Flood-induced Bridge Failures in Papua New Guinea

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Abstract. Papua New Guinea has been experiencing frequent bridge failures and collapses due to flooding rivers in the recent past. According to the records from Papua New Guinea Department of Works, it is estimated that over Two Hundred and Eighty (285) bridges, fords (causeways) and major culverts were damaged by flood action alone in the last five years between 2013-2017. That is approximately at an average rate of 57 bridges in a year. This result is very disturbing and as such this study was undertaken to assess and analyze the flood-induced bridge failure causes and offer applicable solutions. This study will report on the field investigation works and results derived from the twenty-one flood affected bridges in six different major road networks in three provinces of Papua New Guinea. Hence, it was observed in this study that substructure damages due to flooding account for seventy percent (70%) of the bridge damages while superstructure damages account for the thirty percent (30%). The common causes of flood-induced bridge failures were identified as local scour around bridge piers and abutments, contraction scours, sedimentation, debris, and log impact.

1. Introduction

The climatic effects of flood against the road infrastructure such as a bridge are so prevalent that it requires deeper engineering and technological intervention to address this ever-present phenomenon. Papua New Guinea has been experiencing frequent bridge failures and collapses due to flooding rivers in the recent past. According to the records from Papua New Guinea Department of Works, it has shown that over Two Hundred and Eighty (285) bridges, fords (causeways) and major culverts were damaged by flood action alone in the last five years. That is at an average rate of 57 bridges in a year.

Bridge damages have been observed to be mainly at the bridge foundations. More specifically, the flooding waters erode the bridge abutments, scour the bridge piers and weaken the bridge's resistance against the flood load and eventually destroy the bridge. In addition, it is also attested that riverbank and road approach embankment erosion by flooding rivers have been one of the leading causes of bridge failures in Papua New Guinea, according to this study.

The bridge inspections were carried out in three provinces of Papua New Guinea, namely; Morobe Province, Madang Province and New Ireland Province. In Morobe Province, five (5) number of bridges were investigated, three (3) bridges along Wau Highway, one (1) bridge along Highlands Highway and one (1) bridge along Ramu Highway. In Madang Province, eight (8) bridges were inspected and all were along the Ramu Highway section of Madang Province between Pompaquato Bridge and Usino Junction. Moreover, in New Ireland Province, eight bridges were inspected, three (3) bridge along Boluminski Highway, two (2) bridges along Lanzarote Road and three (3) bridges along West Coast Road. All in all, twenty-one (21) bridges were inspected in three

different provinces along five major socio-economic roads that support the livelihood of people in Papua New Guinea.

Richard Davies, a News Reporter for Floodlist Asia, published on 16th October 2016, that Papua New Guinea is vulnerable to both inland and coastal flooding. The country has suffered from severe coastal flooding in 2008 as many as 75,000 people were displaced from eight (8) different provinces. In 2016, around 10,000 people were affected by flooding in West New Britain Province with thirty-five (35) houses, bridges, roads and agricultural farms were damaged across both provinces of Gulf and Southern Highlands such as sampled in Figures 1 and 2 respectively.

Figure 1. Flood-damaged Himutu Bridge, Boluminski Highway, New Ireland Province, Papua New Guinea. Photo Credit: Gibson Holemba (2016).

Rain and its effect of flooding are a natural phenomenon and are here to stay whether we like it or not. Flooding will continue to affect the livelihood of the people as long as the natural law of Water Cycle exists. The only way out to reduce or control and provide a sustainable solution is an innovative way of engineering and technology and better flood mitigation planning and control works.

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1.1 Antiquity of Flood-induced Bridge Failures

It is widely accepted that the critical infrastructure must be designed, located, and/or sufficiently protected to remain operational during an emergency, including floods, storm surges, and power outages, or for long-term sustainability. With the recent climate change effects, flooding is becoming more frequent than ever estimated. Many vital infrastructures now are vulnerable to be damaged during flood events, such as bridges in this case.

Snell and Smith (2012, p. 1) debated that the damage to bridges and their approach embankments during the major floods in South Africa, Mozambique, and Zimbabwe suggest that a review of bridge design procedures be implemented. This statement clearly states that there is now a big need on a global scale to review the bridge design methods and techniques used in flood and storm assessment as it is now experienced everywhere in any country today.

According to United States Federal Highway Administration (FHWA), Hydraulic Engineering Circular No. 18 (2012), it published that the most common cause of bridge failures in the USA is from floods, scouring bed material from around bridge foundations. During the spring floods of 1987, 17 bridges in New York and New England were damaged and destroyed by scouring. In 1985, floods in Pennsylvania, Virginia, and West Virginia destroyed 73 bridges. 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). The flooding rivers than any other action caused most of these bridge failures in the US and many other countries.

