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.*

Key Terms *– Bridge Scour, Flood Monitoring, Hurricane Maria, Scour Critical Bridges.*

INTRODUCTION

Bridge scour is the removal of soil material around the abutments and/or piers of bridges, caused by the flowing water. Moreover, bridge scour is the most common cause of bridge failures [1]. Federal regulations, require that all bridges over water have a documented evaluation of scour vulnerability and that bridges determined to be scour critical have a Plan of Action (POA) prepared to monitor them in accordance with said POA. 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 by Hurricane Maria, many sources consider it as the worst storm to hit Puerto Rico in the last century. Additionally, the magnitude of rain left by the storm is appreciably in the range of a 100-year recurrence event, resembling the design flood conditions used for bridge 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 to compare the inspection findings with the scour evaluation results of the same bridge. This article analyzes the relationship among the scour variables and evaluates the impact of potentially overestimated results on the Puerto Rico Bridge Program.

OBJECTIVE

The main objective of this article is to determine whether the scour evaluation results of a bridge are overestimated compared to its observed scour after the strike of a 100-year storm event that had to have reproduced the conditions for which the bridge was evaluated. Furthermore, this article seeks to weigh the impact of scour overestimation on the evaluation of bridges in Puerto Rico.

BRIDGE SCOUR

Bridge scour is the result of the erosive action of flowing water, which excavates and carries away the material from around the piers and/or abutments of bridges. Scour may occur in the bed and banks of streams, which are composed of different types of materials, each material having a scour rate; ergo, different materials scour at different rates. Generally, loose granular soils are rapidly eroded, whereas cohesive soils are more scour-resistant of flowing water. 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 Scour Concepts

Bridge scour depends of whether it is occurring at clear-water condition, where there is no transport of bed material from upstream of the bridge; or live-bed condition, where there is transport of bed material from upstream. Bridge total scour considers three primary components:

- Long-term Degradation
- Contraction Scour
- Local Scour

Degradation consist in elevation changes at the streambed due to natural or man-induced causes, which can affect the reach of the river on which the bridge is located. Long-term degradation occurs because of deficit in sediment supply from upstream. The opposite process involving deposition of material is called aggradation, although not considered a component of total scour.

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. A decrease in area results in an increase in velocity, thus also increasing the erosive forces in the contraction area and more removal of bed material. Generally, contraction scour involves removal of material across all or most of the channel width. The process continues to lower the bed elevation until the velocity and shear stress decrease accordingly and relative equilibrium is reached.

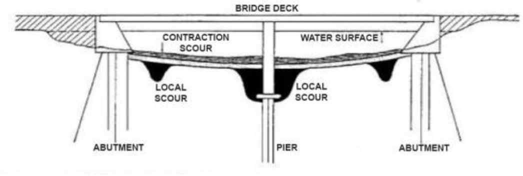

Figure 1
Bridge Elements with Components of Scour

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. As the transport rate of sediment away from the base is greater than the transport rate of sediment into the base, a scour hole is formed. As the scour depth increases, the vortex strength reduces until equilibrium is reached. This occurs when bed material inflow and outflow are even, for the live-bed conditions; or when the vortex shear stress equals the sediment particle critical shear, for the clear-water conditions. Also, scour vortices can be either horseshoe vortex, resulting from pileup of water upstream of the element, or wake vortex, resulting from movement of water downstream. Regardless, both vortices remove the base material.

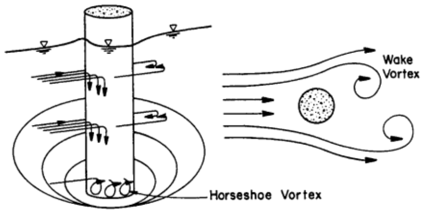

Figure 2
Horseshoe and Wake Vortices of Local Scour [1]

The three scour components previously described are added together to obtain the total estimated scour at a pier or abutment, assuming each component occurs independent of the other. In addition to these components, other types of processes should be assessed when evaluating scour, such as lateral stream migration, which consists of a naturally occurring displacement of the main channel of a stream. Lateral stream migration may affect the stability of piers in a floodplain, erode abutments and the approach roadway, and even affect the total scour by changing the flow angle of attack at the elements.

