Flood Resistant Bridge Design in Papua New Guinea

Hokkaido University　Member　○Gibson Ali HOLEMBA
Hokkaido University　Member　Takashi MATSUMOTO

1. INTRODUCTION

The climatic effects against the road infrastructure such as a bridge, are so prevalent that it requires deeper engineering and technological intervention to address these ever-present phenomena. 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 (280) bridges, fords (causeways) and major culverts were damaged by flood action alone in the last Five years.

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.

As seen in the signing of the Paris Agreement (COP21) on Climate Change by world leaders to decrease the rate of carbon emission into the atmosphere in September 2016. The effects of climate change causing devastating disasters such as shown in Figures 1 and 2 is now a major focus on global front and as engineers, we are entrusted with more responsibility to provide innovative ideas into engineering and technology that can be sustainable to the lives of people using the infrastructure.

Whether it is an effect of climate change or an occurrence of a natural phenomenon, we need to provide solutions to counterbalance these forces of nature, especially the flooding waters that cause damage to the vital structures such as bridges.

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.

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 people as long as the natural law of Water Cycle exists. The only way out to reduce and provide a sustainable solution is an innovative way of engineering and technology and better flood mitigation planning and control works.

Thus, this is now the course of this research, where we can innovate new methods of bridge design that can withstand the predicted flood events.

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

1.1 Antiquity of Flood-damaged Bridges

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), 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.

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

A national study for the Federal Highway Administration (1973) revealed that catastrophic floods caused 383 bridge failures in the US. Furthermore, of these bridge failures, twenty-five percent (25%) involved pier damage and seventy-five percent (75%) were abutment damage (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). 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.

Therefore, this study is so eminent to address the problem of flood-damaged bridges. Most of these damaged bridges have not been maintained and are still waiting for funding from the government since they were damaged. The cost of reconstruction is very high and with economic crisis faced in the country due to a decrease in the world market prices, this is now a dilemma for poor local people.

2. 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.

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 superstructure and damages the floods have caused on the bridge. The general information of these Twenty-one bridges is provided in Table 1. These bridges have fallen victim to flooding having major structural damages while several bridges were destroyed by flood as discussed in the following chapters.

3. RESULTS AND DISCUSSION

The impacts of bridge design and construction on the highways, safety to the traveling public, and the natural environment can be significant. An economically viable and safe bridge is one that is properly sized, designed, constructed, and maintained. The structure at most must withstand the design flood in the serviceability limit state and be able to accommodate overtopping with no or less structural damage in the ultimate limit design state.

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 as summarised in Figure 3. All rivers have natural banks with no bank revetment or scour protection measures. These bridges were constructed for accessibility convenience; hence no adequate investigation works were undertaken. This was proved with no design record.