The antiquity of bridges damaged by a flood in Papua New Guinea dates to the prehistoric days when a man has not invented these modern style bridges like Cable-Stayed Bridges, Suspension Bridges, Arch Bridges, Truss Bridges etc. It was when local people used logs and vines to weave the first ever-manmade temporary bridges in the forests and jungles of Papua New Guinea as the country has the third largest rainforest in the world.

Figure 2. Flood-damaged Asas Bridge, Madang Province, Papua New Guinea. Photo Credit: Solomon Pela (2015)

2. Methods of Field Investigation Works

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. These roads are classified as national roads and provide access and connect businesses and people to major ports and service centers in the country.

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 (freeboard), debris and log sizes. Inspections were carried out on both superstructure and substructure with damages the floods have caused on the bridge. The general information of these twenty-one inspected bridges is 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 succeeding chapters.

2.1 River Cross Section Measurement

The river cross section as shown in Figure 3 was measured manually by measuring tape. The top width of the main river channel was measured from 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. The wetted depth and average channel depth were recorded from these measurements which provided the data for calculating hydraulic radius (R) and wetted perimeter (P) using the Mannings open channel formula. 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.
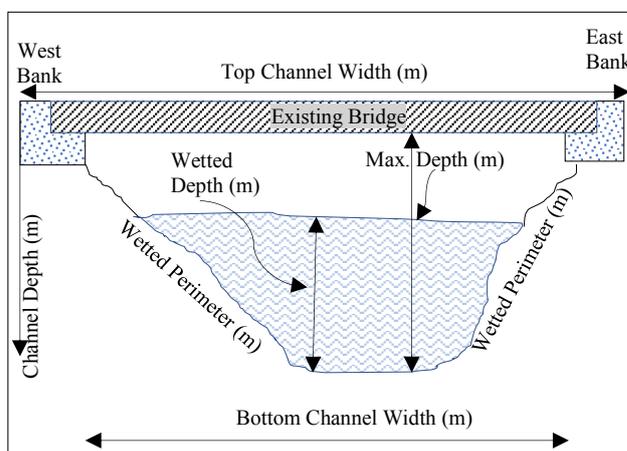

Figure 3. River Channel Cross Sectional Profile

Table 1. Summary of Bridge Investigations in Papua New Guinea

No.	Bridge Name	Road Name	River Type	Catchment Size (km²)	Bridge Length (m)	Bridge Width (m)	Bridge Span	Structure Type
1	Asas Bridge	Ramu Highway	Meandering	11.39	40.0	3.72	1	Bailey Truss
2	Aumea Bridge	Ramu Highway	Braided	68.63	56.0	3.40	2	Bailey Truss
3	Bora Bridge	Ramu Highway	Braided	211.00	48.7	4.34	1	Bailey Truss
4	Cedar Bridge	Wau Highway	Meandering	812.43	35.7	7.50	3	Beam/Slab
5	Daulom Bridge	Lanzarote Road	Meandering	224.09	36.6	3.15	1	Bailey Truss
6	Himutu Bridge	Boluminski Highway	Meandering	41.40	30.84	3.22	1	Bailey Truss
7	Iruan Bridge	Lanzarote Road	Meandering	90.43	124.97	5.20	3	Bailey Truss
8	Kalili Bridge	West Coast Road	Meandering	20.00	21.3	3.14	1	Bailey Truss
9	Kesuai Bridge	Ramu Highway	Braided	56.31	73.5	3.55	2	Bailey Truss
10	Labur Bridge	West Coast Road	Swamp	0.07	21.5	3.15	1	Bailey Truss
11	Marakalang Bridge	West Coast Road	Meandering	17.20	37.0	3.40	1	Bailey Truss
12	Mea Bridge	Ramu Highway	Braided	35.22	146.3	3.64	3	Bailey Truss
13	Menia Bridge	Ramu Highway	Meandering	40.29	45.7	4.40	1	Bailey Truss
14	Pine Tops Bridge	Wau Highway	Meandering	531.62	27.4	3.75	3	Beam/Slab
15	Punam Bridge	Boluminski Highway	Meandering	9.50	35.2	8.49	8 cells	Arch Culvert
16	Rumu Bridge	Highlands Highway	Braided	325.46	30.1	7.38	3	Beam/Slab
17	Sausi Bridge	Ramu Highway	Braided	78.43	137.2	4.40	4	Bailey Truss
18	Surinam Bridge	Ramu Highway	Meandering	280.57	49.5	4.20	3	Warren Truss
19	Wara Pita Bridge	Boluminski Highway	Meandering	11.47	33.0	3.10	6 cells	Arch Culvert
20	Waterbung Bridge	Wau Highway	Meandering	91.79	36.8	4.07	3	Beam/Slab
21	Yakumbu Bridge	Ramu Highway	Meandering	21.56	46.3	4.72	1	Bailey Truss

2.2 Watershed and River Morphology

Watershed is the land area or ridge that separates surface run-offs from precipitations such as rainfall into different river basins, lakes or ocean. The river morphology is the study of river shapes or forms with respect to time. It is referred to as fluvial morphology in the study of hydrology and hydraulics.

