Appendix G: Bank Stabilization and Bridge Scour

1 Background

During an initial site visit conducted on 26 October 2018, the non-federal sponsor and local municipal and state representatives noted areas where flood-induced bank failure caused by Hurricane Maria is threatening key pieces of transportation infrastructure. Infrastructure at risk of failure during future flood events include:

1. PR-6685: PR-6685 runs along the west side of the Rio Grande de Manati and represents the only access route southeast to the City of Ciales (Ciales) and northwest to the City of Manati (Manati) to several communities within the study area.
2. PR-149 Bridge: PR-149 represents a major transportation corridor through Puerto Rico. PR-149 and the associated PR-149 Bridge connect Ciales with the City of Manati, which is the nearest place for residents of Ciales to receive many critical services (e.g., hospitals).
3. PR-145: PR-145 runs along the west side of the Rio Grande de Manati and represents a major route extending eastward from Ciales.

Failure of one or more of these pieces of infrastructure would have considerable transportation (i.e., detours and transportation delays) and life-safety (i.e., evacuation before or during another flood event, ability to access and/or receive critical services and recovery aid) consequences. Consequently, the local sponsor and municipal and state representatives requested these areas of flood-induced bank failure and associated risks be addressed within the Rio Grande de Manati (Ciales), Puerto Rico Feasibility Study.

Although flood-induced bank failure and bridge scour were identified as distinct problems within the study area, no direct link could be made between bank instability/scour and flood inundation. Consequently, neither the study authority nor USACE policy (USACE, 1999) permit the study, recommendation, or implementation of measures designed to address bank instability and/or bridge scour along the Rio Grande de Manati. However, the team did identify bank stabilizataion and scour to protect the eroding streambanks as a related water resource problem. This appendix is provided to inform other resource or Commonwealth agencies that may be the appropriate organization to address these issues.

2 Problem Description

This section provides an introductory analysis of existing data in an effort to characterize the stability and scour problems that contribute to elevated risk to PR-6685 and the PR-149 Bridge. Potential impacts to life and safety risk are also briefly discussed.

2.1 PR 6685

2.1.1 Analysis of Existing Data

Geotechnical data taken from upstream of this focal area in 2008 show silts and clays mixed with sand underlain by granular, broadly graded soils primarily consisting of sand and gravel for a depth from 10 to 15 feet (Table 1).

Table 1. Laboratory test results of particle size distribution, Flood Control Works, Dos Rios, 2005.

Boring	Depth (ft.)	USCS	Gravel (%)	Sand (%)	Fines (%)
B-11	2	MH	0	44	56
B-14	2	SC	4	68	28
B-4	4	SC	0	61	39
B-12	4	SC	14	50	36
B-16	4	SM	11	69	20
B-4	6	SC	0	50	50
B-13	6	SC	0	54	46
B-6	8	GP-GM	82	13	5
B-12	8	GP-GM	72	23	5
B-13	8	GC	61	26	13
B-10	9	CH	5	32	63
B-4	13	SM	0	66	34
B-7	13	SC	0	68	32
B-2	18	SW-SM	3	88	9
B-3	18	GP	58	37	5
B-3	18	SP-SM	32	63	5
B-6	18	SW-SM	47	48	5
B-1	23	SW-SM	26	69	5
B-2	23	SM	27	61	12
B-5	33	GW-GM	64	29	7

Critical velocities for these soils range from 30 to 60 cm/sec as characterized by the Natural Resource Conservation Service (Part 654 Stream Restoration Design National Engineering Handbook, Chapter 8, August 2007) and USACE (EM 1110-2-1601) (Table 2).

Table 2. Critical velocities for soil materials. Italicized values indicate predominant soil material (see Table 1) and associated critical velocities.

Soil Type	Critical Velocity (cm/s)
Clay	60 – 80
Clay and Sand	*30 – 60*
Fine Sand	10 – 30
Coarse Sand	20 – 50

Hurricane Maria resulted in lateral migration of the left bank 35 feet towards PR-6685 (Fig. 1). As of November 2017, PR-6685 was 25 feet from the edge of bank (Fig. 2). Post-Maria Light Detection and Ranging (LiDAR) indicates the current side slope of the left bank is approximately 1.75:1 in this area.

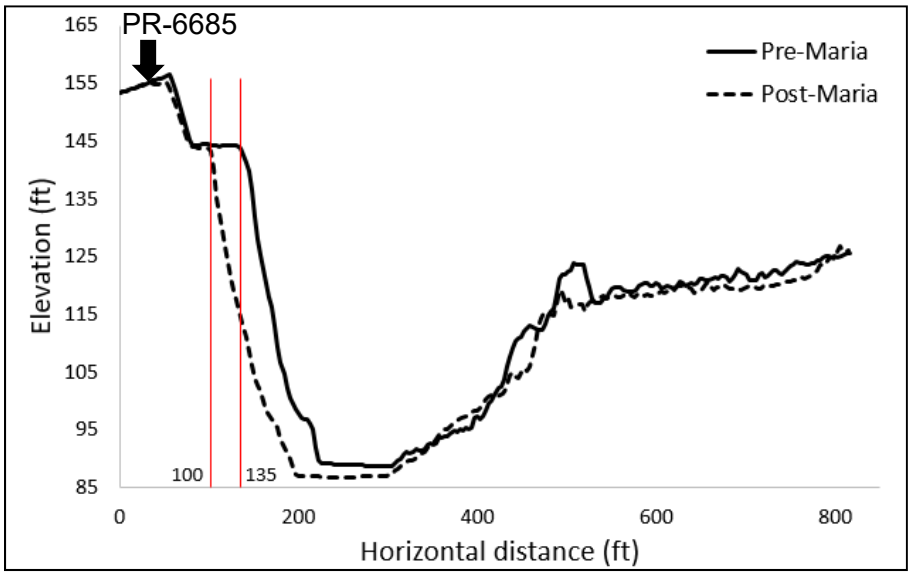

Fig. 1. Cross section (looking downstream) showing pre- (2015) and post-Maria (2018) LiDAR immediately adjacent to PR-6685. Red lines denote lateral migration of 35 feet during Hurricane Maria. Arrow denotes approximate locate of PR-685.

