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Abutment Scouring and Erosion Mitigation Measures for a Bridge on an Active Lahar-Draining River Channel: A Case Study of the Pasig-Potrero Bridge

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ABSTRACT

A case study of a bridge located in the Central Luzon Region in the Philippines is presented. The bridge is situated on the channel bend of a lahar draining river. During the onslaught of a tropical storm in 2013, which was intensified by the Southwest Monsoon, strong currents in the river caused diversion of deposited lahar from the channel, eroding one embankment of the bridge. Due to the erosion of the embankment, and the continuous scouring at the toe of the abutment, a portion of the bridge collapsed. River basin and channel modelling were performed using to evaluate the scouring and erosion risk at the piers and abutments. Geotechnical investigation of the riverbanks was also conducted. Based on the analyses, several mitigation measures were recommended within and outside the Road Right of Way (RROW). Moreover, non-structural measures were also proposed in order to minimize the erosion and scouring risk.

1. INTRODUCTION

The 94-kilometer Subic-Clark-Tarlac Expressway (SCTEx) is the longest expressway in Philippines, which connects the provinces of Zambales, Bataan, Pampanga, and Tarlac. The Pasig-Potrero Bridge carries SCTEx as it traverses the Pasig-Potrero River, an active lahar-draining watercourse whose upper catchment extends up to the Mt. Pinatubo. The bridge, located on the channel bend of the river, is approximately 17km southeast of the Mt. Pinatubo Crater.

The 1991 Mt. Pinatubo eruption caused more than 3km^3 of lahar deposition on its surrounding areas, including areas within the Pasig-Potrero River Basin. Since then, the riverbed is mostly overlain with lahars and cases of lahar flow driven mostly by intense rainfall continuously changes the river morphology. Water containing heavy loads of sediments promotes erosion and scouring along the riverbanks and channel bends. After more than 20 years since the eruption of Pinatubo, lahar has not completely been washed away from its slopes. Moreover, the lahar-draining rivers has yet to begin stabilizing itself by searching for its most stable channel. As such, the Pasig-Potrero Bridge was tagged as high-risk area.

Lahar flow downstream from the Pasig catchment is a long process that takes decades, with varying amounts of rainfall every year. This process is achieved through a continuous process of erosion and deposition of lahar in the channel of the Pasig-Potrero River. Water with heavy loads of sediment scour the banks of the river more intensely in bends of the channel.

During the onslaught of Tropical Storm Maring (Trami) in 2013, which was intensified by Habagat (Southwest Monsoon), strong currents in the river caused diversion of the deposited lahar from the channel, eroding the embankment of the Pasig-Potrero bridge. Due to the erosion of the embankment, and the continuous scouring at the toe of the abutment, a portion of the bridge (first span) collapsed, cutting off the access along SCTEx.

Figure 1. The collapsed approach embankment at Sta. 45+540 in 2013

The erosion and scouring in the Pasig-Potrero River may be best illustrated through satellite images from Google Earth™ in time series from 2003-2014. From the satellite images, almost 150-meter stretch has been scoured from the river banks, which ultimately led to the failure of the Pasig-Potrero abutment in 2013.

