Adequate Selection of Design Flood Frequencies for the Evaluation of Scour and Scour Countermeasures of Critical Bridges, and their Impact on the Puerto Rico Highway and Transportation Authority's Bridge Program

Carlos G. Torres Ruiz
Master of Engineering in Civil Engineering
Advisor: Christian Villalta Calderón, Ph.D.
Civil and Environmental Engineering and Surveying Department
Polytechnic University of Puerto Rico

Abstract *–Federal regulations require all bridges, over waterways, to be designed for scour resistance and all existing bridges to be evaluated for scour vulnerability. Scour evaluations are typically based on the hydraulic design flood frequency of a 100-year flood event. Existing bridges determined to be unstable due to observed scour or assessed high potential for scour are deemed scour critical. When designing a new bridge or evaluating a scour critical bridge to determine the total scour depth, the selection of a hydraulic design flood frequency is one of the most important parameters. Various equations to evaluate scour are available, however many of them are considered conservative and leading to overestimation of the scour total depth. This overestimation could have an impact on the Puerto Rico Bridge Program, which has almost 500 scour critical bridges, all requiring flood monitoring and, consequently, greater resources.*

Key Terms *– Bridge Scour, Hydraulic Design Flood Frequency, Scour Total depth, 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 scours are 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].

The adequate selection of the hydraulic design flood frequencies and the engineering judgment when selecting parameters and scour equations are of the upmost importance when determining the scour total depth.

This article intends to evaluate the hydraulic design floods selection and the impact scour total depth has on the Puerto Rico Bridge Program.

OBJECTIVE

The main objective of this article is to create awareness on the adequate selection of design flood frequencies for the analysis of scour and scour countermeasures of scour critical bridges. Furthermore, this article seeks to invite the professional community to understand how its selection impacts 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 on 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 consists 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, refer to Figure 1. The process continues to lower the bed elevation until the velocity and shear stress decrease accordingly and relative equilibrium is reached.

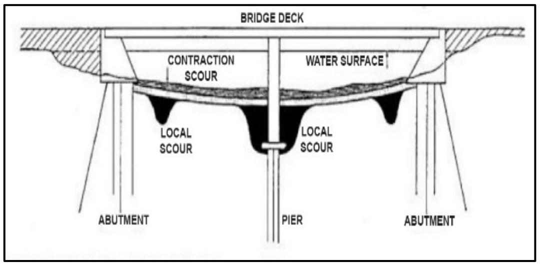

Figure 1
Bridge Elements with Components of Scour

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 shown in Figure 1. 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. Figure 2 [1] illustrates scour vortices that 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.

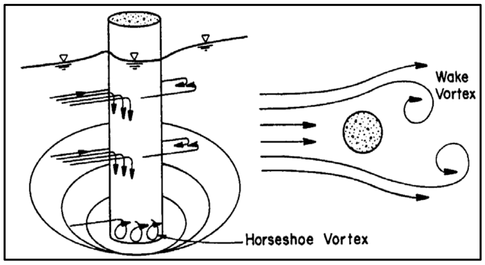

Figure 2
Horseshoe and Wake Vortices of Local Scour

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.

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 on 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:

$$V_c = K_u y^{1/6} D^{1/3} \tag{1}$$

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:

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

$$y_s = y_2 - y_0$$

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:

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

$$y_s = y_2 - y_0$$

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, as depicted in Figure 3, then it becomes vertical contraction scour, and its depth is calculated with the following equation [1]:

$$y_s = y_2 + t - h_b \tag{4}$$

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 bridge opening before scour, ft or m

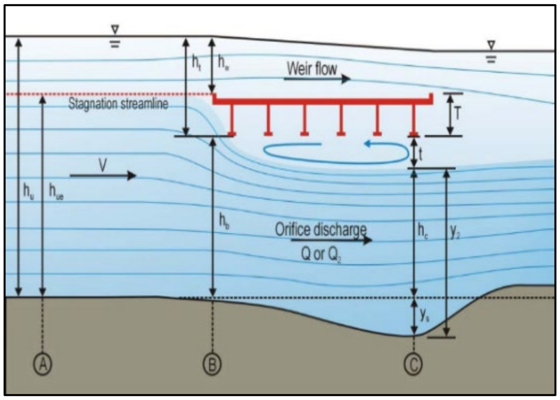

Figure 3
Vertical Contraction Scour

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:

$$\frac{y_s}{y_a} = 2.27K_1K_2\left(\frac{L'}{y_a}\right)^{0.43} Fr^{0.61} + 1 \qquad (5)$$

where:

y_s = local scour depth, ft or m

K_1 = abutment shape coefficient

K_2 = angle of embankment to flow coefficient

L' = length of active flow 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 = length of embankment projected normal 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:

$$yc_{max} \qquad (6)$$

$$y_s = y0_{max}$$

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, refer to Figure 4, the local scour depth is calculated with the following equation [1]:

$$\frac{y_s}{y_1} = 2.0K_1K_2K_3\left(\frac{a}{y_1}\right)^{0.65} Fr_1^{0.43} \qquad (7)$$