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.

Figure 4. Mavic Pro DJI Drone image of Surinam 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.
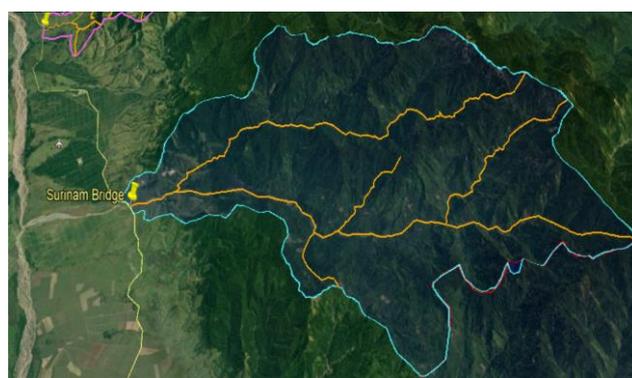

Figure 5. Google Earth Pro© image of the plotted Watershed Area of Surinam Bridge.

2.3 Bridge Inspections and Investigation

This study used the Department of Works Papua New Guinea Bridge Inspection Manual (2005) when undertaking bridge inspection works on all twenty-one bridge sites. Specifically, the Bridge Details Inspection Form and Multi-criteria Assessment Form were used to gather the field information and required data for the research. Prior to the field inspections, pre-meetings were arranged with Department of Works Regional and Provincial Offices were the field visits were undertaken. Hence, formal meetings, briefing, and prior approval were sought with the

responsible agencies and people before actual field investigation and inspection works were undertaken.

Bridge inspections were undertaken at all bridges sites and for the entire structure. The tape measure was used to measure the bridge length, span, and widths while the vernier caliber was used to measure the flange and web thickness of bridge beams. Visual inspection was undertaken on the bridge superstructure over and under the bridge checking all the critical structural members. Measurements were undertaken for members that were damaged and affected by the flood.

All in all, a closer investigation was undertaken at bridge substructures such as bridge abutments, bridge piers, bearings and foundation footings. Riverbanks, bank revetment works such as ripraps, groins, guide banks and other bank protection structures. The overall condition assessment and load ratings were calculated based on the total inspection of the structure with respect to the severity level of the bridge.

3. Results and Discussions

While considerable research has been dedicated to designing of 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.

In some cases, a countermeasure that has been used with success in one province or region is virtually unknown to highway design and maintenance personnel in another province or region. Thus, there is a significant need for information transfer regarding stream instability and bridge scour countermeasure design, installation, and maintenance caused by flooding rivers.

Scouring of bridge abutments and piers, flood debris and log impact 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 Bridge Failure Analysis

From the field investigations, bridge failure analysis was undertaken to correctly identify the resultant factors associated with a flood that caused the damages. The main cause of the bridge damage was flooding, however, principal factors such as scouring, bank erosion, debris impact, and waterway blockage were the root cause of the bridge damages made possible by flooding rivers. Most of

these phenomena are associated with flooding and as such a bridge failure analysis was required.

Flooding causes damage to bridge superstructure and substructure which makes up the bridge. Therefore, the failure factors were further categorized under these two sub-categories related to the structure. Thirdly, the failure analysis was further sorted into failure causes such as local scour at bridge piers and abutments, contraction scour at riverbed and riverbank, bed aggradation and hydrostatic load failure under substructure category. Furthermore, debris/log impact, uplift/buoyancy and overtopping were categorized under superstructure division as they relate to superstructure failures.

Finally, the root element of bridge damage was sorted into respective damage factors as per the field assessments and inspection records observed on site. Blocked waterway area, direct impact, deck displacement, joint movements, parapet/safety barrier damage, roadway damage were some of the common superstructure damages at the twenty-one bridge sites investigated as presented in Figure 9.

While, foundation settlement, abutment damage, road approach damage, channel migration, constriction flow, afflux, sediment deposition, reduced freeboard, slip failure and embankment failure were observed to be at the substructure level.