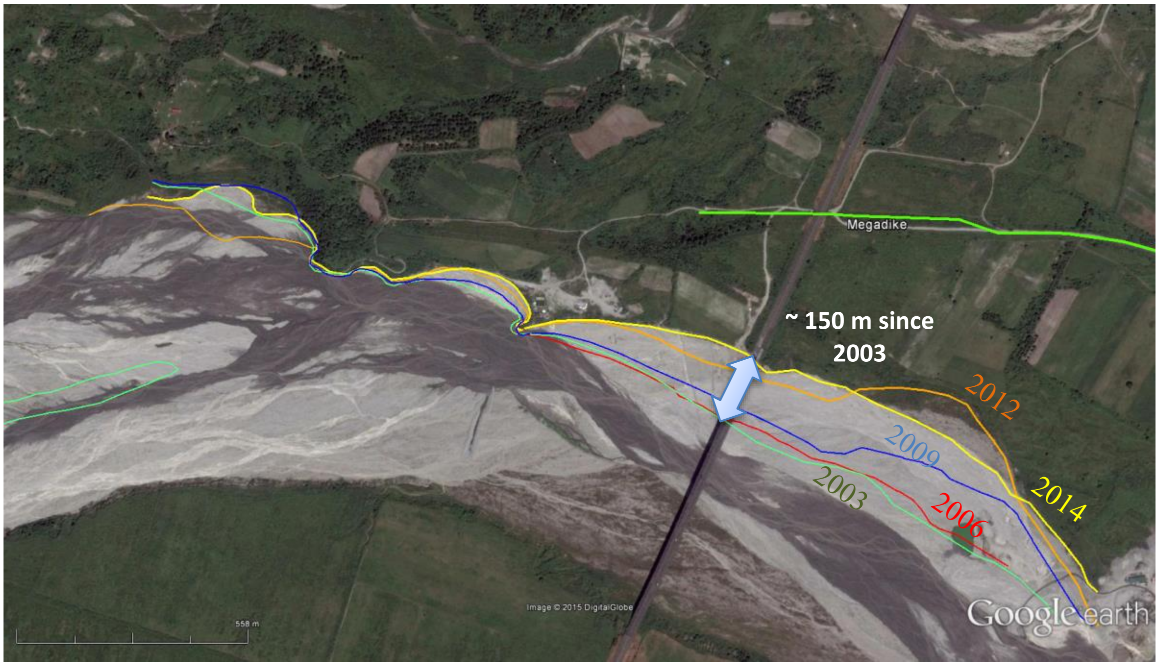

Figure 2. Figure Google Earth Satellite image of the Pasig-Potrero scouring in 2014

2. PASIG-POTRERO RIVER CATCHMENT

Before the 1991 eruption, the eastern flank of Mount Pinatubo was solely drained by the Sacobia River. The Pasig River headed on Mount Dorst, about 7 km from the Pinatubo summit, where it was separated from the upper Sacobia channel by a low dissected fan of pre-1991 pyroclastic flow deposits of modern Pinatubo. The upper Pasig River consisted of the Bucbuc Creek, which joined the Yangca Creek to form the Papatac Creek near Mount Cutuno, about 12 km from the summit. As it emerged from the hilly upland area into the alluvial plains, the Papatac Creek joined the Timbu Creek to become the Pasig River (JICA, 1978). The Pasig River becomes the Potrero River about 12 km downstream of this confluence. Prior to the 1991 eruption of Pinatubo, the total upper catchment area of the Pasig River was about 21 sq. km., measured from the headwaters of the Bucbuc down to the confluence of the Papatac and Timbu Creeks. [Tungol,2002]

After the Mt. Pinatubo 1991 eruption and continuous lahar flows from 1991 to 1993, with major lahar events generated by breaching of temporary blockages, the Pasig-Potrero river catchment significantly changed. At the height of Typhoon Kadiang on October 5-6, 1993, the upper channel of Sacobia River was filled with pyroclastic debris, leaving the filled channel of the Sacobia topographically higher than the Pasig River Channel. Consequent to this, the Upper Sacobia catchment extending up to Mt. Pinatubo became part of the Pasig River Catchment.

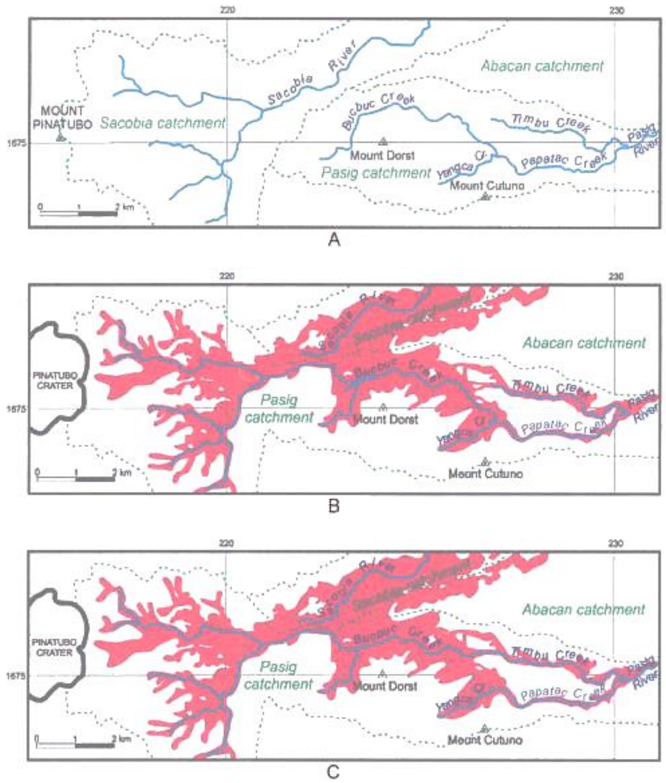

Figure 3. Addition of Tributary Areas to the Pasig-Potrero Catchment (Tungol, 2002)

For the purpose of this study, satellite images, digital elevation models, and Global Information System (GIS) software were used to estimate the current extents of the Pasig Potrero River Basin. The analysis of the land cover of the project site depended on visual interpretation of the most recent satellite images provided by Google Earth, while the slope and length parameters were taken from the Digital Elevation Model (DEM) for the sub-catchments. Conventional method of catchment delineation is done by tracing the contours in National Mapping and Resource Information Authority (NAMRIA) topographic maps. However, the use of the said maps will lead to inaccuracy due to the existence of lahar flows, and the development of erosion and deposition along the waterways. Hence, the contour maps extracted from DEM shall be used to mark the boundaries created by ridges towards and identified outlet. As for this study, the outlet identified was about half a kilometer after the Pasig-Potrero Bridge, to account for tailwater effects of the river hydraulics, as well as scouring.

