Scour Evaluation of Bridge 2487 in Cayey, Puerto Rico

Alberto L Matta
Civil Engineering
Christian Villalta, Ph.D.
Civil and Environmental Engineering Department
Polytechnic University of Puerto Rico

Abstract — *Scour at bridges should be monitored constantly using proper procedures in order to secure the safety of the public. According to The US Department of Transportation the most common cause of bridge failures is from floods scouring bed material from around bridge foundations. Bridge 2487 in Cayey, PR was analyzed in order to understand better how scour affects a bridge. Laboratory tests were conducted on bulk samples collected at the bridges general areas and later classified. This and other information gathered along the bridge was used to conduct a hydraulic and scour model to find out the potential for scouring along the bridge. A potential scour depth of 2.91 meters was calculated using the HEC-RAS (Hydrologic Engineering Center-River Analysis System) computer program. With this information proper countermeasures were elected in order to prevent further scouring along the studied area.*

Key Terms — *Bulk Samples, Countermeasures, HEC-RAS, Scour.*

INTRODUCTION

Severe scour occurs along bridges every year all around Puerto Rico. Scour can be defines as erosion caused by the force of water that removes soil from river vicinities. The severity of the scour depends on factors like water velocity, composition of the soil (its gradation) and presence of bedrock among other things. All engineers, particularly Geotechnical Engineers, should familiarized with the phenomenon of erosion and scouring, especially if one lives on a tropical island which has heavy periods of rain. All bridges that overlay a river in Puerto Rico can be considered susceptible to sour. If this phenomenon is no monitored correctly, the safety of conductors that use these bridges every day can be put at jeopardy. According to The US Department of Transportation the most common cause of bridge failures is from floods scouring bed material around bridge foundations [1]. This is why all bridges should be continuously monitored and equipped with countermeasures that would stop or reduce the effect of scour at bridges abutments.

The projects objective is to familiarized with the appropriate procedures used to monitor the conditions of the bridge abutments and piers, which are the elements of a bridge that are more susceptible to scour. After concluding the project, one would expect to gain a better comprehension of what is scour and what can a engineer do to prevent or reduce the effects of this phenomenon. One will gain experience using hydraulic models and computer programs that will help with the calculation of scour at a bridge.

This paper will focuses on a study and analysis of bridge 2487 located in Cayey, Puerto Rico. Scour susceptibility will be calculated for this bridge and recommendation will be given after carefully analyzing all results.

GENERAL INFORMATION

In order to understand how scour affects bridge foundations first one needs do comprehend some basic concepts related to this phenomenon. These concepts or themes can be classified as: the dynamic of the river, soil characteristics, the scour it's self and techniques used to prevent it.

Information for each author must include name, title, and university.

Dynamic of a River

Rivers are necessary in order to conduct many essential activities that sustain human life. They are utilized for transportation, fishing, as a drinking water source and irrigation among many other things. Chapman (1996) categorizes rivers as "the most important freshwater resource for man"[2]. General development of land depends largely on these bodies of water. With out rivers, cities like Egypt, Rome and many others will probably would not be as prolific as they have been throught the ages.

Natural rivers are self-formed features whose shapes are the result of erosion, deposition and transport of sediments [3]. The path that a river takes depends mainly on the velocity or discharge of water and the erosion process created by the interaction between the water and the soils found at riverbeds and banks. This interaction along the river causes erosion on the outer banks of a river and deposition at its inner banks. With this action, rivers shape landscape while transporting sediment throught the environment (Figure 1)[4].

Figure 1
Meandering River

In Puerto Rico there are as many as 50 rivers around the island. For the purpose of this project the focus will be on rivers located on the South Central region of the island. These rivers originate at the central mountain range and they flow into the Caribbean Sea. They are characterized by their short length and by their great velocity or discharge that causes heavy erosion, especially in the rainy season. The region of the island is characterized by its harsh climate and its agriculture use of land. These factors strongly contribute to the specific dynamic of the rivers of this area [5].

The Beatriz Creek was the body of water studied during this project. This creek shows the same characteristic describe above that are typical for all rivers around this central region of Puerto Rico.