Bridge Design for Scour Resistance

The total cost of designing bridges less vulnerable to scour damage is small compared to the total cost of a bridge failure. Scour evaluations are concerned with the prediction of floods and with the complex physical processes between water and soil during the occurrence of such floods. During the preliminary design phase, hydrologic-hydraulic and site data collection assessments should be completed. The hydrologic section evaluates flood flows to assess flood hazards and meet applicable requirements, while the hydraulic section analyzes the stability of the stream and considers the effect of proposed channel or land use changes. Site data collection includes survey data upstream and downstream of the bridge, estimation of roughness coefficients, subsurface borings or sampling to classify soil, and consideration of previous evaluations or historical information. The recommended procedure for determining the total scour depth at bridge foundations is as follows:

1. Estimate the long-term degradation in the channel considering the bridge service life.
2. Determine the combination of conditions and flood events that might result in the maximum scour depth, and establish water surface profiles both upstream and downstream.
3. Determine the magnitude of contraction and local scour at the bridge elements, and modify the design according to the evaluation results.

With the estimated total scour depth, bridge foundations may be designed. Spread footings on soil shall be located with their bottom below the estimated scour depth, whereas on rock they shall be designed to maintain the integrity of the supporting rock. However, deep foundation footings shall be located with their top below the estimated scour depth. Since foundations are designed to resist bridge scour, it often results in deep foundations. In addition, foundations under design should consider scour countermeasures. Nevertheless, the design of bridge foundations may be modified where necessary, including relocating or redesigning bridge elements to avoid areas of deep scour or overlapping local scour holes in the first place. Bridge designs for scour resistance may also add river training structures, such as guide banks or dikes to provide smoother flow transitions or to control channel lateral movement.

Further, the American Association of State Highway and Transportation Officials (AASHTO) design criteria addresses the problem of scour by requiring that the design of a bridge includes estimated scour depths at piers and abutments [3]. Also, federal regulations require that all existing bridges over water are evaluated for scour. Therefore, every bridge over water, whether existing or under design, must be assessed as to its vulnerability to scour.

100-Year Flood & Overtopping Flood Scenarios

Both the Federal Highway Administration (FHWA) Evaluating Scour at Bridges (HEC-18) [1] and the AASHTO LRFD Bridge Design Specifications [3], require scour at bridge foundations to be assessed for two conditions:

- Scour Design Flood
- Scour Check Flood

Likewise, both publications require that the flow discharge to be selected as the basis for the scour design flood shall be the more severe of the 100-year event or from an overtopping flood of lesser recurrence interval. For the scour check flood, the bridge stability shall be investigated for scour conditions resulting from a designated flood storm not exceeding the 500-year event or from an overtopping flood of lesser recurrence interval. An overtopping flood occurring at a bridge results in a submerged bridge superstructure that can produce significant blockage or pressure because the depth available to convey flow through the opening under the bridge is reduced. The scour depth under pressure flow conditions can be significantly greater than that of non-pressure flow conditions, hence overtopping floods of lesser recurrence intervals than the 100-year or 500-year events are often selected as the scour design flood or scour check flood, respectively.

FEDERAL REGULATIONS & REQUIREMENTS

The National Bridge Inspection Standards (NBIS) [4], requires each state to inspect all bridges located on public roads within the state's boundaries. The Puerto Rico Highway and Transportation Authority (PRHTA) is the state agency in charge of the compliance with the NBIS. FHWA employs the Metrics for the Oversight of the National Bridge Inspection Program [5] to determine the compliance with said regulations, one of which is Metric #18: Inspection Procedures – Scour Critical Bridges. This metric requires that all bridges over water have a documented evaluation of scour vulnerability and those bridges determined to be scour critical have a Plan of Action (POA) prepared to monitor the bridge accordingly. A bridge is considered scour critical if the abutment and/or pier foundations are coded unstable due to either observed scour or an assessed high potential for scour.