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

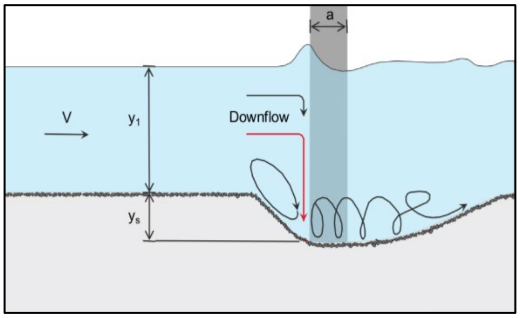

Figure 4
Local Scour at Pier

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.

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 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 [5]. 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 as presented in Figure 5. [4].

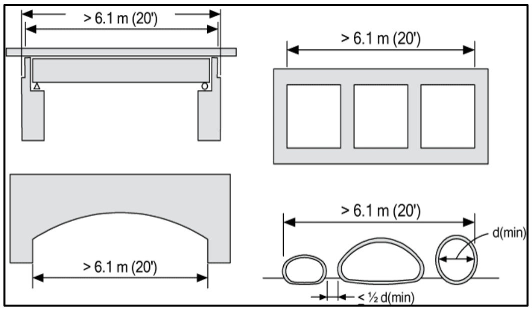

Figure 5
NBIS Bridge Configurations

According to the AASHTO Manual for Bridge Evaluation (MBE), the inspection of bridge substructures comprises the examination and recording of damage, deterioration, movement, and scour [6]. 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 refer to Figure 6 [7]. A 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.

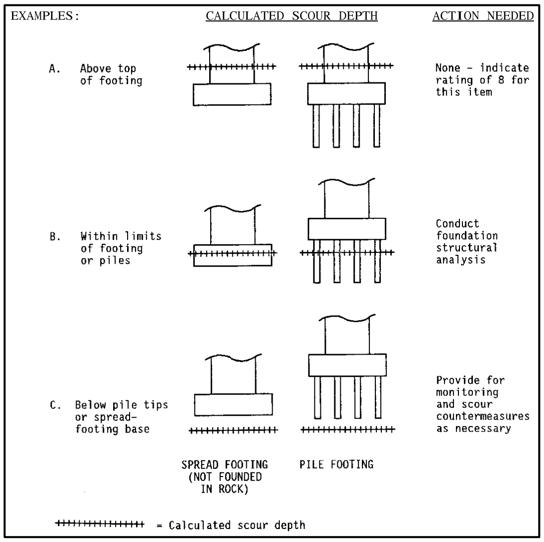

Figure 6
Item 113 – Scour Critical Bridges Rating

Bridge Design for Scour Resistance

In 2010, the U.S. Congress recommended that FHWA apply risk-based and data-driven approaches to its bridge program goals, which include the Scour Program. Risk-based approaches factor in the importance of the structure and are defined by the need to provide safe and reliable waterway crossings and consider the economic consequences of failure. Bridge foundations should be designed to withstand the effects of scour caused by hydraulic conditions from floods larger than the design flood. It is almost always cost-effective to provide a foundation that will not fail, even from very large events. However, it may not be necessary or cost effective to design the bridge foundation to withstand the effects of extraordinarily large floods, if it has lower economic consequences of failure. Based on hydraulic design flood frequencies, Table 1 shows recommended minimum scour design flood frequencies and scour design check flood frequencies for new bridges [1]. The Hydraulic Design Flood Frequencies (Q_D) outlined in Table 1 assume a level of risk that is assumed to be acceptable at a bridge as defined by an agency's standards and the frequency of the floods they are designed to accommodate.

Table 1
Hydraulic Design, Scour Design, and Scour Design Check Flood Frequencies

Hydraulic Design Flood Frequency, Q_D	Scour Design Flood Frequency, Q_S	Scour Check Design Flood Frequency, Q_C
Q_{10}	Q_{25}	Q_{50}
Q_{25}	Q_{50}	Q_{100}
Q_{50}	Q_{100}	Q_{200}
Q_{100}	Q_{200}	Q_{500}

The Scour Design Flood Frequencies (Q_S) presented in Table 1 are larger than Q_D because there is a reasonably high likelihood that Q_D will be exceeded during the service life of the bridge. A bridge must be designed to a higher level for scour than for the hydraulic design because if Q_D is exceeded then a greater amount of scour will occur which could lead to bridge failure. The Scour Design Check Flood Frequencies (Q_C) are larger than Q_S using the same logic and for the same reasons as outlined previously.

