ANALYSIS OF ESTIMATED SCOUR VS INSPECTED SCOUR ON A BRIDGE AFTER HURRICANE MARIA, AND THEIR IMPACT ON THE PUERTO RICO BRIDGE PROGRAM

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Abstract

Bridge scour is considered the main reason for bridge failures due to the holes that can form and compromise the structure stability. Federal regulations require all proposed bridges to be designed for scour resistance and all existing bridges to be evaluated for scour vulnerability. Scour evaluations are typically based on the 100-year recurrence flood event. Bridges determined to be unstable due to observed scour or assessed high potential for scour are deemed scour critical. Various equations to evaluate scour are available, however many of them are considered conservative and leading to overestimation of the scour depths. The pass of Hurricane Maria over Puerto Rico triggered catastrophic flooding in the magnitude of a 100-year recurrence flood and higher, hence replicating the conditions for which bridges are evaluated. To analyze evaluated against observed scour, a bridge within Maria's track was inspected and compared as a case study to its evaluation results. The outcome showed that the equations may have overestimated the scour depths, given no scour was found at the bridge; also implying that this overestimation could have an impact on the Puerto Rico Bridge Program, which currently has 495 scour critical bridges, all requiring flood monitoring and, consequently, greater resources.

Introduction

Bridge scour is the removal of soil material around the abutments and/or piers of bridges, caused by the flowing water. Bridge scour is the most common cause of bridge failures [1]. Federal regulations, require that all bridges over water are evaluated for scour vulnerability and managed accordingly. Empirical methods have provided derived equations for the estimation of scour depth around bridge elements, which are often considered conservative and leading to overestimation of the depths [2].

On September 20, 2017, Hurricane Maria made landfall in Puerto Rico, moving across the island with widespread hurricane force winds spread all over and extremely heavy rainfall that produced major to catastrophic flooding, especially across the northern part of Puerto Rico. Due to the devastation propagated, many sources consider it as the worst storm to hit Puerto Rico in the last century. The magnitude of rain left is in the range of a 100-year recurrence event, resembling the flood conditions used for scour evaluations.

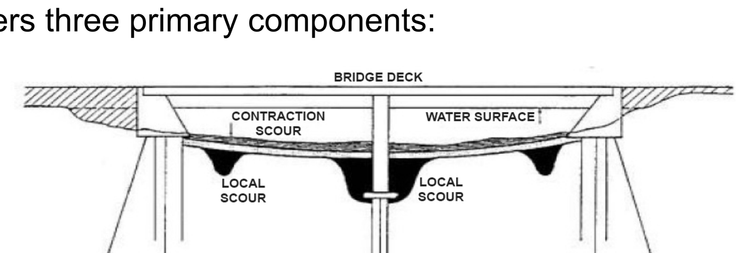
To analyze the contrast between estimated and observed scour depths, a bridge located in the northern part of Puerto Rico, within the storm trajectory, was selected and inspected for scour after the hurricane. The inspection findings were compared with the results of its scour evaluation, while also analyzing the relationship among the scour variables and evaluating the impact of potentially overestimated results on the Puerto Rico Bridge Program.

Bridge Scour

Bridge scour may occur in the streambed and banks, which are composed of different types of materials, each one having a scour rate. Generally, granular soils are rapidly eroded, whereas cohesive soils are more scour-resistant. Maximum scour depth may occur in as short as hours in sand and gravel materials, while may take years in sandstone or limestone materials.

Bridge total scour considers three primary components:

- Long-term Degradation
- Contraction Scour
- Local Scour



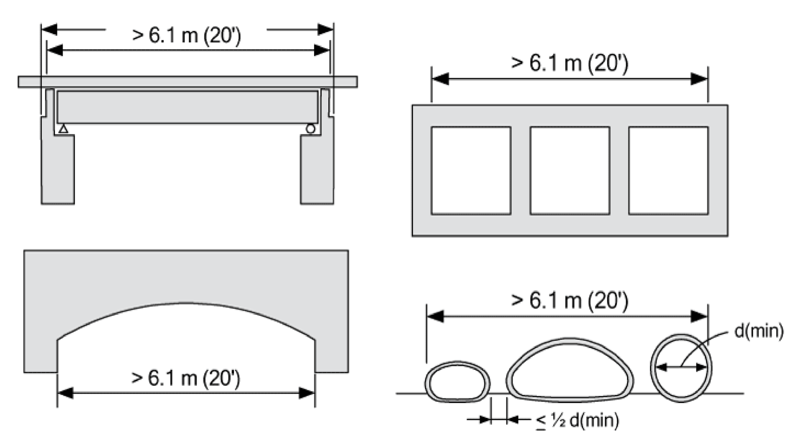
Degradation consist in elevation changes at the streambed due to the deficit in sediment supply by natural or man-induced causes and requires the analysis of changes in sediment load or removal of bed material to calculate it.

