Assessment of Geomorphic Characteristics and Analysis at the Existing Bridge Site in Puerto Rico

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Abstract *– The scour on bridges is considered one of the main reasons for bridge failures. Scour is the consequence of the erosion action that is caused by the water flow, which at the same time excavates and carries away material from the bed and banks of streams particularly on the piers and abutments of the bridges. There are three scour components that are added to obtain the total scour at a pier of the abutment, which are classified by long-term degradation of the river bed, contraction scours at the bridge, and local scour at the piers or abutments. 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 of flood events. Bridges are determined to be unstable due to observed scour or lateral movement of the river. Various equations to evaluate scour are available, however many of them are considered conservative and lead to overestimation of the scour depths. Due to a possible overestimation, it is wise to consider an extremely important geomorphologic analysis of the river during the pre-construction analysis which can give a better understanding of how the river will act because most of the streams that highways or street cross are alluvial. Hurricane Maria hit Puerto Rico and led to a catastrophic flooding event to the magnitude of a 100-year recurrence flood and higher. During the hurricane, the natural conditions for which the bridges were designed were put to task. It is important to consider that the bridges analyzed in this geomorphic analysis were all affected by scours. An analysis of evaluated bridges against observed scour within Maria's track was inspected and compared as a case study to auscultate any direct relation to the scour on the evaluation results. After the geomorphic analysis, the outcome showed that 88% of the bridges were meandering, and sinuous, and only 46% were classified as fair due to the river stability rating analysis which led to a 42% poor classification, and only 12% as good classification on the geomorphologic analysis. The results of this study could give an impact on the Puerto Rico Bridge Program to take into consideration when planning a road that it is crossing an alluvial stream to consider a geomorphic analysis prior to the design to prevent possible scour occurring on the bridge, which shows that in Puerto Rico there are 495 scour critical bridges, all requiring flood monitoring and, consequently, greater resources.*

Key Terms *– Bridge Scour, Geomorphologic Analysis, Stability Rating Analysis.*

INTRODUCTION

Geomorphology is the study of landforms and the processes responsible for making and modifying the land throughout time [1]. Fluvial geomorphology is the study of landforms whose origin and development are affected by the flowing water [1]. Most streams that highways cross or encroach upon are alluvial; that is, the streams are formed in materials that have been and can be transported by the stream [2]. In alluvial stream systems, is it the rule rather than the exception that banks will erode; sediments will be deposited; and floodplains, islands, and side channels will undergo modification with time [2]? Alluvial channels continually change position and shape because of hydraulic forces exerted on the bed banks [2]. A study of the plan and profile of a stream is very useful in understanding stream morphology [2]. Plan view appearances of streams are varied and result from many interacting variables. Small changes in a variable can change the plan view and profile of a stream, adversely affecting a highway crossing or encroachment. [2]. Federal regulations require that all bridges over water have a documented evaluation of scour vulnerability and that bridges determined to scour critically have a Plan of Action prepared to monitor them.

Nearly six years ago on September 20, 2017, a hurricane called Maria reached Puerto Rico Island. While landfall in Puerto Rico, during the hours moving across the island with widespread hurricane-force winds, challenging rainstorms that spread all over, and extremely heavy rainfall that produced major to catastrophic flooding, concentrating on the northern part of Puerto Rico. The devastation propagated on the island by Hurricane Maria was unusual when compared to previous hurricanes many sources consider it as the worst storm to hit Puerto Rico in the last century. The magnitude of rain left by the storm was appreciably in the range of a 100-year recurrence event, challenging the design flood conditions used for a bridge to scour evaluations in Puerto Rico.

An assessment of geomorphic conditions and stability rating was conducted to analyze if the locations of those bridges that resulted in a bridge scour had any relation with location, sinuosity, braided streams, incipient movement, and upstream distance among other parameters of the evaluation.

OBJECTIVE

The objective of this article is to determine whether the location, type of stream, sinuosity, and stability indicators among other parameters of the evaluation could possibly increase the possibility of bridge scour because of lateral movement of instability of the river stream. Furthermore, this article seeks to weigh the importance of a geomorphology assessment based on stability rating when a new bridge is proposed to construct and to take into consideration that a not accurate location on the river site could impact the bridge scour possibility in the future weather extreme events occur or not.