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), the DEM used for delineating the catchment, is a satellite launched by the United States' National Aeronautics and Space Administration (NASA) and Japan's Ministry of Economy, Trade and Industry (METI) in 1999. Data from this satellite is archived by the United States Geological Survey (USGS) and is freely available online on www.earthexplorer.usgs.gov.

Figure 4. Pasig-Potrero Catchment Boundaries (Source: Google Earth)

The Pasig-Potrero catchment is in the east of Mt. Pinatubo's crater, and measures about 50 square kilometers. The upper sub-catchments have steep slopes, forming large gullies and defined ridges. Lower sub-catchments, on the other hand, are flatter, with a wider coverage of lahar. Google Earth images overlain with the catchment boundaries are shown in Figure 4.

From these satellite images, it can be clearly seen that some of the lahar from Pinatubo is still in the in the waterways of Pasig-Potrero, even after 20 years since its eruption. This amount though, is significantly smaller than the apparent lahar cover in the watershed right after the eruption (Tuñgol, 1992). This implies that continuous degradation is occurring throughout the watershed and all that lahar flowed through the Pasig-Potrero River.

3. ANALYSIS OF PIERS AND ABUTMENT SCOURING

The determination of local scouring at the abutment and the general erosion that might occur in the project site was done through a straightforward and analytical approach. The Hydraulic Engineering Circular No. 18, Evaluating Scouring in Bridges, developed by the U.S. Department of Transportation's Federal Highway Administration (FHWA) was considered as the main reference for the study.

The rainfall data was based on the RIDF curves generated by Japan International Cooperation Agency (JICA). Aside from the extreme events, the average annual monthly rainfall was also used to estimate the amount of erosion for long term analysis of scouring. After selecting the appropriate design events in the study, the SCS Unit Hydrograph method was used to analyze the amount of runoff that may be generated over the delineated catchments. The catchment, as well as the rainfall data, was modeled using HEC-HMS.

The Iba Synoptic Station is the closest station to the Pasig-Potrero River with an RIDF curve generated by JICA and DPWH. Hence, the RIDF coefficients for Iba were utilized. Results of the 24-hour duration, 100-year HEC-HMS model over the Pasig-Potrero Basin yielded the following outflow hydrograph. The flow reached about 2,730 cubic meters per second at its peak.