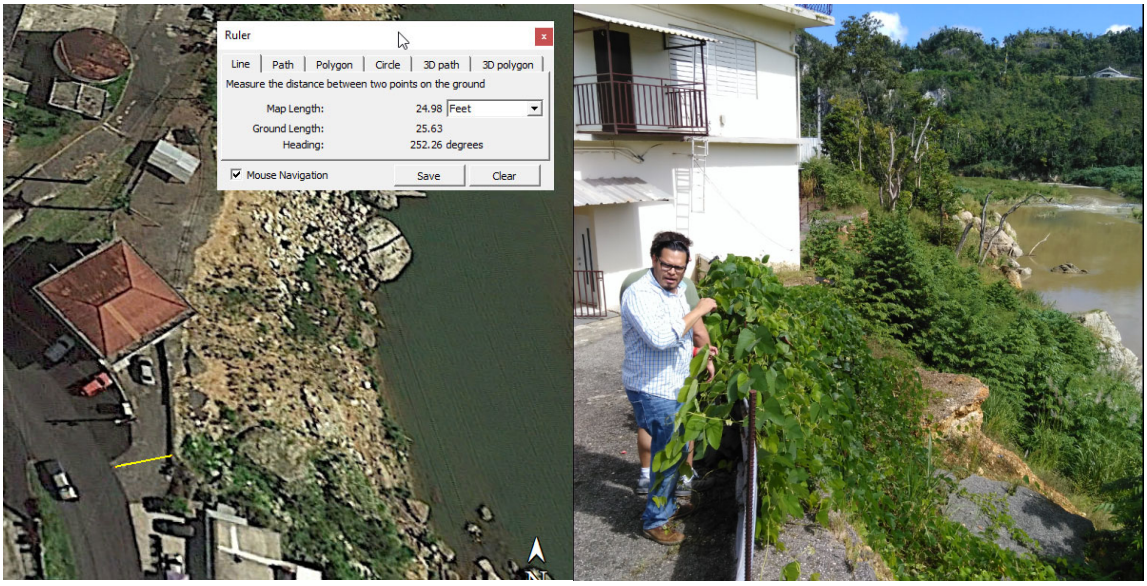

Fig. 2. Left: Aerial image from November 2017 showing post-Maria conditions adjacent to PR-6685. The yellow line and associated ruler measurement indicate the road is 25 feet from edge of bank. Right: Image taken in October 2018 of the bank failure adjacent to PR-6685.

The Rio Grande de Manati United States Geological Survey gauge upstream of Ciales (50035000) indicated an approximate duration of 5 to 6 days with an estimated peak discharge of 284,000

cfs during Hurricane Maria (Fig. 3). The existing FEMA model estimates the Hurricane Maria flood to be between a 0.005 and 0.002 AEP event. The current FEMA model suggests water velocities at this location exceed the critical velocity of 60 cm/sec at the 0.5 AEP flood event (Fig. 4).

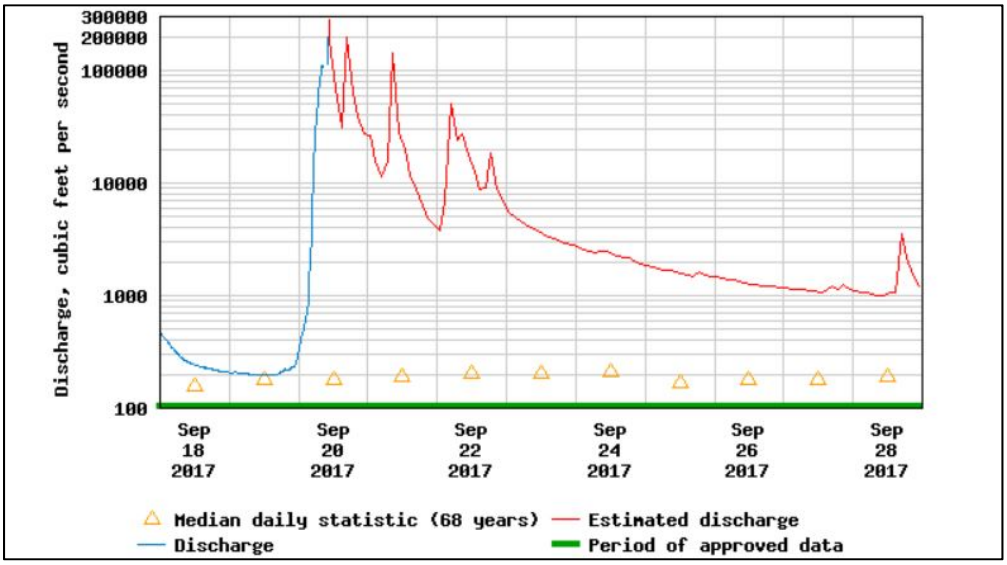

Fig. 3. Hydrograph from USGS 50035000 gage upstream of Ciales during Hurricane Maria.

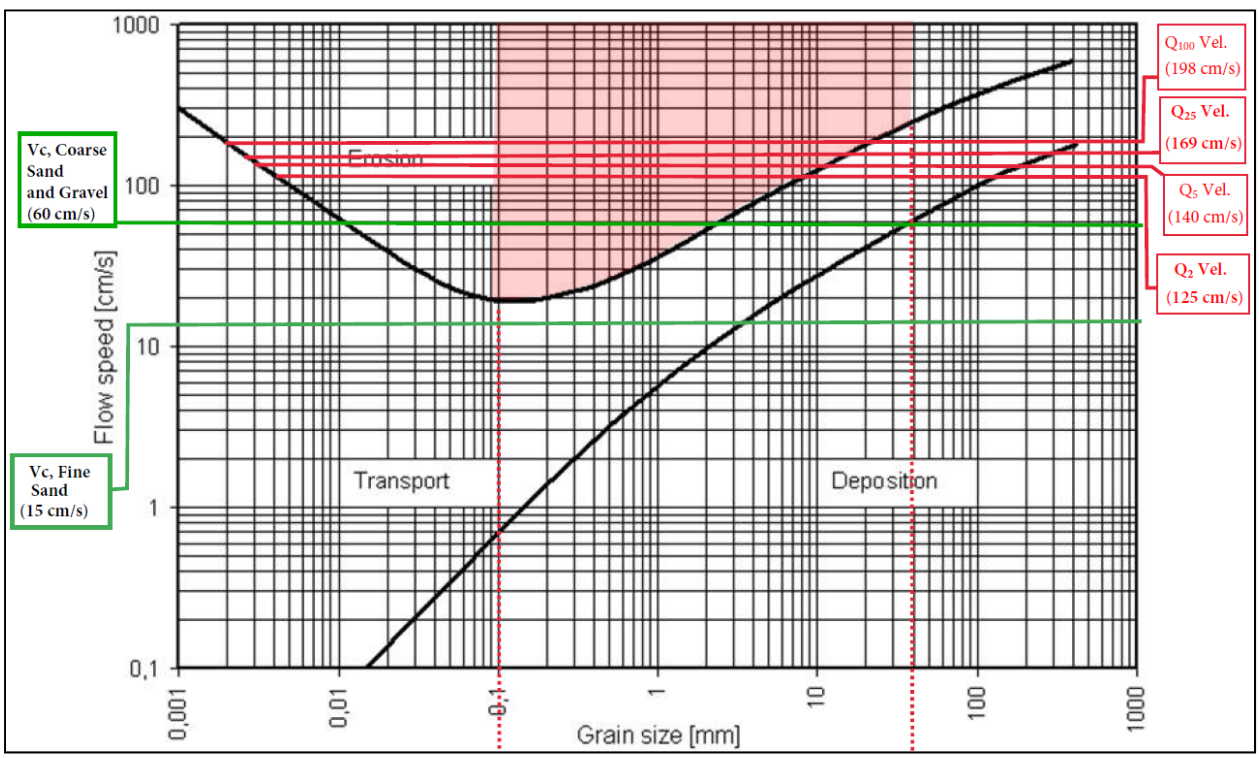

Fig. 4. Hjulstrom diagram characterizing flows at which various particle sizes are eroded, transported, and deposited in river systems. Flood event velocities (Qv, red boxes and lines) are compare to critical velocities (Vc, green boxes and lines). The shaded red area indicates velocities

capable of eroding particle sizes observed in the soil data. Flow velocities reflect frequency analyses included in the FEMA model.