BRIDGE SCOUR

Bridge scour is the eventual removal of sediment as sand and gravel because of the erosive action of flowing from bridge abutments or piers [3]. One of the main causes of bridge failures in the United States is scour, and about 60% of the failures are related to water, which excavates and carries as a common cause [4]. Scour is the result of the erosive action of flowing water, that excavates and carries the material away from the bed and banks of streams [4]. Major floods tend to scour a lot of the material at a bridge crossing during the rising limb of the flood event and redeposit the material at the scour holes during the recession [5]. Generally, loose granular soils are eroded rapidly, as cohesive soils are more scour-resistant to flowing water during the events.

Geomorphologic Analysis

Geomorphologic analysis studies the plan and profile of a stream because it is very useful to understand the stream morphology of the river. A lot of small changes in a variable can change the plan view and profile of a stream [2]. Geomorphologists have been historically very concerned with the documentation and explanation of the changing morphology of the landscape through time [2]. Landform evolution serves as an extremely important indicator to illustrate that change can be very rapid to cause problems [2]. Some landform evolution changes could showcase incised channels where a rapid incision is followed by the channel adjustment showing deepening and widening on the main channel to develop a new condition of relative stability as erosion decreases, sediment storage increases and floodplains grows [2].

Geomorphic Factors Affecting Stream Stability

The geomorphic properties that are evaluated could be used as the basis of a valid stream characterization at a bridge site [6]. The approach presented on this subject is based on stream river properties that are observed on aerial photographs and site visits. Its major purpose is to make available the assessment of streams for engineering purposes, particularly emphasizing the lateral stability of a stream [6].

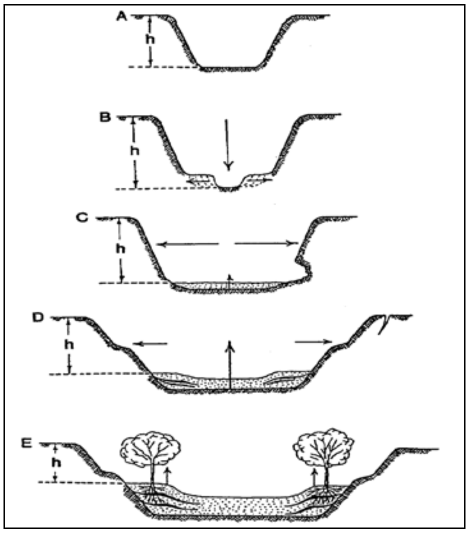

Figure 1
Evolution of Incised Channel from the Initial Incision (A, B) and Widening (C, D) to Aggradation (D, E)

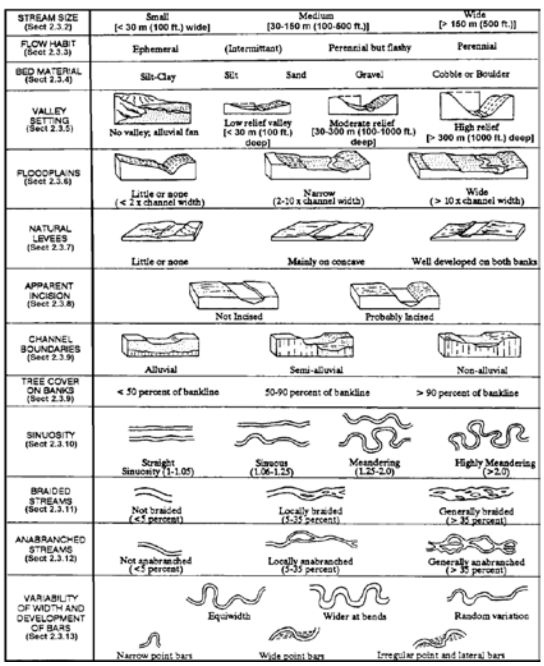

Figure 2
Geomorphic Factors that Affect Stream Stability

Each one of the properties presented in Figure 2 serves as an item of stream evaluation to determine the lateral stability of a stream which serves as a parameter to determine possible mitigation assessments in the future.

