River Bridges with Natural Banks: A Case Study of Twenty-One River Bridges in Papua New Guinea

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1.0 INTRODUCTION

Bridges are structures that make a road network complete by linking the physical and natural barriers such as rivers, lakes, swamps, straits, valleys, gorges, roads, and railways and provide safe passage for the vehicular and pedestrian traffic. Bridges are commonly known to what kind of environment or locality they are being built to such as river bridges, road bridges, bay bridges or lake bridges etcetera. In Papua New Guinea, ninety-nine percent (99%) of bridges are constructed over small streams or major rivers with natural banks that are susceptible to erosion and bank failures, in contrast to guided banks or protected banks.

In this case study, twenty-one river bridges in Papua New Guinea were studied in which, field investigation and inspection works were carried out between April 2017 and September 2018. During the field study, it has been revealed that many river bridges in Papua New Guinea have failed due to flooding waters eroding the bridge embankments that have been weakened by failed riverbanks at an upstream end or downstream end and sometimes both ends of the stream.

Maintenance and management of critical infrastructure such as roads and bridges that provide access to essential goods and services in a developing country like Papua New Guinea is a subject of discussion that has no end. Moreover, to add salt to the wound, the recent change in the global climatic patterns has caused more distress and disasters with high rainfall in intensity and frequency. This is causing more river floods damaging many vital bridges that link roads of high economic and social importance to the people such as shown in Figure 1 below.

Figure 1. Riverbank Erosion induced bridge failure of Himutu Bridge, Boluminski Highway, New Ireland Province, Papua New Guinea. Photo Credit: Gibson Holemba (2016).

To effectively control bank erosion, riverbank management must be compatible with the nature of the river system and the composition of its banks. Before restorative methods are applied to eroding banks, it is essential to understand the mechanism of erosion. Otherwise, large investments of time and money may potentially be wasted in projects that fail or require frequent maintenance. This paper will discuss the riverbank failures in the vicinity of the bridge site that further leads to a bridge failure.

Moreover, river and flash floods resulting from abnormally high rainfall over a relatively short period such as in hours for flash floods and days for river floods can cause major bank erosions due to increase amount of floodwater and debris into the channel. Rapid snowmelt during the winter season in cold regions can bring more water into the hydrological system, leading to what is generally called spring floods causing devastating damages to river structures such as a bridge that is located in its flow path.

In 2016, a typhoon hit the island of Hokkaido in the Tokachi area damaging a lot of structures such as bridges, buildings and community facilities causing major havoc on the residents and businesses. In another incident, a major flood caused by torrential rain measuring up to 488mm on the 31st of August 2016, damaged the 43km road section of Nissyo Pass along the National Road 274 in sixty-six (66) different locations ranging from major to minor infrastructure damages. It was noted that ten (10) of the damaged structures were bridges, three (3) snow sheds, six (6) major road damage, and forty-seven (47) minor road damages. The major cause of the disaster was flooding carrying a high volume of flood debris, huge logs causing landslides along the natural riverbank and road embankments as shown in Figure 2 below.

Figure 2. Riverbank Erosion induced bridge failure of a bridge along National Road 274, Nissyo Pass, Hokkaido, Japan. Photo Credit: Dr. Hiroaki Nishi, CERI (2016).

A national study for the Federal Highway Administration (FHWA) in 1973 revealed that catastrophic floods caused 383 bridge failures in the United States. More precisely of these bridge failures, twenty-five percent (25%) involved pier damage due to local scour and seventy-five percent (75%) were abutment damage due to bank erosion (FHWA 1973). A second more extensive study in 1978 indicated that local scour at bridge piers was a problem about equal to abutment scour problems (FHWA 1978). Flooding rivers cause more river bridge failures than any other factors in many countries today.

2.0 FIELD INVESTIGATION

Field investigations were carried out in Papua New Guinea at twenty-one flood-damaged and affected bridge sites. The bridges that were investigated were all constructed over natural river crossings in three distinctive provinces in the country. These bridges are part of six (6) major road networks in the country that support the socio-economic development. The investigations were undertaken in Madang, Morobe and New Ireland Provinces along Wau Highway, Highlands Highway, Ramu Highway, Boluminski Highway, West Coast Road and Lanzarote Road in Papua New Guinea.

