Scour Analysis and Countermeasures Recommendations for the New Bridge Construction on PR-9 over Rio Cana Ponce, Puerto Rico

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Abstract *— Scour is a natural phenomenon caused by the erosive action of flowing stream on alluvial beds. Failure of bridges due to scour at their foundations, which consist of abutments and piers, is a common incident. An accurate prediction of scour depth at piers is essential for the safe design of bridge foundations. Scour depth estimation at the pier site is necessary for safety and economy of the designed bridge. If sediment or rock on which bridge supports rest is scoured by a river, the bridge could result in a bridge failure resulting from hydraulic conditions, primarily due to scour of foundation material. As part of AASHTO requirements for highway bridges, a hydraulic study is necessary for the preliminary design, as well as the estimation of scouring depths at piers and abutments. The objective of this report is to evaluate the analysis of a new bridge construction presenting scour at the early stages of construction and provide recommended countermeasures to prevent or reduce the severity of hydraulic problems.*

Key Terms *— Bridge, Countermeasure, Hydraulic Study, Scour Design.*

INTRODUCTION

Bridge scour is one of the most common causes of bridge failure after extreme flood events, scouring the bed material from around the bridge foundations [1]. A national study conducted in 1973 by Federal Highway Administration (FHWA), shows that 25 percent of bridge scours involved pier damage to structures [2]. In 1987, a bridge near Fort Hunter in New York collapsed due to scour and undermining of the foundations after a near record rainfall, killing a total of 10 people. This incident resulted as federal requirements for scour critical evaluation and underwater inspections.

JUSTIFICATION

Over the years FHWA have develop guidelines and procedures for designing and improving the nation's infrastructures, including bridges [1]. Federal regulations require that states and bridge owners provide adequate maintenance; including bridge scour evaluations and plan of actions for identified scour bridges [3].

The Puerto Rico Highway and Transportation Authority (PRHTA), in coordination with FHWA, is committed to provide effective countermeasures for existing and new bridge constructions, and the maintenance of our transportation system infrastructures; however, in Puerto Rico scour has been a matter of concern, as many are identified as scour critical. It is for this reason that this research will study the scour analysis performed for a new bridge construction at the PR-9 over Canas River, with the main purpose to provide feasible recommendation for the bridge scour that is developing around the piers.

LITERATURE REVIEW

Scour is the removal of material from the streambed or streambank as a result of the erosive action of streamflow. Is defined as the erosion of streambed or bank material due to flowing water; often considered as being localized (see Figure 1) [1].

Scour rates and the extent of scour vary with discharge, bed material, and bridge alignment and geometry, among other factors.

The types or components of scour are collectively known as total scour. The three components are:

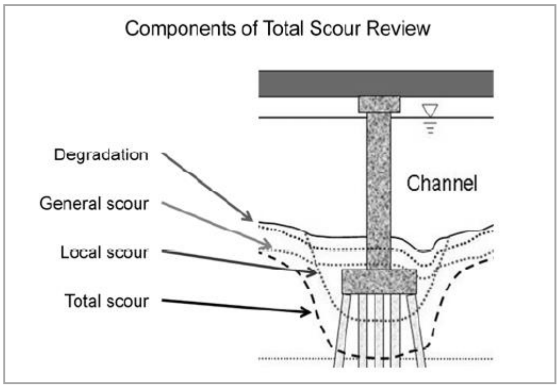

Figure 1
Components of Total Scour

- Degradation and Aggradation
- General Scour
- Local Scour

Degradation is the general and progressive (long-term) lowering of the channel bed due to erosion, over a relatively long channel length. Aggradation in the other hand is the general and progressive build-up of the longitudinal profile of a channel bed due to sediment deposition.

General Scour is the lowering of a streambed across the waterway at the bridge, which may or may not be uniform. This type of scour can be caused by short term changes in the downstream water elevation, which controls water velocity through the bridge opening. It is also cyclic or recurring, and it could be the result of contraction of the flow or from other general scour conditions.

