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Bridge Collapse in Nigeria: A Case Study of Tatabu Bridge in Mokwa Local Government Area of Niger State

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Abstract

Large parts of Niger State are located in low terrain and have proximity to River Niger: the largest river in Nigeria; coupled with the presence of three hydro Electric power stations in the state. Niger State has been confronted annually by flood disaster that has destroyed many lives and properties. The focus of this paper is to investigate the causes behind Tatabu bridge collapse. In this investigation, soil strength and index test, hydrological data, nature of the terrain, concrete strength test and evaluation of flood impact on the bridge and its embankments using ANSYS Finite Element Method were conducted. The results of the investigations revealed that the collapsed bridge was positioned within a valley as well as steady increase in precipitation from 2015 to 2017 which directly increased the stream flow rate and also runoff. It was also observed that the debris settlement within the cell of the collapsed bridge contributed to reduction of the cross sectional area of single cell. The compressive strength test of the bridge members revealed that the strength are within acceptable limit. The authors recommended that there is the need for embankment protection either covers vegetation, stone pitch, slope stabilizer, or concrete interlocking is required for future consideration. Due to increase in water balance, the new bridge capacity should be increased to accommodate the high volume of water. The new bridge should be reconstructed above the valley or repositioned away from the valley. it is also recommended that a complete replacement of the underlain material forming the adjacent slope to the bridge retain wall with a better compacted engineering soil to avoid future pavement failure of the kind.

Keywords: Bridge, Flood, ANSYS, Collapse, Terrain

1.0 Introduction

A bridge failure is often accompanied by a number of losses; the loss of the structure itself, the loss of major aspects of means of livelihood of the citizenry in the affected area and the resultant negative impacts on the larger economy (George et al., 2013). Therefore, it is imperative to take all the necessary measures to reduce the frequency of bridge failures in the country in the light of ensuring the safety of the infrastructure itself and also minimizing the socio-economic losses associated with such tragic incidents

Studies have shown that a substantial component of the body of scientific knowledge concerning bridge engineering has been generated from the previous failures of bridges; however each bridge failure has its distinctive features, thus it is hard to give clear-cut causes of failures (Jamilur and Ariful, 2015). This is perhaps the reason why sufficient data need to be gathered and developed before a cause or causes of bridge failures are established. Hence, trends of failures have to be consistently observed during bridges collapse in order to gain insight as to the reason of the failure of bridges.

Bridge failures do occur as a result of a combination of factors which usually build up to trigger a collapse, because a single factor may not potentially cause a bridge to collapse; for example severe winds may not be enough to cause a structure to come down, but when they hit a bridge that is structurally too rigid to withstand them, it leads to failure (Bridge Masters Incorporation, 2017).

For the causes of bridge failures, there are two major schools of thoughts. The first group believes that bridge collapses are caused by natural and manmade factors; while the second group is of view that there exist the internal (manmade), the external (natural), and cascading factors i.e. a mix of other factors triggering a bridge failure. Typically, Azmat and Sumaira, (2016), argued that, combined dead load stresses with one or more external transient forces lead to a mix of external stresses; thus when the dead load stress is already high and getting to the elastic limit of the member of the bridge, any applied stress or force may exceed the allowable limit thereby causing the failure of bridge. This means that a single factor hardly causes a bridge to fail, but a combination of other successive external or internal factors. According to Wardhana and Hadipriono, (2003), factors such as floods, scour, earthquake, landslide, wind, etc. are natural; while improper design and construction method, collision, overloading, fire, corrosion, lack of inspection and maintenance, etc are classified as human factors. Prominent among scholars who hold that majority of bridge failures are caused by natural factors such as floods, scour etc. Wardhana and Hadipriono, (2003), concluded that, in United States the most common causes of bridge failures were not due to design and construction fault but due to floods and collisions. This is so because of the prevailing climatic changes and their resultant intense weather events which cause more floods around the world (Bridge Masters Incorporation, 2017).

This is perhaps due to distinctive geographical and climatic differentials inherent in some regions of the investigations; and of course the prowess of the engineers in bridge design and construction in certain developed world. But authors like Jamilur and Ariful (2015), argue that the main causes of bridge failures emanate from deficiencies in design, detailing, construction, maintenance, use of weak materials, and paying less attention to external factors. This may be has do with engineering capability of bridge designers and adequate resources in terms of budgetary allocation, man power and priority of government in providing adequate infrastructure especially in developing nations.

1.1 Susceptibility of Mokwa and its Environs to Flooding

Niger state is located between latitudes 8.02°N and 11.20°N and longitudes 3.38°E and 7.03◦E (Figure 1). The 2006 National Population and Housing Census put the total population of the state as 3, 954,772 (National Population Commission, 2009). Mokwa town is geographically situated in Niger State; it is bordered by the Niger River in the south, the Lake Jebba in the west and the confluence of the Kaduna River in the east (Mokwa, 2018). Ayinde O.E. et'al, (2013), reported that, the climate vegetation and the soil of Niger State experiences two distinct seasons; the dry and wet seasons.Terrain wise, however, Mokwa has a landmass of 4058km2: Niger Valley (highly susceptible to flood) constitutes 2841.88km2 (70.02%), Plains (susceptible to flood) represents 1168.59km2 (28.79%), Uplands (marginally susceptible to flood) comprises of 48.03km2 (1.18%) while Highlands is not susceptible to flood disaster at all (Ikusemoran and Kolawole 2014).This may be one of the reasons why Mokwa and its environs have suffered recurrent flood disasters in the last one and half decades.