Figure 3
Active Bank Erosion Illustrated by Vertical Cut Banks

The following properties briefly explain the parameters evaluated on stream stability:

1. Stream Size: The size of a stream can be indicated by discharge, drainage area, or a measure of channel dimensions such as width or cross-sectional area.
2. Flow Habit: The flow habit of a stream may be ephemeral, perennial but flashy, or perennial. Ephemeral stream flows briefly in direct response to precipitation. Perennial flows all or most of the year. Perennial but flashy responds to precipitation by rapid changes in stage and discharge. Perennial streams may be relatively stable or unstable.
3. Valley Setting: Valley relief is used as a means of indicating the surrounding terrain is generally flat, hilly, or mountainous on the river stream. The valley is measured usually on a topographic map from the bottom to the top of the highest adjacent.
4. Floodplains: The nearly flat alluvial lowlands bordering a stream that is subject to inundation by floods. It is also defined by geomorphologists as a surface presently of about 1.5 years.
5. Natural Levees: Streams with well-developed natural levees tend to have a constant width and usually have low rates of lateral migration.

6. Apparent Incision: It is determined from the height of the channel banks at the normal stage relative to its width.
7. Channel Boundaries and Vegetation: This property classifies streams for alluvial, semi-alluvial, or non-alluvial. It is related to the erosional resistance of the earth's material in channel boundaries.
8. Sinuosity: This is the ratio of the length of a stream measured along its centerline, to the length measured along the valley centerline or along a straight line connecting the ends of the reach.
9. Braided Streams: Braided stream is one that consists of a variety of multiple interlacing channels.
10. Anabranched Streams: The flow is divided by small islands on the mainstream rather than long bars.
11. Variability of Width and Development of Bars: The variability of unvegetated channel width is a very useful indication of the lateral stability of a channel. The relationship between width variability and lateral stability is based on the rate of development of local bars and alternate bars on the stream.

Initiation of Motion

On the bed stream the motion of a fluid following across its bed tends to move the material at the bottom of the riverbed [7]. In some critical conditions, the hydraulic forces are so small that a particle will move very rarely of not [7]. A slight increase in the velocity above this critical condition will initiate the motion of some of the particles on the bed [7]. In a cohesionless bed, the sediment movement is first initiated by a single particle which moves or jumps a very short distance before finally stopping [7]. *In 1936 Shields defined the critical condition of incipient motion as the point of zero transport* [8]. This method for estimating the threshold or the critical condition for the movement of cohesionless sediment is by utilizing the linear relationship between critical bed shear stress and grain size Julien (1995) [8]. The Shields diagram is widely used to determine the condition of incipient motion based on bed shear stress [8]. Shields determined that the critical condition could be related to two dimensionless parameters that reflect the ratio of the force producing the motion of sediment to the force resisting motion [8].

The following Equation 1 is used to determine the shields parameter.

$$F* = \frac{\tau_0 d^2}{(\gamma_s - \gamma) d^3} = \frac{\tau_0}{(\gamma_s - \gamma) d} \quad (1)$$

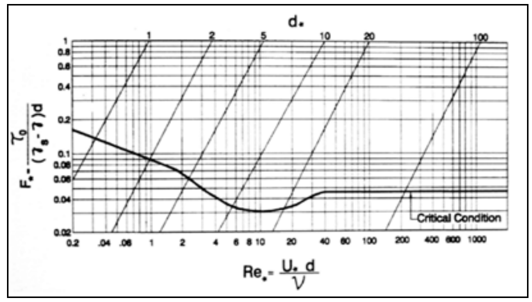

Figure 4
Shields Diagram for Incipient Sediment Motion

By an evaluation of Shields's theory, it is possible to estimate the sediment that can be carried throughout the stream. The result of incipient movement is the beginning of an eventual lateral movement which in fact can result in a bridge scour.