Contraction Scour is the removal of the material under the structure only. This type of scour is a direct result of an accelerated stream velocity due to a reduction in waterway area. It could also be triggered through natural stream constrictions, such as heavy vegetation growth or man-made processes such as an excessive number of piers in the waterway or bridge roadway approach embankments that were built in the floodplain.

Other general scour conditions result from erosion due to streams that have; meandering, braided or straight stream characteristics; variable downstream control, streamflow around a bend; or have any other changes that may cause a decrease in the bed elevation. Other general scour could also result from a short term change in downstream water surface water elevation, which can control the velocity through the bridge.

Local Scour is the removal of streambed material adjacent to an obstruction in a waterway, which has been placed within the stream, such as piers and abutments, and causes acceleration of the flow induced, by the obstruction. Generally scour depths resulting from local scour are greater than those caused by general scour, often by a factor of ten. Local Scour is primarily the result of man-made structures within the stream. However, natural obstructions could also lead to local scour, such as debris accumulation. The obstruction creates vortexes or whirlpools that remove the streambed material, leading to local scour. Typically, the larger the obstruction, the more scour could be expected. In addition, the shape of the obstruction contributes to local scour.

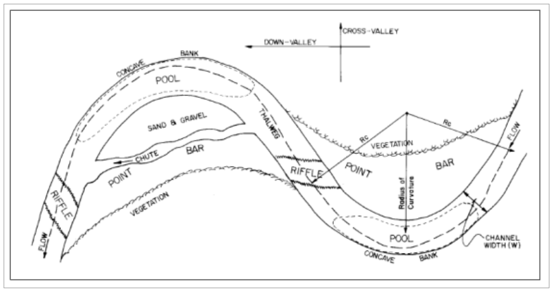

Figure 2
Lateral Stream Migration Concept

Another component that could threaten the stability of a bridge is the lateral stream migration (see Figure 2). The lateral stream migration is the relocation of the channel due to lateral streambank erosion; this is another type of erosion that can cause major embankment instability typically at bride openings. The modes of bank failures associated with lateral stream migration include:

- Streambank damage is the onset or beginning of lateral stream migration.
- Sloughing streambank is the next level; where lateral scour has removed enough toe of slope

that the streambank slides down into the channel.

- Undermined streambank is the third level of streambank damage and is an advanced state of lateral erosion where the overbank area is undercut.
- Channel misalignment is the final stage in lateral migration, this is an adverse channel offset where the streamflow impacts one of the bridge abutments or flows through the under bridge waterway at a skew angle incompatible with the span opening. This resulting from unchecked stream migration, which leads to scour and substructure instability.

Some of the methods to direct streamflow or protect against scour development and lateral migration are commonly known as hydraulic countermeasures; which are man-made devices designed to direct streamflow, and these are broken down into two distinct categories: River training structures and Armoring countermeasures.

The first category of countermeasures, river training structures, alters the flow or path of the river, such as spurs and guide banks. The spurs are linear structures, designed with properly-sized and placed rocks which protect the streambank by reducing flow velocity with the main objective to help minimize or even correct lateral stream migration. Guide banks are dikes that extend upstream from the approach embankment at either or both sides of the bridge opening to direct the flow through the opening. This last method is constructed to alleviate otherwise accelerated streamflow through the bridge waterway and reduce scour behind the abutments. [4]

The second category of countermeasures is Armoring, these resist erosive forces caused by the flow, but do not alter the flow direction. Armoring countermeasures include: Riprap, Gabions, Slope Protection, and Channel Lining.

- Ripraps are layers or facing of properly-sized and graded rock or broken concrete. They are placed adjacent to abutments, piers or along streambanks and are design to resist the force of flowing water.
- Gabions consist or rectangular rock or cobble-filled wire mesh baskets anchored together and generally anchored to the surface they are protecting.
- Slope protection is the placement of geotextiles, wire mesh, paving, revetment, plantings or other materials on the existing channel embankments. Are usually intended to protect the slope from erosion, slipping, or to withstand external hydraulic pressure.
- Channel lining is rigid concrete pavement or flexible protective revetment mats placed on the bottom of a streambed to counter scouring by providing a stable surface for the channel.