Water surface elevations extend to or beyond the top of the left bank slope during floods that equal or exceed the 0.01 AEP event (Fig. 5). Erosion during these events are capable of undermining non-cohesive soils on the left bank. Such erosion was observed during Hurricane Maria, and equivalent erosion under a subsequent floods that equals or exceeds the 0.01 AEP event would likely further erode the bank and cause failure of PR-6685.

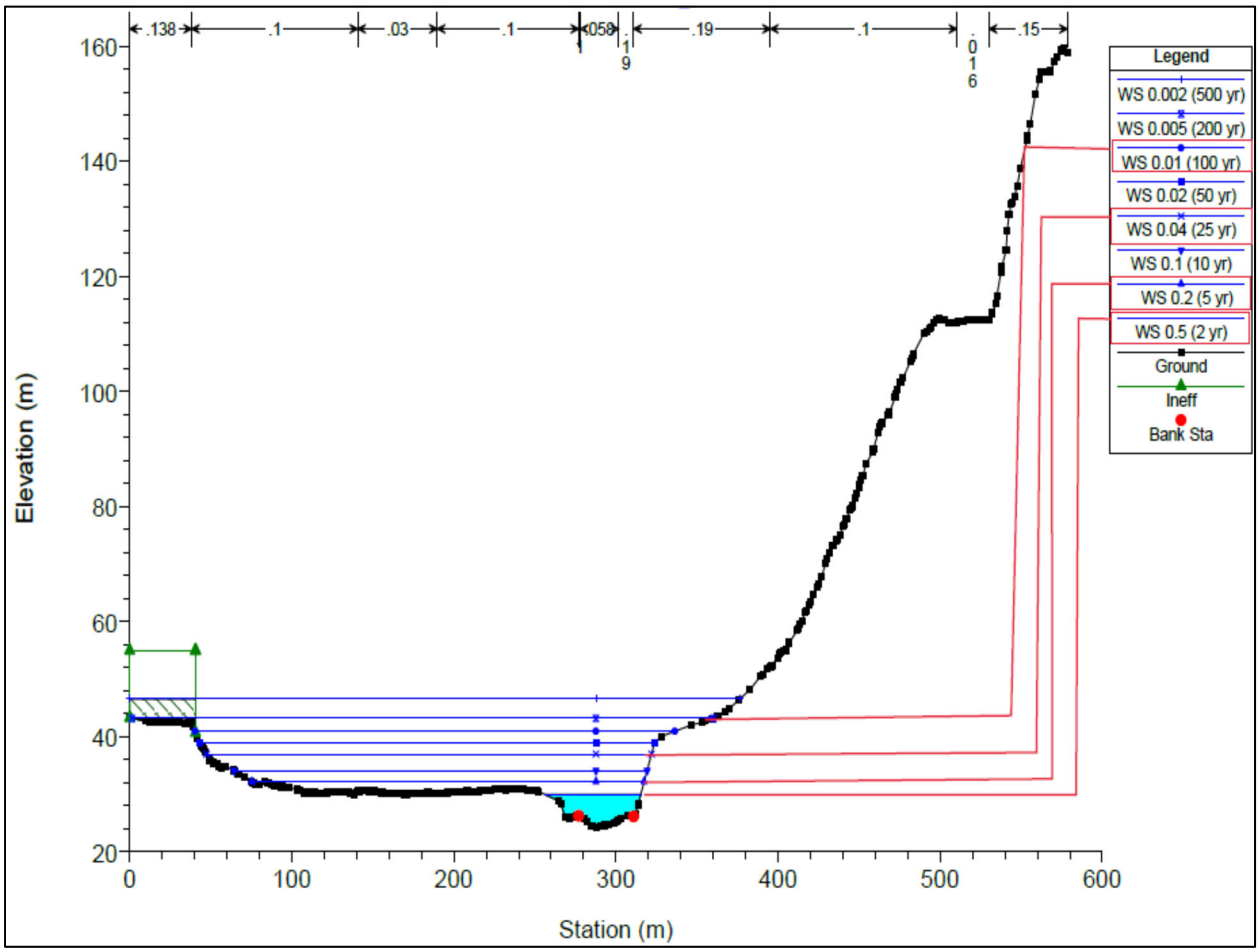

Fig. 5. 1D, steady state HEC-RAS model generated water surface elevations adjacent to PR-6685. Water surface elevations reflect frequency analyses included in the FEMA model. *Note: Location of cross section is different from that shown in Fig. 1. Also note differences in units (m) as compared to those shown in Fig. 1 (ft).*

The second highest flood event with continuous data from the USGS 50035000 gage upstream of Ciales occurred in 1996, with a flow of 128,000 cfs and an approximate 3-day high flow duration (Fig. 6). This event equates to between a 0.05 and 0.02 AEP flood event as characterized by the flow frequency analysis included in the FEMA model. Existing models suggest this event would have velocities in excess of the 60 cm/sec critical velocity; however, flood elevations would only

reach the toe of the left bank slope (Fig. 5). Comparison of historic aerial imagery (1995 – 2016) indicates no significant channel movement during this, or the 15 subsequent events exceeding flood stage, prior to Hurricane Maria (Fig. 7). Thus, erosion during all other observed flood events was not sufficient to cause bank failure.

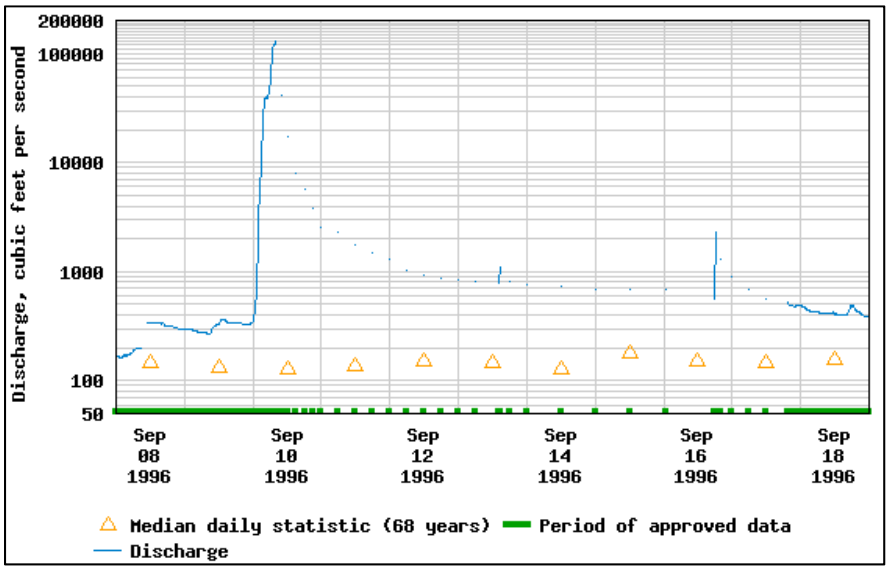

Fig. 6. Hydrograph from USGS 50035000 gage upstream of Ciales during September 1996 event.