Soils Around Study Area

There are different kinds of soils that can be generally observed at riverbeds and banks through a river. They are mostly composed of sedimentary rocks and granular soils. According to West, Terry R., sedimentary rocks are composed of mineral grains or crystals that have been deposited in a fluid medium and subsequently lithified to form rocks [6]. Sediments, in the other hand, are pieces of loose debris that has not been lithified (have not been hardened into rock material). Sediments are product of mechanical and chemical weathering [6]. These soils consist of gravel, sand, silt and clay. As time goes on, these sediments are cemented, compacted or crystallized (lithified) and they combined into sedimentary rocks. Sediment rocks can be divided into clastic, interlocking grains, fined grained, and whole fossils.

There are different soils and formations that are found along rivers of Puerto Rico. They are mostly composed of sedimentary soils but in some cases sedimentary rocks and metamorphic rocks can also be observed. In general, these soils can be described as alluvium, colluvium or terrace deposits. Alluvium is a detrital material, which is transported by a river and deposited, usually temporarily, at points along the river. Alluvium is commonly composed of sands and gravels [7]. Colluvium is a body of sediment that has been deposited by gravity. The mode of occurrence is similar to landslides, falls, avalanches and flows [8]. The resulting deposits are poorly sorted and poorly stratified. Particles of colluvium are not rounded in contrast with alluvium particles [9].Terrace deposits are sedimentary soils that have accumulated at river terraces through the years.

Terraces are former flood plains that developed when a river flowed at a higher level than usual. Terraces consist of a bench on the side of the valley covered with the usual flood plain deposits of clay, sand and gravel. This material is subsequently identified as terrace deposits [7]. All soils described above are generally susceptible to scour.

USGS Geologic Map of Cayey region describes various materials that can be found along Beatriz Creek and around the general area of Bridge# 2487. According to Map I-320, Comerio Quadrangle (Figure 2) [10], some of the soils illustrated at the map are: Alluvium (Qal), Terrace deposits (Qt), and Volcanic Breccia from the Formation J (Kj). The Alluvium and terrace deposits mainly consist of gravel, sand, silt, cobbles, and boulders. Formation J consists of massive volcanic breccia and lava flows containing stratified tuff and volcanic conglomerate. This Quadrangle also depicts a series of faults, dikes, and minor folds. Generally there is not proof that these faults are active.

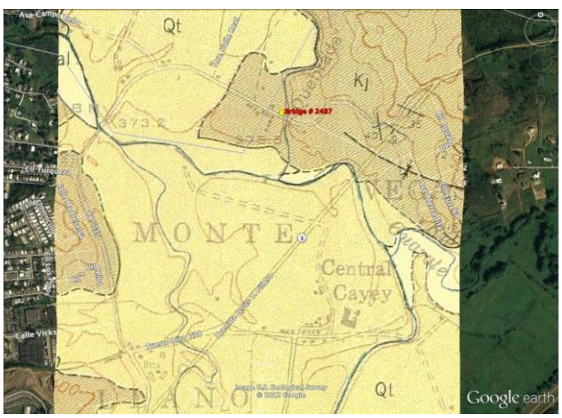

Figure 2
Map I-320, Comerio Quadrangle

It is necessary to understand the geology around the area of study in order to find the potential for scouring at the bridge site. This will help understand the aggradation and degradation process (scouring) that can eventually take place around the bridge foundations. Information like bed material gradations, upstream sediment supply, and depth of alluvium will be essential to use the sediment transport computer models and determine long-term aggradation or degradation trends around the bridges foundations [11].

Scour Phenomenon

In order to understand how scour affect bridges foundation one must first comprehend what scour is. According to Richardson and Davis HEC-18 Manual (2001) Scour is defined as erosion of streambed or bank material due to flowing water and it erosive action [11]. The water excavates and carries away the material that surrounds the piers and abutments of bridges. The amount and time it takes scour to occur depends on the type of material exposed to the phenomenon. Loose granular soils erode faster by flowing water than cohesive soils, which are more scour-resistant therefore they take more time to erode. Scour will reach maximum depth in loose granular material (sand and gravel) in hours while cohesive material will takes days. Sandstones, limestone, and granite will take months, years, and even centuries to erode [11].

