Effects of In-stream Sand and Gravel Mining in Scour at Bridges in Puerto Rico

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Abstract— *Scour of bed material from around bridge foundations is the most common cause for the failure of highway bridges in the United States. In Puerto Rico, millions of dollars are being spent by the Puerto Rico Highway Authority (PRHTA) and the Federal Highway Administration (FHWA) in the rehabilitation and replacement of bridges identified as scour critical. On the other hand, in-stream sand and gravel mining has been an important commercial activity due to the increase of the Construction Industry during the 90's. In Puerto Rico, these activities are regulated by law and a permit is required. The Department of Natural Resources is responsible for granting permits required for in-stream activities. The purpose of this study is to analyze if there is streambed degradation near bridges caused by sand and gravel extraction activities and if this effect is being considered during both, scour evaluation and the evaluation for granting permits by the DRNA.*

Key Terms — *Bridge Scour Evaluation, In-stream Mining, Sand and Gravel Extraction, Scour, Scour Critical Bridge, Streambed Degradation.*

INTRODUCTION

Because of the lower cost of overhauling the aggregates, the ideal location for in-stream sand and gravel extraction pit operators is near roads. It is common to see mining activities near bridges over rivers without assessing the impact this have undermining the bridge foundations.

Bridge BR-741, located at Road PR-181 over the Río Grande de Loíza in the Municipality of San Lorenzo, is a three span bridge constructed in 1975. During years there has been a sand and gravel extraction activity from two different operators. As shown in Figure 1 in an aerial photo of 2014 [1], an operator is located upstream and another operator downstream the BR-741. Permits were granted independently by the DRNA for both operators after fulfilling DRNA requirements under Regulation Number 6916 of December 2004 for Extraction, Excavation, Removal and Dredging of Soil [2].

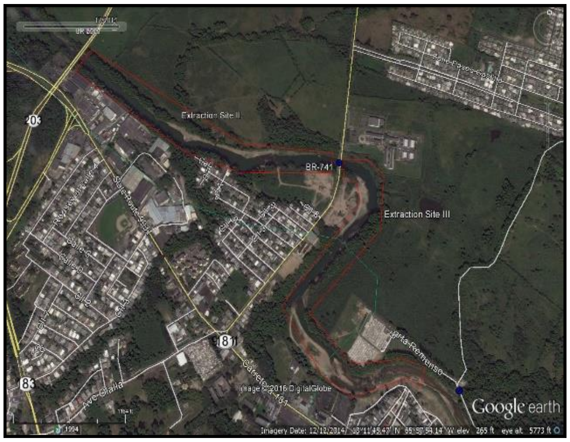

Figure 1
BR-741 PR-181, San Lorenzo

Figure 2 shows sand removal activities being held by operator upstream the BR-741 on the Río Grande de Loíza.

Figure 2
Sand Extraction at Rio Grande de Loíza, San Lorenzo

Bridge BR-2456 is located at Road PR-642, over the Río Grande de Manatí in the Municipality of Manatí as shown in Figure 3 [3]. A sand extraction operation has been held for years upstream the bridge. The river has signs of lateral migration.

Figure 3
BR-2456 PR-642, Manatí

Both bridges are been classified as scour critical after Scour Critical Evaluation was performed by PRHTHA as defined by HEC-18 [4] and following guidelines for the bridge evaluation.

Bridge BR-1374, shown in Figure 4, is located in road PR-149 over the Rio Grande de Manatí in the Municipality of Ciales near another site identified as a gravel pit, but no additional information was a found about the permit for this project. The right abutment of the bridge shows visible scouring and it has been assessed by PRHTA as part of the Scouring Evaluation Program.

Figure 4
BR-1374 PR-149, Ciales

A comparison was made between these bridges and other bridges with similar characteristics that are not subject to an in-stream mining condition to see if a relationship can be establish.

JUSTIFICATION

For compliance with the 2005 National Bridge Inspection Standards (NBIS) bridge owners, like PRHTA, are receiving Federal Funds for the inspection and evaluation of the condition of bridges. A Scour Evaluation and Stream Stability Assessment might be necessary to determine the Plan of Action, if required.

When assessing a bridge stability and safety, HEC-18 includes sand and gravel mining in the observations that will lead to a determination that there has been a potential change in the streambed that can be causing or aggravating a scouring condition in the bridge foundations. If after evaluation, a bridge is identified as scour critical, the rehabilitation or replacement of the bridge might be necessary, as it has become a major concern of safety because of documented history of collapsing bridges due to scouring of their foundations. The Bridge Rehabilitation Program has become one of PRHTA priorities.