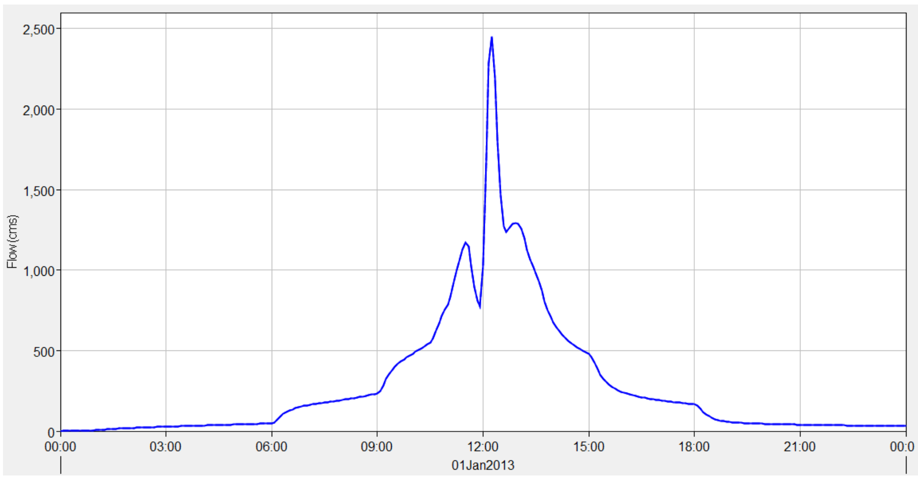

Figure 5. HEC-HMS outflow hydrograph for 100-year flow

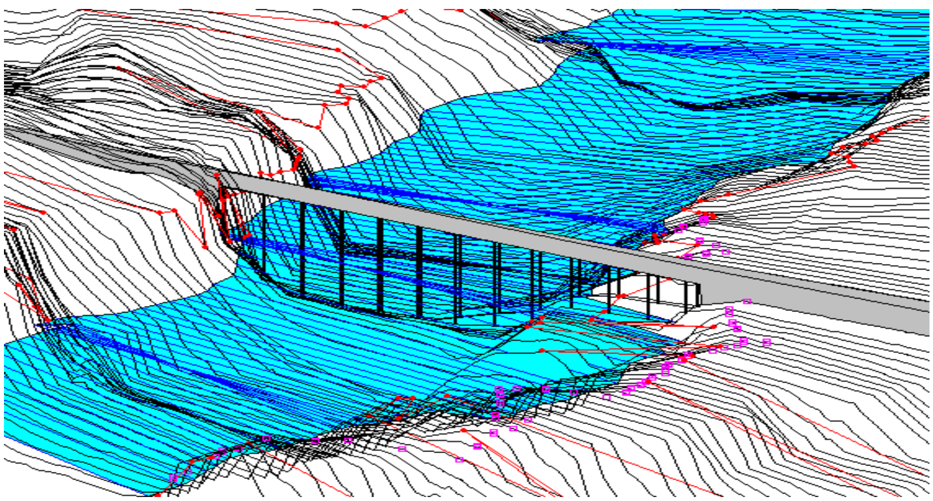

Figure 6. HEC-RAS render of the Pasig-Potrero River at the Bridge

After the completion of the hydrologic model results, the hydrograph above was utilized as input to the hydraulic model in HEC-RAS as unsteady flow data. HEC-RAS included the cross sections of the river, sampled from the ASTER DEM, as well as the locations and geometry of the piers and abutments to account for flow restriction at the bridge. The hydraulic analysis result at the river's cross section at the bridge is shown below.

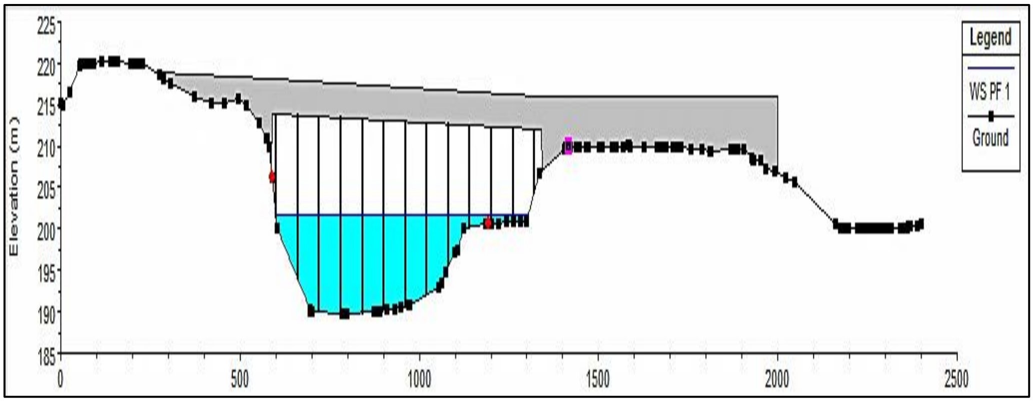

Figure 7. HEC-RAS water levels during peak flow at Pasig-Potrero Bridge

The maximum depth of flood at a 100-year return period can reach up to 10.5 meters. A 3D plot of the Pasig-Potrero River in HEC-RAS that includes the assumed bridge geometry is shown below.

Scouring takes many factors into consideration. Long-term erosion, as well as extreme runoff events, affects the total scouring. HEC-18 recommends that a minimum of 100-year flood should be used to determine potential scour. However, since only secondary data is available for this study, assumptions were made to proceed with the calculations, then recalibrated continuously upon gathering of first-hand data.

HEC-RAS was used for calculating general and local scour that may occur on the piers and abutments. Froehlich's equation was used in determining these scour depths.

$$\frac{y_s}{y_a} = 2.27K_1K_2\left(\frac{L'}{y_a}\right)^{0.43} Fr^{0.61} + 1$$

Where

K1 = coefficient for abutment / pier shape,
K2 = coefficient of angle of embankment to flow,
L' = length of active flow by the embankment,
Fr = Froude Number,
ya = average depth of flow in the floodplain, and
ys = depth of scour.

Physical properties of lahar in the Pasig-Potrero River were researched by Pagbilao in 2000, as they tested its viability to make concrete blocks. In the sieve analysis that they performed, the following results were obtained. These were used as lahar sediment data for scouring analysis.

Table 1. Lahar sieve analysis results (Pagbilao)

Sieve Opening, mm	Cumulative Percent Passing %
9.52	100
4.76	100
2.38	92.6
1.19	80.2
0.59	62.3
02.97	43.9
0.074	12.9

Detailed results of the scour analysis using Froehlich's equation are as follows:

Table 2. Results of HEC-RAS Scour analysis

Pier Scour		
Scour Depth Y_s (m):	4.6	
Froude Number:	0.32	
Equation:	Froehlich's Equation	
Abutment Scour	Left	Right
Scour Depth Y_s (m):	6.95	6.95
$Q_e/A_e = V_e$ (m/s):	3	3
Froude Number:	0.96	0.96
Equation:	Froelich	Froelich

From the results of initial HEC-RAS simulations, it can be seen that the abutments are susceptible to a local scouring depth of around 7 meters. The piers, which are more exposed to scouring, may experience 4.6 meters of local scouring. Because the river is very wide (at least 600m wide), as compared to the width of the piers at 2.5 meters each, the contraction scour is considered negligible. A plot of the possible local scouring at the piers and abutments is shown below.