3.2 Design Flood Estimation

The Papua New Guinea Flood Estimation Manual (SMEC, 1990) provides a standard guideline for the estimation of floods in Papua New Guinea. This manual is intended for general use in the planning and design of small to medium-sized engineering works for the planning and design of bridges, culverts, small dams, drainage works and flood mitigation works in the country.

Therefore, it was important that the flood estimation methods of this manual were used for design flood discharges in which, Regional Flood Frequency Method (RFFM) was used for flood estimation using Eq. (1), Eq. (2), and Eq. (3). The results of the flood estimations are as presented in Figure 6.

$$Q_2 = 0.028 * AREA^{0.70} * P_2^{1.12} * KS \qquad (1)$$

$$Q_{20} = Q_2 + 0.62(Q_{100} - Q_2) \qquad (2)$$

$$Q_{100} = 0.059 * AREA^{0.65} * P_2^{1.12} * SLOPE^{0.11} * KS \quad (3)$$

Q_2 is the two-year return period or the base flood, Q_{20} is the twenty-year return period and Q_{100} is the one-hundred-year return period which is known as Average Recurrence Intervals (ARI) or return periods. The AREA represents the area of the catchment size in km^2, P_2 is the two-year daily rainfall data taken from flood estimation manual, the SLOPE is the mean slope of the river channel and KS is the swamp adjustment factor of the main catchment and 0.62 is the regression factor for Q_{20} return period.
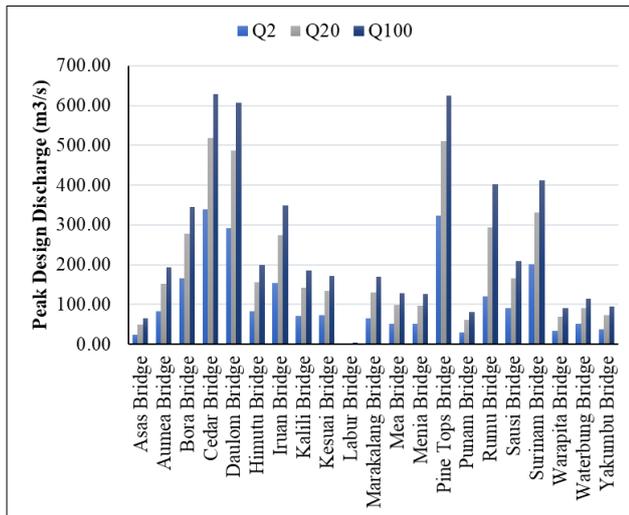
Figure 6. Flood Estimation for Q_2, Q_{20} and Q_{100} ARI

3.3 Scour Estimation

Scouring at bridge piers has been a major cause of bridge failures all around the world due to the hydraulic action of the flowing stream during the flood and in clear water flow. Local scour at piers and abutments is one of the contributing factors of bridge failures in Papua New Guinea.

Water normally flows faster around piers and abutments making them susceptible to local scour as shown in Figure 7. At bridge openings, contraction scour can occur when water accelerates as it flows through an opening that is narrower than the channel upstream from the bridge. Degradation scour occurs both upstream and downstream from a bridge over large areas. Over long periods of time, this can result in lowering of the streambed. Stream channel instability resulting in river erosion and changing angles-of-attack can contribute to the bridge scour.
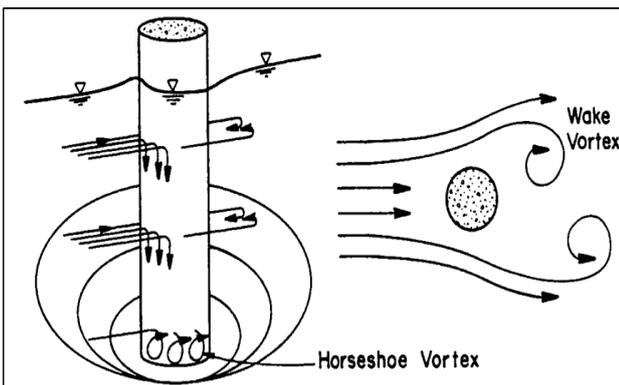

Figure 7. Diagram of Local Scour at a circular bridge pier submerged under flowing water (FHWA HEC-18, 2012).

Scour and stream instability problems have always threatened the safety of our nation's highway bridges. Countermeasures for these problems are defined as measures incorporated into a highway-stream crossing system to monitor, control, inhibit, change, delay, or minimize stream instability and bridge scour problems.