Flooding is one of the most frequent and widespread of all environmental hazards (Ikusemoran et al., 2013) . It occurs in most terrestrial portions of the globe, causing huge annual losses in terms of damage and disruption to economic livelihoods, businesses, infrastructure, services and public health (Ikhuoria et al., 2012). Long term data on natural disasters suggest that floods and wind storms have been by far the most common causes of natural disaster worldwide over the past 100 years (Jubril and Yunusa, 2012).

Studies have shown that flood prone areas of Niger State started experiencing serious flood disasters between 1999 and the year 2000; and one of the perennial causes of this phenomenon in Niger State and some parts of Shonga in Edu Local Government Area of Kwara State was believed to be connected with the release of water from Kainji Dam which subsequently flooded all banks along River Niger areas (Etuonovbe, 2011) and (Muhammad and Iyortim, 2013) . This was corroborated by the findings from Bukka et al., (2017), that the prime causes of flooding at Muwo district situated between Kainji and Jebba Dams, in Mokwa, Niger State were excessive rainfall, the location of area within a flood plain and release of water from Kainji dam; they also observed that the variation in the river water level is determined by the inflow of water from the Kainji hydro power plant while the river of the area is dammed at Jebba Hydro power plant.

This research therefore aimed at investigating the causes of bridge collapse at Tatabu in Mokwa Local Government Area of Niger State and to provide an appropriate recommendation to minimize such failures.

2.0 The Study Area

The collapsed bridge is along Mokwa-Jebba Federal Road, about 10Km from Mokwa town. Tatabu Town is situated on the west side of Mokwa Local Government , Niger State, and located within the Niger valley which are classified as "highly vulnerable, (Figure 1)" to flood disaster cover a land area of 24.94% of the state total land area [9]. In June 2017, this area experience a continuous heavy rainfall which resulted in significant erosion, washed away river banks, landslides and cracks along the road surface. These incidences damaged two bridges; Rail line and Road bridges across River Tatabu, 3km apart, closing down motorist movement along the Mokwa-Jebba Federal Road. The Bridge is on River Tatabu located at Longitude (04°34′47.6″E) and Latitude (09°14′30.9″N). See location map in Figure 2. The heights of the approach embankments on both sides of the abutments were about 3m with side slope of 1v (vertical) to 1.5h (horizontal). These embankments were constructed over a layer of very soft silty clay. The bridge comprises of a single carriage way with the bridge as shown in Figure 3 while Figure 4 shows the collapsed rail line. The bridge was made up of reinforced concrete elements and was built about 43 years ago. The Tatabu Bridge was 7.20 metres long (span) and 7.5 metres carriageway width.