Contraction scour occurs when the flow area of a stream is reduced, either by natural contraction of the channel or by the bridge elements projecting into the channel and blocking the flow area, resulting in an increase in velocity and erosive forces in the contraction area and more removal of bed material.

Local scour consists in the removal of material from around substructure elements, including piers and abutments, due to the acceleration of flow and resulting vortices induced by the elements acting as obstructions.

Bridge Scour Evaluation and Federal Regulations

The National Bridge Inspection Standards (NBIS) [3], requires the Puerto Rico Highway and Transportation Authority (PRHTA), as state agency, to inspect all bridges located on public roads. All bridges over water must have a scour evaluation and those determined to be scour critical shall have a Plan of Action (POA) prepared to monitor the bridge during and after flood events. A bridge is considered scour critical if the abutment and/or pier foundations are coded unstable due to either observed scour or assessed high potential for scour.



Federal regulations also require that the design of a bridge includes estimated scour depths at piers and abutments [4]. The flow discharge to be selected as the basis for both the scour evaluation and design flood shall be the more severe of the 100-year event or from an overtopping flood of lesser recurrence interval. The scour depth under an overtopping flood can be significantly greater because the submerged superstructure can produce significant blockage or pressure flow conditions.

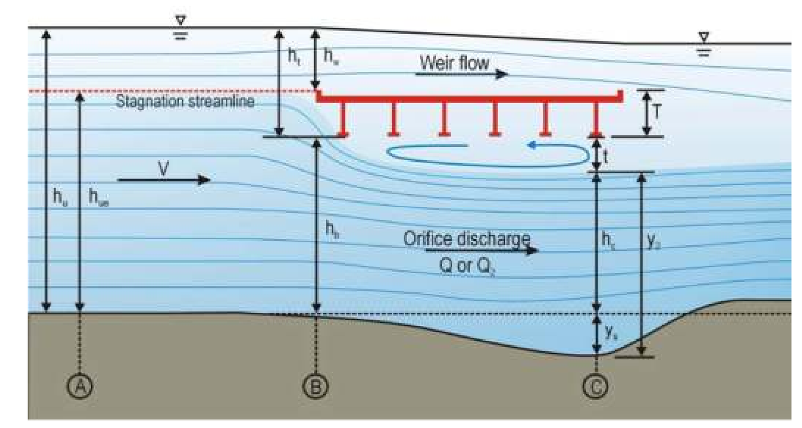
Evaluating scour is complex due to the nature of the acting variables. Several publications provide guidance to estimate scour, one of which is the FHWA Evaluating Scour at Bridges (HEC-18) [1]. The same provides equations to calculate if scour is occurring at clear-water or live-bed condition and to estimate the contraction scour for both scenarios.

If bridge scour is occurring under pressure flow conditions, then the scour depth is calculated with:

$$y_s = y_2 + t - h_b \qquad (1)$$

where:

y_s = pressure flow scour depth, ft or m
y_2 = contracted section average depth, ft or m
t = separation zone thickness, ft or m
h_b = vertical size of opening before scour, ft or m



Local scour is calculated independently for abutments and piers. HEC-18 provides various equations to estimate scour at abutments, including the Froehlich Eq. and NCHRP 24-20 Eq., which estimates total scour rather than local scour only.