Considerable studies have been undertaken in providing design guidelines, procedures and methods of scour at

bridge piers and abutments. In this study, FHWA Scour Estimation method for Contraction Scour and Colorado State University (CSU) method for Local Pier Scour were used for scour estimation as given in Eq. (4), (5) and Total Scour in Eq. (6).

$$\frac{y_u + d_c}{y_u} = \left(\frac{W_U}{W_B}\right)^{k_1} \tag{4}$$

$$d_l = y_u . 2.0 k_1 k_2 k_3 k_4 \left(\frac{W_p}{y_u}\right)^{0.65} Fr^{0.43} \tag{5}$$

$$d_t = d_c + d_l \tag{6}$$

The d_c is the contraction scour depth, d_l is the local pier scour depth, d_t is the total scour depth, y_u is the upstream flow depth, W_U is upstream main channel width, W_B is the constriction channel width at bridge location, W_p is the pier width, F_r is the Froude Number which is a function of gravitational acceleration (9.8 m/s), flow velocity (U) and flow depth. The $k_1 - k_4$ are correction coefficient factors for pier nose shape factor (k_1), angle of incidence flow factor with respect to pier axis (k_2), the correction factor for bed conditions (k_3) and (k_4) which is the correction factor for armoring effects. Using these equations and the field measurements the total scour depths were calculated for each bridge as presented in Figure 9 below. At each bridge foundation subject to scouring action of the flowing stream, the total scour [d_t] is given by the simple arithmetic equation (Eq. 6).
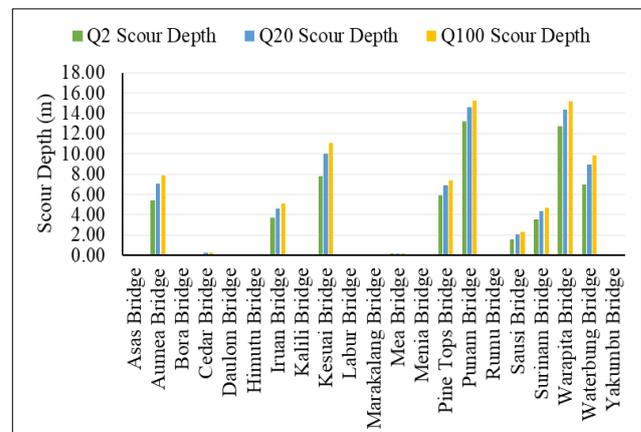

Figure 8. Total Scour Depth Calculation of Q_2, Q_{20}, and Q_{100}

Based on the assumption that local scour and contraction scour are independent, that is to say, that local pier scour can be calculated based on hydraulic parameters which do not take into account the contraction scour effect. An alternative approach is to re-calculate the hydraulic parameters such as velocity and flow depth based on the general scour bed levels. The latter approach is more complex but could be more accurate, particularly in cases where there is significant contraction scour. Improved estimates of scour depth may be obtained if site measurements of scour are available from nearby existing bridges of similar construction to the proposed bridge, particularly if scour have been monitored during flood periods.
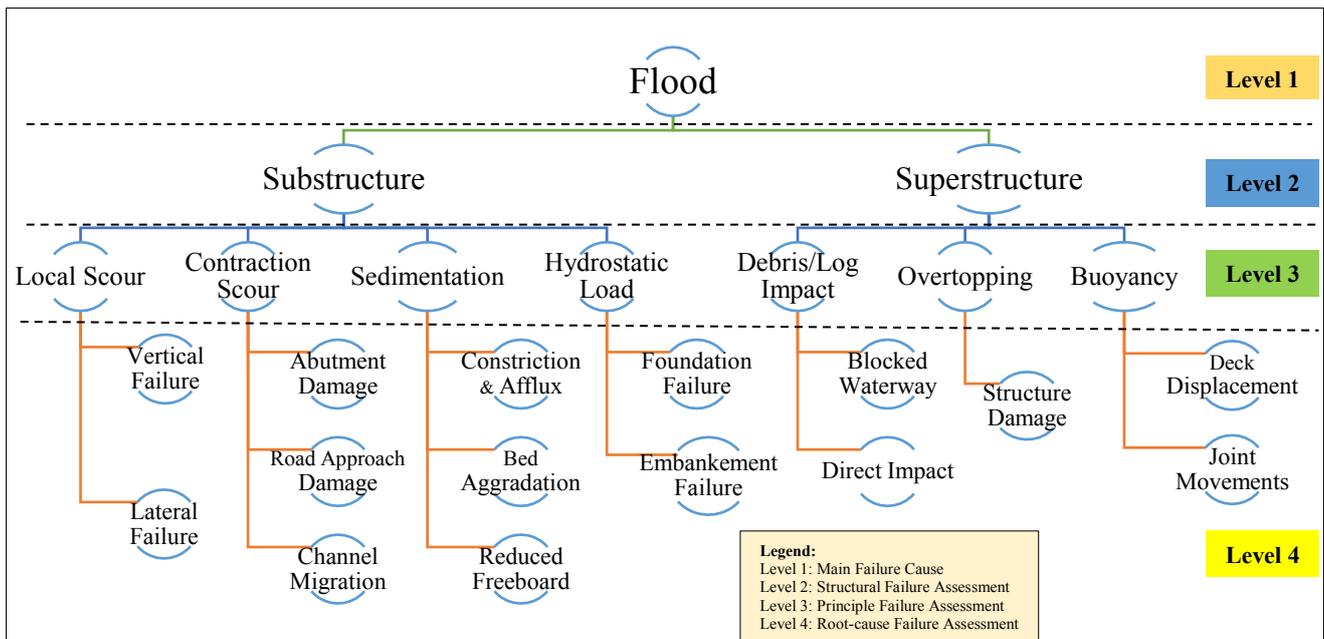
Figure 9. Bridge Failure Analysis