Bridge Inspection and Coding of Scour

Under the NBIS, a bridge is defined as a structure including supports erected over a depression or an obstruction, such as water, highway, or railway, and having a track or passageway for carrying traffic or other moving loads, and having an opening measured along the center of the roadway of more than 20 feet between under copings of abutments or spring lines of arches, or extreme ends of openings for multiple boxes; it may also include multiple pipes, where the clear distance between openings is less than half of the smaller contiguous opening [4].

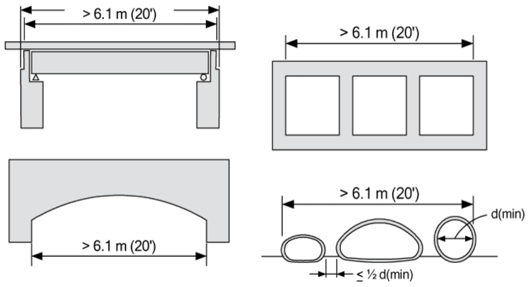

Figure 3
NBIS Bridge Configurations [4]

According to the AASHTO Manual for Bridge Evaluation (MBE) [6], the inspection of bridge substructures comprises the examination and recording of damage, deterioration, movement, and scour. The same also establishes the inspection procedures and policies for determining the condition of bridges. When assessing scour, the inspection findings and evaluated vulnerability are determined by the bridge rating and coding, as defined by FHWA's The Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges [7]. Codes are assigned to the bridge element and condition data. Among the items, the substructure is Item 60 and scour critical bridges is Item 113. Bridge scour focuses on these items because they describe the physical condition of piers, abutments, piles, and footings; and the current condition of the bridge regarding its vulnerability to scour, respectively. Item 113 consists of a rating factor scale from 9 to 0 besides the "tidal", "unknown foundation" and "not over waterway" ratings. As the ratings decrease, the scour condition worsens. 9 indicates the bridge foundations are well above flood elevations, 8 indicates foundations are stable, and 3 and below indicates the bridge is scour critical by either field review or calculated scour. Whenever a rating of 4 or below is assigned for this item, the rating for Item 60 should be revised to reflect the severity.

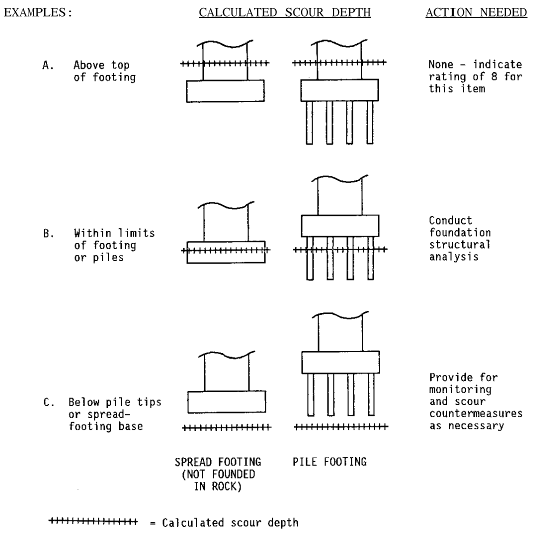

Figure 4
Item 113 – Scour Critical Bridges Rating [7]

Scour Evaluation of Bridges in Puerto Rico

As of 2018, the Puerto Rico National Bridge Inventory (NBI) comprises 2,306 bridges, with 1,602 of which, or approximately 70%, intersecting waterways, thereby requiring scour evaluation, in accordance with the NBIS. Bridge scour evaluation requirements are contained in the PRHTA Bridge Safety Inspection Manual [8]. The evaluation process is divided in the following four phases:

