Río Sabana Streambank Erosion Control and Restoration at Urb. Alamar, Luquillo, Puerto Rico

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Abstract *— The construction of new developments on floodplain areas has become a common practice in Puerto Rico. This practice entails the placement of fill inside the river floodplain causing the re-location of the river channel in order to maximize construction area. With the pass of years the meander that has been moved tries to return to their original condition and proof of this is the erosion problem in the streambank of Río Sabana at Urb. Alamar in Luquillo, PR. Actually, the river is moving into the area of the Alamar community causing erosion on the leftbank and portion of 6 houses has already fallen into the river. The main objectives of this project are to present a sustainable, stable and economical solution and will introduce the use of rock vanes for the streambank erosion of Río Sabana at Alamar Community.*

Key Terms *— Streambank erosion, sustainable erosion control methods, rock vanes, river geomorphology.*

INTRODUCTION

The construction of new developments on floodplain areas has become a common practice in Puerto Rico. This practice entails the placement of fill inside the river floodplain causing the re-location of the river channel in order to maximize construction area. In many cases this process is undertaken without considering the river morphology. Rivers in Puerto Rico, especially those located on Alluvial deposits, tend to be meandering, and this process is clearly observed using historical aerial photographies. With the pass of years the meander that has been moved tries to return to their original condition and proof of this is the erosion problem in the streambank of Río Sabana at Urb. Alamar in Luquillo, PR. The floodway of the river was filled and moved for the construction of the Urb. Alamar on 1980. Actually, the river is moving into the area of the Alamar community causing erosion on the leftbank of the river and portion of 6 houses has already fallen into the river.

The main objectives of this project are to present a sustainable, stable and economical solution to the streambank erosion and stabilization problem of Río Sabana at Urb. Alamar. Several alternatives for erosion control have been used in Puerto Rico. For this project the purpose is consider a structure which minimizes the environmental impact and has a natural aspect. For this type of problem the principal erosion control structures used in Puerto Rico are the gabions, riprap, and with less frequency, concrete and sheet piles. This project will present information concerning of why this type of structures are not feasible for this particular case and will introduce the use of stone for streambank stabilization.

The Alamar community is located on PR-992 in the Municipality of Luquillo, limited on the east by Río Sabana. The community is located 350 meters upstream of the PR-3 Bridge over Río Sabana. Río Sabana has active meanders in the area of the study reach and the streambank erosion is threatening several houses in the community.

STUDY AREA DESCRIPTION AND GEOMORPHIC ANALYSIS

This section summarizes the study area current condition, field obeservations, and presents a geomorphic analysis that has the purpose of documenting this information to establish future changes in the fluvial system.

Watershed Characteristics

Río Sabana originates in the mountains of the Caribbean National Forest at an elevation of 670 m-msl. Río Sabana discharges into the Atlantic Ocean 600 meters downstream of the PR-3 Bridge. The river tends to meander from a topographic elevation of approximately 20 m-msl, where the river slope is less than upstream at this point. River slope at project reach is approximately 0.5%.

Río Sabana has a drainage area of 18.7 Km^2 at the river mouth in the Atlantic Ocean. The upper part of the watershed is mainly forest and the lower part is composed of grass, rural houses, and residential and industrial urbanizations.

Field Observations

On January, and March of 2009 and March 2010, field visits were perfomed to the project site and the following was observed:

- Portion of 6 houses has fallen into the river due bank erosion (see Figure 1).
- There is notable erosion along some areas of the left bank contiguos to the community, an as a consequence the presence of vertical banks in some areas.
- River bed material is composed mainly of gravel. Cobbles and boulders are notable in the river sediment bars.
- The river channel and floodplain are well defined in the study area.
- The river right bank and floodplain is composed mainly of tall grass.
- River has the presence of riffles, pools and point bars.
- The river has the presence of abandoned meanders in the study area and upstream, notable in the field and confirmed with aerial photography.

Aerial Photography

Hitorical aerial photography was obatined from the Puerto Rico Transportation Authority and from GIS resources for the years of 1936, 1981, 2002 and 2007. Figure 2 presents an aerial picture showing the Alamar community and the historical river path. This comparison of alignments shows the process of active meadering of the river and the movement of the river channel for the location of the urbanization.