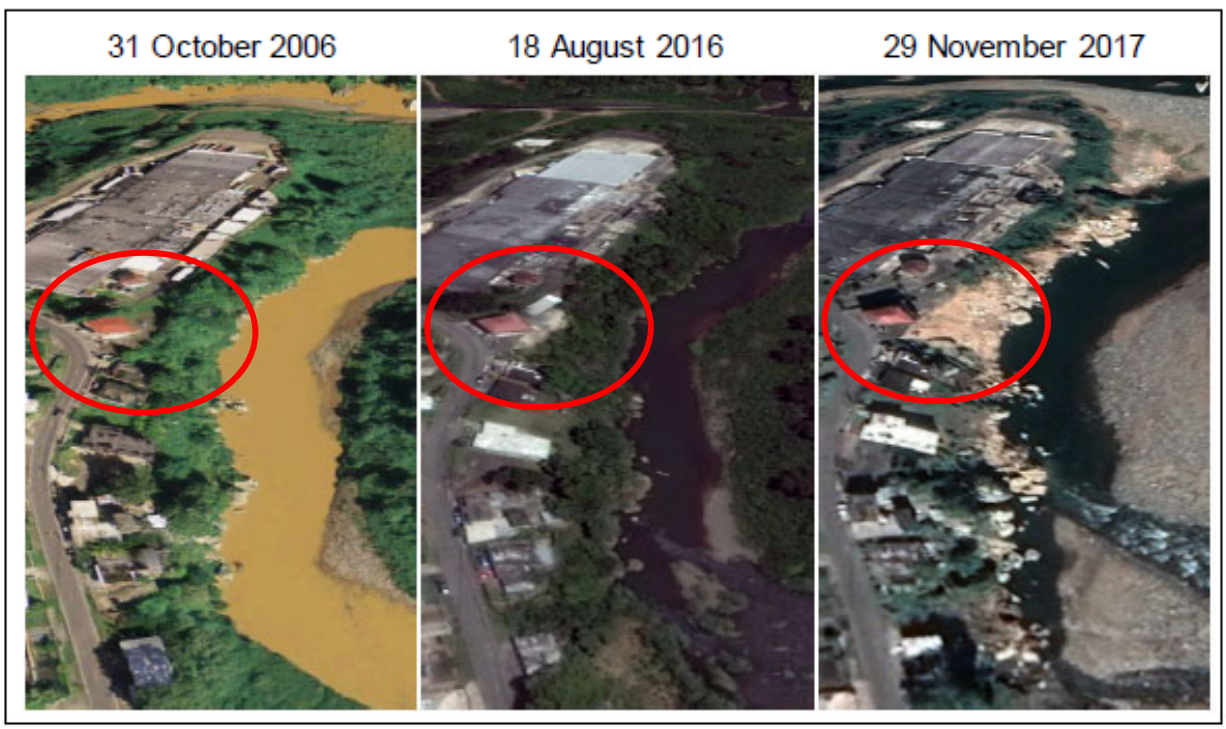

Fig. 7. Time series of aerial imagery indicating a stable stream channel adjacent to PR-6685 from 2006 through 2016 and flood-induced bank failure following Hurricane Maria in 2017 (see Fig. 1). Red circles denote the area of concern.

2.1.2 Life Safety Risks & Socioeconomic Impacts

Failure of PR-6685 would impact the ability of many residents to access Ciales Pueblo—the nearest population center. There is essentially only one possible detour that would provide access to Ciales if this segment of PR-6685 fails. The detour starts at the area of concern, which is located between Alturas De Ciales and the large industrial facility. The detour continues north along PR-6685, across the PR-6685 Bridge, and then back on PR-6685 North. Once PR-6685 ends, the detour briefly goes along PR-6633 and then continues onto PR-149 South. Eventually, the detour leads to the PR-149 Bridge, which leads to the City Center of Ciales. The length of the detour is approximately 3.64 miles. This detour would impact the ability of residents to access critical facilities and recovery aid, as well as have economic impacts to residents utilizing the detour (e.g., time of travel, gas and vehicle wear and tear).

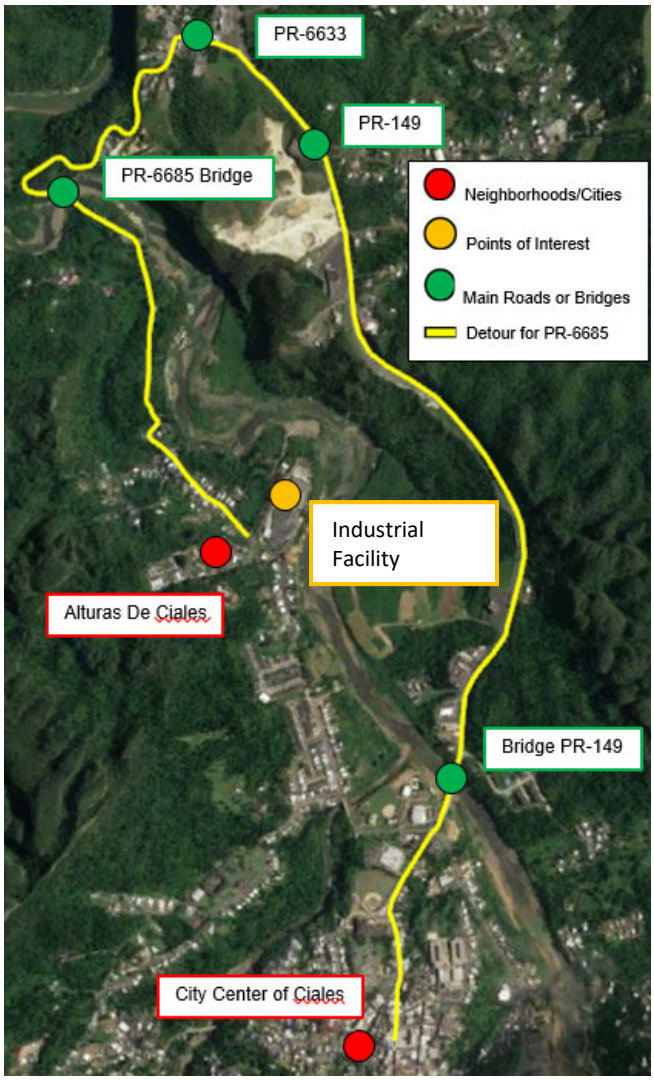

Fig. 8. Map indicating the PR-6685 detour that would be required if the at-risk section of PR-6685 would fail due to flood-induced bank failure.

2.1.3 Conclusions

Preliminary analyses indicate that section of PR-6685 in question is at increased risk of failure during events that equal or exceed the 0.01 AEP flood event. Historic performance suggests single events less than the 0.01 AEP event do not cause erosion capable of undermining PR-6685. Flooding during Hurricane Maria resulted in lateral movement of the left bank an estimated 35 feet toward PR-6685. The area of bank inundated during events greater than or equal to the 0.01 AEP flood consists of cohesionless, broadly graded sand and gravel, which would be erodible under much more frequent events (i.e., 0.5 AEP peak velocity based on existing HEC-RAS model). Given the steep nature of the slope, erosion along the toe would likely result in significant material sliding and subsequent removal.

Failure of PR-6685 would require a 3.64 mile detour to access Ciales Pueblo. This detour would have implications for accessing critical services in Ciales Pueblo and receiving recover aid. The detour would also have economic impacts (e.g., travel time, cost of gasoline, and vehicle wear and tear) to those individuals forced to utilize the detour.