- Phase I – Data Collection and Qualitative Analysis
- Phase II – Hydrologic and Hydraulic Assessment for Scouring Analysis
- Phase III – Geotechnical and Structural Scour Assessment
- Phase IV – Plan of Action (POA)

During Phase I, the bridge is assessed for existing conditions, surroundings, topography, and cross sections. The evaluation could end if, for example, the bridge foundations are determined to be well above floodwater elevations and Item 113 is coded as 9. However, most bridges under study proceed to Phase II, where water surface elevations and scour depths are determined and, at which point, there typically is enough data to rate the stability of the bridge. If determined stable, the scour evaluation ends, or otherwise proceeds to Phase IV, where a POA is prepared. Phase III is only performed when after completion of Phase II, there is insufficient data to define the stability; for example, when the calculated scour depth is within the limits of the footings or piles and thus requires further geotechnical and structural analyses.

Scour Critical Bridges in Puerto Rico

As a result of the scour evaluations, a total of 495 were determined to be scour critical, therefore have a POA prepared to monitor known and potential deficiencies. Flood monitoring is a component of utmost importance, as federal regulation requires that all scour critical bridges are monitored according to the POA. Each bridge has assigned thresholds that could be either rainfall events, which are triggered by a minimum precipitation value forecasted at the watershed; or stage events, which are triggered by a referenced water surface elevation occurring at the bridge site.

A well implemented flood monitoring program requires real-time monitoring solutions during and after flood events, capable of constantly monitoring potential problem areas and providing alerts before scour becomes dangerous to determine which action should be undertaken. PRHTA will use a web-based system that allows to predict, identify, monitor, manage, record, and prepare for potentially scour causing events. The system will collect real-time data from weather-related sources such as the National Weather Service (NWS), National Oceanic and Atmospheric Administration (NOAA) and United States Geological Survey (USGS), among others; compare it against the POA thresholds and alert key personnel via electronic medium to enact monitoring upon trigger events being highly probable to be met, met or exceeded. The program will cost a significant amount of resources to the PRHTA, given each bridge requires individual monitoring and management, hence requiring system cost, inspection personnel and, in case of future outcome, installing measuring devices on bridges to record conditions during events and indicate an inspection when warranted.

EVALUATING SCOUR

The most common cause of bridge failures is from floods scouring bed material from around bed foundations [1]. Evaluating bridge scour is complex due to the nature of the acting variables. The need to minimize bridge scour has resulted in a number of publications seeking to provide guidance in the evaluation of scour, one of which is the FHWA Evaluating Scour at Bridges (HEC-18) [1], whose guidance on the development and implementation of procedures for evaluating bridge scour are in accordance with the requirements of NBIS. Scour evaluation procedures are in constant update, as research and technology advances, to include policy changes, countermeasure design considerations, alternative design approaches, and new guidance.

Scour Estimation Procedure and Equations

The scour estimation procedure requires prior determination of different parameters, which are computed or obtained in the field, including:

- Bridge Information: location, structure type, length, width, and foundation details.
- Waterway Characteristics: bed type, observed velocity and bank description.
- Hydrologic-Hydraulic Data: peak discharge, velocity, and Manning's roughness coefficient.
- Geotechnical Data: soil classification and bed material median size (D_{50}).