Figure 1: Satellite Imagery of collapsed Tatabu (Mokwa) bridge

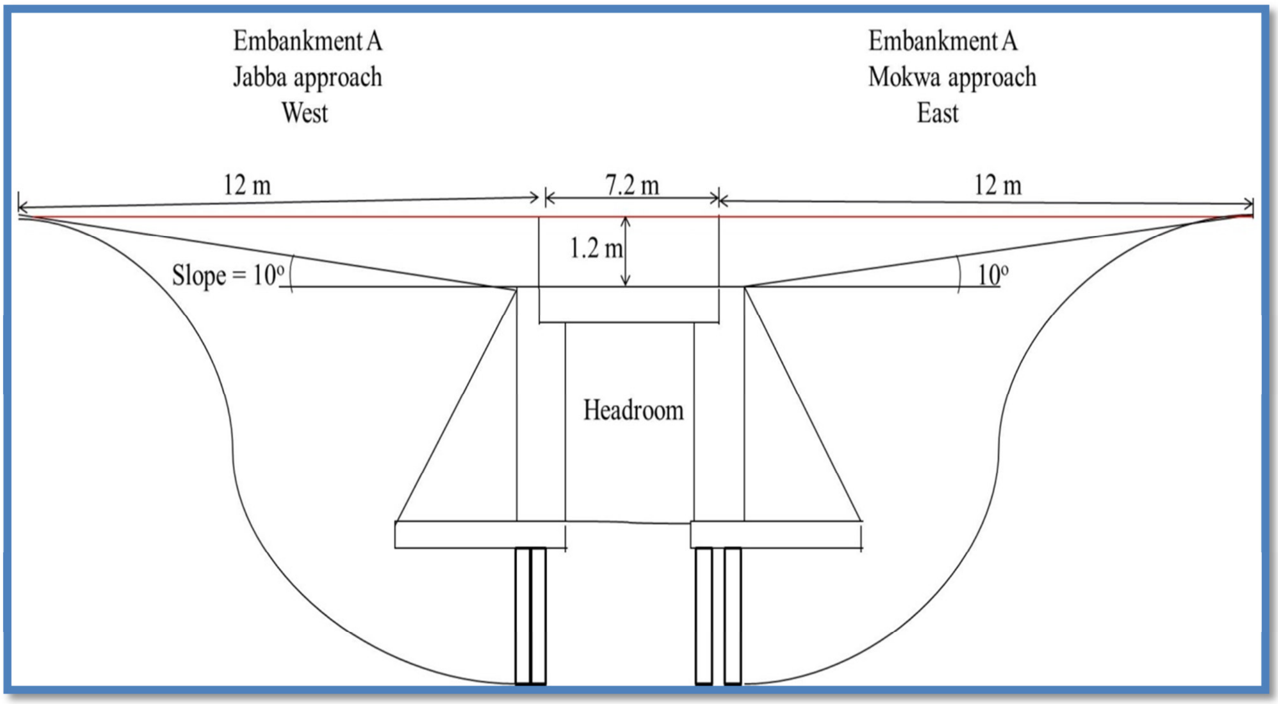

Figure 2: Schematic Diagram showing the sharp slope

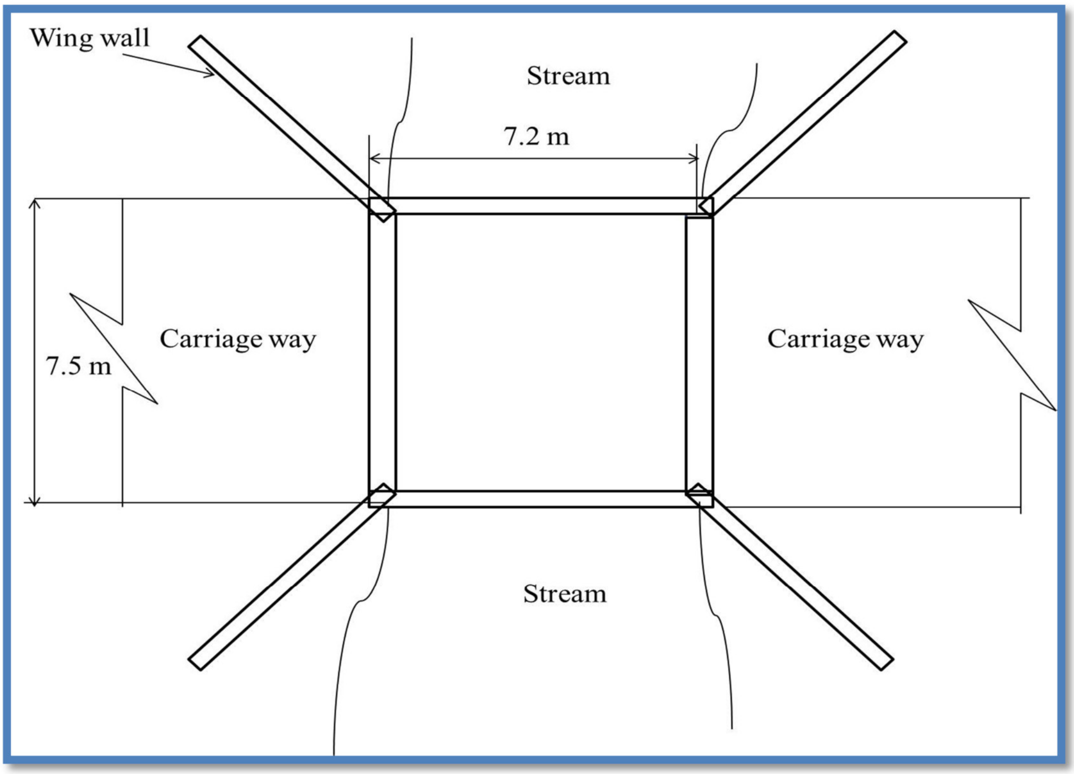

Figure 3: Schematic Diagram showing the plan

3.0 Methodology

Team of three Engineers visited the collapsed site two days after the bridge collapsed. The team went round and conducted a physical assessment of the site with the aid of the following tools; GPS receivers, Digital Cameras, copies of Niger State Maps and base maps, Rebound hammer, Measuring Tapes and ANSYS-Workbench V19.1. The team made some assumptions on the causes of the bridge collapse and also simulation based on the finite element technology was adopted to corroborate the initial assumption made by the team (See Figure 4).

3.1 Hydrological Data

The hydrological data of Mokwa - Bida zone were collected from Nigerian Hydrological Services Agency [16]. The rain data from January 2015 to July 2017 were collected and comprised of water balance and stream flow.

3.1.1Field Work and Sample Data Collection

The team went round and assessed the degree of collapse of the bridge and also trekked along the river upstream as far as 3 kilometer west, in the team expedition to understand the cause of the collapse. Global Positioning System was used for the acquisition of spatial locations of the collapsed bridge. With the help of rebound hammer, the team were able to test the strength of the collapsed bridge structural members, soil samples were collected and subjected to both strength and index test.

3.2 Structural Geometry

The bridge as- built drawing was not obtainable at the time of the research hence the team had to manually take measurement of the collapsed bridge at site as shown in Figure 2 and 3. The bridge structural drawing was used to create the geometry of the bridge site in details in ANSYS Geometry. The in-filled embankments at both Abuja and Jebba approaches were shown in Figure 4. The created geometry was later exported to ANSYS-Fluent and Structural separately. The structural bodies and fluid body were then suppressed in ANSYS-Fluent and Structural respectively, before the meshing. Figure 7 shows the modelled geometry of the site in ANSYS Geometry.