The scour analysis is imperative for bridge design, especially new bridges, as the bridge foundation shall be designed to resist the effects that could result from hydraulic conditions. The hydrology and hydraulic study (H-H) of the area should be completed before moving onto the bridge designing phase, due to the information provided about the river behavior and interaction that will be developed once the structure is constructed.

Scouring excavates and carries away materials from streambeds and bank bridge foundations by the normal flowing water or flood (see Figure 3). Although scour rate may be greatly affected by the presence of structures encroaching on the channel, the shear stress generated by the flowing water on the streambed is the basic erosive stress. Although, the streambed materials provide the resisting stress against erosion, scour reaches its equilibrium status when these two stresses get balanced. Designing the bridge foundation safely needs an accurate estimation of scour depth, due that underestimation may lead to bridge failure, while over estimation will lead to excessive construction cost.

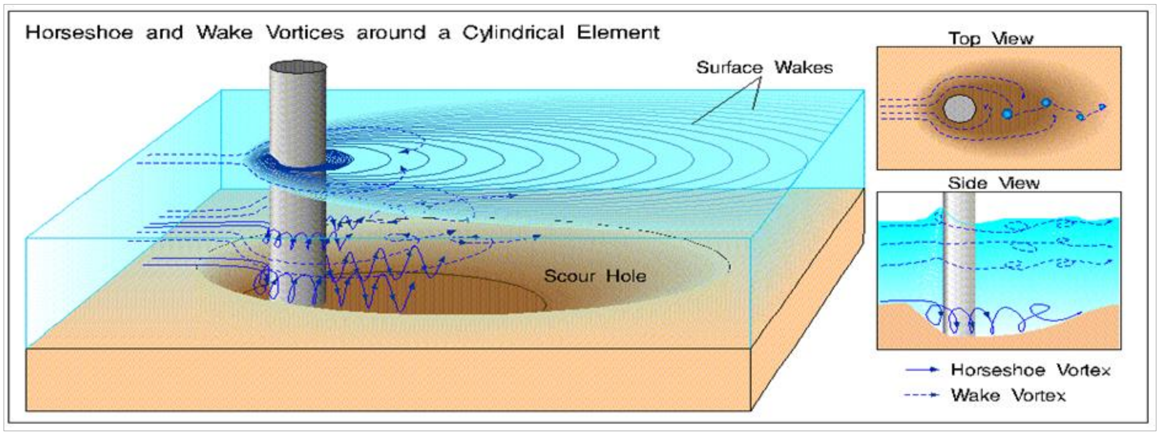

Figure 3
Scour Concept

METHODOLOGY

This research will analyze and compare the procedures followed for the scour analysis and countermeasures design evaluation. The following information explains the methodology used for this project.

- Scour Analysis at the proposed bridge. The individual scour components were calculated to obtain the total scour depths [1].
- Scour countermeasures analysis for the piers [3]?.

Total scour at a highway crossing is comprised of three components: Long-term aggradation and degradation [1], contraction scour, and local scour at piers and abutments. The recommended method is based on the assumption that the scour components develop independently. In addition, lateral migration of the stream must be assessed when evaluating total scour at piers and abutments [1].

Long-Term Aggradation and Degradation

Aggradation and degradation are long-term elevation changes due to natural or man-induced causes that can affect the reach of the river on which the bridge is located. Aggradation involves the deposition of material eroded upstream of the bridge, while degradation involves the lowering of the streambed due to a deficit in sediment supply from upstream.

For this research the long-term trend in bed elevation was estimated using straight-line extrapolation on equivalent cross sections from the U.S Geological Survey Quadrangle, Ponce, 1982 topographic data and surveying data obtained from previous studies conducted requested by PRHTA for the project AC-000911.

Contraction Scour

Contraction scour can be either clear-water or live-bed scour [1]. Clear-water scour occurs when there is no bed material transport in the approach, or is so fine that it washes through the contracted section, whereas, live-bed scour occurs when there is transport of bed material in the approach reach.