Depth is calculated with this set of equations:

$$y_{max} = \alpha * y_c \; ; \; y_s = y_{max} - y_0 \qquad (2)$$

where:

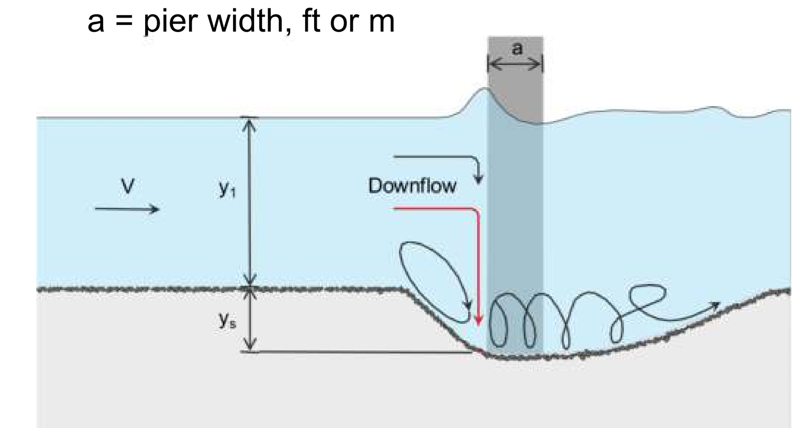
y_s = abutment scour depth, ft or m
y_{max} = maximum flow depth resulting from abutment scour, ft or m
y_c = flow depth including live-bed or clear-water contraction scour, ft or m
y_0 = flow depth prior to scour, ft or m
α = live-bed or clear-water amplification factor

For piers, the local scour depth is calculated with the following equation:

$$\frac{y_s}{y_1} = 2.0 K_1 K_2 K_3 \left(\frac{a}{y_1}\right)^{0.65} Fr_1^{0.43} \qquad (3)$$

where:

y_s = local scour depth, ft or m
y_1 = flow depth upstream of pier, ft or m
K_1, K_2 & K_3 = correction factor for pier nose shape, angle of attack and bed condition
a = pier width, ft or m



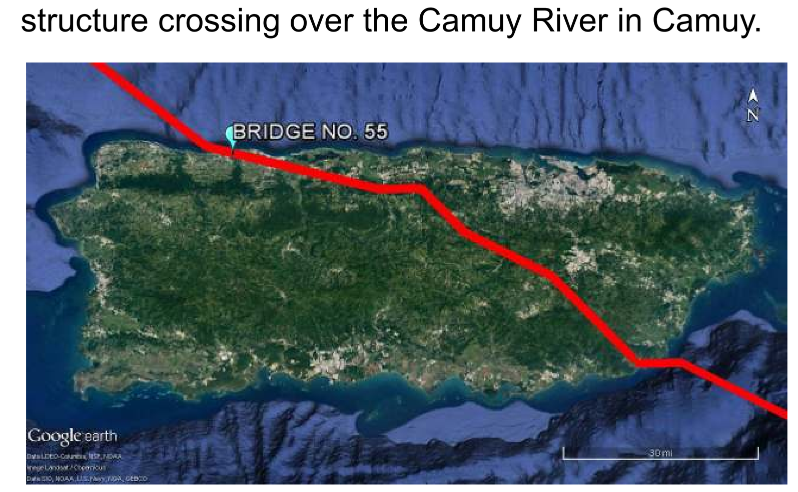
Hurricane Maria and Case Study: Bridge No. 55

Hurricane Maria moved all the way across mainland from its landfall in Yabucoa, southeast, to the northwest coast until offshore in the evening. Hurricane force winds were felt all over mainland, destroying many forests and structures. In a period of 24 hours, the storm exceeded 20 inches of rain in most of Puerto Rico, producing catastrophic flooding with a magnitude of rain in the range of a 100-year recurrence event, or a flood that statistically has a 1% change of occurring in any given year [5].

Flow discharge and rainfall data from the storm was gathered from two stations of the USGS National Water Information System [6]: Rio Camuy (50014800) and Rio Grande de Arecibo (50029000), which are located approximately 6 miles upstream and 9 miles east of the studied bridge, respectively.