To calculate long-term degradation, changes in sediment load or removal of bed material shall be analyzed. As previously stated, scour depends of whether it is occurring at clear-water or live-bed condition. This is determined by calculating the critical velocity for beginning of motion (V_c for D_{50}) and comparing it with the flow average velocity (V) upstream of the bridge. If V_c is greater than V, then clear-water scour is occurring. If V_c is less than V, then live-bed scour is occurring. To calculate the critical velocity, the following equation is used:

$$V_c = K_u y^{1/6} D^{1/3} \qquad (1)$$

Where:
V_c = critical velocity, ft/s or m/s
K_u = 6.19 (SI units) or 11.17 (English)
y = upstream average depth, ft or m
D = bed material size (typical D_{50}), ft or m

In case of clear-water contraction scour, depth is calculated with the following set of equations:

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

$$y_s = y_2 - y_0$$

Where:
y_s = contraction scour depth, ft or m
y_2 = average equilibrium depth in the contracted section after scour, ft or m
Q = discharge through bridge, ft^3/s or m^3/s
D_m = smallest particle diameter (1.25 D_{50})
D_{50} = bed material median diameter, ft or m
W = contracted section bottom width, ft or m
K_u = 0.025 (SI units) or 0.0077 (English units)
y_0 = contracted section existing depth, ft or m

If live-bed contraction is occurring, scour depth is calculated with the following set of equations:

$$\frac{y_2}{y_1} = \left(\frac{Q_2}{Q_1}\right)^{6/7} \left(\frac{W_1}{W_2}\right)^{k_1} \qquad (3)$$

$$y_s = y_2 - y_0$$

Where:
y_s = contraction scour depth, ft or m
y_1 = upstream average depth, ft or m
y_2 = contracted section average depth, ft or m
y_0 = contracted section existing depth, ft or m
Q_1 = upstream channel flow, ft^3/s or m^3/s
Q_2 = contracted channel flow, ft^3/s or m^3/s
W_1 = upstream channel bottom width, ft or m
W_2 = contracted section bottom width, ft or m
k_1 = calculated exponent

However, if the evaluation determines scour is occurring under pressure flow conditions, then it becomes vertical contraction scour, and its depth is calculated with the following equation:

$$y_s = y_2 + t - h_b \qquad (4)$$

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

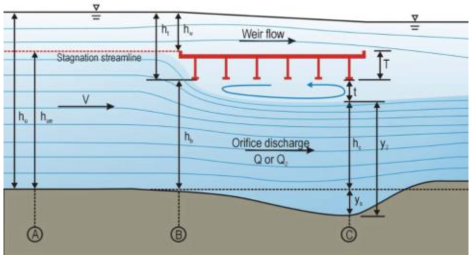

Figure 5
Vertical Contraction Scour [1]

Local scour is calculated independently for abutments and piers. For abutments, different equations are available to estimate the scour depth, one of which is the Froehlich Equation:

$$\frac{y_s}{y_a} = 2.27 K_1 K_2 \left(\frac{L^{'}}{y_a} \right)^{0.43} Fr^{0.61} + 1 \qquad (5)$$

Where:
y_s = local scour depth, ft or m
K_1 = abutment shape coefficient
K_2 = angle of embankment to flow coefficient
L’ = length obstructed by embankment, ft or m
y_a = average depth on floodplain (A_e/L), ft or m
A_e = approach section flow area obstructed by embankment, ft^2 or m^2
L = embankment length projected to flow, ft or m
Fr = Froude number upstream of abutment

Another equation for abutment scour is the NCHRP 24-20 Equation, which estimates total scour rather than only the local scour component, thereby already including contraction scour. Depth is calculated with the following set of equations:

$$y_{\max} = \alpha * y_c \qquad (6)$$

$$y_s = y_{\max} - y_0$$

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 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:

$$\frac{y_s}{y_1} = 2.0 K_1 K_2 K_3 \left(\frac{a}{y_1} \right)^{0.65} Fr_1^{0.43} \qquad (7)$$

Where:
y_s = local scour depth, ft or m
y_1 = flow depth upstream of pier, ft or m
K_1 = correction factor for pier nose shape
K_2 = correction factor for angle of attack
K_3 = correction factor for bed condition
a = pier width, ft or m
Fr_1 = Froude number upstream of pier

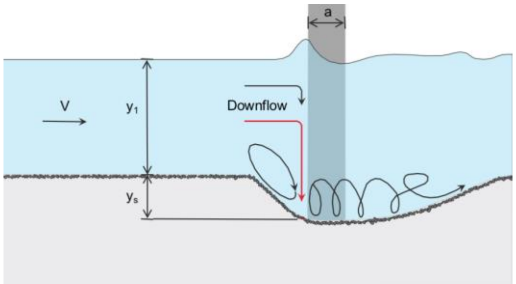

Figure 6
Local Scour at Pier [1]

HEC-18 [1] provides further guidance for the evaluation of pressure flow and local scour depths.