There are different types of scouring processes that take place around a bridge general area. One type is known as general scour or the lowering of the streambed at the bridge area. General scour may be a result from contraction of the water flow. This flow contraction can produce contraction scour, which involves the removal of material from the bed and banks as a result of an increase in water velocity and shear stress on the riverbed caused by the reduction of the flow area. Another type is known as local scour. Local scour is caused by an acceleration of flow and resulting vortices (horseshoe and wake vortices) induced by obstructions to the flow (Figure 3) [1]. It generally occurs around piers and abutments. Local scour can be either clear-water or live-bed scour. Clear-water scour occurs when there is no movement of the bed material upstream of the bridge whereas live-bed scour occurs when the bed material in the channel upstream of the bridge is moving with the flow, causing scour at the bridge [11]. With this action, rivers shape landscape while transporting sediment through the environment.

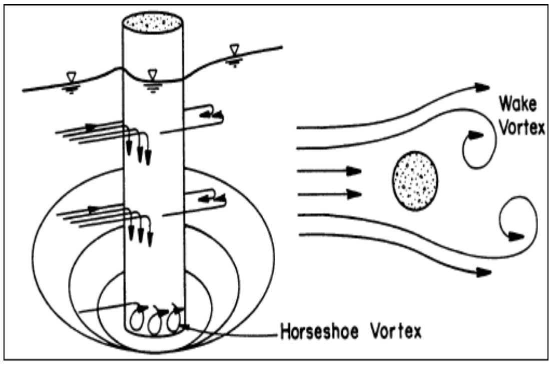

Figure 3
Schematic Representation of Scour

Scour can be deepest at the peak of a flood but it will be hardly visible do to the turbid waters. As floodwaters recede, scour holes will refill with sediment creating the illusion that scour had not affected the foundation. For this reason it is important to use appropriate scour monitoring and measurement equipment accompanied by visual inspections [1]. These instruments (fixed and portable) can be grouped into four different categories:

- **Sounding rods:** manual or mechanical device to probe riverbeds.
- **Buried or driven rods:** device with sensors on a vertical support, placed or driven into riverbeds.
- **Fathometers:** commercially available sonic depth finder.
- **Other Buried Devices:** active or inter buried sensor or transmitter.

It is important for engineers and bridge inspector to understand that these instruments are complementary and not mutually exclusive . Scour problem at bridges will challenge engineers for decades to come. With the help of technology and a better understanding of the scour phenomenon faster and more economic assessments and solutions will facilitate scour monitoring constructing safer routes for public transportation [12].

Scour Prevention

Scouring of the riverbed material around bridge foundations is the most common cause of bridge failures. In order to prevent this from happening engineers needs to design all bridges to resist scour. When planning the bridge foundations one should design for scour caused by the worst conditions (100-year flood) and the bridge should withstand the effects of this scour without failing [11]. In order to design a safe structure careful hydraulic, structural, and geotechnical evaluations must be taken into consideration.

To deal with scour around bridge foundations, countermeasures should be added to the design of the bridge. Countermeasures are objects incorporated into bridges or channel crossings that will monitor, control, inhibit, change, delay, or minimize stream and bridge stability problems. Countermeasures may be installed during or after (retrofitted) the construction of the bridge. The purpose of placing countermeasures at abutments is to prevent scour by improving the flow orientation at the bridge and move local scour away from this area. The purpose of placing countermeasures at piers is to prevent scouring by inhibiting erosive vortices from forming or reducing their strength and intensity if they do form (Figure 3). It is essential that all foundations (piers and abutments) would be constructed deep enough assuring that the structural stability of the bridge will not be at risk if ultimate scour (the maximum depth of scour) happens. When selecting the appropriate countermeasures for a specific case, factors like erosion mechanism, stream characteristics, construction, maintenance, potential for vandalism, and costs has to be taken into consideration [1].

There are numerous types of countermeasures that can be use to controls scouring. They can be divided into hydraulic countermeasures, structural countermeasures, and monitoring (discussed in previous section). These groups are based on their functionality with respect to scour and stream instability. Hydraulic countermeasures primary design is to control the erosive force cause by the flow of the river (Figure 4) [1].