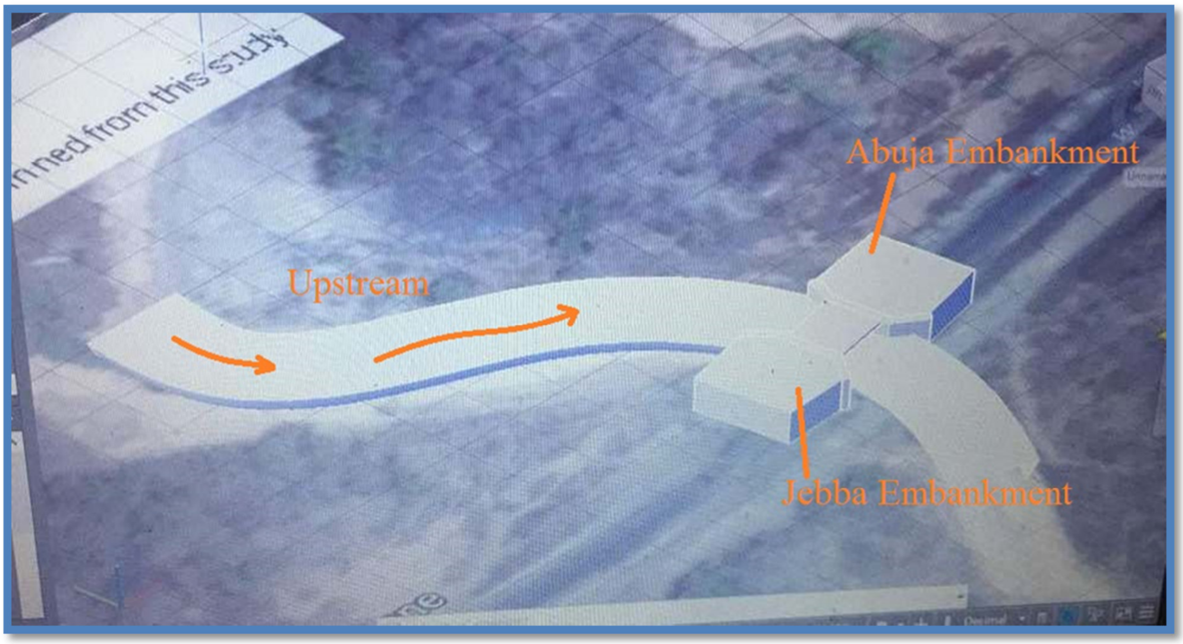

Figure 4: Modelled geometry of the bridge in ANSYS Geometry

4.0 RESULTS AND DISCUSSION

4.1 Hydrological Data

Hydrologic information, which includes stream flow, precipitation, runoff, base flow, and evaporation data from January 2015 to January 2017, is discussed below.

4.1.1 Precipitation

Mokwa and its environment experiences its annual precipitation around March - April. From the result presented in figure 3, it can be observed that the peak period for the 3 years data collected fell within June - September. In 2015 the peak period was in August with precipitation of 241.93 mm/month while 192.377 mm/month in September and 84.114 mm/month day in October respectively. A steady increase in rainfall from 2015 to 2017 was also noticed. The steady increase in precipitation from the past year may have caused the rise in river level and subsequently flood. The team measured the flood height to about 1.7 meters above Jebba approached as shown in Plate 3. Therefore, these results proved that the increase in water volume may have been part of the reasons for the flood and subsequently overtopping of the bridge and its embankments as shown in Figure 5.

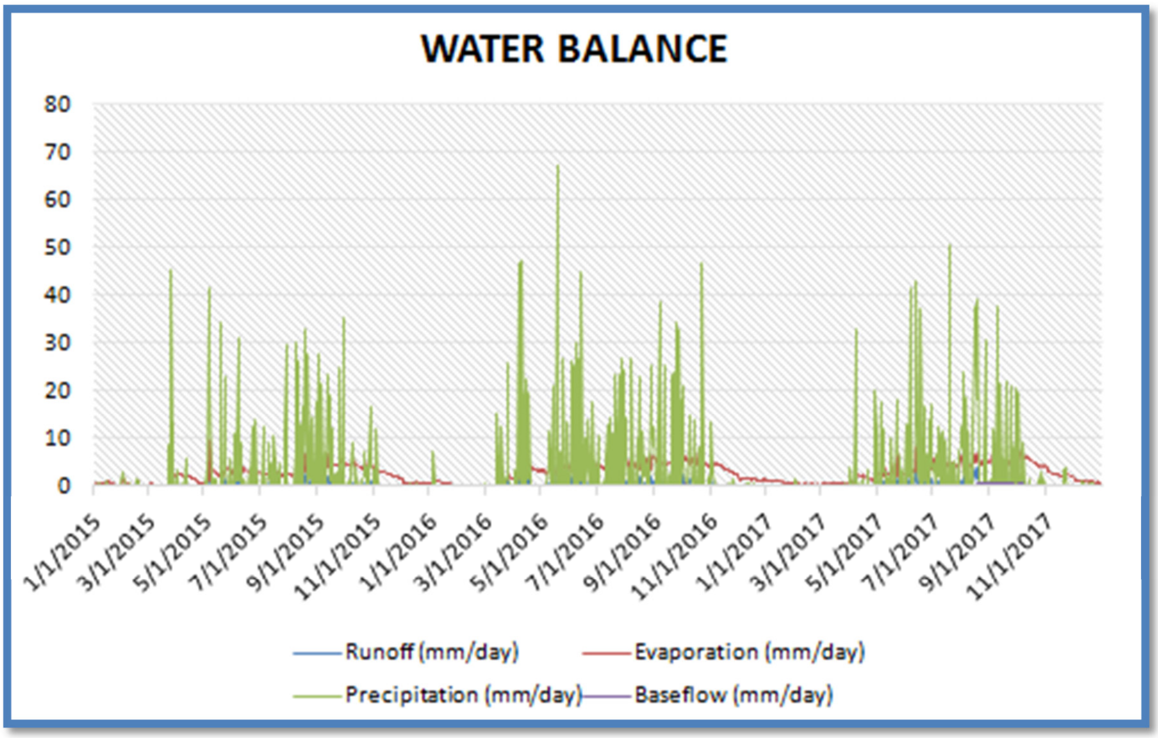

Figure 5: Trend in Rain data variation (Source: NIHSA, 2017)

4.1.2 Surface Runoff

Surface runoff data results are depicted in Figure 5. In August 2015, runoff of 17.632 mm/month was recorded as the peak in the year. While in 2016 and 2017 the peaks were both recorded in September at 25.027 mm/month and August at 23.456 mm/month respectively. Generally it can be observed that the runoff data shows a similarity in trend to precipitation. There was a considerable increase in runoff from 2015 up to 2016 and then a slight decrease was observed in 2017. This decrease however may be due to higher evaporation rate in 2017 as shown in Figure 5, which happened to be much higher in August 2017 with 164.456 mm/month compared to 154.742 mm/month in August 2016. Other factors may be due to higher transpiration or penetration into the surface to become groundwater. The resultant flood due to the increase in surface runoff and high precipitation transported debris into the single span bridge passage reducing its capacity and colliding with the structures as shown in Plate 1 and 2. This repeated action may weaken both the bridge structures and its embankments support and subsequently weighed down the structures as shown in Plate 3.