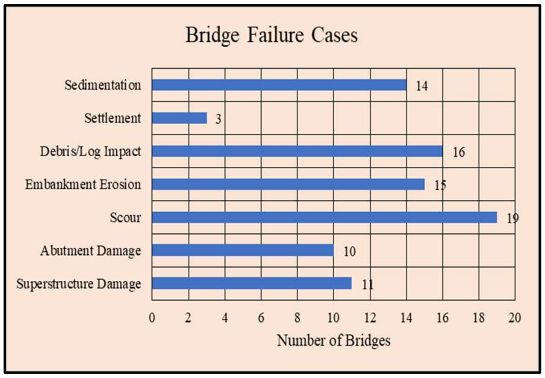

Figure 3 Summary of Bridge Failure Cases

Table 1 Summary of Bridge Investigations in Papua New Guinea

No.	Bridge Name	River Name	Length (m)	Width (m)	Structure Type
1	Asas Bridge	Yakura River	40.0	3.72	Bailey Truss
2	Aumea Bridge	Aumea River	56.0	3.40	Bailey Truss
3	Bora Bridge	Bora River	48.7	4.34	Bailey Truss
4	Cedar Bridge	Wau River	35.7	7.50	Beam/Slab
5	Daulom Bridge	Daulom River	36.6	3.15	Bailey Truss
6	Himutu Bridge	Hilolon River	30.84	3.22	Bailey Truss
7	Iruan Bridge	Iruan River	124.97	5.20	Bailey Truss
8	Kalili Bridge	Kalili River	21.3	3.14	Bailey Truss
9	Kesuai Bridge	Kesuai River	73.5	3.55	Bailey Truss
10	Labur Bridge	Labur River	21.5	3.15	Bailey Truss
11	Marakalang Bridge	Marakalang River	37.0	3.40	Bailey Truss
12	Mea Bridge	Wabut River	146.3	3.64	Bailey Truss
13	Menia Bridge	Menia River	45.7	4.40	Bailey Truss
14	Pine Tops Bridge	Wau River	27.4	3.75	Beam/Slab
15	Punam Bridge	Punam River	35.2	8.49	Arch/Composite
16	Rumu Bridge	Rumu River	30.1	7.38	Beam/Slab
17	Sausi Bridge	Nopu River	137.2	4.40	Bailey Truss
18	Surinam Bridge	Surinam River	49.5	4.20	Warren Truss
19	Wara Pita Bridge	Marr River	33.0	3.10	Arch/Composite
20	Waterbung Bridge	Perenin River	36.8	4.07	Beam/Slab
21	Yakumbu Bridge	Yakumbu River	46.3	4.72	Bailey Truss

3.1 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 is important that the flood estimation methods of this manual were used for design flood discharges in which Regional Flood Frequency Method was used for flood estimation using Eq. (1) and Eq. (2). The results of the flood assessments are as presented in Figure 4.

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

$$Q_{100} = 0.059 * \mathrm{AREA}^{0.65} * P_2^{1.12} * \mathrm{SLOPE}^{0.11} * \mathrm{KS} \quad (2)$$

Q_2 is the two-year return period, Q_{20} is the twenty-year return period and Q_{100} is the one-hundred-year return period which is known as Annual Recurrence Intervals (ARI) or return periods. The AREA represents the area of the catchment size, 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.

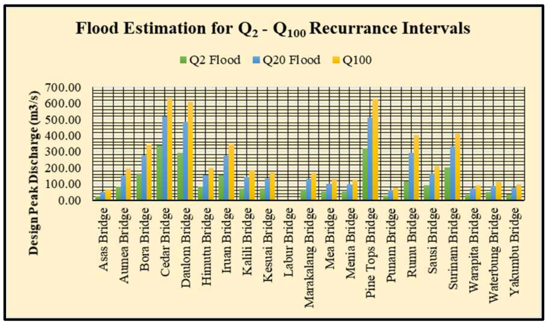

Figure 4 Flood Estimation for Q_2, Q_{20} and Q_{100} ARI

3.2 Scour Estimation

Many researchers have undertaken considerable studies providing design guidelines, procedures and methods of scour at bridge piers and abutments. In this study, FHWA Scour Estimation method for General Scour and CSU method for Local Scour were used for scour estimation as given in Eq. (3), (4) and Total Scour in Eq. (5).

$$\frac{y_u + d_g}{y_u} = \left(\frac{W_U}{W_B}\right)^{k_1} \quad (3)$$

$$d_l = y_u . 2.0 k_1 k_2 k_3 k_4 \left(\frac{W_p}{y_u}\right)^{0.65} \mathrm{Fr}^{0.43} \quad (4)$$

$$d_t = d_g + d_l \quad (5)$$

The d_g is the general scour depth, d_l is the local 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 analyzed in Figure 5 below.

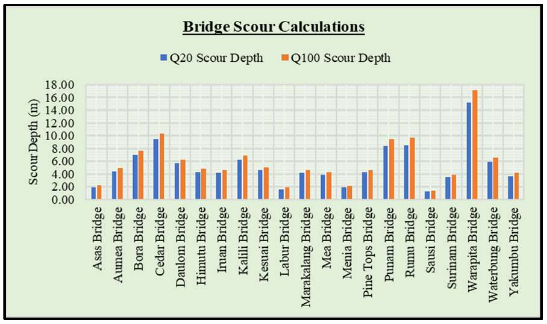

Figure 5 Total Scour Depth Calculation of Q_{20} and Q_{100}

Henceforth, it was observed that almost all the Bailey Truss type superstructure suffered major damage compared to Girder (beam/slab) Bridges. 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.

3.3 Hydrodynamic Loads

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, landslide and plantation agricultural activities along the coast.

The hydrodynamic flow pressure (P) was calculated using the AASHTO formula while Drag Force (F_d) and Lift Force (F_L) were analyzed using the Australian Bridge Standard AS5100 specified Eq. (6), (7) and Eq. (8) as given below respectively.

$$P = 0.51 K U^2 \quad (6)$$

$$F_{du} = 0.5 C_d V_u^2 A_d \quad (7)$$

$$F_{Lu} = 0.5 C_L V_u^2 A_L \quad (8)$$

K is the pier shape adjustment factor, U is the flow velocity, 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.