Likewise, for scour critical bridges the risk-based approach is used when designing scour countermeasures to protect their foundations. Table 2 recommends minimum scour countermeasure design flood frequencies based on hydraulic design and scour design flood frequencies.

Scour Countermeasure Design Flood Frequencies used for the design of bridge scour countermeasures recognizes that countermeasure designs must be stable at floods larger than those associated with the Scour Design Flood Frequency.

Table 2
Hydraulic Design, Scour Design, and Scour Countermeasure Design Flood Frequencies

Hydraulic Design Flood Frequency, Q_D	Scour Design Flood Frequency, Q_S	Scour Countermeasure Design Flood Frequency, Q_{CM}
Q_{10}	Q_{25}	Q_{50}
Q_{25}	Q_{50}	Q_{100}
Q_{50}	Q_{100}	Q_{200}
Q_{100}	Q_{200}	Q_{500}

For both, new and scour critical bridges, if there is a flood event greater than the Hydraulic Design Flood but less than the Scour Design Flood that causes greater stresses on the bridge, e.g., overtopping flood, it should be used as the Scour Design Flood and there would not be a Scour Design Check Flood. Similarly, if there is a flood event greater than the Scour Design Flood but less than the Scour Design Check Flood, for new bridges; or greater than Scour Countermeasure Design Flood, for scour critical bridges; then the latter design floods should be used for new and existing bridges, respectively. Balancing the risk of failure from hydraulic and scour events against providing safe, reliable, and economic waterway crossings requires careful evaluation of the hydraulic, structural, and geotechnical aspects of bridge foundation design.

Experience has shown that the overtopping discharge often puts the most stress on a bridge. However, special conditions (angle of attack, submerged-flow, decrease in velocity or discharge resulting from high flows overtopping approaches or going through relief bridges), may cause a more severe condition for scour with a flow smaller than the overtopping or design flood.

Data-driven approaches, 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 for determining total scour depth in new and scour critical bridges.

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. The recommended procedure for determining the total scour depth at bridge foundations is as follows:

- Estimate the long-term degradation in the channel considering the bridge service life.
- 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.
- 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.

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.

DISCUSSION AND RECOMMENDATIONS

When designing a new bridge or evaluating a scour critical bridge to determine the total scour depth, the selection of a hydraulic design flood frequency is one of the most important parameters.

The hydraulic design flood frequency has a direct impact in the scour total depth determination because many of the scour equations rely on the magnitude of discharges generated by the flood frequencies presented in Table 1 and Table 2 [1], including overtopping. With these discharges and the use of one-dimensional or two- dimensional computer model, the water-surface profiles and many of the input variables such as the discharge, velocity and depth needed for the scour calculations can be determined.

For new bridges, typically the owner of the bridge (normally PRHTA) will establish the hydraulic design flood frequency that will dictate the design and the evaluation process for which the scour total depth will be determined. Scour evaluations are typically based on a hydraulic design flood frequency of a 100-year event. That is the easy part because the hydraulic design flood frequency is a given and the bridge is new, then it can be designed and re-designed to comply with the standards and requirements established by the owner.

For scour critical bridges, PRHTA does not have a clear interpretation on the selection of the hydraulic design flood frequency for scour evaluation and countermeasure design as stated in Table 2. The common practice by designers is to select a hydraulic design flood frequency of a 100-year event and to use engineering judgement. With this approach, design professionals tended to be on the conservative side and without considering risk-based evaluation which can result in the overestimation of the scour total depth.

There are almost 500 scour critical bridges in the Puerto Rico National Bridge Inventory. Many of them exceed their design service-life. Moreover, considering the climate-change and the increase in precipitation values after Hurricane María, their hydraulic design flood frequencies are probably exceeded too. Today’s hydraulic design flood frequencies are higher than in the past. Hence, when evaluating a scour critical bridge and taking advantage of the computer models, the actual hydraulic design flood frequency for the bridge can be determined by reducing the discharges to determine the flood event that can be accommodated through the bridge prior to overtopping. By using this approach, a hydraulic design flood frequency can be assigned and recommended frequencies on Table 2 be used for scour evaluation and countermeasure design.

The adequate selection of the hydraulic design flood frequencies and the engineering judgment when selecting parameters and scour equations are of the upmost importance when determining the scour total depth.

The PRHTA has limited resources and a great quantity of bridges, and more to come. An overestimation of scour total depth may result in expensive and unnecessary countermeasures to protect the bridge foundations.

To maximize the use of resources, it is recommended that PRHTA:

- Establish and implement a Risk-Based approach for the design of new bridges.
- Establish and implement a Risk-Based approach for the design of countermeasures for scour critical bridges.
- Establish, implement, and maintain a Web-Based GIS with the available data of all bridges to monitor, manage and record the design and scour evaluation parameters used. In addition, it could help in creating evacuation and access routes in case a bridge fails or collapses.

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