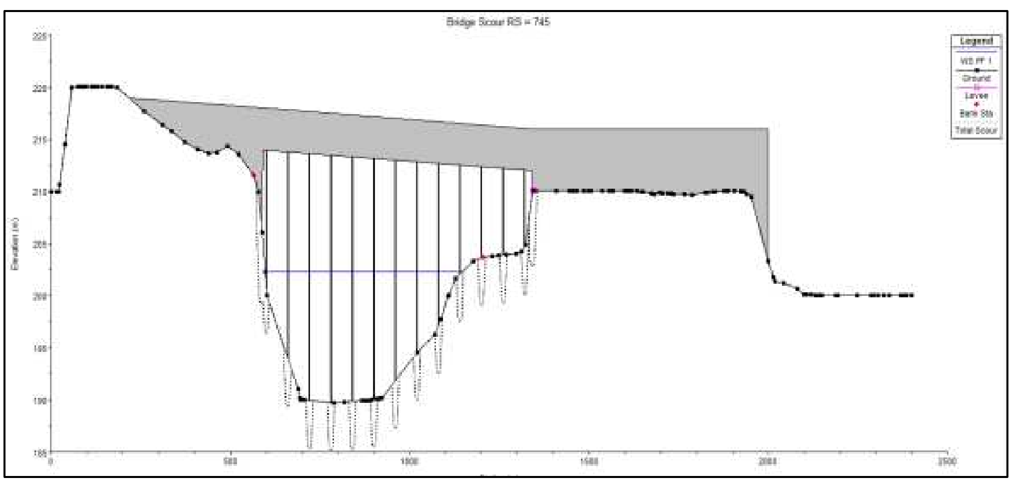

Figure 8. HEC-RAS local scouring analysis results

4. FORMULATION OF REHABILITATION MEASURES

Two (2) proposed rehabilitation measures within the Road Right of Way (RROW) were initially considered and the details are presented in the succeeding subsections.

4.1. Rehabilitation Scheme 1 – Bridge Extension with Partial Revetment

The old approach embankment was scoured and left a 25-meter (approximate) gap between the road and the bridge abutment. This 25-meter gap plus the horizontal distance that a 1V:2H slope makes (considering a height of 20 meters), rounding up the results to a bridge length of 60 meters. A conceptual design of the proposed scheme 1 is presented in the rendered 3D image below:

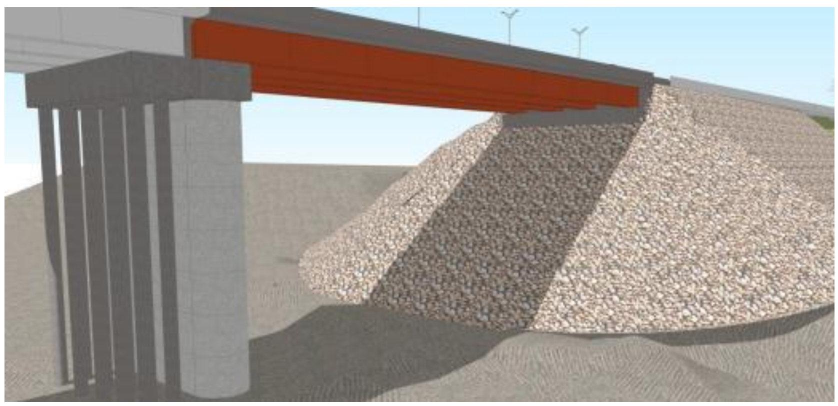

Figure 9. Conceptual design of 60m bridge extension with revetment

The proposed slope of the new approach embankment was modeled and analyzed to establish its long-term stability. Further analysis is imperative during the detailed engineering design.

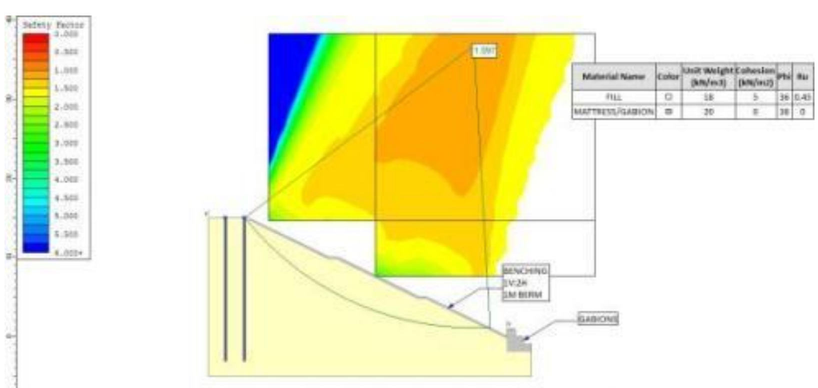

Figure 10. Slope stability analysis model for the proposed abutment slope protection

The results of the slope stability analysis show that the embankment slope of the proposed scheme is generally stable, with factors of safety (FS) greater than the allowable FS for both static and pseudo-static (seismic) conditions, as summarized in the table below.