2.2 PR-149 Bridge

2.2.1 Analysis of Existing Data

2.2.1.1 Structural Information

The PR-149 Bridge was constructed in 1975. The bridge is four-span with two spill through abutments and three pile bents (Fig. 9). The bridge superstructure is composed of a concrete flat slab deck poured in place over top concrete, pre-cast, pre-stressed girders. Each concrete-reinforced pier is composed of a concrete column with a round tip supported on piles. Intermediate bridge piers are founded on concrete pile caps supported by vertical and battered driven steel HP 12x53 piles. Piles are assumed to be driven and tipped in very dense sand and gravel/boulder to volcanic rock. The right abutment is founded on spread footing bearing on weathered rock. The left abutment is founded on vertical and battered driven steel HP 12x53 piles. Information on bridge construction was obtained from the Puerto Rico Highway and Transportation Authority (PRHTA) Scour Phase 1 Bridge 1374 (i.e., for the PR-149 Bridge).

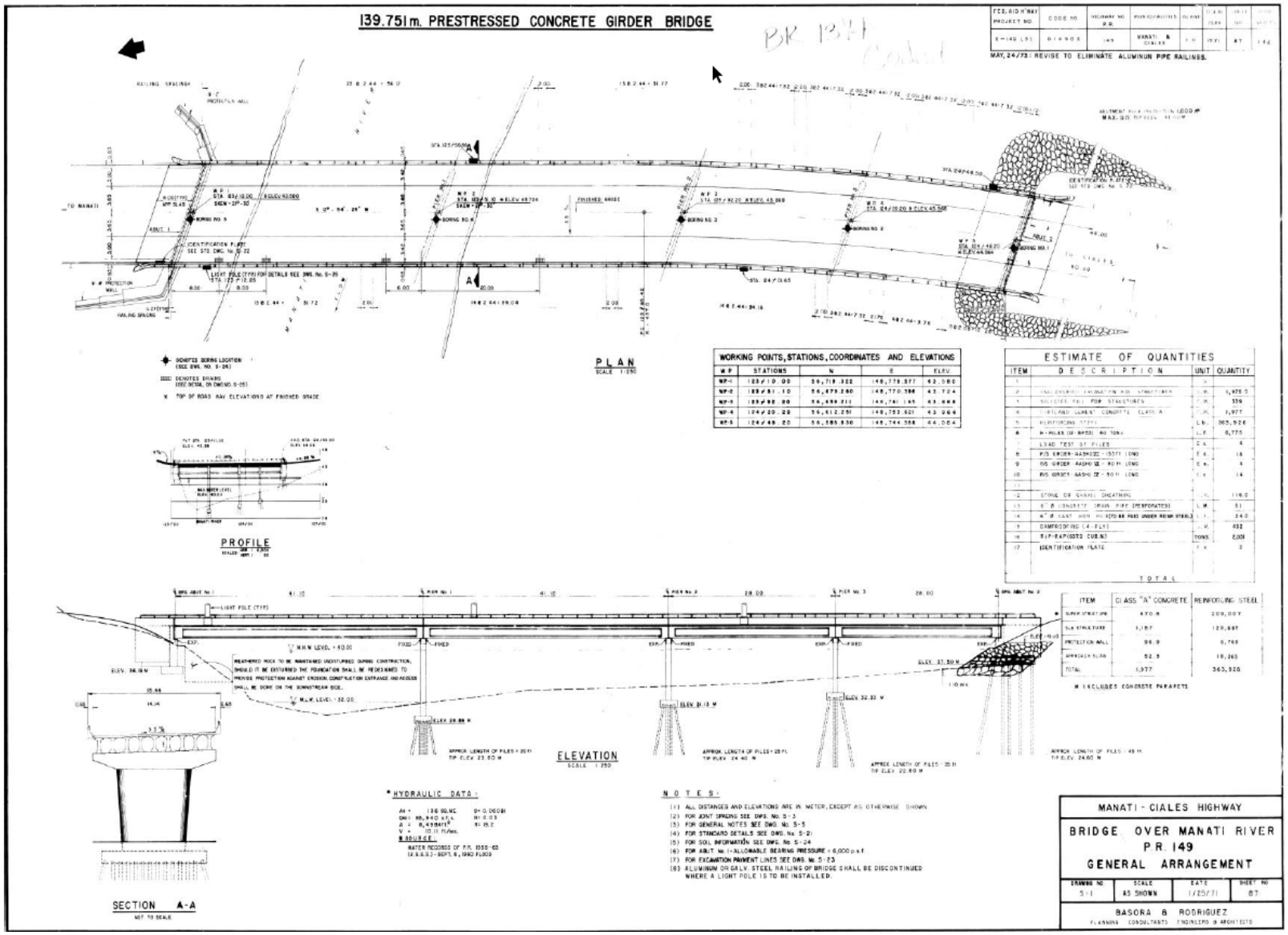

Fig. 9. General arrangement and construction of the PR-149 Bridge. Obtained from the Phase 1 Scour Report (Scour Evaluation Report Phase 1, Data Collection & Qualitative Analysis, Bridge Number 1374, April 2011)

2.2.1.2 Geotechnical and Hydrologic Information

The PR-149 Bridge was designed for (at the time of analysis) a 0.02 AEP flood event with a discharge of 85,940 cfs. The design flood is lower than the 0.02 AEP flood reported by the current HEC-RAS model (FEMA FIS, 2009; 143,731 cfs). The estimated peak flow during Hurricane Maria (284,000 cfs) was 3.3 times the 50-year design discharge. The existing FEMA FIS model indicates flow velocity increases as it passes the bridge due to contraction and end effects and that these velocities exceed critical velocities (Fig. 10).