The first step in contraction scour calculations is determining if the scour is live-bed or clear-water:

- If $\boldsymbol{V_{c50}} \leq \boldsymbol{V}$; Scour is live-bed, where $\boldsymbol{V_{c50}}$ is the critical velocity for the beginning motion of the D_{50} size of bed material, and V is the mean velocity of flow upstream of the bridge. $\boldsymbol{V_{c50}}$ can be calculated using equation (1).

$$\boldsymbol{V_{c50} = 6.19 Y^{1/16} D_{50}^{1/3}} \tag{1}$$

Where;
Y = Depth of flow at the approach (m).
D_{50} = Particle size in a mixture of which 50% are smaller (m).

For live-bed conditions the Laursen's 1960 equation is used to calculate scour in the contracted section:

$$\boldsymbol{Y_S = Y_1(Q_2/Q_1)^{6/7}(W_1/W_2)^{K_1} - Y_0} \qquad (2)$$

Where;
Ys = average scour depth (m).
Y1 = average depth in the upstream main channel approach (m).
Q2 = Flow in the contracted channel (m^3/s).
Q1 = Flow in the upstream main channel approach (m^3/s).
W1 = Width of the upstream main channel approach (m).
W2 = Width of the contracted channel (m).
K1 = Exponent dependent on the shear velocity on the upstream section and the fall velocity of the bed material.
Y0 = existing depth in the contracted section before scour (m).

For clear-water conditions the Laursen's 1963 equation is used to calculate scour in the contracted section;

$$\boldsymbol{Y_S = \left\{0.025Q^2/\left({D_m}^{2/3}W^2\right)^{3/7}\right\} - Y_0} \qquad (3)$$

Where;
Q2 = Discharge through the bridge on the overbanks associated with the width (m^3/s).
Dm = 1.25D50 = Diameter of the smallest non transportable particle of bed material in the contracted section (m).
W = Bottom width of the contracted section (m).

Local Scour

Local scour involves the removal of material from around piers and abutments caused by an acceleration of flow and resulting vortices induces by the flow obstruction. The horseshoe vortex, located at the base of the pier or abutment, is a horizontal vortex produced by the pileup of water on the upstream surface of the obstruction. Wake vortex is a vertical vortex that is forms downstream of the obstruction.

Local scour at piers is a function of bed material size, flow characteristics and the geometry of pier. To determine pier scour Colorado State University (CSU) equation is recommended:

$$\boldsymbol{Y_S = 2.0K_1K_2K_3K_4a^{0.65}Y_1^{0.35}Fr_1^{0.43}} \qquad (4)$$

Where;
$\boldsymbol{Y_S}$ = Scour depth (m).
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 by bed material size.
$\boldsymbol{a}$ = pier width (m).
Y_1 = Flow depth directly upstream of pier (m).
$Fr_1 = V_1/(gY_1)^{1/2}$ = Froude number directly upstream of the pier.

The top width of scour holes at each side of the pier in cohesionless bed materials can be estimated from equation (5).

$$W = Ys\,(K + \cot \phi) \qquad (5)$$

Where;
W = Top width of the scour hole from each side of the pier (m).
Ys = Scour depth (m).
K = Bottom width of the scour hole as a fraction of scour depth (m).
ϕ = angle of repose of the bed material ranging from 30° to 44°.

Since it is difficult to estimate the bottom width of the scour hole, FHWA suggests using W = 2.0 Ys from each side of the pier for practical applications.

Local scour at abutments depends on the interaction of the flow obstructed by the abutment and the flow in the main channel at the abutment. Nevertheless, the equations developed assume the discharge returned to the main channel is simply a function of the abutment length, since laboratory research has failed to replicate field conditions. Therefore, the results are excessively conservative and engineering judgment is required in designing foundations for abutments.

Lateral Migration of the Stream

The lateral migration of a stream may be gradual or the result of a single flood event. A meandering stream whose channel moves laterally and downstream into the bridge can erode the approach embankment and can affect contraction and local scour because of changes in flow direction [1]. Factors that affect lateral shifting of a stream are the geomorphology of the stream, location and crossing of the stream, flood characteristics, bed and bank characteristics material, and wash load (see Figure 2).