Possible Overestimation of Scour Results

Scientific literature has provided many empirical equations for estimating scour. However, all of the equations for estimating contraction and local scour are based on laboratory experiments with limited field verification [1]. Laboratory-derived equations are related to site-dependent parameters, being the experiments typically performed in straight, rectangular flumes while assuming steady flow and non-cohesive material. Some equations have velocity as a variable, while others are independent from velocity, thus leading to different scour depths for the same evaluation due to the variability of parameters involved. Therefore, equations should be carefully selected based on bridge and site characteristics. Nevertheless, the usage of conservative equations leads to an overestimation of the scour depths, and consequently higher design and construction costs, and in many cases, unnecessary deep foundations.

In recent years, research and technology advances in scour evaluation has provided alternative methods for estimating scour depths more accurately, being capable of modeling the complex scour processes occurring under different conditions. Data driven methods like Artificial Neural Networks (ANN) for instance, distribute computations to relatively simple processing units called neurons, grouped in layers and densely interconnected. The structure of an ANN consists of the input layer, the hidden layer, which computes the data; and the output layer, which produces the scour depth as the final output [2]. Data driven methods provide an alternative to the empirical methods, yet there is room for improvement, as large data sets are required for proper training and validation, and might be unsuccessful if exported outside the range of training and validation.

HURRICANE MARIA

On September 20, 2017, Hurricane Maria made landfall in Yabucoa, Puerto Rico with maximum sustained winds of 155 mph. The center of the storm moved all the way across mainland from the southeast to the northwest until offshore in the evening. Hurricane force winds were felt all over mainland, destroying many forests and structures. Maria was the first category 4 hurricane to strike Puerto Rico in more than 80 years, even considered as the worst storm in the last century.

Figure 7
Hurricane Maria Radar Image [9]

In a period of 24 hours, Hurricane Maria dropped over 10 inches of rain along its track, and even exceeded 20 inches in most of Puerto Rico, producing catastrophic flooding, thus suggesting 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. Additionally, the storm resulted in 26 bridge collapses and over 400 bridges with associated damages, such as scoured approaches and elements.

Hurricane Data & Records

NOAA uses data collection networks such as the NWS [9] and the National Hurricane Center [10], to monitor, observe, and subsequently research, systems occurring around the world. Hurricane Maria data, including time, description and trajectory was gathered from these networks. Furthermore, the USGS National Water Information System [11] provides real-time water conditions, including water levels, streamflow and precipitation, that are constantly being measured at USGS stations across the nation. Two of these stations, are USGS Station 50014800 Rio Camuy, which is located approximately 6 miles upstream the bridge under study; and USGS Station 50029000 Rio Grande de Arecibo, which is located approximately 9 miles east of the bridge. These stations were researched to gather the flow discharge and rainfall activity, respectively.

Table 1
USGS Stations 50014800 & 50029000 Data [11]

Parameter	Measurement
Rainfall	13.67 in
Flow Discharge	12,900 cfs

CASE STUDY: BRIDGE NO. 55

For the sake of comparing observed scour after Hurricane Maria versus scour evaluation results, Bridge No. 55 was selected given its location within the trajectory of the storm and the availability of measured data. Bridge No. 55 is a 19.30 meters long single-span structure located at State Road PR-4491 and crossing over the Camuy River in the municipality of Camuy, Puerto Rico.