Figure 1
River Bank Eroded and Part of the Houses that Fallen into the River

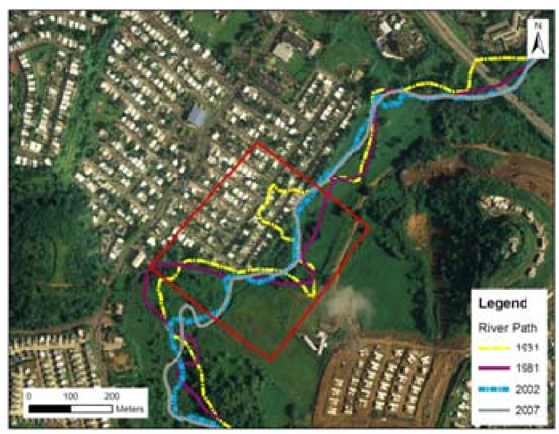

Figure 2
Historical Río Sabana Movement Path

Geomorphic Analysis

A geomorphic analysis was performed to establish existing geomorphic conditions along the study reach. The geomorphic analysis was analyzed to identify the stream type using the Rosgen system [1], which takes in consideration mainly the form of the river channel and valley, and channel properties. The purpose of this system is to classify streams based on quatifiable field measurements to produce consistent, reproducible descriptions of stream types and conditions. There are four levels in the Rosgen's classification (1996) hierarchy; geomorphic characterization (Level 1), morphological description (Level 2), stream condition assesment (Level 3), and validation and monitoring (Level 4). In this study the analysis was performed up to the Level 2.

Six parameters are required to classify streams in the first two levels of the Rosgen stream classification analysis. First, is the stream a single channel or multiple channels, second through fifth, the stream's entrenchment ratio, width/depth ratio, sinuosity, and slope. Finally, what is the dominant material that lines the stream channel. The field measurements used to calculate the second throught fifth parameters are taken at the stream's bankfull stage.

Río Sabana river reach is classified as a C stream type because is a low gradient, meandering, point-bar, riffle/pool, and well defined floodplain reach, and has a slope of 0.5%. Table 1 summarizes the stream classification parameters obtained for the study reach. Using the parameters of the river reach for the stream classification; the studied river reach can be classified as a C-4 stream type.

Table 1
Río Sabana Study Reach Parameters for Stream Classification

Parameter	Value
Slope	0.5%
Entrenchment ratio	3.8
Channel material	Gravel
Width-to-depth ratio	36.4
Sinuosity	1.31

Figure 3 shows the criteria for the major stream types. The Rosgen stream classification at Level II classifies the form of the stream. This classification system by itself only provides information about the existing pattern, dimension, profile, and bed materials. If it can be assumed that streams with the same general form also tend to have the same geomorphic processes, the classification can be used to predict typical stream processes, sensitivity, and behavior. This geomorphic analysis can be used to short and long term monitoring and in a short term study if the proposed bank stabilization measure cause changes to the river reach.

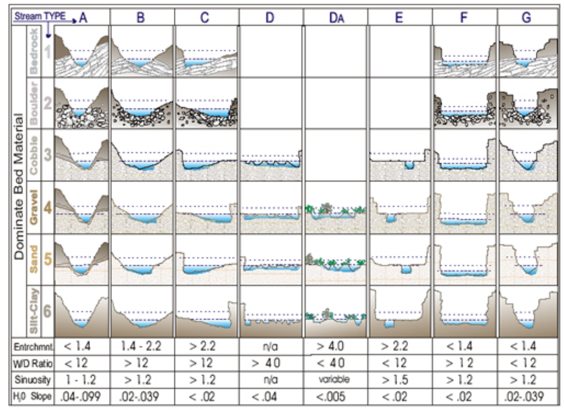

Figure 3
Criteria for the Major Stream Types

STREAMBANK EROSION AND EROSION CONTROL METHODS

Streambank erosion is the direct removal of banks and beds by flowing water. Streambank erosion is a natural process, but acceleration of this natural process leads to a disproportionate sediment supply, stream channel instability, land loss, habitat loss and other adverse effects. When a stream is straightened, widened, encroached or moved streambank erosion increases. In the case of Río Sabana at Urb. Alamar, the river was moved and filled for the construction of the urbanization. Figure 4 shows the erosion process in streambanks.