Countermeasures

The selection and design size for riprap stones shall be able to have the ability to resist high flow velocities and buoyant forces, which could prevent the selected material from eroding later on with time [4]. FHWA guidelines to determine the size rock is as follow:

$$\boldsymbol{D_{50}} = \frac{\mathbf{0.692}(\boldsymbol{V_{des.}})^{\mathbf{2}}}{(\boldsymbol{S_g}-\mathbf{1})\mathbf{2}\boldsymbol{g}} \qquad (6)$$

Where;

$\boldsymbol{D_{50}}$ = Particle Size for which 50% if finer by weigth (m)

$\boldsymbol{V_{des}}$ = Design Velocity for local conditions at the pier, (m/s)

S_g = Specific Gravity (Usually taken as 2.65)

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

DESCRIPTION OF STUDY AREA

The project selected for this research is located at the State Road PR-9; located between Canas and Magueyes Urbano Wards in the municipality of Ponce shown in Figure 4. The project consists of a new bridge at the crossing of the State Road PR-9 over the Rio Canas and the State Road PR-123 which runs parallel to the river. The bridge is a six-span high bridge consisting of reinforced concrete deck 13.30 meters wide placed on top of girders. Five semicircular nose and tail piers 1.8 meters wide and 3.6 meters long spaced at 37 meters and two abutments support the deck. The foundations of each pier consist of a group of steel piles and 1.0 meters deep concrete pile cap.

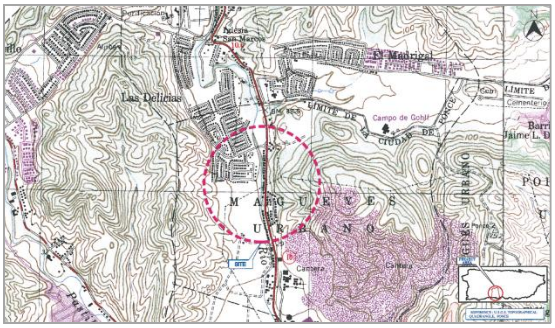

Figure 4
Bridge Location

The project will cross the Rio Canas and this analysis will addresses the scour impact on the bridge piers located in the waterway crossing, with the objective to present the results of a scour analysis based on the 100-year storm flood levels following the guidelines established by the Federal Highway Administration [1].

RESULTS AND DISCUSSION

The data used for the scour analysis were: H-H study and boring log and soil classification from previous studies performed for PRHTA. The watershed delimitation is presented in Figure 5 and from the previous study it was determined that there is potential lateral migration due to the current conditions of the floodplain.

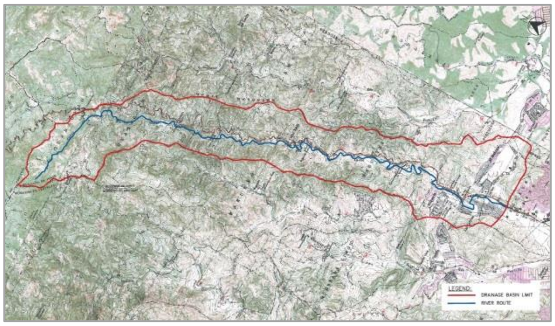

Figure 5
Watershed Delimitation

From the H-H analysis the HEC-RAS profile output summary was used to obtain data needed for the scour analysis to determine depth of the flow, average velocities, cross sections, and discharge of the section (see Figure 6).

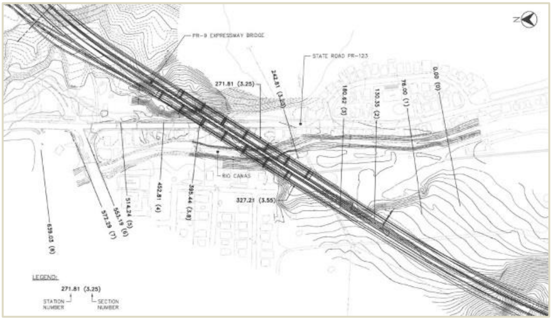

Figure 6
Cross Sections Locations

The summary of this output is presented in the following table:

Table1
HEC-RAS Output Summary for 100 Year

River Station	Water Surface Elev. (m)	Velocity (m/s)
688.86	36.54	3.87
639.03	36.02	4.36
572.29	36.07	3.17
563.00 (Bridge)		
553.19	34.83	4.65
514.24		3.93
452.81	34.10	4.68
395.44	33.53	5.31
327.31	33.33	2.13
300.00 (Bridge)		
271.81	33.31	1.92
242.81	32.77	4.05
180.62	31.60	5.36
130.35	32.05	2.76
76.00	32.08	1.95
0.00	31.35	4.05

The total scour in the piers and abutments estimated long-term aggradation in the area is 3.78 meter. Only degradation is considered in the total scour depth because a major flood can occur and reverse the aggradation trend. As a result of the estimated contraction scour analysis, no scour at the right overbank (West abutment) occurs, therefore, the total scour depth will be equal to the addition the local scour at piers and abutments. Summary for the scour analysis are presented in table 2.

For the countermeasure calculations; it was selected a coefficient shape of 1.5 for a round nose, as per HEC-23 guidance [4]. The second step was to calculate appropriate design velocity; it was calculated for the highest flow velocity as there are indications of lateral shifting that could cause form velocity changes. Third; the D_{50} was determined in order to select the nominal class for the riprap [4]. Nominal riprap class selections for the piers are shown in table 3.

Table2
Scour Analysis Results 100 Year

Pier ID	Local Scour(m)	Total Scour (m)	Scour Hole Top Width (m)
Pier 3	3.35	3.35	6.74
Pier 4	3.35	3.35	6.74

Table3
Nominal Class for Piers 3 & 4

Pier ID	Median Particle Size	Size (in)	Weight (lbs.)
Pier 3	II	9	60
Pier 4	II	9	60

Additional steps were taken into consideration by proposing an addition countermeasure to provide stability to the river lateral migration. The recommended design is a J-hook bendway with the main objective to prevent from any future realignment of the river that could cause further bank erosion [5]. The typical J-Hook plan view is presented in Figure 7 and the recommended preliminary layout results are illustrated in table 4.

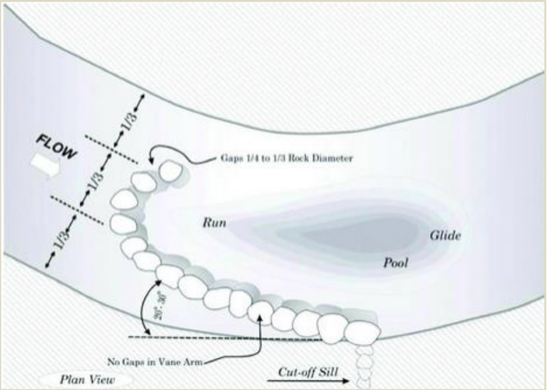

Figure 7
Typical J-Hook Plan View

Table4
J-Hook Recommended Preliminary Layout

Weir Height (m)	Weir Length (m)	Weir Spacing (m)	Key Length (m)	1/3* Flow Width (m)
3.4	8.0	31.8	5.03	34.8

CONCLUSIONS AND FUTURE WORK

Due to the economic situations that PRHTA is presenting at the moment, the countermeasure design selected was to armor the existing piles in order to present a real viable solution for the Authority; however, the PRHTA should consider to further assess the existing conditions of the river, as it might change the direction of flow or continue with lateral migration, incurring on extra costs for design and construction.

Some of the recommended countermeasures that it could be considered, with the existing conditions presents at the site location, are the evaluation and design for river training structures, like the one proposed on this study, such as spurs and guide banks. These structures would provide the adequate measure to prevent lateral movement, and energy dissipation.

Future work ideas that emerged during this research that could improve river analysis for Puerto Rico are research related to effectiveness of possible indicators of a system of bendways weir, and design guidelines that could be specifically directed to different conditions presented for the island of Puerto Rico. Another recommendation would be create a database where it could indicate when and where these types of structures have been design, to monitor their efficiency in Puerto Rico specific conditions.

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