Stability Indicators

The indicators identified for the study are complemented by 13 parameters which give an indication of obtaining a poor, fair, good, or excellent river stream based on the descriptors listed [9]. After a rating for each indicator is assigned an overall score is computed by adding the 13 ratings [9]. The total score obtained provides the overall relative stability of the river.

Table 5.6. Overall Scores for Three Classifications of Channels.

Category	Score, R		
	Pool-Riffle, Plane-Bed, Dune-Ripple, and Engineered Channels	Cascade and Step-Pool Channels	Braided Channels
Excellent	$R < 49$	$R < 41$	N/A
Good	$49 \le R < 85$	$41 \le R < 70$	$R < 94$
Fair	$85 \le R < 120$	$70 \le R < 98$	$94 \le R < 129$
Poor	$120 \le R$	$98 \le R$	$129 \le R$

Figure 5
Classification of Channels Scores

Lateral and Vertical Stability

The indicators that are used to calculate the rating can be divided into two types which are vertical stability and lateral stability. Indicators 4-6 are used to determine the vertical stability of the river, while indicators 8-13 determine lateral stability [9]. The lateral and vertical stability scores were normalized by the total number of points possible on each one of the categories so the results can be represented as a fraction [9]. By comparing the lateral fraction with the vertical fraction whichever is bigger it allows the geomorphologist to determine in which direction the channel instability is moving.

Figure 6
Google Earth Image 2006 Lateral Movement

Figure 7
Google Earth Image 2009 Lateral Movement

Figures 6 & 7, which were obtained by satellite image google earth, illustrate, and bridge with a three-year difference, and it is possible to observe that lateral movement occurred during that time. Observing the image, a lateral movement on the river was shown which indicates that a possibility of lateral instability occurred at that time.

Stability Indicators

The stability indicators, descriptions, and ratings that were used to determine the stability of a channel are briefly described as shown. The classification determining the stability indicator gives a score on each category that is labeled as excellent (1-3), good (4-6), fair (7-9), and poor (10-12). After the evaluation of the 13 parameters, a score is determined, and a classification is assigned.

Figure 8
Poor Rating Classification Channel [9]

Figure 9
Fair Rating Classification Channel [9]

Figure 10
Good Rating Classification Channel [9]

The stability indicators used to determine the score on the study are mentioned to give a better understanding of the scoring process:

1. Watershed and floodplain activity and characteristics.
2. Flow habit
3. Channel pattern
4. Entrenchment/channel confinement
5. Bed material
6. Bar development (slope, width-to-depth ratio)
7. Obstructions, including bedrock outcrops, armor layer, large woody debris, jams, grade control, bridge bed paving, revetments, dikes or vanes, and riprap.
8. Bank soil texture and coherence
9. Average bank slope angle
10. Vegetative or engineered bank protection
11. Bank Cutting
12. Mass wasting or bank failure
13. Upstream distance to bridge from the meander impact point and alignment.

CASE STUDY OF 26 BRIDGES

A geomorphologic study was conducted for 26 bridges that were previously selected that were affected by scour. The geomorphologic study performed evaluated the bridges considering 11 factors of stream stability that were used as a starting point for the analysis. All the bridges were selected because, for the purpose of the analysis, it is important to consider all possibilities on the evaluation as location, meandering of the river, sinuosity, type of material on the riverbed, and slope among other important factors.

Figure 11
Bridges Location in Puerto Rico

Geomorphologic Analysis

The geomorphologic analysis performed at the 26 bridges that relate to the river stream revealed that out of the 26 bridges evaluated only 4 were classified as straight when sinuosity was calculated. It is precisely important to mention that straight river streams in the study were the least influenced by lateral movement or vertical movement.