Parameter	Measurement
Rainfall	13.67 in
Flow Discharge	12,900 cfs

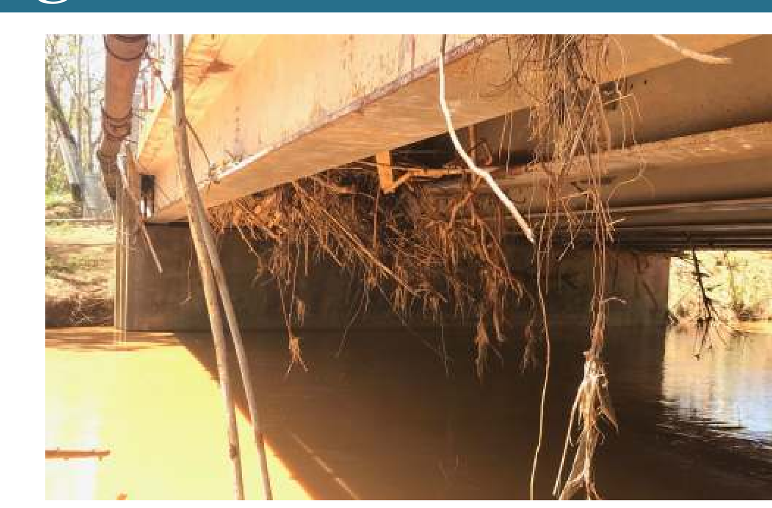
To analyze the scour variables, Bridge No. 55 was selected given its location within the trajectory of the storm and the availability of measured data. The bridge consists of a 19.30 meters long single-span structure crossing over the Camuy River in Camuy.



Flow discharge and rainfall data for the scour evaluation was obtained from the Federal Emergency Management Agency (FEMA) Flood Insurance Study [7] and from the NOAA Atlas 14 [8], respectively. Since the hydrologic-hydraulic (H-H) modeling determined the bridge was overtopped by the 100-year flood, the computed overtopping flood was selected as the basis for the evaluation.

Equation (1) was employed to estimate a vertical contraction scour of 2.22 m, given the pressure flow; and Eq. (2) was used to estimate the total scour depth at the abutments, which resulted in 1.72 m.

Parameter	Value
100-year 24-hr Rainfall	9.96 in
100-year Flow Discharge	12,915 cfs
Overtopping Flow Discharge	5,699 cfs



On October 4, 2017, Bridge No. 55 was inspected for damage after Hurricane Maria. Inspection findings included debris accumulation and moderate erosion at the river banks. However, after inspecting for scour at abutments by means of wading, no scour was found, therefore the inspected scour Post-Maria was determined to be 0.00 m [9].

As of 2018, the PRHTA National Bridge Inventory (NBI) comprises 1,602 bridges over waterways, thereby requiring scour assessment. 495 bridges have been determined scour critical, thus have a POA with assigned thresholds that indicate when to monitor the bridge before it might become unstable.

Flood monitoring programs consist of real-time systems capable of constantly collecting weather data from various sources and comparing it against the POA thresholds to alert key personnel upon trigger events being highly probable to be met, met or exceeded. These represent significant amount of resources to the PRHTA, given each bridge requires individual monitoring and management.

Results and Discussions

In pursuit of analyzing the estimated scour against the inspected scour after Hurricane Maria, both set of results of Bridge No. 55 were compared.

Parameter	Scour Evaluation Results	Hurricane Maria Results
100-year 24-hr Rainfall	9.96 in	13.67 in
100-year Flow Discharge	12,915 cfs	12,900 cfs
Overtopping Flow Discharge	5,699 cfs	N/A*
Design Flood Scour Depth	2.22 m	0.00 m

*Not available because of USGS data providing total discharge.

The results showed that the design rainfall of 9.96 inches was exceeded by almost 4 inches of rain during the period of 24 hours registered, thus certifying that Hurricane Maria surpassed the 100-year recurrence event. Similarly, the 100-year flood discharge of 12,915 cfs was roughly the discharge registered for the storm. To that end, the overtopping flood conditions of 5,699 cfs from the evaluation must have been replicated during the storm. Nonetheless, neither the vertical contraction scour of 2.22 m for the design flood nor the total scour depth at the abutments of 1.72 m were observed during the inspection, implying that the scour evaluation results were overestimated compared to its observed scour after the strike of a 100-year storm event.

Laboratory-derived equations are considered conservative given the experiment conditions for which they are developed, particularly in Puerto Rico, where the topography and stream characteristics are considerably distinct from the conditions resembled in the laboratory, hence beyond the range of applicability and possibly leading to farther overestimation of the scour depths. Although not all of the 495 scour critical bridges from the NBI may have reached the list by overestimation, there certainly are some bridges that did, which could impact the Puerto Rico Bridge Program with more bridges to monitor and manage accordingly, ergo more costs and resources.

Hurricane Maria resulted in 26 bridge collapses and over 400 damaged. However, most of said collapses may have been an effect of transported debris accumulating around the bridge and blocking the opening. Large amounts of debris can cause heavy lateral and vertical forces capable of pushing and carrying the structure away.

References

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