Lack of communication between to Governmental Agencies can be the cause that the DRNA could be granting permits inadvertently near bridges that are classified as scour critical. At the same time PRHTA might not be taking into consideration the closeness of gravel pits and the incisions made in the streambed that could lead to channel instability.

An overview of both processes and the parameters required by them could help to improve the monitoring and reduce the scour potential at bridges.

LITERATURE REVIEW

Scour on Bridges can be related to the following factors:

- Channel slope and alignment,
- Channel shifting

- Bed sediment size distribution
- Antecedent floods and surging phenomena
- Accumulation of debris, logs, or ice
- Flow contraction, flow alignment, and flow depth
- Pier and abutment geometry and location
- Type of foundation
- Natural or man-induced modification of the stream
- Failure of a nearby structure [5].

Sand and gravel extraction in the river is one activity that is going to cause changes in the streambed due to the removal of the bed material. Streambed mining for sand or gravel can be beneficial or detrimental, depending on the balance between sediment supply and transport capacity but the usual result of streambed mining is an imbalance between sediment supply and transport capacity.

As shown in Figure 5, when the sediment supply exceeds the transport stream capacity, controlled removal of gravel bars and mining could be beneficial for lateral and vertical streambed stability [5].

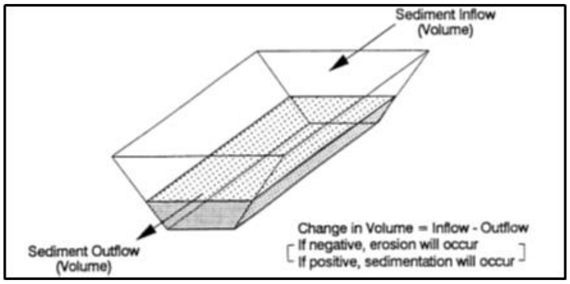

Figure 5
Sediment Continuity Concept Applied to a Given Channel

On the contrary if there is a sediment deficit downstream the point of removal, erosion of the streambed will occur.

The effect of the interruption of the continuity of sediment transport has been called "hungry waters" implying that flow will become sediment starved and therefore, prone to the erosion of channel bed and banks [6].

The response of the streambed to changes was expressed in 1955 by hydraulic engineer E. W. Lane with a stream balance equation. Lane concluded that a stream's energy (function of speed and volume of water), must be in balance with the sediment size and volume being transported by the stream. Figure 6 is a sketch of the relationship between these parameters [7].

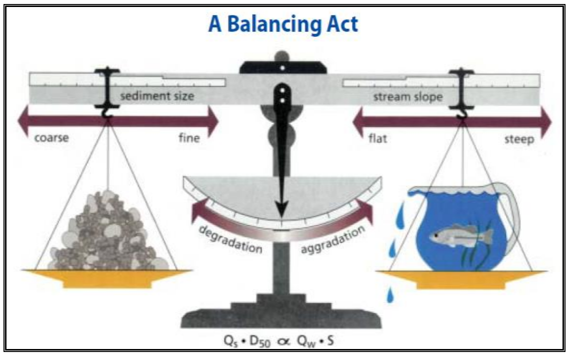

Figure 6
Stream Balance Equation (Lane, 1955)

In other words, a stream is stable when these parameters are at equilibrium as given by (1):

$$Q_s \cdot D_{50} \; \alpha \; Q_w \cdot S \qquad (1)$$

Where:
Q_s = Sediment discharge
D_{50} = Median stone diameter
Q_w = stream flow
S = stream slope

When there is a channel incision, upstream of an extraction operation, the water surface slope may be increased and bank erosion and headcutting or a nickpoint may result as shown on Figure 7 [6].