Streambank Erosion Control Methods Most Used in Puerto Rico

In Puerto Rico several streambank erosion control methods are used, but these methods fail with time, do not look natural as part of the river or are a barrier for the species. The hydraulic and geomorphic functions of the river systems are not well considered or understood by designers for the sustainable design of river structures. It is important to know river properties for the effectively design of structures that maintain river stability. Some of the erosion control methods commonly used in Puerto Rico are described below:

- Concrete or sheet piling - Both methods act to limit the stream's access to its floodplain and often lead to down-cutting into the channel bed. Similarly to channelizing, concrete or sheet piling creates a smooth channel with no resistance to stream flow increasing the water velocity causing erosion damage downstream. Vertical walls also create barriers to the movement of wildlife such as turtles, frogs, and lizards. These measures also often make it difficult to access the stream due to their steepness. In addition these methods do not look natural in the river environment. Figure 5 shows a concrete streambank and Figure 6 presents sheet piles walls used in rivers.

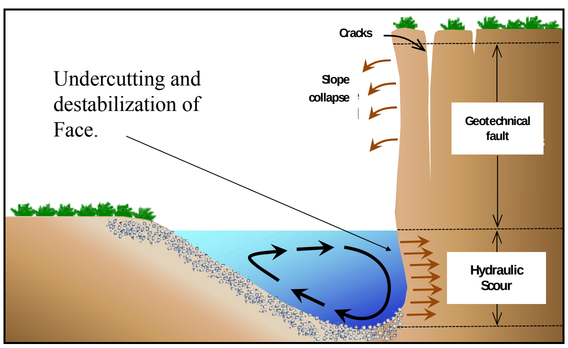

Figure 4
Erosion Process in Streambanks

Figure 5
Concrete Streambank (Río Yauco, PR)

- Gabions - Gabions are used to slow the velocity of runoff or to stabilize slopes with erosion problems. This method are not feasible because tends to fail due to abrasion of wire mesh by the movement of stones in streams with high velocity flow and also over the time fail due to corrosion of the wire. Gabions are considered to be a "hard"structural solution that has minimal habitat and aesthetic value. Figure 7 shows a gabion structure when constructed and Figure 8 a time after failed.

Figure 6
Sheet Piles used in Rivers

Figure 7
Río Mameyes, PR Newly Installed Gabions (2000)

- Riprap - Riprap is a layer of large rocks used to protect a streambank from the erosive power of a stream. The riprap may present a barrier to organisms entering and leaving the river wetland and to people who wants to access the river. In addition, riprap has an unnatural appearance. A common reason for failure is the undersized stone that can be displaced by river currents. Figure 9 shows a riprap used for streambank erosion control.

Figure 8
Failing Gabions on Río Mameyes, PR (2004)

Figure 9
Riprap used for Streambank Erosion (Río Caguitas, PR)

Proposed Streambank Erosion Control Method

The proposed streambank erosion control method for the Río Sabana at Alamar reach is the rock-vanes. Rock vanes are linear structures that extend out from the streambank into the stream channel in an upstream direction and are built below the water level to control the direction of flow within a stream. The rock-vane is used to direct stream's energy toward the center of the channel and relieve pressure on an eroding stream bank. The cross-vanes provide the integral structure to the banks that allows meander pattern and also causes the creations of pools, which is necessary for fish habitat. Rock-vanes has a natural appearance and do not look as an engineered structure in a river. Rock-vanes is a method that is stable, economical, sustainable, and habitat friendly. Figure 10 shows a rock vane structure used for streambank erosion control.

Figure 10
Rock Vanes used for Streambank Erosion Control

HYDROLOGIC ANALYSIS

The Río Sabana hydrologic analysis has been performed using the HEC-HMS model by the Hydrologic Engineering Center of the US Army Corps of Engineers. The frequency storm methodology was selected for runoff computations; this method uses statistical data to produce balanced storms with specific exceedance probability. Discharges were computed for precipitations events having return interval of 2-, 5-, 10-, 25-, 50- and 100-year. The 100-yr discharge will be used to determined flood levels in the hydraulic analysis. The 2-, 5-, 10-, 25 and 50-years discharges will be used to estimate the bankfull discharge that corresponds to the 1.5-year discharge.