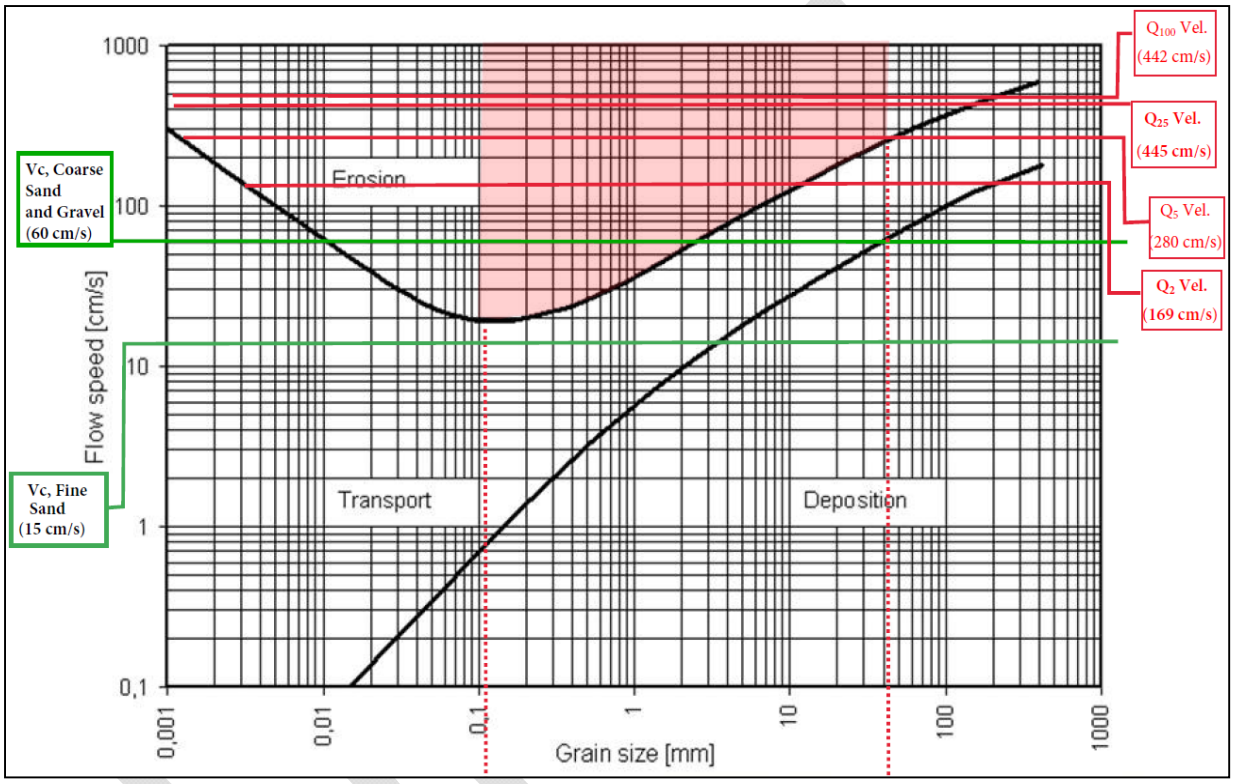

Fig. 10. Hjulstrom diagram characterizing flows at which various particle sizes are eroded, transported, and deposited in river systems. Flood event velocities (Qv, red boxes and lines are compared to critical velocities (Vc, green boxes and lines). The shaded red area indicates velocities capable of eroding particle sizes observed in the soil data. Flow velocities reflect frequency analyses included in the FEMA model.

Five borings were performed as part of subsoil investigation for the Bridge over Manati River (PR-149 Bridge) in March 1971. The soil profile described by the test borings indicate except at the right abutment, the presence of deep flood plain and channel deposit. Individual borings indicate scourable material associated with the left abutment (clayed sand top10 feet followed by sand and gravel to the depth of 42 feet), pier 3 (sandy clay and sand top 8 feet followed by sand gravel and boulders to the depth of 41 feet), pier 2 (clayey sand top 2 feet followed by sand, gravel and boulders up to 47 feet), and pier 1 (sand, gravel and boulders top 17 feet). The boring at the right abutment shows the top 12 feet of brown stiff clay followed by clayey sandy silt (heavily weathered volcanic rock) to the depth of boring of 55 feet. In general, the top 10-12 feet of

alluvial soils is loose to medium dense. Below this depth, the sand and gravel are dense to very dense. Existing hydrologic and geotechnical data were obtained from the Puerto Rico Highway and Transportation Authority (PRHTA) Scour Phase 1 Bridge 1374.

2.2.1.3 Pre-Maria Scour Analyses

PRHTA contracted a four-phase scour evaluation report for the PR-149 Bridge conducted from 2011–2013. Phase 1 (Scour Evaluation Report Phase 1, Data Collection & Qualitative Analysis, Bridge Number 1374, April 2011) included an analysis of existing data and a field investigation to determine the susceptibility of the bridge to scour. This report documented the following evidence of scour susceptibility:

- The foundation of pier 1 is exposed.
- Scour was observed around pier 1 and right abutment concrete protections.
- Pressure flow might aggravate existing scouring at the pile cap foundations.
- Sand bar accumulations and exposed pile cap foundations indicate vertical and horizontal instabilities.

Phase 2 (Scour Evaluation Report Phase 2, Hydrologic/Hydraulic Assessment for Scour Analysis, Bridge Number 1374, April 2012) used the FEMA hydraulic model (based on HEC-RAS 4.1.0) to model scour under the pressure flow (165,978 cfs) and 0.01 (211,075 cfs) and 0.002 (399,338 cfs) AEP flood events. The pressure flow was determined to be the most critical scour condition. Estimated scour depths were between 2.92 and 5.05 meters during pressure flow (Table 4)

Table 4. Estimated scour depths under pressure flow for the PR-149 Bridge. Refer to Fig. 10 for locations and relative depth of scour for each bridge component.

Bridge Component	Scour Depth (m)	Scour Elevation (m)
Pier 1	2.92	24.87
Pier 2	3.37	29.95
Pier 3	5.05	32.80
Left Abutment	3.60	36.96
Right Abutment	4.73	35.78

Estimated scour depths under pressure flow are within the limits of the piles for pier 1 and pier 2, within the limits of the pile cap for pier 3, and below the right abutment foundation (Fig. 11).