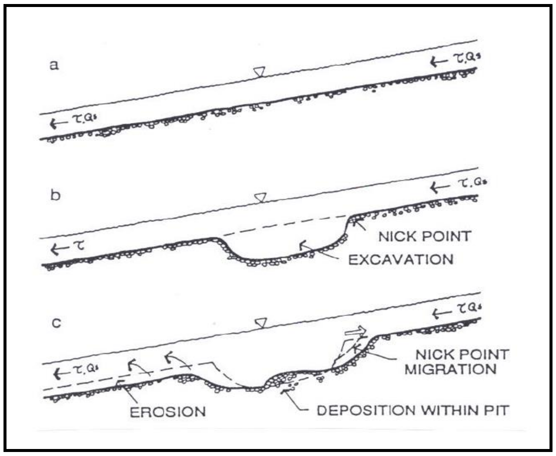

Figure 7
Channel Response to In-stream Gravel Removal

The magnitude of the damage is a function of the volume and depth of the sand and gravel pit relative to the size of the stream, bed material size, flood hydrographs, upstream sediment transport, and the location of the pit. If the size of the borrow pit is large, a large amount of the sediment inflow will be trapped in the pit and degradation will occur downstream. If bank erosion and headcutting upstream of the pit produce a sediment supply greater than the trap capacity of the pit and the transport capacity downstream, aggradations could occur. However, this circumstance is unlikely and streambed mining generally causes degradation upstream and downstream of the pit [5]. The most frequent response is a degrading streambed followed by bank erosion and a new meander pattern.

An important parameter in the sediment transport capacity is the incipient motion which is the condition at which a sediment particle will start moving under the action of the flow. One method commonly used is Shield's approach. Shields uses the critical shear bed stress at which the particle will start to move. The first step in this method is to calculate the critical velocity (2).

$$u_*=(gR_hS)^{1/2} \qquad (2)$$

Where g is the gravitational acceleration, R_h is the hydraulic radius and S the channel slope. With the critical velocity, the Reynolds's number (3) is computed.

$$R_{e*} = \frac{u_* d_{50}}{\nu} \qquad (3)$$

With the value of Re^*, F^* value, from Shield's diagram (Figure 8), is compared with critical stress τ^*, calculated (4) where F^* from the diagram is the shear stress necessary to start a particle motion.

$$\tau^* = \frac{\nu^2}{(S-1(gd_{50}))} \qquad (4)$$

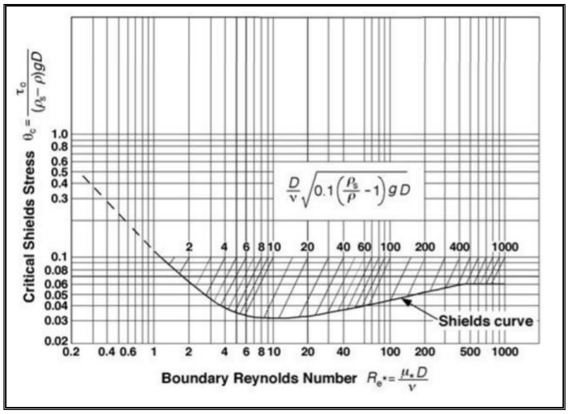

Figure 8
Shield's Diagram

Case Studies

On 1995, the Kaoping Bridge over the Kaoping River in Taiwan, was suffering the undermining of its piers due to the effect of headcutting of over 7 m from in-stream gravel mine located downstream the bridge. As a countermeasure, the downstream margin was protected with gabions and concrete jacks to control the incision as shown on Figure 9 and the gravel mining was prohibited 1 mile from the bridge [6].

Figure 9
Channel Response to In-stream Gravel Removal [4]

But on August 2000, after a typhoon, the bridge had a sudden settlement at one of the piers that caused the bridge to collapse as shown on Figure 10. An investigation headed to erosion of the river bed due to extensive gravel quarrying as the cause for the pier failure [8].

Figure 10
Failure of the Kaoping Bridge

The Cache Creek in California, USA have records of gravel mining since 1940. A plot from a specific gage data for 500 cfs (Figure 11) from 1910 to 1980, shows that the river bed has degraded more than 10 ft (3 m) in this period.