Figure 8
Bridge No. 55 and Maria Trajectory Satellite Image [10]

Scour Evaluation of Bridge No. 55

Parameters for the scour evaluation were obtained either from computations, previous studies or site visit. Rainfall data was obtained from the NOAA Atlas 14 [12], flow discharge from and the Federal Emergency Management Agency (FEMA) Flood Insurance Study (FIS) [13], and the material median size (D_{50}) from a geotechnical report. The hydrologic-hydraulic modeling determined Bridge No. 55 was overtopped by the 100-year flood, hence the overtopping flood was computed and selected as the basis for the scour design flood, and the 100-year event as the scour check flood.

Table 2
Bridge No. 55 Scour Evaluation Parameters

Parameter	Value
100-year 24-hr Rainfall	9.96 in
100-year Flow Discharge	12,915 cfs
Overtopping Flow Discharge	5,699 cfs
Bed material Size (D_{50})	0.169 mm

Following the scour estimation procedure and equations, the calculated critical velocity, $V_{c,}$ was 0.46 m/s (1), which compared to the stream velocity of 3.28 m/s, indicates live-bed contraction scour is occurring ($V_c < V$). Given pressure flow conditions, (4) was employed to calculate a vertical contraction scour of 2.22 m for the design flood and 0.75 m for the check flood. Equation (6) was then used to estimate the total scour depth at the abutments, which resulted in 1.72 m for the design flood and 0.00 m for the check flood. Long-term degradation could not be estimated due to insufficient information available. Since the resulting pressure flow scour depth was greater than the calculated abutment scour, the total scour depth for Bridge No. 55 was determined to be 2.22 m.

Post-Maria Scour Inspection of Bridge No. 55

On October 4, 2017, Bridge No. 55 was inspected to assess any damage as a result of Hurricane Maria. During the inspection, moderate erosion at the river banks as well as light accumulation of debris was found at the bridge site. However, after inspecting for scour at abutments by means of wading, no scour was found. Further, the detected conditions were similar to those noted in the last bridge inspection report, thus the inspected scour Post-Maria was determined to be 0.00 m.

Figure 9
Bridge No. 55 Inspection Photo Post-Maria [14]

RESULTS AND DISCUSSIONS

In pursuit of analyzing the estimated scour against the inspected scour after Hurricane Maria, the evaluation results of Bridge No. 55 were compared to the inspection results and the measured water data.

Table 3
Bridge No. 55 Scour Evaluation and Inspection Results

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
Check Flood Scour Depth	0.75 m	N/A*

*Not available because of USGS data providing total discharge.

The results show 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. With respect to the flow discharges, the 100-year flood 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 0.75 m for the check flood were observed during the Post-Maria inspection, implying that the scour evaluation results were indeed overestimated compared to its observed scour after the strike of a 100-year storm event.

Moreover, the laboratory-derived equations that are considered conservative given the experiment conditions for which they are developed, are perhaps even more beyond the range of applicability for Puerto Rico. The topography and stream characteristics of Puerto Rico are significantly distinct from the conditions resembled in the laboratory, thereby possibly leading to farther overestimation of the scour depths. As of 2018, the PRHTA has a total of 495 scour critical bridges, and although not all of them may have reached the list by overestimation, there are without question some bridges that did, which could impact the Puerto Rico Bridge Program with more bridges to monitor and manage, ergo more cost and resources.

Furthermore, the inspections performed after Hurricane Maria have shown that most of the 26 bridges that collapsed during the storm may have been a consequence of floating debris being transported by the rivers and accumulating around the bridge elements, partially or totally blocking the opening. Large amounts of accumulated debris can generate significant lateral and vertical forces capable of pushing and carrying the structure away. Debris accumulation is more common in unstable streams with modest slopes, characteristics more comparable to the streams of Puerto Rico.

Figure 10
Debris Accumulation on Bridge after Hurricane Maria [14]

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