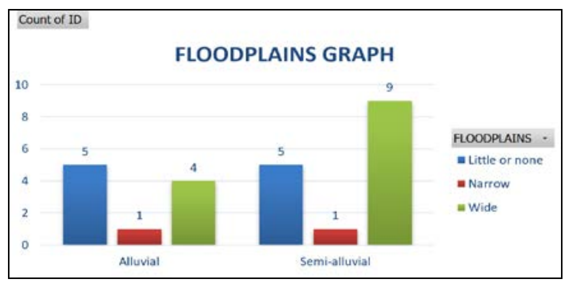

Figure 12
Classification of Floodplains Graph

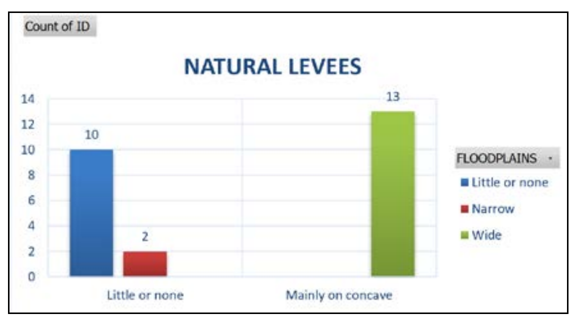

Figure 13
Natural Levees

The highlands of an area are worn down, the stream erodes their banks over time, and the material eroded is utilized father downstream to build banks and bars [10]. In figure 12 it shows a total of 13 rivers are wide which relates to a high meandering on the river section that leads to lateral movement.

Streams classified with well-developed natural levees tend to have a constant width and low rates of lateral migration. As observed in Figure 13 since there is mainly concave and little concave it is a high possibility of lateral movement.

Figure 14
Apparent Incision

On the apparent incision of a stream, it's classified from the height of its bank. The high on the banks indicates incision which means the river is eroding which can result in an event scour if the eroded material is not re-deposited at the same rate that is eroding. By observing the results obtained on the bridges it is possible that most of the bridges are eroding due to incipient movement of the particle as stated by Shields.

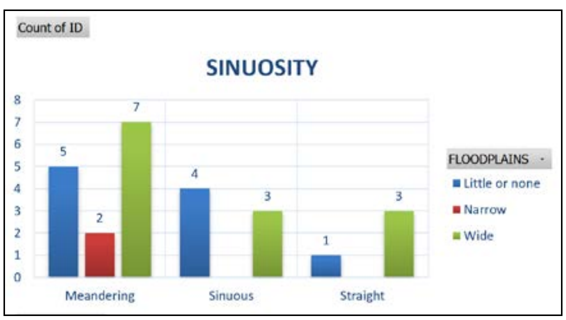

Figure 15
Sinuosity of Stream

Sinuosity is the ratio of the length of a stream reach measured along the centerline to the length that is measured along the valley [10]. On the bridges evaluated only 4 out of the 26 were straight. It is possible to conclude meandering and sinuous streams are more likely to show lateral movement over time due to the geomorphology of the river. Straight streams usually have a small sinuosity at the bank full stage [10]. Meandering streams transversely oscillate and initiate the formation of bends in a straight stream [10]. On this type of stream alternate bars and the thalweg are continually changing causing sinuosity. Coriolis force due to Earth's rotational movement has been cited as a cause for the meandering of streams [10].

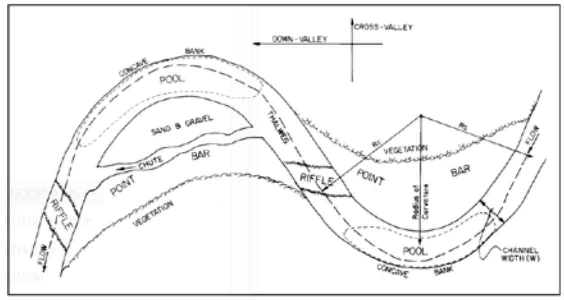

Figure 16
Plan View of a Meandering Stream [10]

The angle of deflection of the current is affected by the curvature formed in the eroding bank and the lateral depth of erosion. Figure 16 shows bars, pools, and crossings typical of a meandering stream channel [10].

Stability Rating Analysis

The stability rating uses 13 indicators that were put to task to evaluate the bridges. The indicators are evaluated and divided into lateral stability and vertical stability to provide the overall relative stability of the channel.