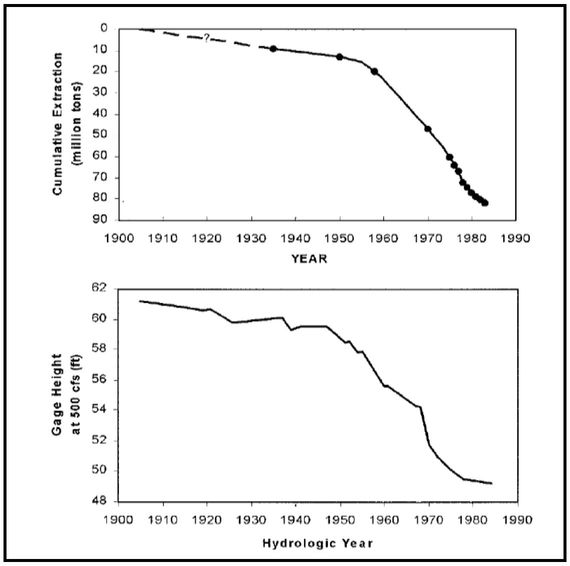

Figure 11
Specific Gage Data for Cache Creek, California

An incision of 4m was made 1400 m downstream the Capay Bridge where the extraction was being held. After a flood in 1992, a nickpoint over 3 m deep extended 700 m upstream. Another heavy flow in 1993, caused the nickpoint to migrate another 260 m excavation and in a 50- yr flood in 1995, the nickpoint migrated under the Capay Bridge, contributing to the near- failure of the structure.

METHODOLOGY

The following steps were taken in the development of this study.

DRNA Records Revision

Over eight Permit Files were reviewed from sand and gravel extraction projects located in two rivers, Río Grande Loíza and Río Grande de Manatí. Both Rivers have bridges classified as scour critical and are known for being a source of aggregates for commercial use. Table 1 summarizes relevant information compiled from these files.

Table 1
Gravel Pits Projects Information

Stream	Mining Projects	Approximate Years of Operation	Approximate Total Volume Extracted per Year (m^3)
Río Grande de Loíza	1	10	109,899
	2	13	80,000
Río Grande de Manatí	3	25	100,000
	4	17	100,000
	5	13	120,000
	6	10	114,000

DRNA Regulations do not authorize dredging activities 100 meters of distance from any structure including bridges. On 2012 the rule was amended to increase that distance to 400 meters. When the excavation exceeds 5,000 cubic meters, an Environmental Impact Assessment is required. An H-H Study and a Sediment Transport Study might also be required. Permits are granted for a year after it can be renovated.

After reviewing selected files, bridges nearby were identified as being scour critical.

PRHTA Records Review

PRHTA Bridge Inspection Reports were also reviewed for highway structures upstream and downstream sand extraction projects.

For bridge BR-741 and BR-2456, PRHTA have completed Phase II, that is, a Hydrologic-Hydraulic Assessment and Scour Analysis Report [9] [10]. A recommendation for a Phase III analysis was given in which a structural stability evaluation under the scour conditions calculated will be made.

Hydrologic-Hydraulic Analysis and Scour Analysis were made using HEC-RAS models for both bridges by PRHTA. Table 2 and Table 3 summarize the HEC-RAS Output for BR-741 and BR-2456 respectively for the 100 YR and the 500 YR events. In both reaches the stream has a subcritical flow.

Table 2
HEC-RAS Output BR-741

River Sta	Profile	Q Total (cms)	Vel (m/s)	Froude #	Slope
1	100 YR	1909	4.33	0.46	
1	500 YR	3246	5.22	0.49	0.0035
2	100 YR	1909	4.40	0.47	
2	500 YR	3246	5.57	0.52	0.0021
3	100 YR	1909	5.20	0.55	
3	500 YR	3246	6.71	0.62	0.0000
3.5		Bridge			
4	100 YR	1909	4.25	0.46	
4	500 YR	3246	4.74	0.42	0.0046
5	100 YR	1909	3.16	0.34	
5	500 YR	3246	3.58	0.32	0.0107
6	100 YR	1909	4.25	0.49	
6	500 YR	3246	4.56	0.43	

Table 3
HEC-RAS Output BR-2456

River Sta	Profile	Q Total (cms)	Vel (m/s)	Froude #	Slope
1.00	100 YR	6,112	5.98	0.58	0.0036
1.00	500 YR	11,574	9.48	0.90	
2.00	100 YR	6,112	6.29	0.62	0.0038
2.00	500 YR	11,574	8.55	0.79	
3.00	100 YR	6,112	4.23	0.40	0.0000
3.00	500 YR	11,574	5.18	0.44	
3.50		Bridge			
4.00	100 YR	6,112	3.99	0.37	0.0027
4.00	500 YR	11,574	4.71	0.39	
5.00	100 YR	6,112	3.25	0.32	
5.00	500 YR	11,574	3.45	0.30	
6.00	100 YR	6,112	2.68	0.26	0.0029
6.00	500 YR	11,574	3.14	0.27	

Inspection Reports files were reviewed for two additional bridges that were on the same river but not near the extraction sites. BR-1149 is on Río Grande de Manatí but 3,000 miles downstream BR-2456 while BR-2505 is 1,000 miles downstream BR-741.