The field investigation works gathered field data such as, river channel width, bridge dimensions, river cross-sections, flow depth, scour depth, flow angle, clearance height (soffit), debris and log sizes. The general information of these twenty-one inspected bridges are provided in Table 1. These bridges have fallen victim to flooding sustaining major structural damages while several bridges were destroyed by flood as discussed in the following chapters.

2.1 River Cross-section Measurement

The river channel cross-section as sketched in Figure 3 was measured manually by measuring tape. The width of the main river channel was measured from the top of the east bank to the top of the west bank in three different locations upstream, at bridge and downstream. A 10m of offset distance was taken from the centreline of the bridge both upstream and downstream from the bridge.

In addition, the average river channel depth was measured with survey stuff at 3m intervals across the main channel in accordance with the respective channel widths. These field measurements provided the data for calculating the volume of eroded soil at the measured cross-section. Most of the studied rivers had trapezoidal channels while few were rectangular open channels, especially those that have non-erodible bank slopes. The accuracy of the measurements was dependent on the site conditions of the rivers and bridge inspection accessibility. Some sites had fast flowing rivers with thick vegetation on steep slopes which made the measuring very challenging.

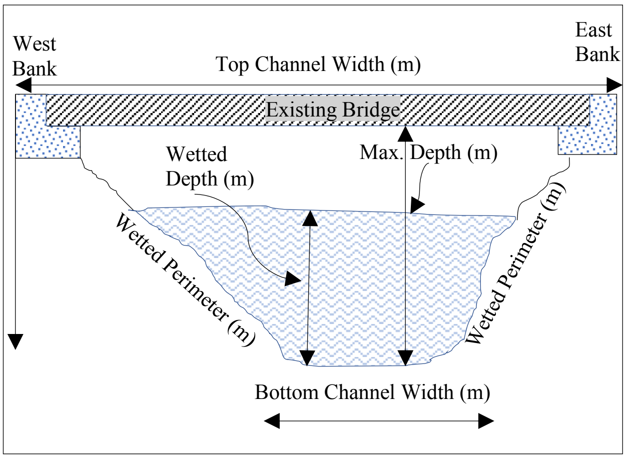

Figure 3. River Channel Cross-section Profile

Table 1. Summary of Bridge Investigations in Papua New Guinea

No.	Bridge Name	River Type	Bank Soil Composition	Failure Mechanism	Catchment Size (km^2)	Flow Angle (degrees)	Flow Velocity (m/s)	Bridge Length (m)	Bridge Width (m)
1	Asas Bridge	Meandering	Silty Sand	Combine Failure	11.39	45.00	1.00	40.0	3.72
2	Aumea Bridge	Braided	WG Gravel, Sand, Silt	Fluvial Failure	68.63	90.00	1.28	56.0	3.40
3	Bora Bridge	Meandering	Silty Sand	Mass Failure	211.00	30.07	2.89	48.7	4.34
4	Cedar Bridge	Meandering	Silty Sand & Gravel	Combine Failure	812.43	45.00	2.62	35.7	7.50
5	Daulom Bridge	Meandering	WG Gravel, Sand, Clay	Fluvial Failure	224.09	90.00	3.00	36.6	3.15
6	Himutu Bridge	Meandering	Silty Sand & Gravel	Combine Failure	41.40	65.26	1.56	30.84	3.22
7	Iruan Bridge	Meandering	Silty Sand & Gravel	Fluvial Failure	90.43	56.98	1.32	124.97	5.20
8	Kalili Bridge	Meandering	Organic Clay	Fluvial Failure	20.00	47.12	1.31	21.3	3.14
9	Kesuai Bridge	Braided	Silty Sand & Gravel	Combine Failure	56.31	60.63	0.75	73.5	3.55
10	Labur Bridge	Swamp	Organic Silt	Mass Failure	0.07	41.91	1.52	21.5	3.15
11	Marakalang Bridge	Meandering	WG Gravel, Sand, Clay	Mass Failure	17.20	90.00	1.35	37.0	3.40
12	Mea Bridge	Braided	Silty Sand & Gravel	Fluvial Failure	35.22	90.00	0.70	146.3	3.64
13	Menia Bridge	Meandering	WG Gravel, Sand, Silt	Combine Failure	40.29	21.49	0.72	45.7	4.40
14	Pine Tops Bridge	Meandering	Silty Sand & Gravel	Combine Failure	531.62	28.70	5.53	27.4	3.75
15	Punam Bridge	Meandering	Silty Clay with Gravel	Fluvial Failure	9.50	90.00	0.90	35.2	8.49
16	Rumu Bridge	Braided	WG Sand	Fluvial Failure	325.46	90.00	4.79	30.1	7.38
17	Sausi Bridge	Braided	Silty Sand & Gravel	Fluvial Failure	78.43	90.00	0.53	137.2	4.40
18	Surinam Bridge	Meandering	Silty Sand & Gravel	Fluvial Failure	280.57	90.00	2.57	49.5	4.20
19	Wara Pita Bridge	Meandering	Silty Clay with Gravel	Fluvial Failure	11.47	55.35	1.84	33.0	3.10
20	Waterbung Bridge	Meandering	WG Gravel, Sand, Silt	Mass Failure	91.79	90.00	1.14	36.8	4.07
21	Yakumbu Bridge	Meandering	Silty Sand & Gravel	Fluvial Failure	21.56	36.00	0.81	46.3	4.72