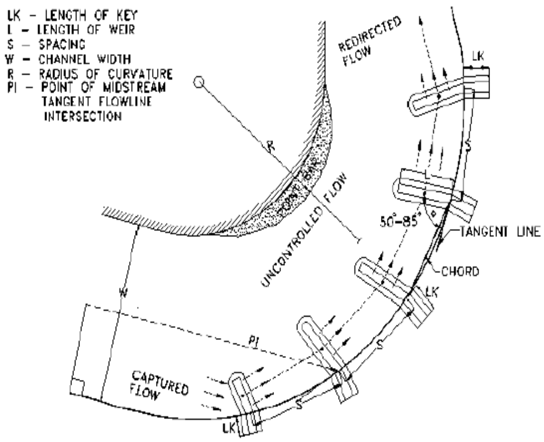

Figure 4
Bendway Weir

Hydraulic countermeasures are subdivided into river training structures and armoring countermeasures. River training structures are those that modify or change the orientation of the river flow. They can be traverse (perpendicular), longitudinal (parallel) or areal (neither perpendicular or parallel) river training structures. The armoring countermeasures act as a resistant layer to shear stresses created by the flow (Figure 5 and 6) [1]. They provide protection to the erodible materials underneath the structures.

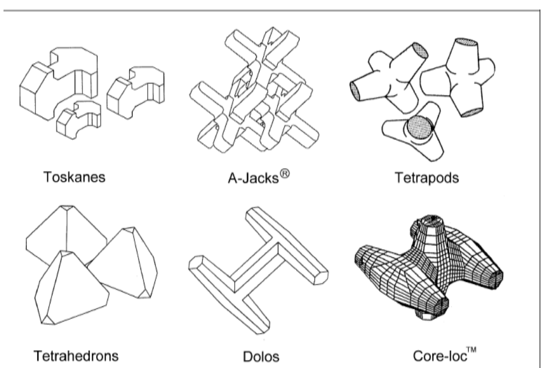

Figure 5
Armor Units

Figure 6
Wire Enclosed Riprap

Structural Countermeasures involve the modification of the foundations of a bridge in order to prevent scour from occurring. These modifications can be foundation strengthening or pier geometry modifications. Foundation strengthening structures will reinforce and extend the foundations of the bridge preventing failure after the channel bed elevation is lowered by scour. Modifying a bridge its self into a continuous span bridge could serve as a countermeasure after scour has occurred [1]. Pier geometry modifications either reduce local scour or transfer it to another location.

In order to select an appropriate countermeasure for a specific case, the US Department of Transportation has created a table or matrix that identifies distinctive characteristics for different types of countermeasure. The matrix subdivides in five categories: functional application, suitable river environment, maintenance, installation, and design guidelines references. These categories were created with the purpose of aiding in the selection and implementation of the correct countermeasures for each case.

DESIGN FOR SCOUR

This section will describe the principal tasks and procedures used to calculate the scour depth at Bridge # 2487 through this project.

The procedure conducted through the project can be divided into different steps. First of all, an in-depth study of the scour phenomenon that included different information from rivers, soils, bridges and scour countermeasures was conducted. The principal goal during this process was to understand the mechanics of scour in order to analyze it later on. This process represented all the information already discussed in previous sections.

Bridge Selection and Site Visit

The next step was the selection of the specific bridge that would be suitable to study. Different bridges were analyzed and Bridge # 2487 was selected (Figure 7). This bridge was selected after visiting the location and observing that the structure could be susceptible to scour. Important information like channel measurement and flow rate were obtained from Stanley Consultants Scour Evaluation Reports [13]. During the field visit it was observed that severe scour had occurred along the base of the bridge right abutment (Figure 8). Scouring had exposed the abutment foundation. Most of the soil found at the affected areas consisted of fill placed for the construction of the abutment. A sharp constriction of the creek channel was observed due to the downstream presence of the old bridge (this constriction was not accounted for the scour calculations).

Figure 7
Bridge # 2487

Figure 8
Scour at Right Abutment

Laboratory tests were performed on both samples (BS# 1 and BS# 2) and later classified according to ASTM D422. The results from sieving procedure were the following:

- **Bulk Sample #1**- It was gathered just in front of the right abutment. According to ASTM D422 the sample was classified as GM (silty gravel with sand).
- **Bulk Sample #2**- It was gathered just in front of the left abutment. According to ASTM D422 the sample was classified as CL (Sandy clay of low plasticity).

Figures 9 and 10 represent the laboratory test results obtained after sieving and weighting the collected samples. The following figures illustrate the granulometric curves or grain size distribution for each bulk sample.