Table 3. Results of slope stability analysis

Analysis used: Bishop simplified	**Material**	**Unit Weight (kN/m^3)**	**Cohesion (kPa)**	**Friction Angle (degrees)**
	Lahar	18	5	38
Condition	**Case**		**Factor of Safety**	
Benching 1V:2H	**R_U**	**K_h**	**FS**	**Remarks**
	0	0	2.040	FS ≥ 1.300
	0.10	0	1.830	FS ≥ 1.300
	0.20	0	1.620	FS ≥ 1.300
		0	1.410	FS ≥ 1.300
	0.45	0	1.097	FS ≥ 1.100
	0.20	0.10	1.274	FS ≥ 1.000

4.2. Rehabilitation Scheme 2 – Bridge Extension with no Revetment

The second scheme is similar to the first. However, a 240m bridge shall be installed rather than just a 60m bridge span. The 240m bridge shall have bored piles which shall act as columns when eroded. The scheme accounts for future scouring and erosion. It can be constructed in phases depending on the rate of erosion in the succeeding years, and it requires comprehensive monitoring program. A satellite image with the 3D visualization of the bridge are shown below.

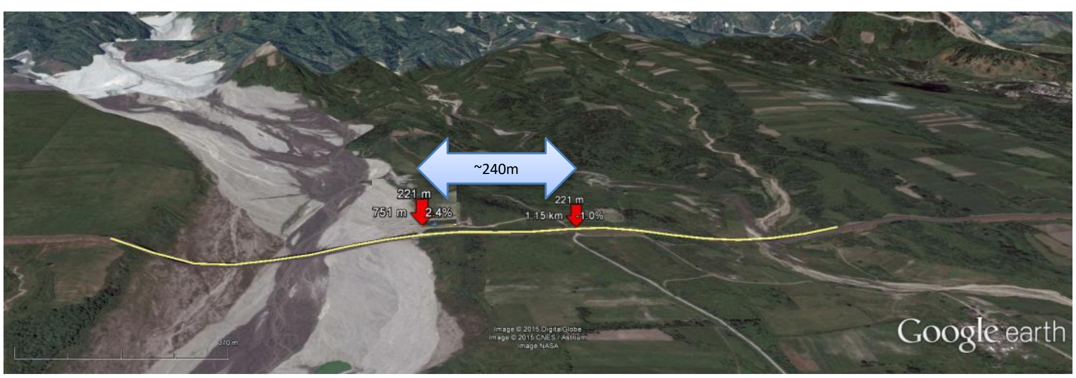

Figure 11. Extent of the 240m bridge (Source: Google Earth)

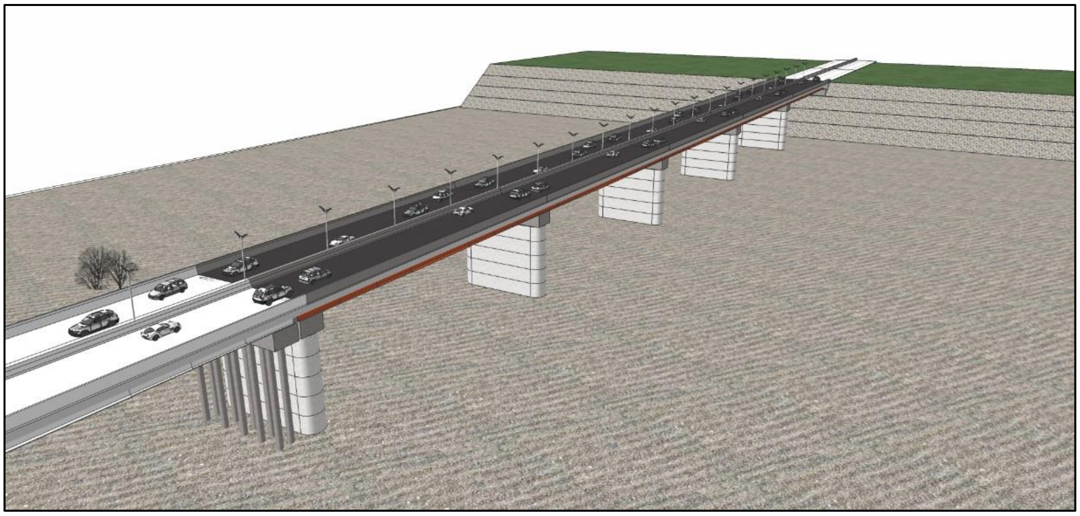

Figure 12. Conceptual design of 240m bridge

4.3. Supplemental measure: Sheet Piling

The depth of lahar, given its soil properties and how easily it can be eroded can be provided for with additional sheet piling (Figure 13). This is a recommended supplemental measure on top of the bridge rehabilitation. An estimated length of 200 meters of sheet piles, at 20 meters depth, is recommended to be installed. On top of the 4.6m calculate potential scour depth, stability of sheet piles was also considered given that it will be embedded on lahar materials. The recommended depth is only based on pre-1991 and current NAMRIA topographic maps and would require further investigation.