It is recommended that bed levels and foundation levels be plotted onto several cross-sections of the bridge sites. Contraction scouring levels can then be adjusted to take account of its non-uniformity across the section. Local scour depths may then be superimposed on the Contraction Scour bed profiles.

3.4 Forces on Superstructure due to Water Flow

The resistance to flow can be divided into shear resistance and resistance due to the difference in pressure from the upstream side to the downstream side of an object which creates drag force. When flow passes over an object, a resistance to flow is created that depends upon the shape or form of the boundary of the object. The shape of the boundary (i.e., a bridge pier) causes a deflection of the streamlines and local acceleration of the fluid.

Consequently, a change in pressure takes place from the upstream to the downstream side of the boundary, which is also referred to as a normal stress. The summation of the forces over the surface results in a drag force on the boundary and a pressure resistance against the fluid.
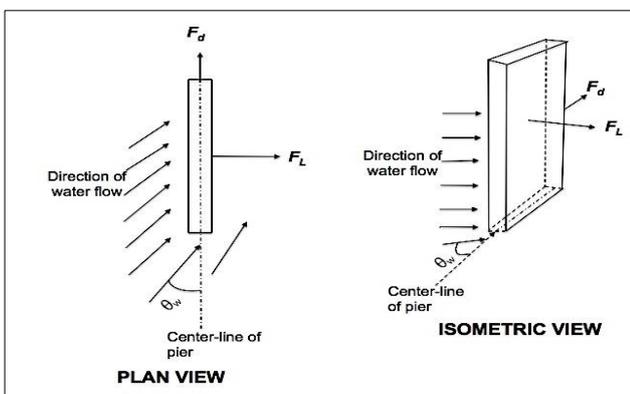

Figure 10. Drag Force (F_d) and Lift Force (F_L) on submerged bridge piers and abutments (AS 5100, 2004).

The Australian Bridge Design Standard (AS5100, 2004) specifies that the bridge structures subject to water flow effects; the fluid forces on the piers are dependent on the pier shape, the water velocity and the direction of the flow. The diagram in Figure 10 further describes how the body of water behaves against the submerged body of the structure during a flood or in a normal flow condition.

The hydrodynamic flow pressures such as Drag Force (F_d) and Lift Force (F_L) for bridge piers were analyzed using the Australian Bridge Standard AS5100 specified Eq. (7), and (8) respectively. The Buoyancy Force (F_B) of the submerged parts of the bridge superstructure was estimated based on Archimedes Principle as expressed in Eq. (9), Hydrostatic Water Pressure (P_h) was estimated using Eq. (10) while forces due to Log Impact (F_I) was determined based on kinetic energy or inertia force equation given in Eq. (11) as per clause 15.6 of AS5100.

$$F_{du} = 0.5C_d V_u^2 A_d \tag{7}$$

$$F_{Lu} = 0.5C_L V_u^2 A_L \tag{8}$$

$$F_B = \gamma_w V_w \tag{9}$$

$$P_h = \gamma_w H \tag{10}$$

$$F_I = \left(\frac{0.5m V_u^2}{L}\right) \tag{11}$$

γ_w is the specific (unit) weight of water (9.81kN/m^3), V_w is the volume of water displaced by the submerged object which is equal the volume of an object submerged under water based on Achmedes Principle, H is the flow depth. C_d is the drag force coefficient, C_L is the lift force coefficient, V_u is upstream flow velocity, A_d and A_L are projected areas of the pier with respect to the flow angle. *L* is the log impact stopping distance measure from the pier and *m* is the mass of log assumed as 2 tones as per clause 15.6 of AS5100.