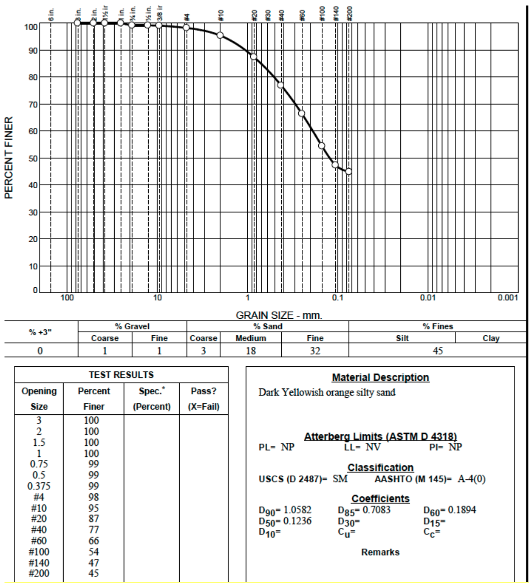

Figure 9

BS # 1 Grain Size Distribution

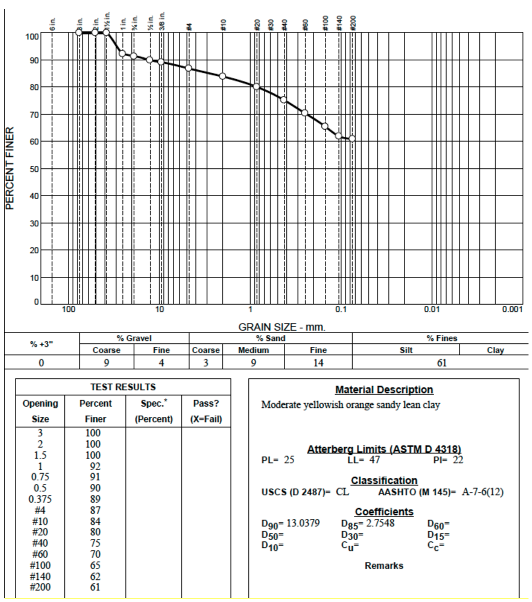

Figure 10

BS # 2 Grain Size Distribution

After analyzing both samples it was decided to calculate the hydraulic model using BS# 1 because it was the most scour susceptible sample do to its higher percentage of granular material (53% sand).

HYDRAULIC MODEL SCOUR ANALYSIS

The following step was to compute the scour depth at the site using all the information gathered and HEC-RAS computer program developed by the US Army Corps of Engineers. This program uses the following parameters to estimate the potential scour at the bridge: river discharge, Manning N values, and ground slope among other [14].

The HEC- RAS model used two equations to calculate the live-bed scour at the abutments. When the wetted embankment length divided by the approach depth is more than 25 it uses the HIRE equation (1) [14].

$$y_s = 4y_1(k_1/0.55)k_2Fr^{0.33} \quad (1)$$

When the result of the division is less than or equal to 25 it uses the Froehlich equation.

$$y_s = 2.27K_1K_2(L')^{0.43}y_a^{0.57}Fr^{0.61}+y_a \quad (2)$$

$$Fr = V_e/(gy_a)^2 \quad (3)$$

The Froehlich equation (2, 3) [14] was used to compute the scour depth (y_s) at Bridge 2487.

Flow/velocity distributions were set for the main channel and channel overbanks. The analysis indicates that the live bed equation was used for the contraction scour calculation.

The creek discharges and the bridge general area dimensions were provided by Stanley Corporate. The discharge for the 100- year flood event was 282 m3/s [13]. According to Chapter 3 of the HEC-RAS Reference Manual the Manning N values for the main channel and the overbanks are 0.050 and 0.065 respectively.

Other input used in the HEC- RAS model included a ground slope of 0.0131 m/m and the channel bottom width at the bridge of 29 m [13]. The results obtained from the scour analysis for the 100-year flood event are illustrated in Figure 11.