The results in Figure 6 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 3, 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.

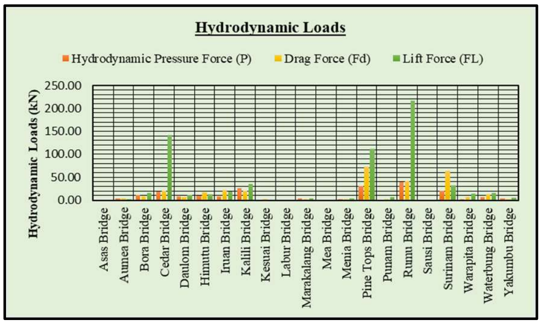

Figure 6 Hydrodynamic Pressure Loads in Ultimate Limit State

4. CONCLUSION

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 minimise stream instability and bridge scour problems.

According to Figures 3 and 5, it has proved that scouring is a major cause to bridge failures in Papua New Guinea. Therefore, as a flood-resistant measure against scouring, this research has proposed Eq. (9) for use in bridge design, where Z_d is the designed bed elevation, Z_0 is the natural bed elevation, d_t is the total scour depth and 1.0m is the conservative depth as a scour countermeasure.

$$Z_d = (Z_0 - d_t) + 1.0m \qquad (9)$$

Numerous measures are available to counteract the actions of humans and nature, which contribute to the instability of alluvial streams. These include measures installed in or near the stream to protect highways and bridges by stabilizing a local reach of the stream, and measures, which can be incorporated into the highway design to ensure the structural integrity of the highway in an unstable stream environment.

The second most cause of bridge failure in this study is flood debris and log impact. Hence, as design countermeasure, Eq. (10) is recommended to use for estimating flood levels and determining bridge foundation elevations.

$$F_b = HWL_{Q10} \;\; + 0.5L + 1.0m \qquad (10)$$

Where F_b is the freeboard, HWL_{Q100} is the high water level or flow depth at the 100-year flood, L is the largest log/debris diameter and 1.0m is the safety margin for bridges prone to flood debris or log impact. Bridges built over rivers require multi-disciplinary inputs, and it is often advisable for the bridge engineer to involve hydraulics engineer, environmentalist and geotechnical engineer at planning and design stage.

The selection, location, and design of countermeasures are dependent on hydraulic and geomorphic factors that contribute to stream instability, as well as costs and construction and maintenance considerations. One of the countermeasures to be incorporated at the planning and design stage is the use of Eq. (11).

$$L = W + (F_p) + 10.0m \qquad (11)$$

Where L is the bridge length, W is the river channel width, F_p is the floodplain width parallel to the bridge along the road alignment and 10.0m is the safety margin for bridges estimated to experience overtopping in a 100-year flood. If the bridge is not located in a floodplain then the designer can neglect the floodplain width.

The flowchart given in Figure 7 is for use in the design of a new bridge over a river or stream crossing or in assessing countermeasure for existing bridge. If the structure is stable the design process can proceed to consideration of environmental impacts, cost, constructability, and maintainability, however, if the bridge is unstable then revise the design and repeat the analysis.

For an existing bridge, the finding of structural stability at this stage will result in a low-risk evaluation, with no further action required. However, a plan of action must be developed for an unstable existing bridge where flood-related damage is critical.

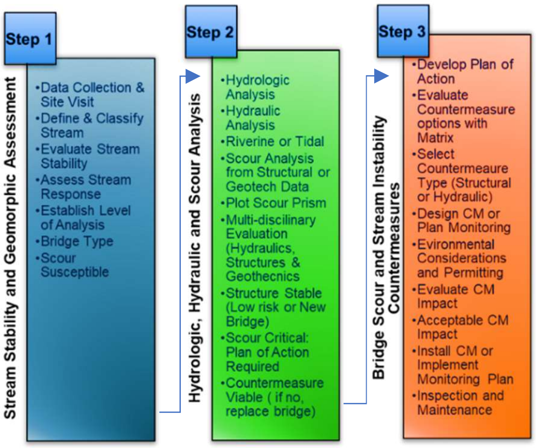

Figure 7 Flood-resistant Countermeasure Design Flowchart

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