Watershed limits for the project reach were determined based on USGS topographic quadrangle and aerial photography. The Río Sabana drainage area tributary to PR-3 Bridge is 18.13 Km^2.

The time of concentration was calculated using Soil Conservation method (TR-55). The time of concentration for Río Sabana watershed was estimated as 117 minutes.

The Curve Number represents the runoff potential within a watershed and is estimated based on soil type (hydrologic soil group), land use and Antecedent Moisture Condition (AMC). In this study an AMC-II was used. The soil types within the watersheds were obtained from Soil Survey Geographic data base (SSURGO), which contains the most detailed level of soil mapping performed by the Natural Resources Conservation Service (NRCS). Curve Number for Rio Sabana watershed was estimated in 72.

The 2- to 100-years rainfall depths for the Rio Sabana drainage area were obtained from the National Oceanic and Atmospheric Administration (NOAA) Atlas 14, published on October 26, 2006. This publication updates and replaces similar data contained in Technical Paper-42 (1961).

Table 2 shows the 2-, 5-, 10-, 25-, 50- and 100-year 24 hour peak discharges for the Río Sabana as analyzed by HEC-HMS.

Table 2
Peak Discharges by Return Interval

Return Interval	Peak Discharge
2-yr	83.8
5-yr	154
10-yr	205
25-yr	271
50-yr	322
100-yr	373

Bankfull Discharge Estimation

The river bankfull is the fundamental parameter for the design of rock vanes. Bankfull discharge is the dominant channel forming flow with a recurrence interval seldom outside the 1 to 2 year range, with an average of 1.5 years. Bankfull discharge often is determined using physical indicators like deposits of sand or silt at the active scour mark, break in stream bank slope, perennial vegetation limit, rock discoloration, and root hair exposure. When physical indicators are not easy visible, a discharge of a recurrence of 1.5 year can be used. The 1.5 year discharge was estimated graphing the discharge of 2-, 5-, 10-, 25-, 50- and 100-year and generating a logaritmic equation. The equation (1) generated by the graph is:

$$y = 73.727\ln(x) + 34.218 \qquad (1)$$

where:

y = discharge (m^3/s)

x = recurrence (yr), 1.5 year

Equation result in a 64.1 m^3/s discharge for a recurrence of 1.5 year.

HYDRAULIC ANALYSIS

The hydraulic analysis of Río Sabana was performed using the Corp of Engineers HEC-RAS (version 4.0) software. The HEC-RAS program uses uniform, steady and one-dimensional flow to estimate the effects produced by changes in geometry, roughness and flow. The program also considers hydraulic structures like culverts and bridges. Given the type of analysis, the one-dimensional flow regime, the availability of routines to simulate encroachments, and the lack of significant storage effects along the study reaches, HEC-RAS is considered the appropriate model for this analysis. The hydraulic analysis was performed for the 1.5- and 100-year 24 hour duration events, for a sub-critical flow regime.

The 100-yr hydraulic analysis was performed to determine flood levels along the study reach using a model of the Río Sabana prepared by FEMA for the October, 2009 Flood Insurance Study (FIS). Four cross sections were added to the FEMA model, between cross sections 2121 and 1709 to best represent the changes in the cross sections due to the bank stabilization, using FEMA LIDAR for Río Sabana.

The 1.5-yr discharge was also considered in the hydraulic analysis because channel characteristics results will be used for the design of the rock vanes.

Cross sections are from FEMA model, only four new cross sections were added to the model, and were taken from FEMA LIDAR. These cross sections were selected based on field reconnaissance to best represent the hydraulic characteristics of the proposed stabilization measures. Figure 11 shows the lcoation of the study reach and the cross sections location.

Two models were prepared for the study reach and are describe below:

- Existing Condition Model - An existing condition model was performed to determine current flood levels in Río Sabana.
- Proposed Condition Model - The proposed condition model simulates the proposed bank stabilization measures in cross sections 2052,

2011, 1778 and 1728. These cross sections were modified to include the proposed channel modification. Channel modification consists in fill the left bank of the river (eroded side) and excavated the right side to create the same river cross-sectional area as in the current conditions. Figure 12 shows one of the model cross sections under the existing and proposed conditions.