The last step of this study was to develop a Hydraulic model using a Scour Evaluation previously prepared in HEC-RAS by PRHTA and adding a Sediment Transport Analysis including a Dredging Event to compare the scour depths obtained by the two models.

RESULTS

As part of this analysis, a series of comparisons were made to see if there is a difference between parameters like channel streambed degradation and measured scour potential level in bridges located near gravel pits in comparison with structures that are not affected by this condition.

Bed Degradation Comparison

By comparison of field inspection reports, since 1977, it is noticeable a bed degradation on BR-741 in the Río Grande de Loíza. Figure 12 shows a plot of the measurements taken at the field during the last 37 years. The bed elevation on Pier 3 has dropped approximately 3 meters.

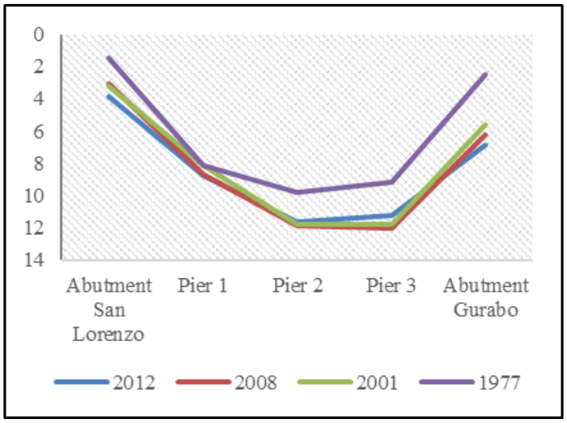

Figure 12
Bed Elevation Plot for BR-741

Figure 13 summarizes the change in bed elevation along a period of time recorded by field inspections from PRHTA for five different bridges. Bridge BR 2505 is located downstream BR 741 in the Rio Grande de Loíza while BR 1149 is downstream the BR 2456 and BR 1374. It is noticeable that higher long term degradation had occurred in bridges that are in a reach with in-stream mining near them.

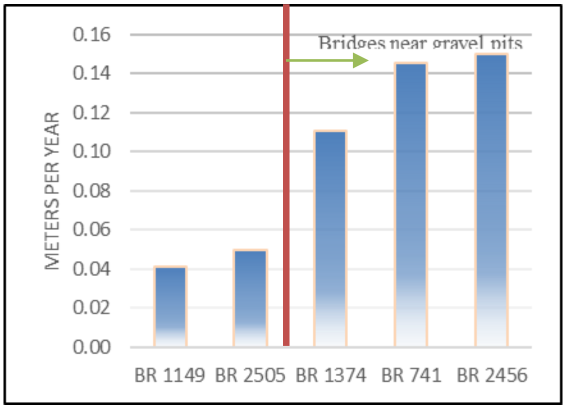

Figure 13
Bed Elevation Change per Year

Incipient Motion Calculation

To understand the behavior of the streambed in the river reach being analyze, the incipient motion was calculated. Results included in Table 4 and Table 5 shows that with the 100 YR and 500 YR event, there will be movement of the sediment particles.

Table 4
Incipient Motion Analysis BR-741

XS	d_s (mm)	τ*	F* Shields
6	0.1917	253.9100	0.053
5	0.1917	288.1033	0.053
4	0.1917	123.6767	0.049
3	0.1917	61.2959	0.045
2	0.1917	96.9041	0.048
1	0.1917	95.5931	0.048

Table 5
Incipient Motion Analysis BR-2456

XS	d_s (mm)	τ*	F* Shields
6	18	1.065	0.06
5	18	0.996	0.06
4	18	0.986	0.06
3	18	1.396	0.06
2	18	1.168	0.06
1	18	1.197	0.06

If transport capacity exceeds sediment supply from upstream reaches, scour will occur. Silty sand like the material from Rio Grande de Loíza Reach will scour more rapidly and could hit maximum depth within hours. This physical characteristic of the bed material can mean that upstream sediment supply might not be filling gravel pits as it was expected from the Sediment Transport Analysis submitted to DRNA.

Scour Depth Comparison

Another comparison made was scour depth within three bridges. BR-741 and BR-2546 were compared a bridge that has also been classified as scour critical. Bridge BR-1917, has some similarities with BR-2456, being located at Rio Grande de Arecibo, it has records of high flows during the last 30 years.

The scour depths found by this analysis are listed in Table 6.