It should also be noted that if the soil is undermined behind the piles due to erosion, the sheet piles will be rendered ineffective. This is mainly why the sheet piles are recommended to be used as additional protection only to the previous schemes presented.

The following table presents the description, the various advantages, and the limitations of each scheme. Between the two schemes, cost of scheme 1 was estimated to be cheaper as compared with the second scheme.

Table 4. Summary of proposed schemes within RROW

	SCHEMES		**Supplemental Measure: Sheet Piling**
	Scheme 1 60-m Bridge Extension with Partial Revetment	**Scheme 2 240-m Bridge Extension with no Revetment**	

Description	• Adds one span to the current bridge alignment • Revetment limited upstream protection • Complemented by continuous monitoring	• Construct the multi-span bridge extension anticipating further scouring.	• Functions as a cutoff wall that protects the active side of the river bank against long-term scouring and degradation of the riverbed
Advantage/s	• Bridge extension of the 60m will be relatively straightforward • Rehabilitation can be undertaken within a few months	• Will address the scouring and erosion concern within RROW of the bridge • May be constructed in phases	• will have long service life above or below water
Disadvantage/s	• The revetment or river protection will not completely prevent future erosion problems • May be complemented with continuous monitoring	• May result to large surface area as entry points of seepage • Will create an unnecessary tributary of the river.	• May be difficult to install due to depth of lahar • Will not be effective on its own due to small thickness • A supplemental measure only

5. FORMULATION OF MITIGATING MEASURES OUTSIDE RROW

In addition to the rehabilitation measures supplemented by sheet piling, three (3) additional mitigating measures were recommended. Nonetheless, these proposed measures are outside the RROW of SCTEx and will require coordination with government agencies and stakeholders. Summary of the mitigating measures are presented in (Figure 13) and the details are presented in the succeeding subsections.

5.1. Scheme 1 – Gabion Revetment

An intermittent lahar-covered gully located northeast of the collapsed abutment may also pose risk on the proposed bridge extension. Gabion revetments may be installed to address this risk. According to U.S. Federal Highway Administration Hydraulic Engineering Circular No. 11, the longitudinal extent of protection required for a particular bank protection scheme should be continuous for a distance greater than the length that is impacted by channel-flow forces enough to cause scouring. The vertical extent of protection, including the design height and toe depth, should account for the estimated depth of scour to prevent undermining. With consideration of the above discussion, the extent of the revetment totals to 3,625 meters.

5.2. Scheme 2 – Spur Dikes

Copeland (1983) states that "a spur dike can be defined as an elongated obstruction having one end on the bank of a stream and the other end projecting into the current." This scheme is used extensively as river retaining structures for navigation enhancement, flood control improvement and erodible banks protection. The effect of the installation of spur dikes along a channel includes current reduction along the streambank, which reduces the erosive capability of the stream. For Pasig-Potrero, the spur dikes aim to reduce the velocity of water which erodes the banks of the river. Due to the geotechnical properties of lahar that flows in the river (light unit weight, fine gradation), and the anticipated water flow rate (catchment area ~50 sq. km.), the spur dikes to be installed are expected to be massive.

No design guidelines present a complete design scheme for spur dikes that suit the situation in Pasig-Potrero. Hence, the design of spur dikes for the river come from several sources, consolidated to produce the necessary design. Input values shall come from the hydraulic parameters, along with 650m as the channel width and 10.5m as the design flood level. The following table and figures summarize the conceptual design dimensions for the spur dike scheme.

Table 5. Initial design of Spur Dikes based on FHWA guidelines

Dimension	Value
Length	65 m
Height	10 m
Crest Slope	1:100
Crest Width	2 m
Depth of Embedment	3 m
Spacing	130 m
Side Slope	3:1

5.3. Scheme 3 – River Re-channelization

River re-channelization is the process of planned human intervention in the course and characteristics of flow of a river with the intention of producing some defined benefit. Basically, an earth embankment is constructed to divert the water away from the abutment. The re-channelization involves continuous moving of deposited sediments from the center of the river to its banks with each extreme event. The damages caused by scouring may be easily repaired. For Pasig-Potrero, scouring and erosion are aimed to be addressed by the re-channeling scheme.