Plate 1: Image showing remnant debris

Plate 2: Overtopped Bridge

Plate 3: Image Showing Flood height

4.1.3 Base flow

Base flow results are presented in Figure 5. A steady increase is observed from 3.659mm/month in September 2015, 9.17 mm/month and 13.82mm/month in October 2016 and September 2017 respectively. Over saturated surfaces can cause flood, as water is unable to infiltrate and move by base flow through it, then this water will instead run along the grounds surface, known as overland flow. With more overland flow and a quicker overland flow rate, this can cause flooding strong enough to overtop the bridge and its embankments.

4.1.4 Stream Flow

Figure 6 below shows the Flow results from 2015 to 2017.The peak flow in 2015 was recorded in September with flow rate of 1655.58 m3/s, in 2016 the flow has double the previous year to about 3978.32m3/s in September , while in 2017 it maintain the same flow rate of 3830.58 in August. One of the important factors that can induce erosion of approach embankments, especially on the upstream faces, is the high flow that can occur near parallel to the embankment with intense concentrations at the abutments.

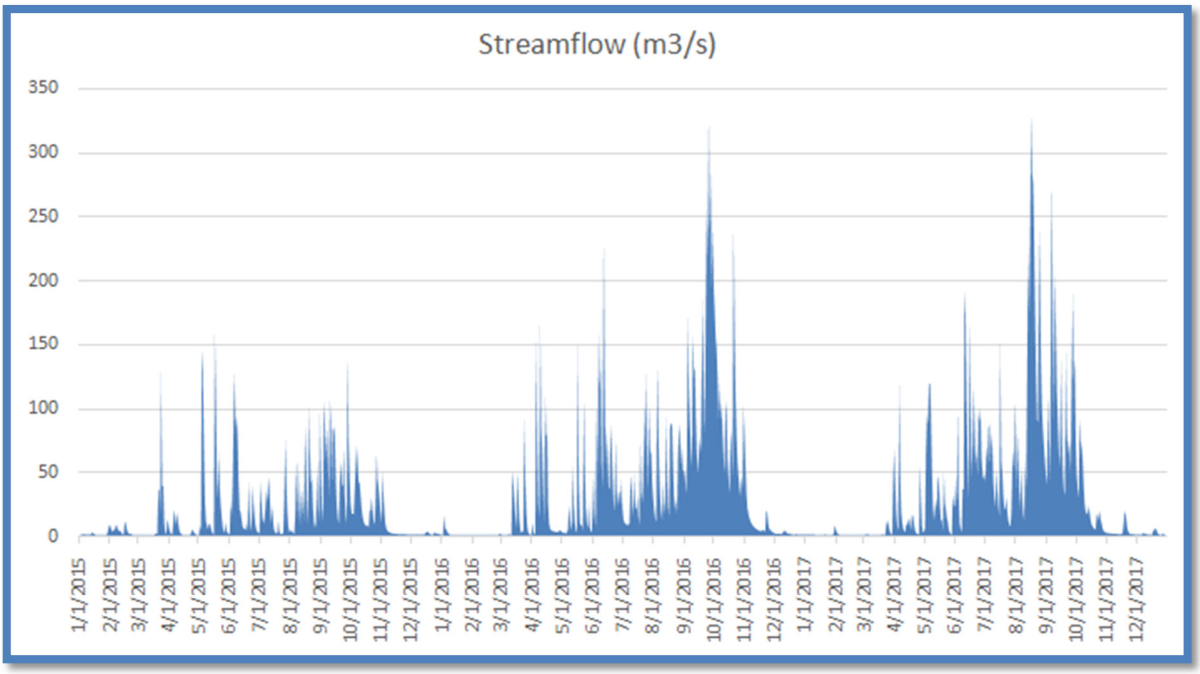

Figure 6: Stream flow (Source: NIHSA, 2017)

4.2 Field Assessment

4.2.1 Site Topography

Tatabu bridge is directly positioned in a lower part of a valley. Due to the steep nature of the valley, surface water quickly runs down into the bottom of the valley and subsequently into the river. High volume water with high velocity at the same time transporting debris exerted its force into the single span bridge at a rate that overwhelmed the capacity of the bridge. The bridge and its two embankments were overtopped and also cars and trucks parked at the approaches were washed down the river by the flood as shown in Plate 4.

Plate 4: Bridge positioned between a valley

4.2.2 Soil

The soil sample of the collapsed bridge embankments were collected and re-examine to check the reliability as presented in Table 1 below. It was clear that the compacted pavement material having GI=1 and A-2-6 been a good soil used for the sub-grade material. The collapse of the pavement may have resulted from the underlain soil material beneath the prepared pavement material that became weaker over time as resulted to leach and erosion by the flood, forming a gully collapse cave that later breaks the pavement and subsequently the bridge.

Table 1: Particle Size Distribution

SAMPLE	GRADATION (%)				ATTERBERG LIMITS				CLASSIFICATION
	GRAVEL	COARSE SAND	FINE SAND	SILT-CLAY	LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX	SHIRINKAGE LIMIT	AASHTO
TATABU BRIDGE	0	27.15	44.15	26.42	16.8	NP	16.8	3.78	A2-4.(***GI:*** 0)

Though, the soil in the areas of the flood affected bridge sites was noted to be highly erodible and the erosion typically occurred down to the underlying shale where it then spread out. The erodibility of these soils resulted in significant embankment and scour damage at the affected bridge sites.