The results in Figure 11 (a) and (b) shows that as the flow velocity increased, the magnitude of hydrodynamic loads was increased. The projected area and angle of incidence and pier or abutment shapes and sizes contributed to high impact forces. Therefore, it is very important to undertake accurate assessments of the hydrodynamic loads during the design stage of the bridge. As presented in Figure 12, debris and log impacts accounted for a lot of bridge superstructure damages and even causing bridge failures. Hence, more research is required to improve the debris and log impact forces on bridges constructed over natural river crossings.
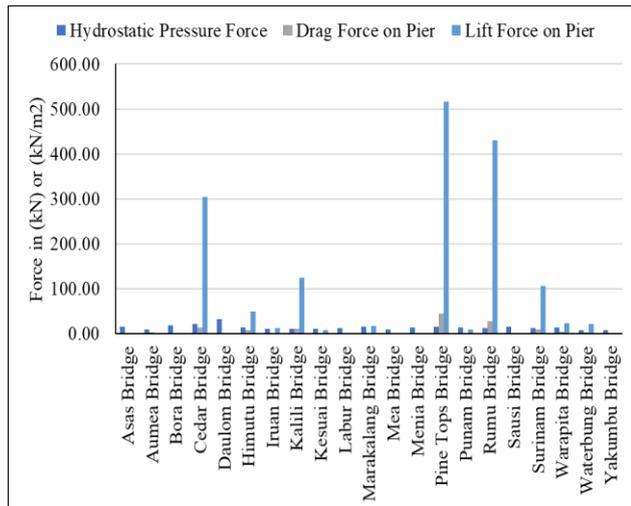

Figure 11 (a). Hydrostatic Pressure Force (P_h), Drag Force (F_d), Lift Force (F_L)
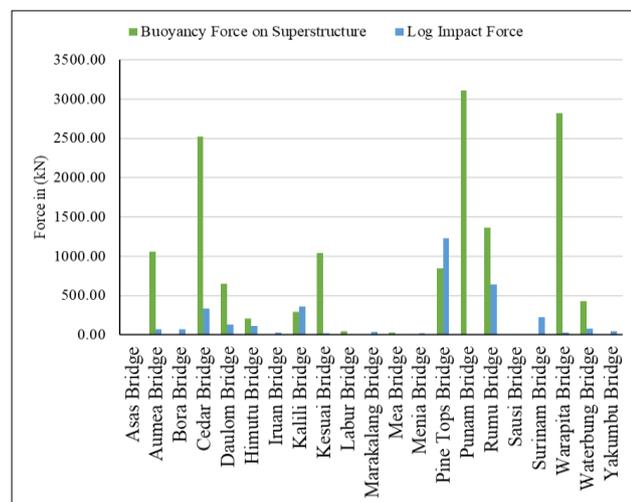

Figure 11 (b). Buoyancy Force (F_B), and Log Impact Force (F_I)

In the design of bridge superstructure for flood resistance, the structural stability checks must be carried out on the deck and girder or beam connections to the bridge abutment and pier due to uplift forces from the flood. The superstructure must be able to withstand the 100-year flood and be able to submerge under 2000-year flood with no or less structural damage.

The design is made sure to meet all the required design criteria in accordance with the bridge design standards of the relevant government bodies. In the context of Papua

New Guinea, the design must conform to Australian Bridge Design Specification (AS5100, 2004 update) and other relevant standards such as PNG Flood Estimation Manual and Department of Works Roads & Bridges Specification (2015).

4.0 Analysis of Bridge Failure Cases

It gives us more evidence that bridge failures due to hydraulic effects and its related causes require detail investigation, study and development of more rigorous oversight of bridge failures due to flooding. Many bridges have suffered substantial damages and even some were completely washed away by the flood. The major causes of the damages were observed to be flood-related such as scour, embankment erosion and debris/log impact.

Henceforth, it was observed that almost all the Bailey truss type superstructure suffered major damage against Girder (beam/slab) bridge. Two composite arch bridges were both damaged during the storm event. Therefore, we can surmise that Bailey bridge steel truss superstructure is not able to withstand flood load in the event of a major storm or designed peak discharge. Abutment scours and embankment erosion leading to road approach damage putting the bridge at flood risk of the collapsible state was observed in almost all bridges.

