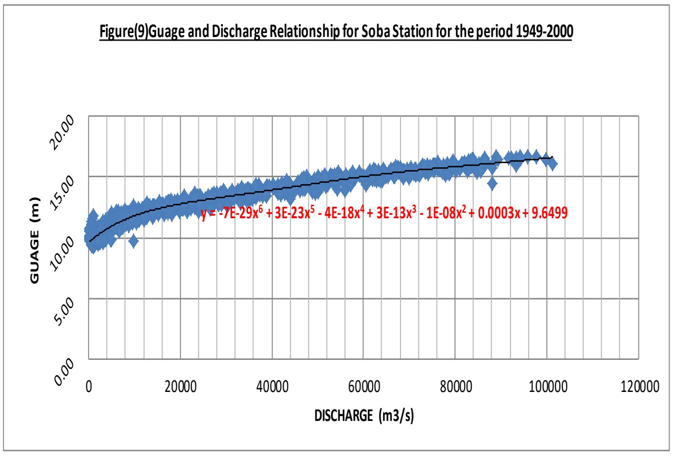

Fig .9. Gauge discharge relationship for soba station

Spur dikes: Dikes to be used are rocks formed, 10 m long, 3m wide with angle 120 degree toward upstream

Protection scenarios:

1- One spur dike 30m upstream the bridge on the east bank
2- Two spur dike 30m and 60m upstream the bridge on the east bank.
3- Three spur dike 30m, 60m, 90m upstream the bridge on the east bank.
4- Course rock around the abutment .
5- Combination of the four mentioned scenarios.

4. Computations, results and discussion:

4.1 Scour analysis:

Contraction, pier and abutment scour results:

It is worth mentioning that, HEC-RAS model gives results for calculated scour in long term, contraction due to the bridge and local scour at piers and abutment for all the piers using the maximum velocity and water depth at the bridge cross section, table (2) shows result of scour.

4.2 Scour Profile:

4.2.1 Short-Term General Scour

The short-term general scour is related to the peak flood event, 1988 flood is used to generate short-term scour profile that shows degradation of 4,000 ton per bridge cross section. Fig No.(10) Shows the short- term scour at bridge station.

4.2.2 Long-term General scour:

Scour profile is examined for 26 (km) reach , for three different methods shows local degradation at the bridge station 41,000 ton per bridge cross section as average followed by aggradation downstream which indicate the effect of the Constrictions of the bridge.

Table 2. Results of different types of scour

Scour type	Equation	Scour depth (m)	Equation	Scour depth (m)
Contraction scour	Live bed	0.46		
Pier scour	CSU equation	2.63/4.13(two size of piers)	Froehlich`s equation	2.16/4.18(two size of piers)
Abutment scour	Hire equation	31.44	Froehlich`s equation	12.47

Table 3. Long term aggradation degradation scour results

method	Aggradation (ton)
Toffaleti	40,000
Ackers-white	35,000
yang	50,000

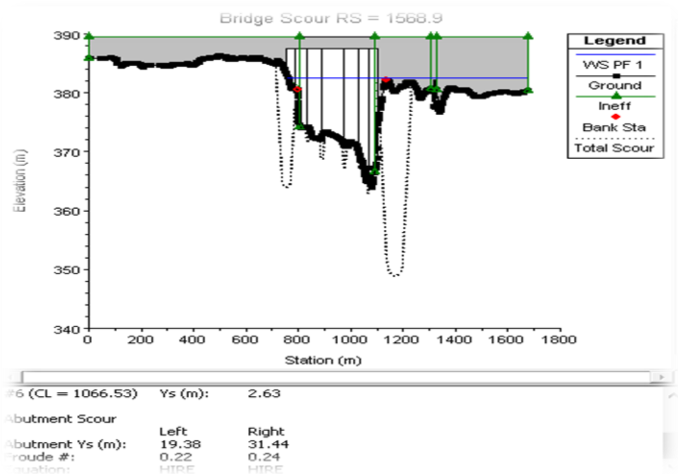

Fig .10. Bridge cross section scour results obtained from HEC RAS

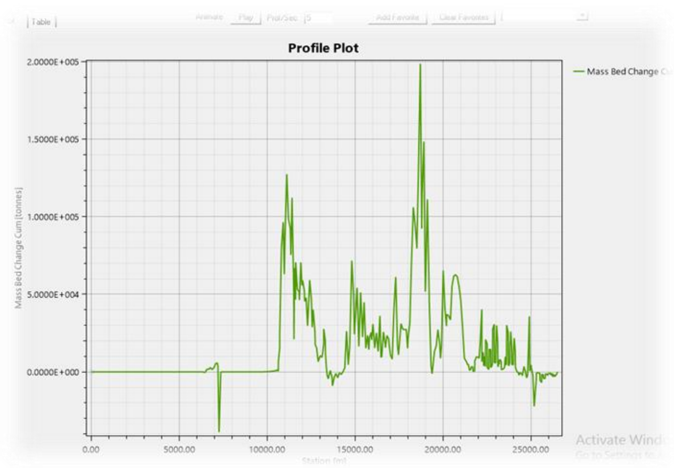

Fig .11. Short term aggradation - degradation scour (flood event)

Countermeasures scenarios: Steady state model shows high velocity at bridge station compared to upstream and downstream stations (2.8m/s at bridge, 1.7 at the upstream side and downstream).

Fig .12. Long term aggradation degradation using Toffaleti method (10 years)

Table 4. Results of countermeasures scenarios

Modeled scenario	Flow velocity m/s
Bridge only	2.8
1	2.2
2	2.2
3	2.2
4	2.2

5. Conclusions and recommendations:

After evaluation of Al Manshiya bridge location, Geomorphic and hydraulic factors, many combined factors had caused scouring in the east embankment. The bed material effect, bend areas tend to have higher scour than straight streams and the factors of the geomorphic changes due to the artificial changes upstream the bridge.

To study the scour occurred in al Manshiya Bridge a mathematical model was built in HEC-RAS hydraulic software. This model was set-up based on bathymetric surveys includes a considerable amount of cross sections starting from soba upstream until Khartoum station downstream

Results have shown high local scour at right abutment, more lower results for piers scours, but also considerable and need further studies. Contraction scour is relatively small compared with previous local scour mentioned.

Countermeasures matrices are studied to define the best alternative to enforce stream stability and reduce local scour, countermeasures are selected based on the characteristic of the area, aiming to reduce velocity at bridge cross-section and diverting flow from abutment. Spurs are selected to enhance stream stability and reduce velocity, and riprap is used to protect embankment and reduce local scour.

Studying different scenarios for aligning spur transversely on the adjacent stream shows significant reduction in velocity, although the first spur was the dominant in the reduction of velocity it is recommended to use the two others in order to stabilize the stream and control the thawed movement.

Bathymetric survey is very valuable so it is recommended to continue bathymetric surveys and monitoring of the bridge area, sediment measurement is absent at the bridge station it is also recommended to have observation station because of its unique morphological location and deficiency of sediment measurement near to it.

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