2.2 Watershed and River Morphology

River morphology assessments were undertaken by visual inspection within the bridge periphery while upstream and downstream environment were studied with the use of drone survey. Mavic DJI Pro® drone was used to undertake the aerial survey by taking photographs along the stream length with short video recordings of the river flow characteristics. The aerial photographs were taken at 200m-500m spacing both upstream and downstream as shown in Figure 4. Fifteen (15) of the rivers had meandering river systems whilst five had braided systems and only one was a tidal swamp as given in Table 1.

Figure 4. Mavic Pro DJI Drone image of Kesuai Bridge, Ramu Highway, Madang Province, PNG. Photo Credit: Jeremy Mark (2017).

The catchment area of the river from the bridge site was estimated using the Google Earth Pro© software. The catchment size was determined by plotting the lines along the ridge dividing the watershed. The catchment areas were automatically calculated by the software and were used for flood design estimations. The accuracy of the calculations is limited to the accuracy of the software used and as such the data used in this study is for this purpose only and should not be used for design purposes. It is highly recommended that adequate investigation must be carried out using the topographic contour maps or the hydrographic charts when undertaking design for these studied bridges for permanent works.

3.0 RESULTS AND DISCUSSION

While considerable research has been dedicated to designing of bank protection countermeasures for scour and stream instability, many flood protection countermeasures have evolved through a trial and error process. In addition, some countermeasures have been applied successfully in one locality, state, region or country, but have failed when installations were attempted under different geomorphic or hydraulic conditions in other localities.

Scouring of bridge abutments and piers, flood debris and embankment erosions were observed to be the main leading cause of bridge damages in this study. All rivers have natural banks with no bank revetment or scour protection measures. It was revealed during the study that; no adequate flood protection countermeasures were constructed to safeguard the structure. The gabion basket used as bank protection works were poorly designed and installed, and with lack of enough preventive maintenance, the structure failed in all sites visited that had gabion basket structures.

3.1 Riverbank Failure Mechanism

All stream banks erode to some degree. Because it is a natural ongoing process of weathering and it is unrealistic to believe that bank erosion can be or should be totally eliminated. Major floods can always make significant changes in bank lines despite steps taken to prevent it. Thus, it is important to understand that the concern is not that erosion occurs, but rather the location and rate at which it occurs. Riverbank failure near the bridge abutments distresses the overall safety of the structure and the public. Therefore, understanding the bank failure mechanisms and causes is key in determining the appropriate riverbank erosion prevention structures at a bridge site. Hence, from visual inspection and by calculating the scour depths of the rivers upstream, at bridge and downstream the dominant failure modes of the banks were determined. It was identified that eleven (11) of the bridges failed due to fluvial erosion while four (4) of the bridges failed due to mass failure and six (6) bridges due to combined failure mechanisms which are summarised in Table 1.