4.2.3 Structure

The team also had a thorough investigation on the collapsed bridge concrete structural component which consists of bridge deck, single span beams which is fixed and free supported on abutment walls. Compressive tests were performed per ASTM D198 (2005) using rebound hammer. The dimensions were measured at the top, middle and bottom of each of the visible members of the bridge as presented in Plate 5.

Plate 5: Concrete strength test using rebound hammer device

The compressive strength results obtained are shown in Table 2. From the standard (Main Roads Western Australia level 3 Inspection Guide lines for concrete and steel bridges) the concrete strength are within the acceptable limits.

Table 2: Reinforced Concrete Bridge

Component	**Location**	**Rebound Hammer Values(Q)**			
		Mean Value (KN/m^2)	**Variance Value (KN/m^2)**	**Standard Deviation Value(KN/m^2)**	**Quality Of Concrete.**
Deck Slab	1	32.67	12.33	3.51	Good
Deck Slab	2	32.67	12.33	3.51	Good
Column	3	36.00	9.00	3.00	Good
Column	4	42.00	4.00	2.00	Very Good
Column	4	45.67	2.33	1.53	Very Good
Beam	6	44.67	9.33	3.06	Very Good
Beam	7	36.67	9.33	3.06	Good

4.3 Fluent Model for One-Way FSI Analysis

In this particular scenario, a finite element method was adopted using ANSYS-Fluent structural analysis software to calculate the meandering path of the flood waters by applying pressure to the fluid onto the structural elements and to determine the velocity profile of the flood and it entered the channel and exited after passing under the single span bridge, see Figure 7. The simulated pressure value obtained was then exported to the structural model as input forces. The ANSYS-Fluent software uses the finite volume methods to solve the equation at each node. Smaller mesh value was used in order to obtain accurate results. The minimum and maximum sizes of the mesh were selected as 15mm and 2000mm respectively. The standard k-ε mode was used for the turbulence modelling. The density of water also was increased to 1500 kg/$m3$ to consider the weight of particles and mud in the water during the flood. Velocity Inlet and Pressure Outlet was calculated from the stream flow results using Manning Equation below. The velocity of the flood used was 133 m/s from Equation 1.

Manning Equation: Qs= A x V

V = Qs /A ....Equation 1

V =3978/30= 133m/s

Where A - Area of the stream,

V- Velocity of the stream

Qs -Stream flow/Discharge

The contours adaptation of velocity and pressure during the flood are shown in Figure 8. As presented in Figure 9, the pressure of the flow within the Abuja approach bridge abutment is higher than the other parts. Possibly, this happened as a result of the meandering nature of the flood path. This high pressure flood collide and wash off the relatively soft in-fill soil providing support to the embankments resulting to collapse of the entire structure. Figure 9, Figure 10 and Figure 11 shows von Mises stresses in the bridge and displacement of embankment soil respectively.

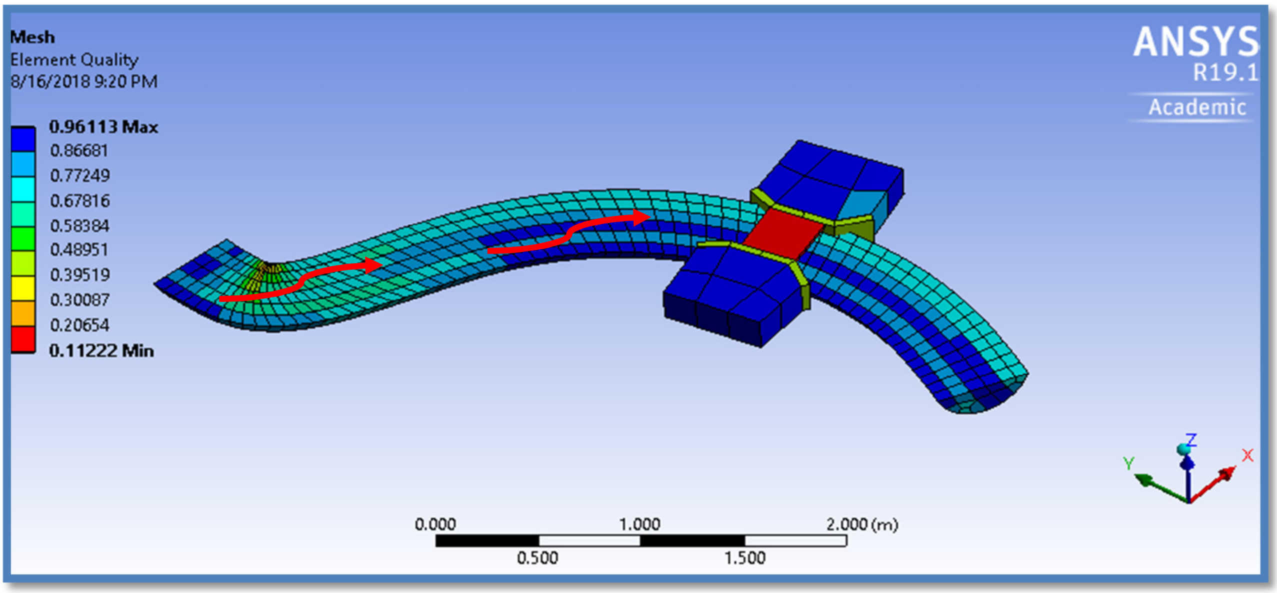

Fig. 7: Geometry and mesh diagram of Tatabu Bridge Site.