DRAFT

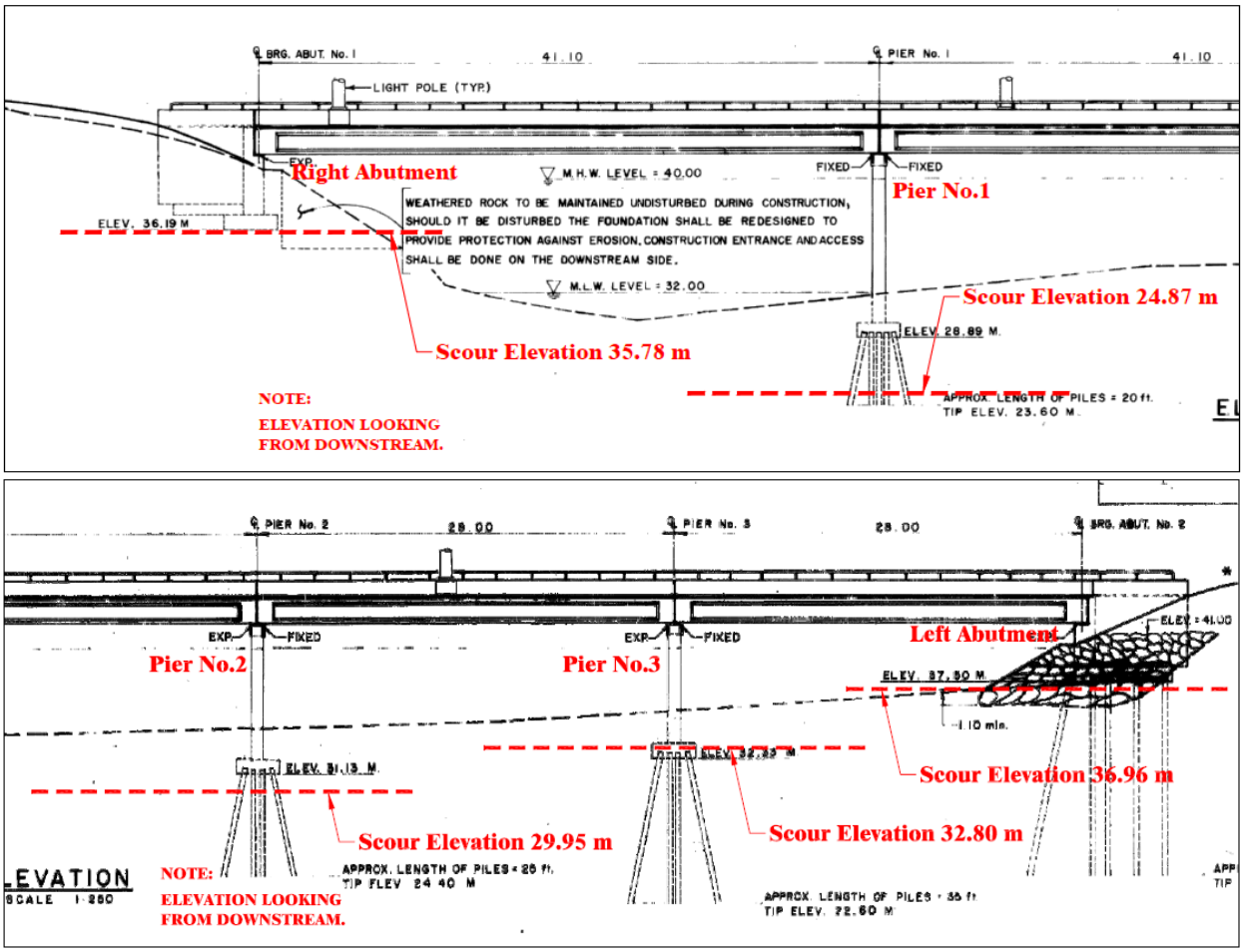

Fig. 11. Elevations and depths of estimated scour under pressure flow relative to affected components (i.e., abutments, piles and pile caps) of the PR-149 Bridge (Scour Evaluation Report Phase 2, Hydrologic/Hydraulic Assessment for Scour Analysis, Bridge Number 1374, April 2012).

Phase 3 (Scour Evaluation Report Phase 3, Bridge Number 1374, October 2012) entailed a geotechnical and structural evaluation of the PR-149 Bridge to determine stability of the abutments and piers. Lateral load capacity analysis suggests the foundations would be laterally unstable at estimated scour depths under pressure flow (Table 4, Fig. 11). Consequently, the PR-149 Bridge was rated as scour critical.

These scour estimates were for the pressure flow as characterized by the FEMA HEC-RAS model. The pressure flow had an estimated discharge of approximately 166,000 cfs and was characterized as between a 0.02 and 0.01 AEP flood event as characterized by the FEMA model.

2.2.1.4 Post-Maria Bridge Inspection & Analysis

A post-Maria bridge inspection was completed to assess damage and determine if the bridge was safe for traffic. The footing on pier 2 was exposed (Fig. 12) and the rock protection on the right abutment had collapsed (Fig. 13) – the latter of which has since been repaired.

Fig. 12. Exposed footing on pier 2 following Hurricane Maria.

Fig. 13. Damaged left abutment protection following Hurricane Maria.

This scour is likely the result of vertical and horizontal turbulence downstream of the Bridge observed during Hurricane Maria (Fig. 14).

Fig. 14. Photo showing turbulence downstream of PR-149 Bridge that likely led to erosion of piers and the right abutment.

Scour immediately upstream of the left abutment observed during the post-Maria bridge inspection suggests bank materials are susceptible to erosion (Fig. 15).

Fig. 15. Scour adjacent to pier 1 and the right bridge abutment following Hurricane Maria.

Pre- and post-Hurricane Maria LiDAR-based elevation data indicate failure and loss of up to 6 vertical and 52 feet horizontal feet of stream bank in the vicinity of the PR-149 Bridge (Fig. 16).

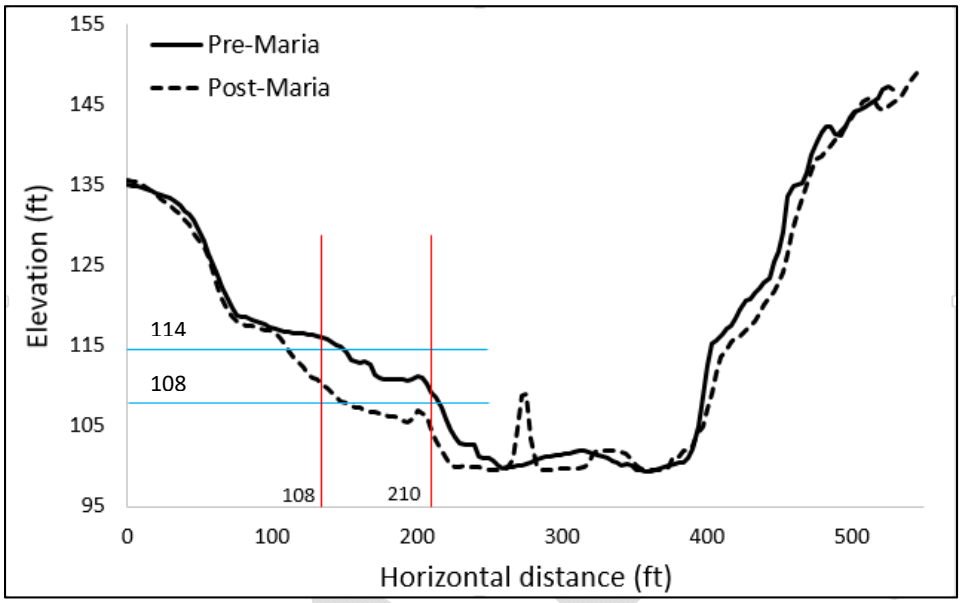

Fig. 16. Comparison of pre- and post-Maria LiDAR showing extent of vertical (blue lines) and lateral (red lines) erosion adjacent to pier 3 and the left abutment.

2.2.2 Life Safety Risks & Socioeconomic Impacts

PR-149 represents a major highway connecting the northern and southern portion of Puerto Rico. The PR-149 Bridge provides residents of Ciales access to nearby populations centers, such as Manati Morovis, and associated critical services and facilities (e.g., hospitals). There are several possible detours available to residents of Ciales should the PR-149 Bridge fail. The shortest detour starts at the area of concern (northeast of PR-149 Bridge) and continues through unnamed streets in the neighborhoods of Residencial Colinas De Jaguas and the outskirts of Jaguas Ventana, which eventually intersect PR-145 and the PR-145 Bridge (Fig. 17). Shortly after crossing the bridge, the detour follows CII Muñoz Rivera, which leads to the city center of Ciales. The length of this detour is approximately 1.3 miles. It should be noted at the PR-145 Bridge was washed away during flooding associated with Hurricane Maria and has been replaced with a temporary bridge.