For Pasig-Potrero, the proposed initial section is about 25 meters at the crest, 45 meters at the base, and a height of about 5 meters from the design water level. This will be applied to about 400 meters upstream and 100 meters downstream. The embankment then will act as a first layer of defense against scouring at the abutment before it even reaches the sheet piles and the abutment. This will also divert the water away from the abutment and into the center of the river during low but continuous amounts of water flow.

The general location of the proposed schemes is laid out in Figure 13. It can be observed that the proposed works complement the ongoing works in terms of additional protection against scouring. It may also be noted that most of the schemes presented are flexible instead of rigid structures, so that repairs and additional protection may be easily implemented without compromising the rigid bridge structure.

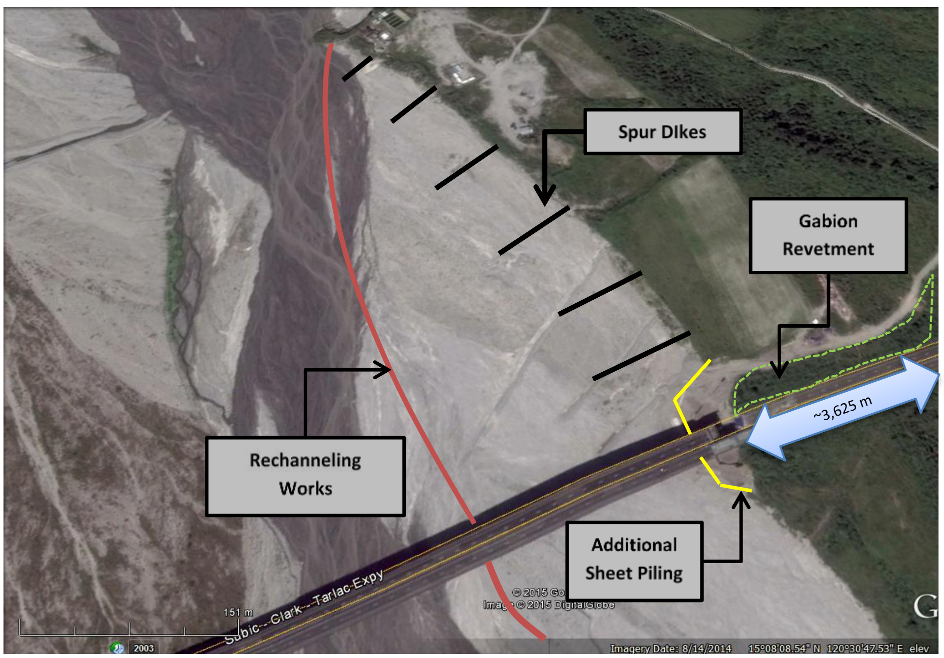

Figure 13. Schematic layout of proposed additional schemes outside RROW

6. CONCLUSION AND WAY FORWARD

Major roads play an important role during natural disasters as they provide access to cities and provinces. Without road transport, it would be difficult to provide help and support to areas affected by calamities.

Several infrastructure projects have been implemented to mitigate the effects of lahar flows since the eruption of Mt. Pinatubo in 1991. The lahar deposits in the Pasig-Potrero River has significantly been reduced. However, it should be noted that lahar sediment flow still pose a danger to SCTEx, a major access road, and the downstream settlements and communities.

Pasig-Potrero is a highly active river in terms of geomorphology due to the geotechnical properties of lahar and increasing rainfall from upstream. From available satellite images, it can be observed that erosion and scouring continue to threaten SCTEx and other adjacent areas. Hence, conceptual design schemes are formulated for hazard mitigation and risk reduction:

- Two (2) rehabilitation schemes within RROW were proposed: 60-m bridge extension with revetment; and 240-m bridge extension without revetment. Both measures should be supplemented with sheet piling.
- Three (3) additional mitigating measures outside RROW were also identified: gabion revetments for the intermittent gully located northeast of the collapsed abutment; spur dikes; and river re-channelization. It should be noted that coordination with government agencies and other stakeholders are required if measures outside the road right of way shall be implemented.

At present, the first scheme within the RROW was immediately implemented given the urgency to rehabilitate the Pasig-Potrero Bridge. Erosion protection using riprap abutment as the revetment was constructed.

Although riprap effectively protects the bridge from further scouring, it is still imperative to provide additional measures in the reduction of excessive velocity, and diversion of river flow. The selection of additional optimum scheme will require immense data gathering and a comprehensive sediment transport analysis. Moreover, it will take considerable time to gather all the necessary data required for a comprehensive analysis. The proposed schemes will then be simulated for its adequacy.

Moreover, continuous monitoring in the river movement, as well as the scouring should be considered. Satellite imagery may be a good source of information for monitoring scouring and erosion, as well as the flow patterns in the river. This may also be a good basis in determining future action and measures. In addition, remote-sensing data can be acquired more easily and costs cheaper than 20 years ago. It is therefore encouraged to monitor the river morphology through a combination of remotely sensed data and ground measurements using instrumentation. It should also be complemented with regular inspections.

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