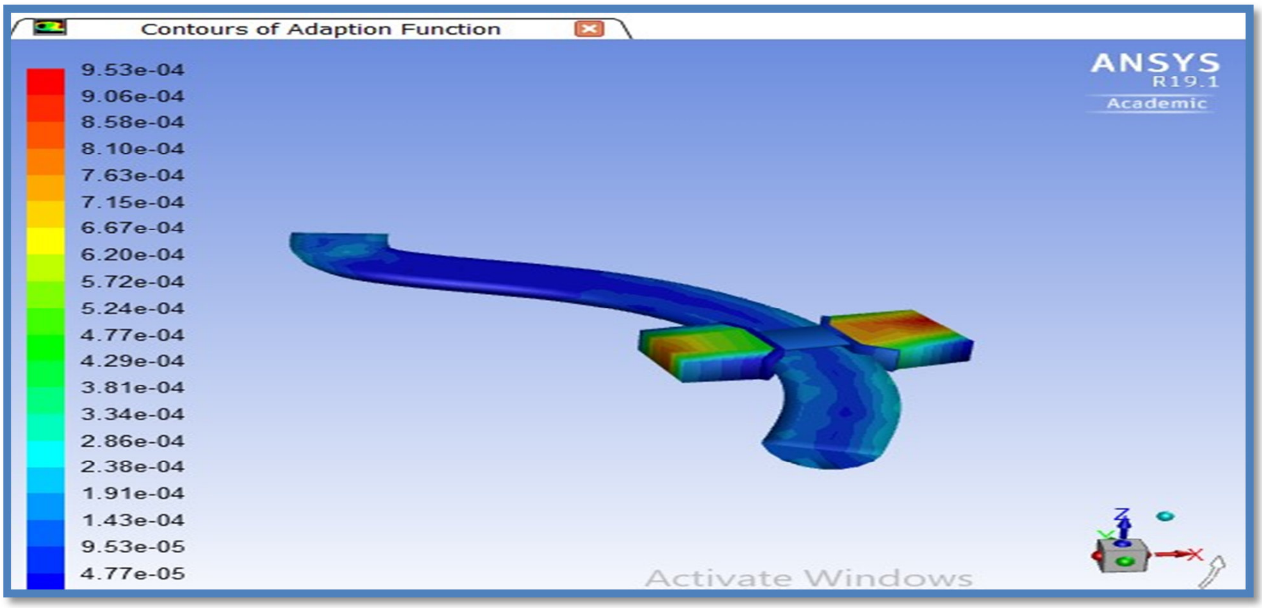

Figure 8: Image showing Fluid Flow.

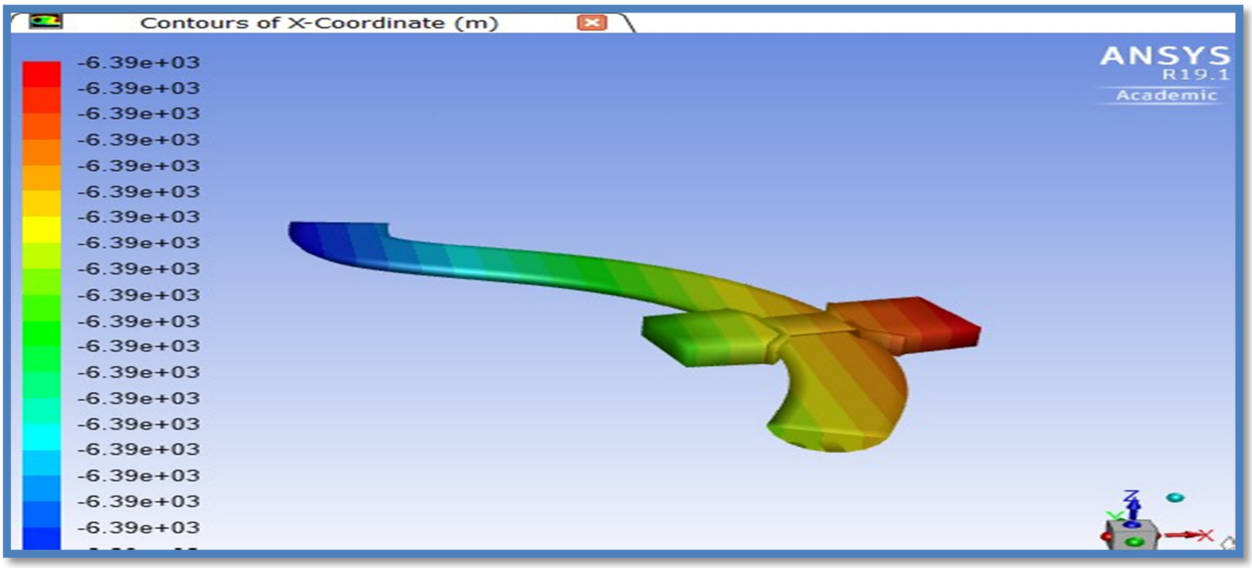

Figure 9: Pressure Contour of the Fluid F low.