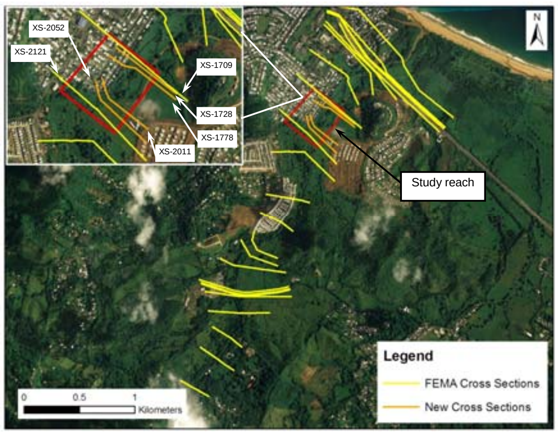

Figure 11
Cross Sections used in the HEC-RAS Hydraulic Model

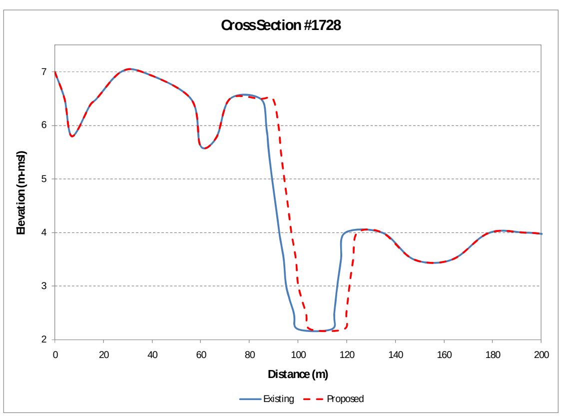

Figure 12
Cross Section under Existing and Proposed Condition

Proposed condition shall not increase 100-yr existing condition flood levels along the river by more than 0.15 meters (Puerto Rico Planning Board Regulation #13). From hydraulic computations the proposed project does not increase by more than 0.05 meters the 100-year flood level along Río Sabana.

BANK STABILIZATION DESIGN

Vanes are linear structures that extend out from the streambank into stream channel in an upstream direction. They are placed along the streambank where erosion is ocurring along the toe of the slope. The purpose of vanes is to reduce erosion along the stream bank by redirecting the stream flow toward the center of the stream. Rock vanes are designed to operate under submerged conditions, deflecting the currents at the bottom of the river, away from the toe of the eroding bank, and creating quiescent conditions adjacent to the bank which will encourage the accumulation of sediment. D. Rosgen Geomorphic Channel Design [2] parameters are used for design specifications.

Design Specifications

The vane arm portion of the structure is generally 20 – 30 degrees measures upstream from the tangent line where the vane intercepts the bank. The 20-degree angle provides the longest vane length and protrects the greatest length of streambank. The flatter and smaller vane angle arm will extend farther upstream to intercept proportionately more water and increase the length of bank protected.

The slope of the vane extending from the bankfull stage bank should vary between 2 to 7 percent. Vane slope is defined by the ratio of bank height/vane length. Vane length is the distance measured from the bankfull bank to the intercept with the invert elevation of the streambed at a third of the bankfull channel width.

The structure should only extend to the bankfull stage elevation. If the bank is higher, a bankfull bench is constructed adjacent to the higher bank and the structure is integrated in to the bench.

The minimum footer depth at the invert for cobble and gravel bed stream is associated with a ratio of 3 times the protrussion height of the invert rock.

Rock Size

A rock will be stable until the lift and drag forces of moving water exceed the critical value threshold. For a given rock size subjected to a given force of moving water, there is some unit discharge where the rock will move and become unstable. Some methods are based on a particle force balance, all rock sizing methods are essentially empirical techniques. Velocity-based approaches and boundary shear or stress based approaches are the two prominent classes of methods that have been used to evaluate the erosion resistance of materials. While shear or stress based approaches are considered more academically correct, velocity bassed methods are still widely used.

D. Rosgen related the bankfull shear stress to minimum rock size for the vane structure. The application is an empirical relation that is limited to the following: (1) rivers where bankfull discharge varies from 0.56 m3/s to 113.3 m3/s, (2) stream channel bankfull depths from 0.26 to 1.5 meters, and (3) bankfull shear stress lower than 25 kg/m2. Values obtained in the hydraulic analysis for the Río Sabana reach do not comply with Rosgen rock size application requirements, methods from the "Stone Sizing Criteria", Technical Supplement 14C (Part 654 National Engineering Handbook) and from the Reservoir Sedimentation Handbook will be compare for the selection of the stable stone size.