Table 6
Scour Depth

Bridge	**Profile**	**Worst Abutment (m)**	**Worst Pier (m)**
BR 741	100 YR	3.92	8.38
	500 YR	8.15	11.82
BR 2456	100 YR	8.99	8.61
	500 YR	26.96	12.56
BR 1374	Pressure Flow	4.73	5.70
BR 1917	Overtopping Flow	2.97	5.16

These estimated scour depths for the 100 YR, 500 YR and overtopping or over pressure flood events will cause the structures to become unstable and possibly fail.

HEC-RAS Model

HEC-RAS can be used to model the long term changes in bed elevation due to removing bed material in a river stream, by adding a Sediment Transport Analysis with a Dredging Event to a hydraulic model.

A Bridge Scour Evaluation was prepared by PRHTA for Bridge BR-1917 at State Road PR-627, crossing over Río Grande de Arecibo in the Municipality of Arecibo [11]. BR-1917 is an 8 span and 105.31 length structure constructed in 1988. It was classified as an “Unknown Foundation Bridge” and included in the “Scour Evaluation at Various Existing Bridges in Puerto Rico” program for assessment after showing some signs of instability at the river banks and exposed abutments although they were found to be in good condition.

To see if there is a potential scouring problem, a Hydrologic and Hydraulic Assessment and Scour Analysis was performed as established in the NBIS procedures. The overtopping flow was determined iteratively using the HEC-RAS model and was used for the scour analysis instead of the 100 YR flow from recorded data or FEMA flow data. A steady flow analysis was used for the Hydrology-Hydraulic Study for the overtopping, 10YR, 100YR and 500 YR flows.

The parameters used and results for the hydraulic analysis are in Table 7.

Table 7

Hydrologic and Hydraulic Parameters and Results

Parameters	
Overtopping Flow	725 m^3/s
Manning’s Roughness Coefficient	0.036 and 0.24
Hydraulic Results	
Water Surface Elevation	18.98 m
Channel Velocity	2.31 m/s

For the piers, Live-Bed contraction and local scour was computed using Laursen’s Equation and the Colorado State University Equation respectively. For the Abutment scour, Froehlich’s Equation was used. A summary of the results of Scour Analysis are included in Table 8 considering only the worst piers.

Table 8

Scour Analysis Results for BR-1917

Type of Scour	Scour Depth (m)					
	LA	P3	P4	P5	P6	RA
Long-term	-	-	-	-	-	-
Contraction	0.35	0.35	0.35	0.35	0.35	0.35
Pier	-	1.81	1.9	2.19	1.99	-
Vertical Contraction	2.62	2.62	2.62	2.62	2.62	2.62
Abutment	-	-	-	-	-	-
Total	2.97	4.78	4.87	5.16	4.96	2.97

Figure 14 is a Plot of the results obtained for the Bridge showing the elevation and the depth of scour for each abutment and pier.

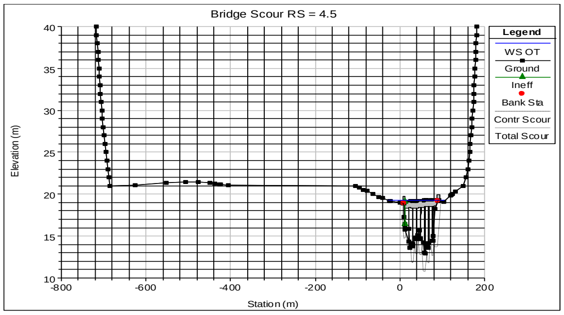

Figure 14

Bridge Scour Results Plot using Steady Flow

A Sediment Transport Simulation was added to the Hydraulic Model in HEC-RAS developed by PRHTA to ponder is there is a change in the amount of scour when using quasi-unsteady flow hydraulics and a Dredge Event which is one of HEC-RAS capabilities.

For the quasi-unsteady flow boundary condition, a flood hydrograph was developed using historic data for the Rio Grande de Arecibo from USGS station 50027600. The flow was calibrated using Suspended Sediment Concentration Rating Curve (See Figure 15).