DRAFT

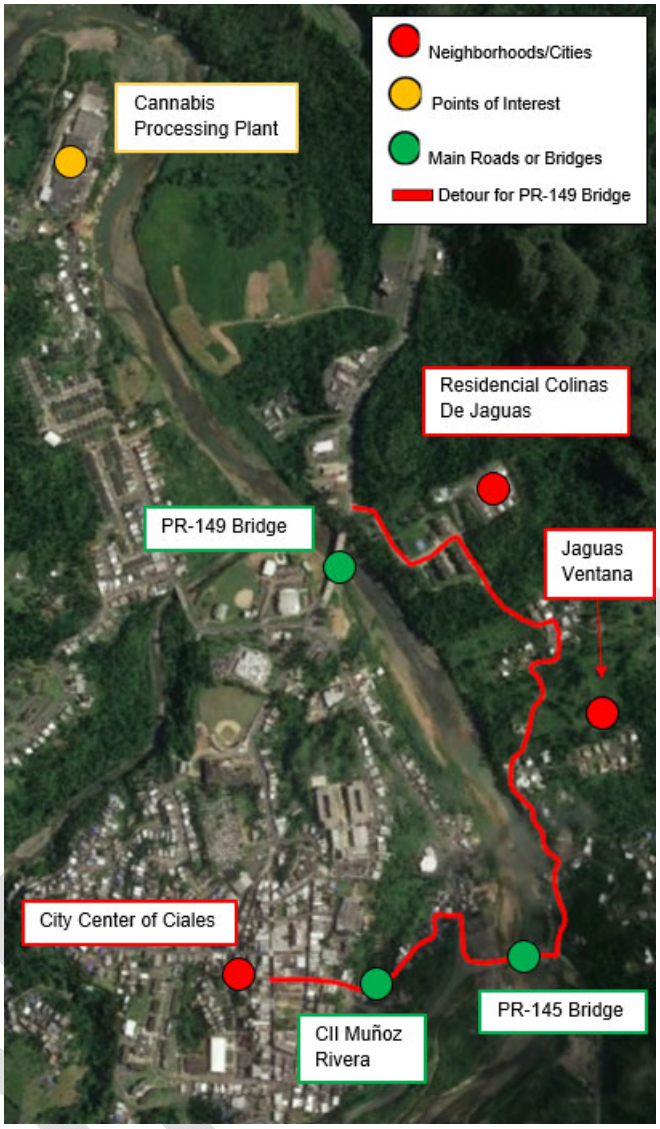

Fig. 17. Map indicating the PR-6685 detour that would be required if the at-risk section of PR-6685 would fail due to flood-induced bank failure.

2.2.3 Conclusions

Preliminary analyses indicate that section of PR-6685 in question is at increased risk of failure during events that equal or exceed the 0.01 AEP flood event. There is well-documented and photographed evidence of scour within the channel and on the banks where the PR-149 Bridge is located. Photographs taken during and following Hurricane Maria provide evidence of turbulent flow adjacent to the right abutment and first pier that corresponds to documented scour. A bridge inspection report immediately following Hurricane Maria showed evidence of scour at the PR-149 Bridge piers (see Fig. 12) and on the left bank upstream of the right bridge abutment toward the PR-149 Bridge (see Fig. 15). Geotechnical information indicates the soils

associated with the PR-149 Bridge are cohesionless, broadly graded sand and gravel with lenses of clay and silt. The hydraulic model indicates that flows passing through the bridge increase in velocity due to constriction and end effects, resulting in velocities far in excess of the soil critical velocities (see Fig. 10). Flows during Hurricane Maria cleared the bridge low chord by a minimal amount (Fig. 14).

2.3 PR-145

2.3.1 Analysis of Existing Data

Pre- and post-Hurricane Maria imagery (Fig. 18) and LiDAR-based elevation data (Fig. 19) indicate loss of up to 11 vertical and 115 feet horizontal feet of stream bank in the vicinity of PR-145.

Fig. 18 Google images taken prior to Hurricane Maria (2016, left image) and post-Hurricane Maria (2017, right image) depicting flood-induced bank failure adjacent to PR-145.

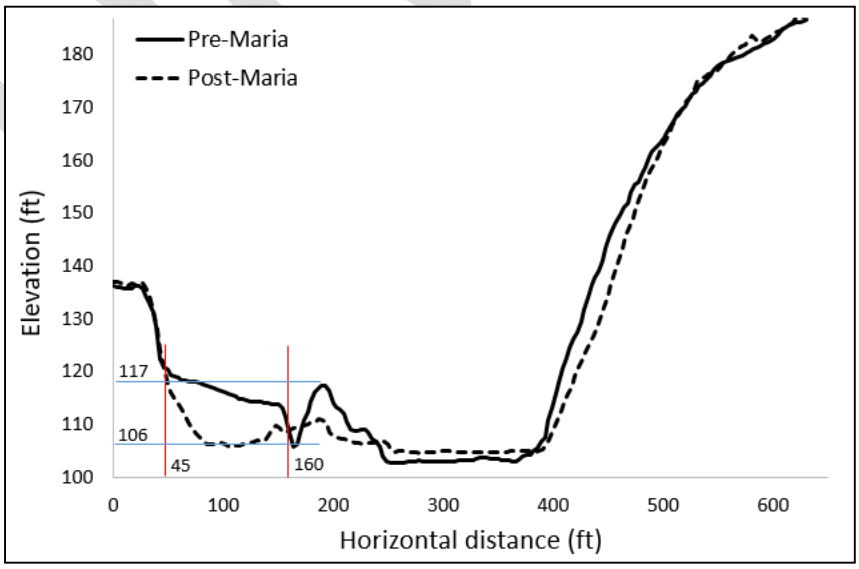

Fig. 19. Cross sections showing variation in elevation between pre-Hurricane Maria (2015) and post-Hurricane Maria (2018) LiDAR on the left bank adjacent to PR-145.

PR-145 is approximately 200 feet from the edge of flood-induced bank failure caused by Hurricane Maria. Site conditions (e.g., slope, distance from stream bank to road, channel geometry) indicate that it would take a flow significantly greater than the 0.01 AEP and calculated 0.002 AEP to have sufficient duration and velocity to laterally scour 200 feet of material between the stream bank and PR-145. Based upon aerial imagery and basic hydraulic principles and assumptions, it appears that the channel constriction presented by the PR-149 Bridge is the main contributing factor to the left bank erosion adjacent to PR-145. The PR-149 Bridge and flow restrictions presented by it would be removed prior to the erosion of the PR-145 embankment.

2.3.2 Conclusions

The likelihood of PR-145 failing as a result of bank instability and scour is extremely remote.

3 Summary of Findings

Preliminary analyses indicate that PR-6685 and the PR-149 Bridge are at elevated risk of failure due to flood-induced bank failure and scour during floods equal to or in excess of the 0.01 AEP event. It was determined that the risk of failure for PR-145 due to bank failure is extremely remote. Table 5 provides examples of management measures that could be implemented to protect against future flood-induced bank failure and bridge scour. Appropriate technical analyses would need to be completed to ensure selected measures are appropriate.

Table 5. Common management measures for preventing against bank failure and bridge scour.

Management Measure	**Description**
Riprap Revetment	Armor stream banks with large stones to protect against future flood-induced failure.
Concrete Revetment	Armor stream banks with concrete lining or fillable concrete bags to protect against future flood-induced failure.
Gabion Baskets & Mattresses	Armor stream banks with gabion (i.e., cage filled with stone) baskets/ mattresses to prevent future flood-induced failure.
Retaining Wall	Construct a post and panel retaining wall to protect stream banks from future flood-induced failure.
Vegetation Planting	Plant native vegetation to protect stream banks from future flood-induced failure.
Turf-Reinforcement Mats	Armor stream banks with a high-performance-turf-reinforcement mat to prevent future flood-induced failure.
Bridge Scour Protection	Place riprap in excavated areas around bridge piers and abutments to protect from scour.