Hydraulic Design Parameters

Rock vanes design parameters are related with the bankfull depth and width. For the design of the rock vane stable stone the hydraulic results of the 100-year event were used. The design parameters where obtain from the results of the HEC-RAS model hydraulic analysis for the bankfull (1.5 year) and 100-year events and are presented in Table 3 for the cross sections of interest. Figure 13 shows the proposed location of the rock vanes within the study reach. Figure 14 presents the rock vanes conceptual profile, cross-section and plan view.

Table 3
Hydraulic Design Parameters

Cross section	Bankfull (1.5 year)		100-year		
	Flow depth (m)	Channel width (m)	Velocity (m/s)	Flow depth (m)	Shear stress (N/m^2)
2121	2.23	89.69	0.87	4.06	30.0
2052	1.59	38.57	4.10	3.22	287
2011	2.12	42.30	2.87	3.81	136
1778	1.64	112.9	3.12	3.07	170
1728	1.41	46.11	3.42	2.88	214
1709	2.05	12.79	3.49	3.83	543

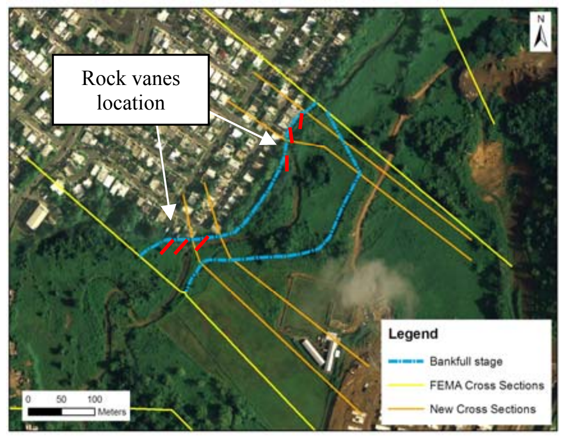

Figure 13
Proposed Location of Rock Vanes

Stable Stone Sizing

The methods to determine the size of the stable stone for the rock vanes were obtained from the "Stone Sizing Criteria", Technical Supplement 14C [3] and the Reservoir Sedimentation Handbook [4].

The 100- yr hydraulic values results (Table 3) will be used for the calculation of the stable stone sizing. The methods considered for this study were the following:

Isbash method - The Isbash formula (2) (Isbash 1936) was developed for the construction of dams by depositing rocks into moving water. A coefficient is provided to target high and low turbulence flow conditions. The equation is:

$$V_C = C * \left(2 * g \frac{\gamma_S - \gamma_W}{\gamma_W} \right)^{0.5} * (D_{50})^{0.5} \quad (2)$$

where:

V_C = critical velocity (ft/s), 13.5 ft/s

C = 0.86 for high turbulence

C = 1.20 for low turbulence

g = 32.2 ft/s^2

γ_s = stone density (lb/ft3), 165 lb/ft^3

γ_w = water density (lb/ft3), 62.4 lb/ft^3

D_{50} = median stone diameter (ft)

Solving this equation for the diameter, results in 2.3 ft (0.70 m).