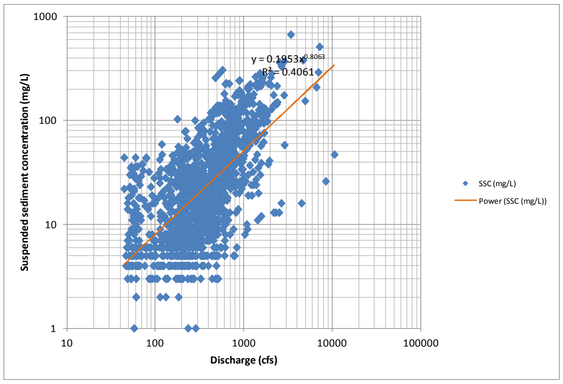

Figure 15

Suspended Sediment Concentration on RGA

The Sediment data used was the same obtained from the Particle Size Analysis from PRHTA Study, defined by class percent. Sediment boundary condition was set as a Rating Curve with the calibrated flows and the total suspended sediment.

The transport function used was Yang's Equation and the fall velocity method used was Ruby's.

HEC-RAS capabilities can include dredging events modeling in which sediment can be removed during a time series defined by the user. A Dredge Event was added to the model in which a 60 m wide by 1 m, 2m and 3m depth of the river bed material is removed between Station 6 to Station 8 for a 21 days period in the 41 days period analyzed. This considers that DRNA prohibits excavating 100 m and more recently 400 m from any structure.

After performing a Sediment Transport Analysis, a computation of the bridge scour was made with HEC-RAS Bridge Scour application using the new hydraulic parameters. Figure 16 and Figure 17 shows the Bridge scour plot for the day 1 and 41 respectively.

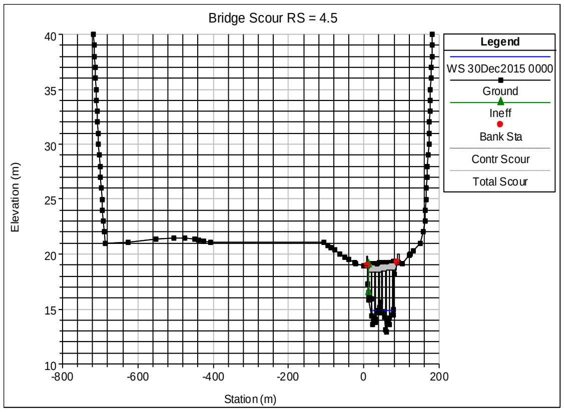

Figure 16
Scour Results Plot with Quasi- Unsteady Flow (Day 1)

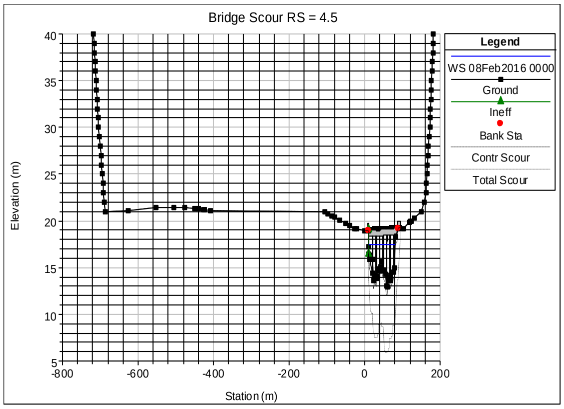

Figure 17
Scour Results Plot with Quasi- Unsteady Flow (Day 41)

The Results of HEC-RAS scour computations are summarized in Table 9.

Table 9
Scour Analysis Results for BR-1917

Profile	Total Scour Depth (m)			Flow (cms)
	LA	Worst Pier	RA	
Day 1	0.00	0.00	0.37	1.36
Day 23	0.00	4.09	0.72	80.94
Day 41	0.99	6.26	4.98	725.00

*Results for 1m depth excavation

The difference in scour depth for the worst pier when using this approach is 1.1 m larger when comparing with results of the steady flow analysis. Nevertheless, the right abutment will suffer an increase of 2.01 meters of its scour depth.

When the depth of the excavation is increased in 1 m, the scour depth is increased in 0.68 m which has to be taken into account (See table 10).

Table 10
Scour Analysis Results for BR-1917

Channel Incision Depth (m)	Profile	Worst Abutment Scour (m)	Worst Pier Scour (m)
1m	Day 41	4.98	6.26
2 m	Day 41	5.24	6.78
3m	Day 41	5.04	6.94

Figure 18 shows the difference in bed elevation at Station 4 where the bridge is located. The plot illustrates the change in elevation in a time period before and after the dredging event.