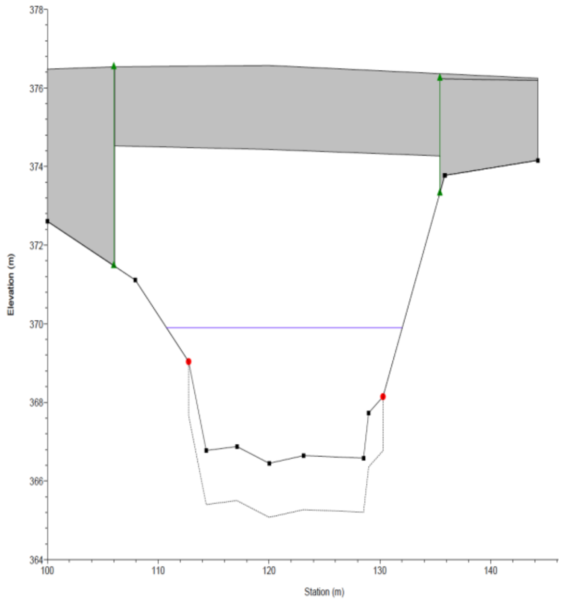

Figure 11
Estimated Scour Depth for 100-Years Flood

The potential total scour depth for the worst condition around the site area was reported as 2.91m.

Taking into consideration the results from the whole project, the appropriate countermeasure was selected using the parameters described in the US Department of Transportation HEC-23 manual and its Countermeasure Matrix tables. According to the matrix for bridge 2487 riprap or gabion baskets could be installed in order to prevent the continue degradation of the granular material at the bridge abutments.

Conclusion

Rivers flowing through bedrock commonly expose only massive rock because the river would have already scoured any previously existing highly weathered and fractured rock. It is expected that the rock underlying the scour susceptible material observed along the creek should be massive and of good quality. The scour depth will not precede ones it reach the massive bedrock. Therefore, the potential scour depth calculated in this project (2.91m) probably would never be reach do to the presence of bedrock possibly underlying the scour susceptible granular soils.

Never less, the appropriate countermeasures should be installed at the affected areas to prevent the development of additional scour along the bridge abutments. The countermeasures should include the protection of the riverbanks and side slopes around the bridge.

The development of further scour will continue to remove the alluvial deposits and further expose the abutments foundations (until it reaches the scour depth or the bedrock). The integrity of the entire bridge would be in doubt if scour continues to affect the studied area.

References

[1] Lagasse, P.F., Zevenbergen, L.W., Schall, J.D., and Clopper, P.E. "Bridge Scour and Stream Instability Countermeasures: FHWA Hydraulic Engineering Circular No. 23 Second Edition" Ayres Associates, Colorado. March 2001.

[2] Chapman, Deborah. "Water Quality Assessments: A Guide to the Use of Biota, Sediments and Water in Environmental Monitoring". Taylor & Francis, 1996.

[3] Dohmen-Janssen, C. Marjolein and Hulscher, Suzanne J. "River, Coastal and Estuarine Morphodynamics: RCEM 2007". Taylor & Francis, September 2007.

[4] Frascati, Alessandro and Lanzoni, Stefano. "Long Term Behavior of Meandering Rivers" Taylor & Francis Group. London, England, 2008.

[5] Veve, Thalia D. and Taggart, Bruce E. "Atlas of Ground-Water Resources in Puerto Rico and the U.S. Virgin Islands".U.S. Geological Survey. Water-Resources Investigations Report 94-4198. San Juan, Puerto Rico. 1996.

[6] West, Terry R., "Geology Applied to Engineering" Prentice Hall, Inc. New Jersey, 1995.

[7] Whitten, D.G.A and Brooks, J.R.V. "Dictionary of Geology" The Penguin Group. London, England, 1972,

[8] Hunt, Roy E. "Characteristics of Geologic Materials and Formations: A Field Guide for Geotechnical Engineers" CRC Press 2006.

[9] Longwell, Chester R., Flint, Richard Foster., and Sanders, John E. "Physical Geology" John Wiley & Sons, Inc. New York, 1969.

[10] Pease, Maurice H. and Briggs, Reginald P. "Geologic Map of The Comerio Quadrangle, Puerto Rico" Map I-320. U.S. Geological Survey. Virginia, 1960.

[11] Richardson, E.V. and Davis, S.R. “Evaluating Scour At Bridges: FHWA Hydraulic Engineering Circular No. 18 Forth Edition” Ayres Associates. Fort Collins, Colorado, 2001.

[12] Fenner, Thomas J. “Civil Engineering: Scoping Out Scour (Article)“ American Society of Civil Engineers, 1993.

[13] Oben-Nyarko, Kwaku nad Perez, José. “Scour Evaluation Report Phose 2” Stanley Consultants (Engineers). Guaynabo, PR, 2011.

[14] HEC-RAS River Analysis System “Hydraulic Reference Manual” Version 4.0. US Army Corps of Engineering, Davis, CA. 2008.