The bank erosion rate was calculated by the volume of eroded bank soil estimated from the change in channel cross-sections divided by period of two years (2017-2018) of research. The maximum bank erosion rate on the western banks was recorded for Cedar Bridge at 1306.5m^3/annum and Pine Tops Bridge at 1200m^3/annum. On the eastern banks, the maximum bank erosion rate was observed at Kesuai Bridge with 1113.75m^3/annum. On the contrary, Sausi, Surinam and Yakumbu Bridges were observed to have zero bank erosion on the west bank whilst Cedar, Himutu, Hirudan, Kalili and Marakalang Bridges on the eastern bank had nil erosion. This phenomenon is due to meandering streams flowing at an angle less than 90-degrees as shown in Table 1 and/or from a change in flow direction during the flood, influenced by bedforms and geomorphology of the banks. Interestingly, all these rivers with high erosion rates have similar riverbed and bank soil composition and that is silty-sand and gravel and they failed by combine failure. Given in Figure 5 are the bank erosion rates for the twenty-one bridges studied.

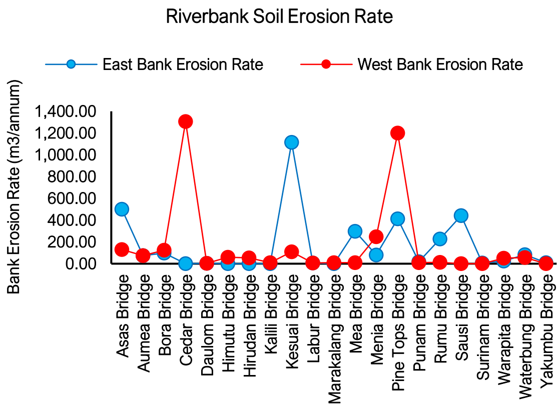

Figure 5. Riverbank Erosion Rate for Twenty-One Bridges

According to Wisconsin Department of Natural Resources (WDRN 2009), the key streambank erosion factors are; riverbank materials, the hydraulic influence of structures, maximum bank height divided by the bankfull height, bank slope, stratification or bank layering, bank vegetation and thalweg location in relation to the assessed bank. It further stated that streambank failure is highly related to the composition of the streambank material. Although these materials can be vastly mutable, they can be broadly divided into four categories such as bedrock, cohesionless banks, cohesive banks, and stratified banks. Bank failures in fluvial systems generally occur in one of the three ways and that is by hydraulic forces removing erodible bed or bank material, geotechnical instabilities resulting in bank failures, or a combination of hydraulic and geotechnical forces causing a bank failure (Fischenich 1989).

Furthermore, the Queensland Department of Natural Recourses and Water (QDNRW 2006) further debated that the various mechanisms of streambank erosion generally fall into two main groups, fluvial failures such as bank scour and undercutting due to hydraulic forces along the riverbank and mass failure due to geotechnical instabilities and the combination of both. In many cases of bank instability, both will be evident, often with either bank scour or mass failure being dominant. Thus, this study has adopted these generalized bank failure modes in grouping all the sub-failure mechanisms into three major categories of fluvial failure, mass failure and combine failure. Bank scour is the direct removal of bank materials by the physical action of flowing water and is often dominant in smaller streams and the upper reaches of larger streams and rivers. Mass failure, which includes bank collapse and slumping, is where large chunks of bank material become unstable and topple into the stream or river in single events. Mass failure is often dominant in the lower reaches of large streams and often occurs in association with scouring of the lower banks.

3.2 Causes of Riverbank Failure

Although bank failures result from three different mechanisms as have stated, the actual causes of erosion are complex and varied (Fischenich 1989). Successful bank protection projects need to address the causes of failure. Erosion from hydraulic forces is usually connected to flow velocities and/or its direction which is to do with the flow angle (Fischenich 1989). Human actions such as farming, logging, gardening, gravel extraction, and mining are often responsible, and these human activities were evident at the bridge sites as ninety percent (90%) of Papua New Guineans heavily depend on subsistence farming activities. Channelization and constrictions caused by bridges are examples that change flow velocities and flow angle which often results from an obstruction such as pier or bridge abutment along or in the channel. Any unnatural destruction of bank vegetation promotes erosion by hydraulic forces. Geotechnical failures are usually the result of moisture conditions in the streambank which create forces that exceed bank resistance.