Overtopping of the approach roadways and turbulent flow adjacent to approach embankments caused erosion and scour of the side slopes and toes of the embankments. This can lead to instability of the approach embankments and possible loss of the road. Loss of fill material around and behind abutment wing walls lead to instability and failure of the wing walls. The summary of the bridge failure cases based on this investigation works is as presented in Figure 12 below.
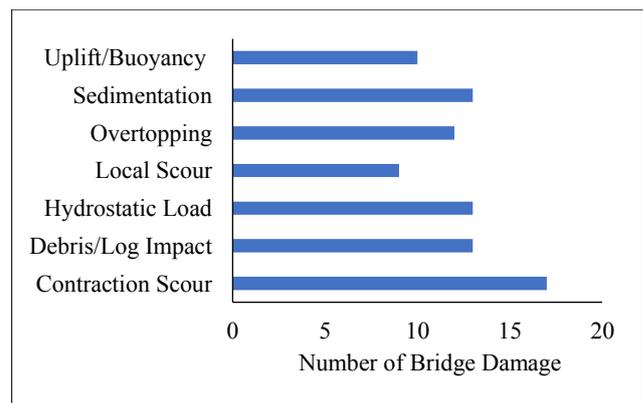

Figure 12. Summary of Bridge Failure Cases

Figure 12 presents the bridge failure cases in the third level category based on the bridge failure analysis given in Figure 9. The figure describes the number of bridges that were subjected to bridge damage caused by the flood. The major cause of bridge failure according to this figure is contractor scour, flood debris and log impact on the structure, sedimentation, and hydrostatic load.

Bed aggradation due to high sediment deposition reducing high water level clearance (freeboard) created an

opportunity for log and debris impact in flood event which damaged Aumea Bridge, Asas Bridge, Kesuai Bridge, Surinam Bridge, Waterbung Bridge, Punam Bridge and Wara Pita Bridge. Huge logs were observed to be part of the flood debris generated from heavy logging, subsistence farming, alluvial mining, landslide and plantation agricultural activities along the coast.

Furthermore, all bridges were constructed over a natural stream or river crossings and they vary in lengths and superstructure types. The common superstructure type was Bailey truss, while four (4) were beam/slab or Girder bridges and two (2) were Arch/Composite bridges constructed of Multi-plate Supercor culverts. It was recorded during the inspection that, five (5) bridges were completely damaged by flood, ten (10) bridges sustained major damages and six (6) bridges had minor damages and all are under the critical condition for replacement and urgent maintenance.

Most of the bridges are single span bridges whilst five (5) bridges are multi-span. Half of the bridges were founded on shallow spread footing foundations with gabion baskets as embankment retaining structure while others are on a steel H-pile foundation. Bailey truss and two arch/composite bridges sustained major superstructure damages during storm events under submersible condition compared to girder bridges.

The bridges investigated were all river bridges and these rivers begin from steep mountains and valleys. Thus, have high flow velocity and carries huge flood debris and logs due to erosion upstream. Most rivers have meandering system while few were braided and swamp systems. Rivers near the coastline experienced tidal surges and swelling. Therefore, it is established in this research that the major cause of these bridge failures in Papua New Guinea was flooding giving rise to debris and log impact, overtopping, sedimentation, scour and embankment erosion and channel migration.

Multi-plate Supercor culverts must not be installed on streams with wide channel and high volume of sediment and flood debris. In a case where such structures are required, proper site investigation and engineering designs must be undertaken to accommodate all aspects of bridge design. Poor design of Punam and Warapita Bridges have caused the bridges to fail which have resulted in high cost of maintenance and replacement.

Finally, it is a sincere recommendation that all Bailey bridge superstructures must not be used as permanent structures on major economic highways and on river crossings located on major floodplains predicted to experience overtopping in-service stage. It is established in this study that they succumb easily to floods with a high volume of debris and fail due to fatigue loads. Thus, with the current increase in demand in mining and infrastructure projects in Papua New Guinea, bridges of higher order must be preferred over Bailey bridges.

5.0 Conclusion

In this study, twenty-one (21) flood-damaged or affected bridges in Papua New Guinea were investigated and studied. The bridges are part of the six (6) national roads in the country that provide access to the local people and the business community at large. The study was undertaken in three (3) distinctive provinces of Papua New Guinea, namely; Morobe Province, Madang Province and New Ireland Province.

It was observed that substructure damages due to flooding account for seventy percent (70%) of the bridge damages while superstructure damages account for the thirty percent (30%). Local scour around bridge piers and abutments, contraction scours, sedimentation, debris, and log impact were the common causes of bridge damage observed in this field of study.

Both types of scouring 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. Flood debris and logs were observed to be dominant in areas were logging activities, plantation agriculture and heavy subsistence farming activities were prevalent causing erosion and landslides.

Therefore, this study shows that flood-induced bridge failure in Papua New Guinea is a major challenge and appropriate actions must be undertaken to protect the vital road structures. 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 flood damage during the service life of the structure.

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