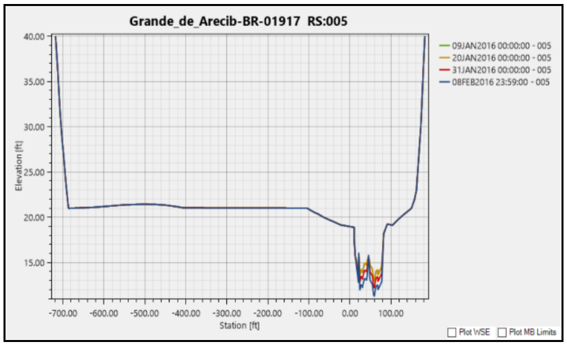

Figure 18
Channel Bed Change in Elevation at Station 4

CONCLUSIONS AND RECOMMENDATIONS

Different factors in the dynamic streambed of a channel can affect stream stability. Natural changes can have an impact in river morphology but if these factors are combined with human activities like sand and gravel mining, it can adversely affect the river stream. When a bridge substructure is already being scoured, dredging activities are going to accelerate possible failure of the structure putting at risk lives and property.

The findings on the research of documents and historic data available of the sample of bridges selected suggest that a relationship can be established between in-stream mining and the undermining of bridge foundations. Comparing the amount of streambed degradation between the river reaches that are being impacted with extraction activities and highway structures that are not affected by this type of human activities it is patent that is a strong factor aggravating if not causing the condition.

The other factor that became evident during this study and that add up to the problem is the misinformation caused by the disconnection between PRHTA and DRNA.

Some actions can be taken to minimize these effects:

- When granting a permit for dredging or sand and gravel extraction, DRNA should include PRHTA as part of the Agencies that has to endorse these projects. If the bridge is already scour critical permit shall not be granted.
- As part of DRNA requirements, when there is a bridge, a scour evaluation analysis should always be included with the H-H Study and Sediment Transport Study.
- Improvements in DRNA recordkeeping and divulgation of the location of gravel pits will help PRHTA in the monitoring and countermeasures maintenance when there is know that dredging activities are been develop near bridges.
- PRHTA has to improve channel stability monitoring as this could prevent future scouring by assessing promptly any instability or channel migration signs. Bed cross sections should be taken every two years as part of field inspection.
- Improvements in data collection, mapping and interagency communication.

Future work in this field could include a larger sample of bridges in rivers that are known to be impacted by in-stream mining and consider difference in type of foundation, bed material and take into account other factors that could be affecting the river balance.

REFERENCES

[1] Google Earth v. 7.1.5.1557. (October 31, 2006) Road PR-741, San Lorenzo, Puerto Rico. 18º11"47.83"N, 65º57'57.57.23" W. Eye alt, 7029 ft. Image U.S. Geological Survey 2016. http://www.earth.google.com. [Accessed: May 20, 2015].

[2] *Reglamento para Regir la Extracción, Excavación, Remoción y Dragado de los Componentes de la Corteza Terrestre,* Reglamento Núm. 6916 de 17 de diciembre de 2004.

[3] Google Earth v. 7.1.5.1557. (December 8, 2014) Road PR-627, Manatí, Puerto Rico. 18º23"47.29"N, 65º29'42.79"W. Elevation 55 ft. Image Digital Globe 2016. http://www.earth.google.com. [Accessed: May 20, 2015]

[4] *Hydraulic Engineering Circular No. 18 – Evaluating Scour at Bridges*, 5th Ed., USDOT - FHWA, D.C., April 2012.

[5] *Hydraulic Engineering Circular No. 20 – Stream Stability at Highway Structures*, 4th Ed., USDOT - FHWA, D.C., 2012, pp. 3.22, 2.24-8.2.

[6] G. Mathias Kondolf, "Hungry Waters: Effect of Dams and Gravel Mining on River Channels", Environmental Management Vol. 21, No. 4, 1997, pp. 533-551.

[7] *"The Effects of Human Activities on Stream Dynamics"* May 2001. Available at: http://www.nrcs.usda.gov/ Internet/FSE_DOCUMENTS/nrcs141p2_029232.pdf.

[8] Chuang Chi-ting, "Safety of bridges to be investigated following collapse", *The Taipei Times,* August 29, 2000.

[9] "Bridge Inspection Report Bridge 741", PRDOT – PRHWA, S.J., P.R., April 2014.

[10] "Bridge Inspection Report Bridge 2456", PRDOT – PRHWA, S.J., P.R., February 2012.

[11] "Bridge Inspection Report Bridge 1917", PRDOT – PRHWA, S.J., P.R., September 2012.