Moreover, to predict the complete erosion of the riverbank soil near the bridge abutment, the balance of remaining soil volume within the investigation limit was used. The balance volume of remaining soil was divided by the respective erosion rate of each bridge both at east and west banks and the time periods for complete erosion were estimated. These assessments were based on the riverbank soil type, submerged soil density, flow behavior of the river and the rate of erosion and given in Figure 6 below are the measure of the remaining volume of riverbank soil. Hence, it can be noted from Figure 6 that the bridge sites with a high amount of remaining riverbank soil are the sites that have lower bank erosion rates compared to those that have low bank soil remaining which are the ones experiencing high bank erosion. This type of assessment is very crucial during the feasibility study and site investigation stage of bridge design so that an appropriate bank protection structure can be selected, designed and constructed.

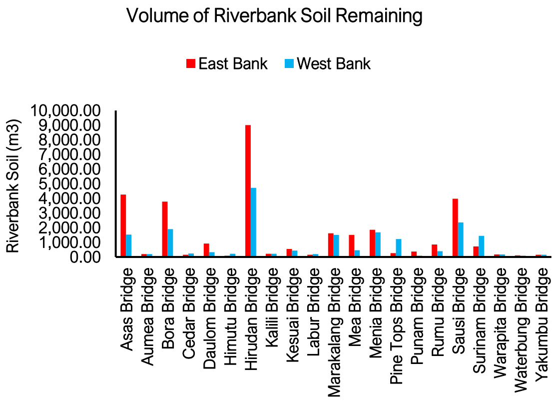

Figure 6. The volume of Remaining Riverbank Soil

4.0 CONCLUSION

It is concluded that fluvial failure due to hydraulic forces accounts to fifty-two percent (52%) of the riverbank failure at bridge sites in Papua New Guinea while mass failure due to geotechnical instabilities accounts for the nineteen percent (19%) and balance of twenty-nine percent (29%) due to combining failure mechanisms. It was observed that as the flow speed increases as given in Table 1, the erosive power of flowing water also increased, and bank scour occurred along the angle of flow with respect to the edge of the riverbank. Increase in flow speed can be the result of natural and human-induced processes such as constrictions from bridge abutments and extended natural banks into the waterway within the bridge site exacerbating the erosive processes of the banks. Both fluvial and mass failure was dominant in all bridge sites.

The highest bank erosion rate was recorded for Cedar Bridge at 1306.5m^3/annum with a flow velocity of 2.62m/s, at a flow angle of 45-degrees at the western bank whilst the lowest was zero for a total of eight bridges on both banks as shown in Figure 5. The average rates of erosion were 161.67m^3/annum on the eastern banks and 165.33m^3/s on the western banks. The median values were 24m^3/annum for the eastern banks and 50m^3/annum on the western banks. As a rule of thumb, if the flow angle is less than 90-degrees with respect to the longitudinal axis of the channel, the riverbank is likely to experience bank erosion.

Combined bank failures were observed in almost all bridges except for only three bridges that were experiencing sedimentation. However, during the change in flood flow conditions such as a change in flow angle, direction, channel migration, and formation of bedforms gave rise to contraction and local scouring at the riverbank within the vicinity of the bridge sites. Flood debris and logs were observed to be dominant in areas where logging activities, plantation agriculture, and heavy subsistence farming activities were prevalent causing erosion and landslides that contributed to human-induced streambank failures.

Therefore, this can be summarized that bank erosion induced bridge failure in Papua New Guinea is a major challenge and appropriate actions must be undertaken to protect the vital road structures such as bridges. Adequate multidisciplinary bridge investigation and design must be undertaken during the initial stage between structural, hydraulics and geotechnical engineers. During the design stage, possible flood risk assessments and damage causes must be investigated, and satisfactory countermeasures must be included in the design to protect bridges against stream instability during the service life of the structure.

5.0 REFERENCES

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