Table 1
Channel Stream Category in Bridges

Parameter	Num. of Stream
Poor	11
Fair	12
Good	3
Excellent	0

The channel stream category on the stability rating analysis shows the category in which every stream channel was classified after the evaluation. Out of the 26 stream channels evaluated only 3 were classified as good as stated on the HEC-20 guide for the U.S. Department of Transportation.

Table 2
Upstream Distance to Bridge from Meander Category

Parameter	Num. of Stream
Poor	4
Fair	3
Good	6
Excellent	13

The upstream distance to the bridge from the meander is a very sensitive category in the rating stability analysis because it brings very precise information about the bridge location related to the distance from the meander. Based on the study only 3 bridges were located at 115ft or more from the meander.

Table 3
Channel Instability Result

Parameter	Num. of Stream
Lateral	12
Vertical	14

The indicators shown in Table 3, are the results that indicate vertical instability or lateral instability. Each of the lateral and vertical indicators was normalized by the total number of possible points on each parameter [10]. The results obtained were represented as a fraction and compared to find the lateral or vertical instability classification on the channel.

Federal Regulations & Requirements

The National Bridge Inspection Standards (NBIS) [11], requires bridge owners in each state to keep and maintain an inspection bridge program which includes procedures for underwater inspection [11]. To inspect the 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 enforcing the procedures with the NBIS.

Results and Discussions

In the process of studying and investigating the geomorphologic behavior of the 26 bridge stream channels, all of them had either lateral movement or vertical movement. On the geomorphologic analysis when normalizing the rating stability analysis on the specific parameters the result of the evaluation difference calculated on the fraction was distant on every stream channel, none of the stream channels were neutral. Neutral is the term in which the difference in the fractions is so small that it is not possible to conclude vertical or lateral movement has occurred.

Table 4
Stability Ratings and Results on Geomorphological Analysis

Stream	Total Score Results	Rating
1	70	Fair
2	90	Fair
3	80	Fair
4	103	Poor
5	64	Good
6	96	Fair
7	71	Fair
8	110	Poor
9	85	Fair
10	119	Poor
11	131	Poor
12	103	Poor
13	75	Fair
14	67	Good
15	56	Good
16	77	Fair
17	78	Fair
18	75	Fair
19	108	Poor
20	103	Poor
21	94	Fair
22	101	Poor
23	89	Fair
24	118	Poor
25	98	Poor
26	113	Poor

The results shown in Table 4 give a view of only 12% of the stream channels being classified with a good rating, 46% of the stream channels classified as fair, and 42% of the stream channels classified as poor. Only 12% of the streams that were studied had a good classification and none of them had an excellent classification. The overall result is shown in Table 3 which gives the exact quantity of streams classified with lateral or vertical movement as method states on HEC-20 of the U. S. Department of Transportation Stream Stability at Highway Structures.

On the lateral and vertical movement analysis, 46% of the stream channels obtained a lateral movement score, and 54% of the stream channels obtained a vertical movement score. At the end of this classification parameter, none of the streams were neutral which provides a stable result analysis when it comes to lateral or vertical classification which results in a small difference when the normalized scores are evaluated to conclude lateral or vertical movement.

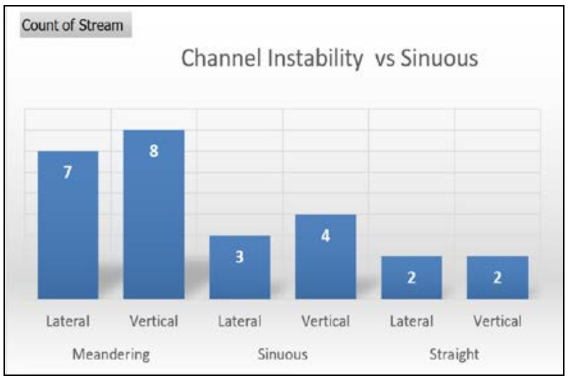

Figure 17
Channel Instability vs. Sinuous Result

In Figure 17, it is possible to identify that 15 of the stream channels analyzed were classified as meandering, and it is adequate to see that a lower number of streams were identified under the straight classification parameter.

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