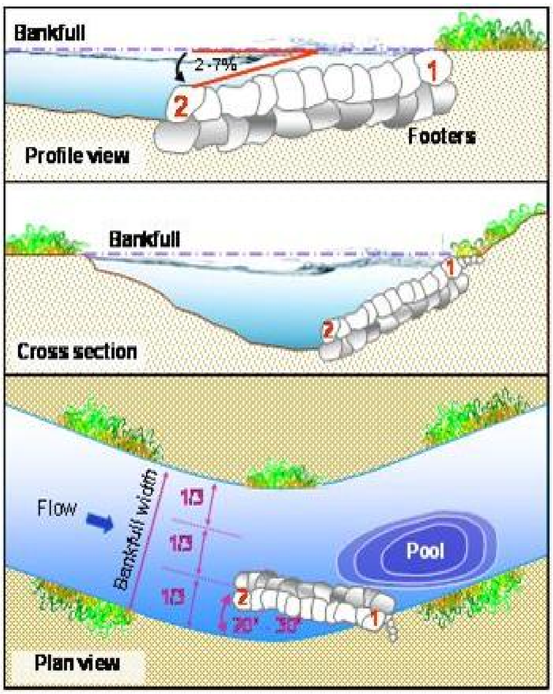

Figure 14
Rock Vanes Conceptual Profile, Cross-section and Plan View

U.S. Bureau of Reclamation method – This is a high energy technique outlined in U.S. Bureau of Reclamation (USBR) EM-25 (Peterka 1958) and wass developed for sizing riprap below a stilling basin. It was empirically developed using 11 prototype instalations with velocities ranging from 1 ft/s to 20 ft/s. The formula (3) is:

$$D_{50} = 0.0122 V^{2.06} \quad (3)$$

where:

V = average channel velocity (ft/s), 13.5 ft/s

D = median stone diameter (ft)

Solving this equation results in a diameter of 2.58 ft (0.79 m).

U.S. Geological Survey Method (Blodgett 1981) - This technique is based on analysis of field data of 39 large events from sites in Arizona, Washington, Oregon, Nevada and California. Riprap protection failed in 14 of the 39 cases. An enveloped curve was empirically developed to represent the difference between sites that performed without damaged and those that were damaged by particle erosion. This method typically provides overly conservative results. The formula (4) is:

$$D_{50} = 0.01 V^{2.44} \quad (4)$$

where:

V = average channel velocity (ft/s), 13.5 ft/s

D = median stone diameter (ft)

Solving this equation results in a diameter of 5.67 ft (1.73 m).

Shields Critical Sheart Stress Method - In this technique the stone diameter anticipated to remain stable was computed based on the bed shear stress and the Shields procedure (5). Bed shear stress is computed as:

$$\tau = \gamma_W RS \quad (5)$$

where:

τ = Bed shear stress (Newtons/m^2)

γ_W = unit weight of water (Kg*m/s^2)

R = hydraulic radius (meters)

S = dimensionless slope

The incipient motion is defined by the Shield's relationship based on the critical value of the dimensionless Shield's parameter, taken as F_{CR} = 0.047 for turbulent flow. The Shied's relationship (6) is given by:

$$F_{Cr} = \frac{\tau}{[(\gamma_S - \gamma_W)d]} \quad (6)$$

where:

F_{Cr} = Shield's parameter, 0.047

τ = Bed shear stress (Newtons/m^2), 543 N/m^2

d = stone diameter (m)

γ_S = unit weight of sediment (Kg*m/s^2), 26,000 Kg*m/s^2

γ_W = unit weight of water (Kg*m/s^2), 9,810 Kg*m/s^2

The HEC-RAS model indicates the values of bed shear stress (τ) for each cross section. The higher shear stress for the Río Sabana at Alamar reach for the 100-year event is 543 N/ m^2.

The stone diameter selected to use in the rock vanes is 1.73 meters, result from the U.S. Geological Survey method. The bigger stone size result was chosen because it will resist the forces of flowing water during the design event (100-year). In addition, this complies with the purpose of the project that was proposed as a sustainable structure.

Any safety factor will be applied to the stone diameter because the U.S. Geological Survey method results in a very conservative value in comparison with the other methods studied.

Conclusions and Recommendations

The following summarize the findings of the study and the recommendations associated with the proposed streambank erosion control measure:

- The Río Sabana study reach was classified as a C-4 river in the Rosgen river classification system.
- The selected bank stabilization measure was the rock vanes.
- The channel modification at river reach consists in: fill the left bank of the river (eroded side) and excavated the right side to create the same river cross-sectional area as in the current conditions, and install rock vanes to re-direct the flows energy to the center of the channel.
- The proposed bank stabilization measures do not increase by more than 0.10 m the 100-year existing condition flood levels.
- The minimum size of the rock to be used in the rock vane is 1.7 meters. Smaller rocks can be used to fill the gaps between rocks.
- Rock should be of sufficient hardness to resist weathering and shall free of cracks and other blemishes.
- Monitoring after construction is recommended to ensure that the objective of the stream bank stabilization and restoration are met over time.

References

[1] Rosgen, D. *Applied River Morphology*, 1996.

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