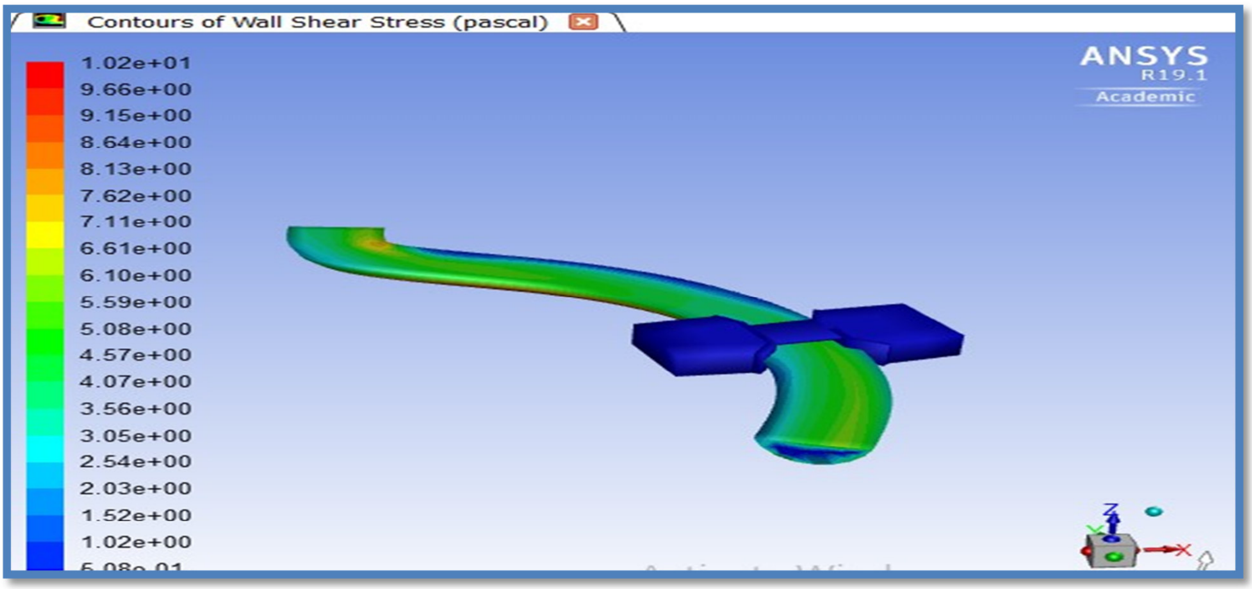

Figure 10: Von-Mises Stresses of the Bridge Due to the Flood.

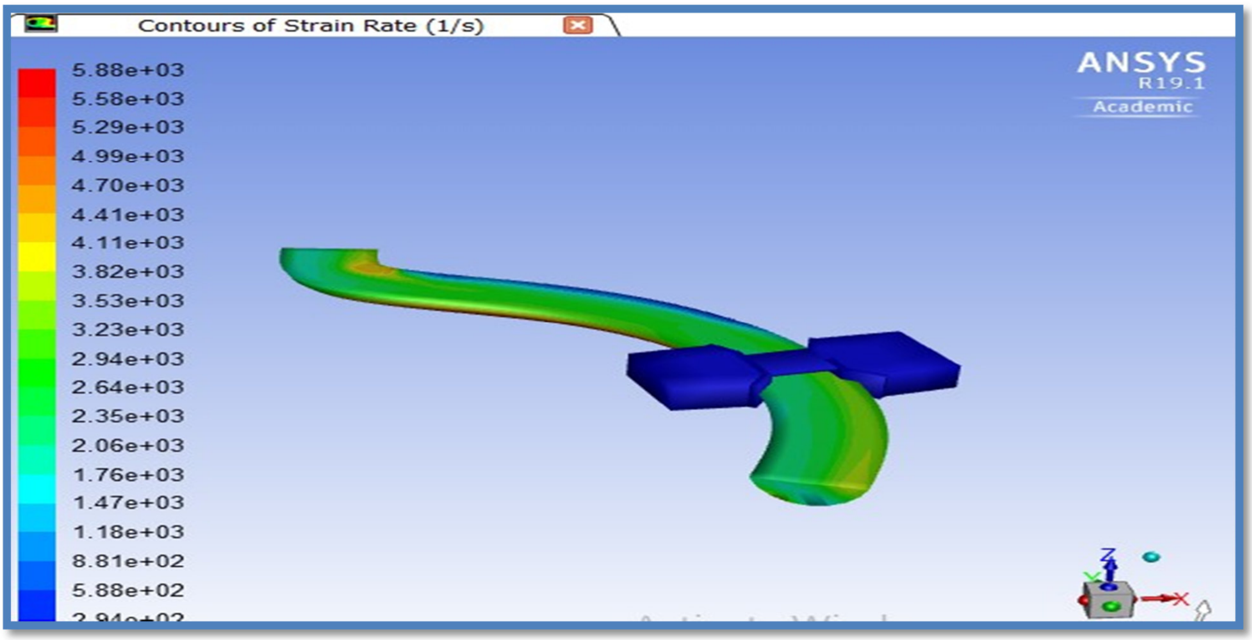

Figure 11: Von-Mises Stresses of the Bridge Due to the Flood.

5.0 Conclusions and Recommendation

The following conclusions and recommendation were drawn from the results

1- Due to small cell capacity to allow free volumetric passage of runoff, seepage weaken the aged highway compacted embankment and subsequently both toe, slope and top carriage embankment collapse.

Hence, the need for embankment protection either covers vegetation, stone pitch, slope stabilizer, or concrete interlocking is required for future consideration.

2- Aside the change in precipitate which also plays a part at increment in the volume runoff. It can also be seen in the field work observation that a change in the land use had also played a major role in the increment of the surface runoff as at the time of the initial design if at all really put into account at the initial design phase.

Hence, recommended that the present approach design should take note of land use, population increment together with the rainfall intensity over the flooded catchment area, in other to design a culvert or bridge of flood passage capacity to avoid a future failure after construction.

3- It is also observed that the debris settlement within the cell of the collapsed bridge contributed to reduction of the cross sectional area single cell.

Hence, this can be averted if the flood sediment analysis previewed had been consider during the initial design phase, which will caterer for both flood and debris when delay had been attributed to expect periodic dredging and maintenance.

4- The collapse of the pavement most have resulted from the underlying soil material beneath the prepared pavement material that became weaker over time as resulted to leach and eroded by the flood forming a gully collapse cave that later breaks the pavement.

It is therefore recommended that, a complete replacement of the underlain material forming the adjacent slope to the bridge retain wall with a better compacted engineering soil to avoid future pavement failure of the kind.

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